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Virtualisation and Resource Allocation in MEC-Enabled Metro Optical Networks

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Dirigida por:
Dr. Ramón J. Durán Barroso

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Lidia Ruiz Pérez

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Director: Dr. Ramón J. Durán Barroso

A mi familia

Abstract

The appearance of new network services and the ever-increasing network traffic and number of connected devices will push the evolution of current communication networks towards the Future Internet.

In the area of optical networks, wavelength routed optical networks (WRONs) are evolving to elastic optical networks (EONs) in which, thanks to the use of OFDM or Nyquist WDM, it is possible to create super-channels with custom-size bandwidth. The basic element in these networks is the lightpath, i.e., all-optical circuits between two network nodes. The establishment of lightpaths requires the selection of the route that they will follow and the portion of the spectrum to be used in order to carry the requested traffic from the source to the destination node. That problem is known as the routing and spectrum assignment (RSA) problem, and new algorithms must be proposed to address this design problem.

Some early studies on elastic optical networks studied gridless scenarios, in which a slice of spectrum of variable size is assigned to a request. However, the most common approach to the spectrum allocation is to divide the spectrum into slots of fixed width and allocate multiple, consecutive spectrum slots to each lightpath, depending on the requested bandwidth. Moreover, EONs also allow the proposal of more flexible routing and spectrum assignment techniques, like the split-spectrum approach in which the request is divided into multiple "sub-lightpaths".

In this thesis, four RSA algorithms are proposed combining two different levels of flexibility with the well-known $k-$shortest paths and first fit heuristics. After comparing the performance of those methods, a novel spectrum assignment technique, Best Gap, is proposed to overcome the inefficiencies emerged when combining the first fit heuristic with highly flexible networks. A simulation study is presented to demonstrate that, thanks to the use of Best Gap, EONs can exploit the network flexibility and reduce the blocking ratio.

On the other hand, operators must face profound architectural changes to increase the adaptability and flexibility of networks and ease their management. Thanks to the use of network function virtualisation (NFV), the necessary network functions that must be applied to offer a service can be deployed as virtual appliances hosted by commodity servers, which can be located in data centres, network nodes or even end-user premises. The appearance of new computation and networking paradigms, like multi-access edge computing (MEC), may facilitate the adaptation of communication networks to the new demands. Furthermore, the use of MEC technology will enable the possibility of installing those virtual network functions (VNFs) not only at data centres (DCs) and central offices (COs), traditional hosts of VFNs, but also at the edge nodes of the network. Since data processing is performed closer to the end-user, the latency associated to each service connection request can be reduced. MEC nodes will be usually connected between them and with the DCs and COs by optical networks.

In such a scenario, deploying a network service requires completing two phases: the

VNF-placement, i.e., deciding the number and location of VNFs, and the VNF-chaining, i.e., connecting the VNFs that the traffic associated to a service must transverse in order to establish the connection. In the chaining process, not only the existence of VNFs with available processing capacity, but the availability of network resources must be taken into account to avoid the rejection of the connection request. Taking into consideration that the backhaul of this scenario will be usually based on WRONs or EONs, it is necessary to design the virtual topology (i.e., the set of lightpaths established in the networks) in order to transport the traffic from one node to another. The process of designing the virtual topology includes deciding the number of connections or lightpaths, allocating them a route and spectral resources, and finally grooming the traffic into the created lightpaths.

Lastly, a failure in the equipment of a node in an NFV environment can cause the disruption of the SCs traversing the node. This can cause the loss of huge amounts of data and affect thousands of end-users. In consequence, it is key to provide the network with fault-management techniques able to guarantee the resilience of the established connections when a node fails.

For the mentioned reasons, it is necessary to design orchestration algorithms which solve the VNF-placement, chaining and network resource allocation problems in 5G networks with optical backhaul. Moreover, some versions of those algorithms must also implements protection techniques to guarantee the resilience system in case of failure.

This thesis makes contribution in that line. Firstly, a genetic algorithm is proposed to solve the VNF-placement and VNF-chaining problems in a 5G network with optical backhaul based on star topology: GASM (genetic algorithm for effective service mapping). Then, we propose a modification of that algorithm in order to be applied to dynamic scenarios in which the reconfiguration of the planning is allowed. Furthermore, we enhanced the modified algorithm to include a learning step, with the objective of improving the performance of the algorithm.

In this thesis, we also propose an algorithm to solve not only the VNF-placement and VNF-chaining problems but also the design of the virtual topology, considering that a WRON is deployed as the backhaul network connecting MEC nodes and CO. Moreover, a version including individual VNF protection against node failure has been also proposed and the effect of using shared/dedicated and end-to-end SC/individual VNF protection schemes are also analysed.

Finally, a new algorithm that solves the VNF-placement and chaining problems and the virtual topology design implementing a new chaining technique is also proposed. Its corresponding versions implementing individual VNF protection are also presented. Furthermore, since the method works with any type of WDM mesh topologies, a techno-economic study is presented to compare the effect of using different network topologies in both the network performance and cost.

Resumen

La aparición de nuevos servicios de red, así como el creciente tráfico y número de dispositivos conectados a las redes de comunicación, impulsarán la evolución de dichas redes hacia la Internet del Futuro.

En el área de las comunicaciones ópticas, las redes ópticas con encaminamiento por longitud de onda (wavelength routed optical networks, WRONs) están evolucionando hacia las redes ópticas elásticas (elastic optical networks, EONs) en las que, gracias al uso de técnicas como OFDM o Nyquist WDM, es posible crear super canales con ancho de banda adaptable. El elemento básico en ambos tipos de redes es el camino de luz o lightpath, que es un circuito totalmente óptico que se establece entre dos nodos de la red. El establecimiento de los caminos de luz requiere la selección de la ruta que seguirá dicho camino, así como de la porción de espectro que usará para transportar el tráfico solicitado desde el origen hasta el destino. Ese problema, en EONs, se conoce como el problema de asignación de ruta y espectro (routing and spectrum assignment problem, RSA), y será necesario proponer nuevos algoritmos de asignación de recursos que solucionen este problema de diseño.

Los primeros estudios sobre redes ópticas elásticas consideraron escenarios en los que se asignaba una porción variable del espectro a una solicitud de transmisión de tráfico. Sin embargo, la tendencia más estudiada es considerar al espectro dividido en tramos de un ancho fijo y asignar, a cada solicitud, un número determinado de tramos consecutivos, que dependerá del ancho de banda requerido. Además, las redes ópticas elásticas permiten utilizar técnicas más flexibles de asignación de ruta o espectro, como el espectro dividido (split-spectrum), que permite repartir el tráfico solicitado entre múltiples caminos de luz.

En esta tesis se proponen cuatro algoritmos RSA combinando dos niveles distintos de flexibilidad con las técnicas de asignación de ruta y espectro $k-$shortest paths y first fit. Tras comparar el comportamiento de dichos métodos, se propone unan novedosa técnica de asignación de espectro llamada Best Gap, con el objetivo de solventar las ineficiencias que aparecen cuando se aplica la técnica first fit a redes con gran flexibilidad en la asignación de espectro. Por último, se realiza una simulación mediante el desarrollo de un simulador de redes elásticas en C++, utilizando el simulador de eventos discretos OMNeT++, para demostrar que las redes ópticas elásticas son capaces de explotar mejor la propia elasticidad, mejorando la tasa de bloqueo, gracias al uso de la técnica Best Gap.

Por otra parte, las operadoras deben realizar cambios profundos en la arquitectura de las redes de comunicación para aumentar su adaptabilidad y flexibilidad, así como para facilitar su gestión. Gracias al uso de tecnologías como la virtualización de funciones de red (network function virtualisation, NFV), las funciones de red, necesarias para poder ofrecer cualquier servicio, podrán desplegarse como aplicaciones software instaladas en servidores que podrán estar localicados en centros de datos, en los nodos de la red o incluso en los equipos del

usuario. Además, la aparición de nuevos paradigmas de computación y de red como multi-access edge computing (MEC) hará posible instalar las funciones virtuales de red (virtual network functions, VNFs) no solo en centros de datos o en la oficina central, que han sido lugares tradicionales donde alojar estas funciones, sino en los propios nodos de la red. Puesto que, de esta manera, el procesamiento de datos se hace más cerca del usuario final, la latencia asociada a cada servicio se verá reducida. Será común que los nodos equipados con recursos MEC estén conectados entre sí y con los centros de datos y las oficinas centrales mediante redes ópticas.

En este escenario, desplegar un nuevo servicio requiere completar dos fases: el emplazamiento de VNFs (VNF-placement) en el que se decide el número y localización de las VNFs, y la concatenación de VNFs (VNF-chaining), en el que se decide qué instancias atravesará el tráfico asociado al servicio desplegado para poder establecer la conexión mediante cadenas de servicio (service chains, SCs). En el proceso de concatenación deberá tenerse en cuenta no solo los recursos computacionales disponibles en la red, sino también los propios recursos de red disponibles para evitar el rechazo de la solicitud de conexión. Si consideramos que la red de retorno o backhaul estará basada en redes WRON o EON, es necesario diseñar también la topología virtual de la red, es decir, el conjunto de caminos de luz que habrán de establecerse en la red para transportar el tráfico de un nodo a otro. El proceso de diseño incluye decidir el número de caminos de luz, asignarles una ruta y recursos espectrales y, finalmente, encaminar el tráfico a través de ellos.

Por último, un fallo en el equipamiento de un nodo en una red NFV puede interferir en las cadenas que atraviesan dicho nodo. Un fallo podría causar la pérdida de grandes cantidades de datos y afectar a miles de usuarios. Por tanto, es clave que la red disponga de técnicas para la gestión de fallos que garanticen la resiliencia de las conexiones establecidas cuando un nodo falla.

Por las mencionadas razones, es necesario diseñar algoritmos de orquestación que resuelvan el emplazamiento y la concatenación de VNFs, así como la asignación de recursos de red, en redes 5G con redes de retorno ópticas. Además, algunos de esos algoritmos deberán implementar técnicas de protección que garanticen la resiliencia del sistema en caso de fallo.

Esta tesis hace contribuciones en esta línea. En primer lugar, se propone un algoritmo genético que resuelve el emplazamiento y la concatenación de VNFs en una red 5G con red de retorno óptica basada en una topología en estrella: GASM (genetic algorithm for effective service mapping, algoritmo genético para el mapeo efectivo de servicios). Posteriormente, se propone una modificación del algoritmo para su aplicación en redes dinámicas en las que se permite llevar a cabo reconfiguraciones periódicas de la planificación de la red. Además, esta versión se mejora con la inclusión de una etapa de aprendizaje para mejorar su comportamiento.

En esta tesis también se propone un algoritmo que resuelve tanto el emplazamiento y la concatenación de VNFs como el diseño de la topología virtual, considerando que la red de retorno de la red 5G, que conecta los nodos MEC y la oficina central, está basada en redes WRON. Se desarrollan además cuatro versiones que incluyen protección individual de VNFs frente a fallos en los nodos de la red, analizando el efecto de considerar recursos de protección dedicados/compartidos, así como el comportamiento de los esquemas de protección de cadenas extremo a extremo.

Finalmente, se propone un nuevo algoritmo que resuelve el emplazamiento, la concatenación y el diseño de redes virtuales utilizando una nueva técnica de encadenado.

También se desarrollan las versiones correspondientes que incluirán una técnica de protección individual de VNFs. Además, dado que este método es capaz de trabajar sobre redes WRON con cualquier tipo de topología en malla, se presenta un estudio que compara el efecto de desplegar distintas tipologías tanto en el comportamiento de la red como en el coste. Todos los algoritmos se han desarrollado y probado mediante el desarrollo de un simulador de redes WRON/EON utilizando OMNeT++.

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Chapter 1

Introduction

Future Internet must overcome the challenges that will emerge with the appearance of new network services and the ever-increasing number of connected devices. The appearance of new applications as Cloud Computing or the Internet of Things (IoT), and the deployment of 5G, which promises to reduce the latency to figures never seen before (less than 1 ms) require flexible, adaptable and easily manageable networks. Traditional network deployments, which rely on proprietary hardware from different vendors, are not able to offer these capabilities since adapting the networks to offer new applications requires high capital and operational expenditures (CAPEX and OPEX) and time. In consequence, network operators must face a profound architectural change in order to adapt their networks and IT resources to the new services and requirements.

The access segment will evolve to 5G, a broadband access technology that promises to shake up the communications panorama by bringing new network capabilities like high bandwidth, low latency, high scalability, heterogeneous technologies convergence, coordinated automation, or on-demand and service-oriented resource allocation, among other features. Furthermore, 5G will have to cope with the increasing number of connected devices, up to 100-fold, while reducing the CAPEX and OPEX [11]. The backhaul of these networks is expected to be built upon optical technologies, given their high capacity and flexibility [12].

Optical networks, particularly in the core/metro segments, will also experiment a profound change in order to better exploit the capacity of optical fibres and cope with the future increase of traffic and connected devices. In particular, Wavelength Routed Optical Networks (WRON) are evolving to Flexible or Elastic Optical Networks (EON), which make better use of spectrum by adjusting the allocated bandwidth to a connection to the actual demanded capacity, instead of allocating fixed bandwidth to each connection, like WRONs do.

Moreover, future networks will change their control plane in order to increase the flexibility and adaptability of networks and ease their management. Thanks to that increment in flexibility, future networks will allow faster deployment of new services. Software Defined Networking (SDN) is considered as the technology that will allow that evolution and it is based on the separation of the Control Plane and the Data Plane in networks. In this manner, the Data Plane will be composed by simple packet forwarding devices, while the Control Plane, responsible for orchestrating the networks, can be deployed using software appliances.

Finally, two technologies will be also responsible of the “softwarisation” of networks: Multi-access Edge Computing (MEC) and Network Function Virtualisation (NFV). MEC provides cloud computing capabilities to the edge nodes of networks, pushing the data processing closer to the end-user [13]. NFV proposes the deployment of common network functions like packet inspectors or firewalls in the form of software appliances, instead of using the traditional, vendor-based hardware devices. In this manner, the adaptability and the flexibility of the network increases, since deploying new network services only requires the creation of software instances instead of the purchase and installation of new network equipment.

This thesis has been developed in the context of two national research projects ONOFRE (TEC2014-53071-C3-2-P) and ONOFRE-2 (TEC2017-84423-C3-1-P), the fellowship program of the Spanish Ministry of Economy, Industry and Competitiveness (BES 2015-074514), the research network Go2Edge (RED2018-102585-T), and the European Regional Development Fund (ERDF) through the proyect DISRUPTIVE of the cooperation programme Interreg V-A Spain-Portugal (POCTEP) 2014-2020, and makes contributions in two research fields: control algorithms for EONs and methods for the orchestration of 5G network with optical backhaul.

All the contributions of this Thesis were evaluated by means of simulations and compared with techniques with similar objectives from the literature.

1.1 Thesis objectives

This thesis makes contributions in the development of the orchestration of 5G optical access and metro networks, and in the evolution from WRONs to EONs, by proposing a set of algorithms to solve the RSA problem. The objectives of this thesis can be divided as follows:

1. To review of the state-of-art of circuit-based optical networks (from WRONs to EONs), and NFV, MEC, and SDN paradigms.

2. Proposals on Elastic Optical Networks:

   2.1 To analyse of the integration of four levels of flexibility (regarding to two different spectrum division techniques and the allowance of split-spectrum) in two well-known RSA heuristics as $k-$shortest paths and first fit.

   2.2 To propose of a new spectrum allocation technique to exploit the flexibility of EONs and improve the network performance in terms of blocking ratio.

3. VNF-placement and VNF-chaining problems:

   3.1. To propose of an algorithm to solve the VNF-placement and chaining problems in a static 5G network: GASM.

   3.2. To extend the algorithm to solve the VNF-placement and chaining problems in a dynamic 5G network by performing a periodical reconfiguration of the network.

4. VNF-placement, chaining and virtual topology design problems in 5G networks with optical backhaul:

   4.1. To propose an algorithm to solve the VNF-placement, chaining and virtual topology design problems in 5G networks with WDM-ring backhaul: GASM-VTD.

4.2. To extend the algorithm including individual VNF protection against node failure.

4.3. To conduct a performance comparison of individual VNF protection and end-to-end SC protection schemes.

4.4. To conduct a techno-economic study to compare the effect on the network cost and performance in terms of service blocking ratio of deploying different topologies in the backhaul of 5G networks considering only the NFV design problems.

1.2 Thesis structure

The thesis is structured as follows:

Chapter 2, introduces the circuit-based optical technologies WRON and EON. The most important design problems, like the virtual topology design, the static and dynamic RWA problem in WRONs, the static and dynamic RSA problem in EONs and other issues as survivability are reviewed, including the methods proposed in the literature to address them.

Chapter 3 presents two sets of algorithms that solve the RSA problem in Elastic Optical Networks. The first set combines two different types of flexibility with the classical RSA algorithms $k-$shortest path and first fit. Furthermore, a new spectrum assignment technique is proposed to more efficiently exploit the flexibility of EONs compared to other classical RSA algorithms. Moreover, a simulation study is presented to evaluate the performance of the proposals.

Chapter 4 introduces the network technology NFV and briefly describes SDN and MEC, as related technologies to NFV. The Chapter reviews the most important NFV design problems, as the VNF-placement and chaining, and issues like the survivability in NFV environments. Moreover, the proposed methods in the literature to address these problems are reviewed.

Chapter 5 presents an algorithm to solve the VNF-placement and chaining problems in 5G networks to minimise the service blocking ratio and resource consumption. In this Chapter, the same algorithm is adapted to be able to perform a periodical reconfiguration of the network planning, i.e., the location and number of VNF instances, in a dynamic scenario. Moreover, a learning technique is implemented to improve the performance of the algorithm when reconfiguration is allowed.

Chapter 6 proposes an algorithm to solve the VNF-placement, chaining and virtual topology design in 5G networks with optical backhaul built using WDM-mesh topologies. The algorithm includes techniques to solve the virtual topology design problem, and exploits the MEC capabilities of the nodes to reduce the service blocking ratio. Our proposal is compared to other proposals in the literature. Furthermore, versions of this algorithm are proposed to implement protection techniques that ensure the resilience of the established connections against single-node failure. The versions of the algorithm implementing the proposed protection techniques are also compared to other protection approaches proposed in the literature. Moreover, a new algorithm is proposed to implement a novel chaining technique whose objective is to make better use of the collaboration between the MEC-nodes of the network. Versions of the algorithm are proposed to implement individual VNF protection techniques to ensure the resilience of the established SCs in case of node failure. Finally, a techno-economic study is conducted to analyse the cost of deploying 5G networks with different WDM topologies and compare the performance of these topologies in terms of service blocking ratio.

Chapter 7 presents the conclusions and future research lines.

Lastly, appendix A introduces the simulators developed in this thesis.

Chapter 2

Evolution of Optical Networks

Over the past few years, the capacity of the commercial networks has experienced an enormous increase, accompanied by the apparition of new and varied network services. As a consequence, the amount of carried traffic has also suffered a huge expansion, and it is expected that the future bandwidth demands, due to new network services and the increment of connected devices will continue growing, forcing an evolution of the communication networks.

Fibre-optic technology is a perfect candidate to meet the increasing bandwidth needs due to its capabilities. Fibre offers high capacity, low signal distortion, low signal attenuation, low power requirements, small space requirement, and cost [12]. The challenge is to implement the network technologies which better exploit the capacities of optic fibre to give response to the new traffic demands.

In this Chapter, we review the evolution of optical network technologies appeared to give response to the new service demands on bandwidth, flexibility, and management of networks. Firstly, we review the Wavelength-Routed Optical Networks (WRON), which are transport networks based on Wavelength Division Multiplexing (WDM), a transmission technology capable of efficiently exploiting the capacity of optical fibres, thanks to the transmission of multiple channels over the same fibre, using different wavelengths. We will not only describe the different types of WRON but also the different design approaches proposed to implement networks of each kind. Furthermore, we review the Elastic Optical Networks (EON), an evolution of WRON deployed to improve the optical network capacity by allocating portions of spectrum to bandwidth requests, and we describe different techniques proposed to design EONs.

2.1 Wavelength-Routed Optical Networks

Wavelength Division Multiplexing (WDM) is a transmission technology that allows to efficiently use the capacity that optical fibres offer, saving the gap between the fibre and the electronic component processing capacities, by allowing the fibre to carry multiple aggregated channels at electronic speeds [14]. In WRONs, the traffic is transmitted through all-optical channels or circuits called lightpaths. This kind of channels is able to connect two nodes of the network, not necessarily adjacent between them, so that the transported traffic does not need to undergo any electrical processing between the source and destination nodes of the lightpath [12]. A lightpath is described by the set of fibres it must traverse, i.e., the route, and a wavelength. More than one wavelength can be transmitted through a fibre simultaneously. Therefore, more than one WDM channel transporting end-user traffic coexists in the same fibre, making a better use of the available bandwidth while requiring the end-user equipment to operate only at electronic rate, although it must be able transmit and/or receive at different wavelengths. The only condition, if the network is not equipped with wavelength converters, is to allocate different wavelengths to two different lightpaths if they share a fibre along their route. Similarly, if two lightpaths are routed through completely different physical paths, they can share the same wavelength. In the absence of wavelength converters in the network, the lightpaths must use the same wavelength throughout the route. This constraint is known as the *wavelength continuity constraint* and can be relaxed if all or part of the nodes of the network are equipped with these converters [12, 15].

The number of wavelengths that a fibre can carry depends on the fibre capacity and the state of the technology of the optical technology of the employed equipment [16]. WRON can support multiple bit rates and modulation formats. Nowadays, the equipment supports up to 120 wavelengths [17], whereas the bit rate has incremented from the 10 Gb/s systems deployed in the early 2000s, to the 40 Gb/s systems in 2004 and the more recent 100 Gb/s systems [18, 19]. In order to standardise WDM technology, the International Telecommunications Union (ITU) defines sets of WDM channels known as ITU grid. The 100-GHz grid is a set of frequencies centred at 193.1 THz ($1,552.52$ nm) with 100 GHz channel-spacing. In this case, the frequency of the channels would be $193.1 + n\,0.1$, where n is an integer number [20]. The second is a 50 GHz set, centred at the same frequency but with smaller channel spacing, 50 GHz, that allows for the utilization of more WDM channels. The Dense Wavelength Division Multiplexing DWDM also includes the 25 and 12.5 GHz channel spacing.

To establish a connection or lightpath, it is necessary to assign an available wavelength and route through which transmit the traffic. This problem is known as the Routing and Wavelength Assignment (RWA) problem. There are different approaches to solve this problem according to three different network scenarios: static, semi-static and dynamic lightpath establishment. In a static scenario, the traffic that the network must carry and, therefore, the number of connections that must be established is known in advance and, once the connections are established, they are modified only if a significant change in the traffic appears. The set of established lightpaths compose the so-called virtual topology [12]. The virtual topology conforms an optical transport layer which abstracts the physical layer from the protocols in the upper layer, i.e., IP, SDH/SONET, etc. In a semi-static scenario, the established lightpaths can smoothly change to adapt the virtual topology to the current traffic variations. Finally, in a dynamic scenario, the requests are not known in advance. Consequently, the lightpaths are established at the moment in which a connection request arrives at the network.

2.1.1 Static and Semi-Static WRON

In static and semi-static WRON, the number of optical connections or lightpaths requested between nodes in the physical network is known in advance, and these lightpaths are set up permanently or semi-permanently.

As we have mentioned in the introduction of this section, lightpaths are all-optical channels, which means that the only electrical processing that the traffic undergoes is performed at the source and destination nodes. In the absence of wavelength converters, the traffic is transmitted using the same wavelength throughout the entire route. This condition is known

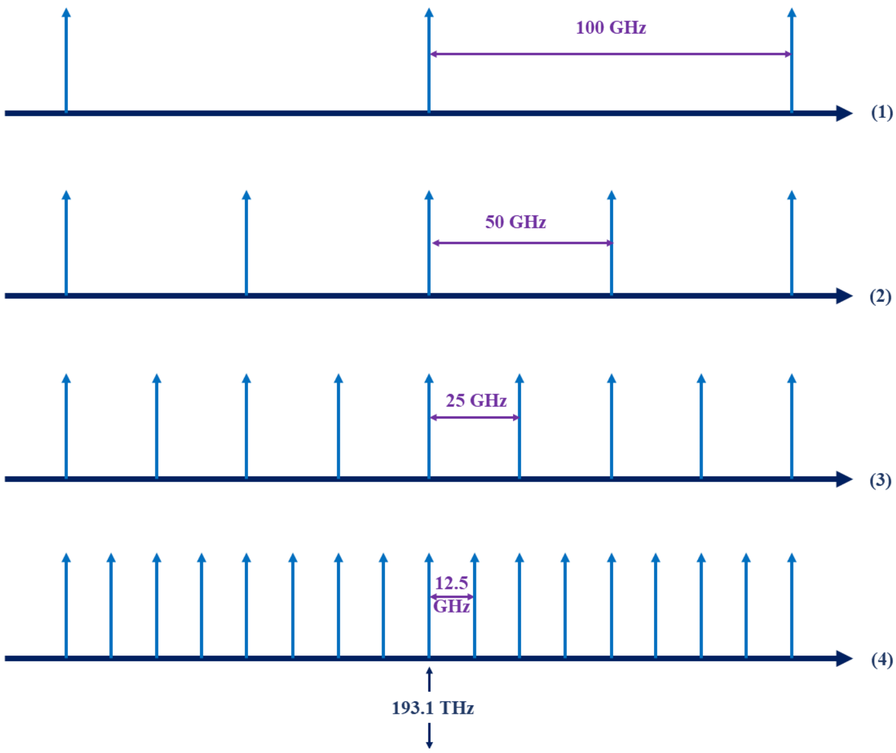


Figure 2.1: ITU-T Grid for (1) 100 GHz, (2) 50 Ghz, (3) 25 GHz and (4) 12.5 GHz channel spacing.

as the *wavelength continuity constraint*, and can be relaxed adding wavelength converters. However, equipping the network with these devices not only increases its cost but adds extra design problems, as the converter tuning and placement. Consequently, it is common to design wavelength-routed optical networks assuming that no converters are present in the network, although a set of works investigate on the topic, either including converters only at some nodes of the network [21] or at all nodes of the network [22]. Furthermore, these converters can translate to a limited range of the working wavelengths of the network [23], [24], or to the full range of wavelengths as in [21]. In this Thesis, we assume that no wavelength converters are present at the network.

The design of a virtual topology, given a physical topology and the traffic requirements in the form of a traffic matrix, is shown to be an NP-hard problem [16]. Therefore, it is usually divided into three different problems [14]:

Selection of the lightpaths to be established (connectivity problem). The first option is selecting a full connectivity approach in which all nodes of the network are connected to the rest of the nodes with, at least, one lightpath. However, given the nature of the traffic and the cost of the equipment, this might not be the most efficient manner to design the topology. However, since the traffic is expected to not be uniform between each pair of nodes in the network, an efficient design requires establishing one or more lightpaths between some pairs, while not establishing any lightpath between other pairs of nodes. Furthermore, connecting each node with the rest of the nodes of the network will require $N-1$ transceivers (i.e., transmitters and receivers) and will also increase the complexity of the optical equipment, such as the Optical Crossconnects (OXC) or Optical Add and Drop Multiplexer (OADM), hence increasing the cost of the network. Consequently, it is usual to design the virtual topology aiming at establishing just a set of the total possible lightpaths. Since it is likely than one or more pairs of nodes would not be directly connected through a lightpath, transporting traffic between these pairs of nodes would require routing the traffic through two or more lightpaths, leading to a Multi-hop scenario, in which the traffic will undergo an optical/electrical/optical (O/E/O) conversion at intermediate nodes.

Selection of a Route and a Wavelength to allocate to a lightpath (RWA problem). This is known as the Routing and Wavelength Assignment (RWA) problem and consists in finding a set of fibres and a wavelength which are not assigned to other lightpath traversing any of the fibres of the set [12]. This problem can be solved jointly or looking separately for a route and then a free wavelength.

Traffic Routing. That is, deciding how to route the traffic by utilising the set of established lightpaths in the virtual topology in the case of a multi-hop scenario.

There are several manners to solve these subproblems. The first one is solving the problems jointly, as in [14], [25], [26], [27] as they are closely related. However, since there might be an enormous number of potential solutions, especially for medium to large networks, solving the three subproblems jointly may be a complex process which requires large computational time. On the other hand, solving the problems separately may reduce the number of solutions, hence simplifying and speeding up the process. However, this approach may produce infeasible solutions. For example, if the connectivity problem is solved first but there are no physical or bandwidth resources to establish the requested lightpaths, the solution of the connectivity problem, i.e., the virtual topology, cannot be embedded in the physical topology and, consequently, it must be designed again. Therefore, the most common approach is to solve some of the subproblems jointly and some others separately. We can find works in literature that solve the virtual topology design and the routing problems jointly, and then the RWA separately as in [14], [28].

In the following subsections, we will explain the different subproblems in which the virtual topology design is divided, and the most common techniques employed to solve each of these subproblems.

2.1.1.1 The Topology Subproblem

The objective of this subproblem is to determine which connections or lightpaths should be created according to their source and destination nodes. We can find two kinds of strategies for solving the topology design, which are either designing regular topologies or arbitrary topologies. In regular topologies the connectivity is systematic and well-defined [29], present an intrinsic load balancing capacity [16] and, generally speaking, routing traffic through this kind of topologies is simpler compared to the other option. However, this kind of topologies cannot handle not-uniform traffic properly and cannot be embedded in all physical topologies. The second option is to design arbitrary topologies adapted to the particular problem, with the objective of optimally (or almost optimally) satisfying some design criteria. We will focus on this approach.

Several studies can be found in literature aiming at optimally solving the arbitrary topology design problem. This approach usually leads to the proposition of an optimisation problem formulation, which includes the objective function or criterion to be optimised, variables and restrictions. Depending on the type of variables used in the formulation, we can find this problem solved using Non Linear Programming (NLP) formulations, in which the objective function and the restrictions are not linear, Linear Programming (LP) formulations, in which the objective function and the restrictions are linear and the variables are real numbers, Integer Linear Programming formulations (ILP), in which the variables are integers or Mixed Integer Linear Programming (MILP) formulations, where just part of the variables are constraint to be integers.

We can find an example of topology design using NLP formulations in [14], where Mukherjee *et al.* either minimise the average packet delay or maximise the scale factor of the traffic matrix to maximise the traffic capacity upgrade.

Studies in [30], [31], [32] propose ILP formulations to solve the topology design problem. Chen et al. [30] proposed a formulation to design stable virtual topologies for time-varying traffic demands that minimises the number of transceivers in use and, therefore, capital expenditures (CAPEX). Cinkler *et al*. [31] solve the three subproblems jointly with a formulation which minimises the resources in use at the electronic layer. In [32], Banerjee *et al*. solve the topology design and traffic routing problems minimising the congestion, i.e., the traffic carried by the most loaded lightpath, by maximising the single-hop traffic. Xin *et al*. proposed in [33] two ILP that design static virtual topologies for dynamic traffic grooming, the first one minimising the resource usage and the second one maximising the revenue.

Examples of the topology design solve using MILP can be found in [15], [27], [28], [34], [35]. Labourdette and Acampora proposed in [34] a MILP formulation which jointly solves the topology design and the traffic routing problem, maximizing the traffic to be routed in one hop. Ramaswami and Siravajan proposed in [15] a MILP formulation for topology design and traffic routing with the objective of minimizing the congestion while fulfilling the delay requirements. Durán *et al*. [36] proposed a MILP formulation that jointly solves the topology design, route and wavelength allocation, and traffic routing subproblems, minimising network congestion. In [28], Asghar *et al*. propose a MILP formulation to optimise the resource consumption and minimise the delay. Whereas Huiban and Mateus in [35] propose a MILP to minimise congestion and wavelength usage. Table 2.1 shows a summary of the explained NLP, ILP and MILP methods.

Nevertheless, this kind of formulations requires large computational time to solve the topology design problem, especially when the network is of medium-large size, given that this problem is known to be NP-Hard [16]. Consequently, we can find in literature several proposals that aim at finding a close-to-optimal solution to the topology design problem based on heuristics and meta-heuristics since this kind of formulations can shorten the computational time, at the expense of not ensuring the optimality of the found solution.

Ramaswami and Siravajan proposed in [15] four heuristics to solve the three subproblems, i.e., the topology design, route and wavelength assignment, and the traffic routing problems. In [38], Zhang and Acampora presented a heuristic whose objective is to maximise the single-hop traffic. Banerjee *et al*. [32] presented a heuristic to minimise the maximum link congestion by designing a fully connected topology, to which the algorithm eliminates the least congested lightpaths and reroutes the traffic over the remaining edges. The algorithm repeats the process until the desired node degree, i.e., the desired number of incoming or outcoming lightpaths to a given node is achieved. Sengezer and Karasan [39] proposed a method for static

Authors	*Subproblems*	*Formulation*	*Characteristics*
Mukherjee *et al*. [14]	1 – 3	NLP	Minimises either delay or congestion
Chen *et al*. [37]	1 – 2 – 3	ILP	Reduces CAPEX minimising the number of optical transceivers
Cinkler *et al*. [31]	1 – 2 – 3	ILP	Minimizes electric resource utilization
Banerjee *et al*. [32]	1 – 3	ILP	Minimises single hop traffic
Xin *et al*. [33]	1 – 3	ILP	Minimises resource usage or maximises revenue
Labourdette and Acampora [34]	1 – 3	MILP	Maximises routed traffic in a single hop
Ramaswami and Siravajan. [15]	1 – 3	MILP	Minimises congestion
Durán *et al*. [36]	1 – 2 – 3	MILP	Minimises congestion
Asghar *et al*. [28]	1 – 3	MILP	Optimises resource utilization and delay
Huiban and Mateus. [35]	1 – 3	MILP	Multiobjective optimisation: congestion and active wavelengths

Table 2.1: Topology design proposals based on NLP, ILP and MILP formulations.

virtual topology design that minimises the number of utilised transceivers and wavelengths, considering physical layer impairments. Asghar *et al.* proposed in [28] a heuristic to design virtual topologies reducing the number of O/E/O conversions and the established number of lightpaths. Pavón *et al.* [40] proposed a heuristic for virtual topology design that minimises the network cost by reducing the necessary number of transceivers. Mukherjee *et al.* [14] presented heuristics based on simulated annealing and flow-deviation for topology design and routing. The objective of the simulated annealing algorithm is to minimise congestion, whereas the flow-deviation algorithm minimises the average packet delay.

Saha *et al.* [41] took Mukherjee's work as a starting point for solving the topology design problem, but employed genetic algorithms instead of simulated annealing, obtaining better scaleup and total delay results. In [42], Gazen and Ersoy proposed a genetic algorithm to design topologies by means of applying classical genetic operations as crossover or mutation to predefined virtual topologies, until the resulting topologies outperform the existing, predefined ones. Furthermore, Ghose *et al.* [43] proposed a heuristic an a genetic algorithm that solves the topology design and the RWA problem minimising the delay. Durán *et al.* [27], [44], [45] proposed a set of genetic algorithms to solve the topology design, RWA and routing problems, minimising the delay, the congestion or the utilized resources (number of transceivers and active wavelengths). Fernández *et al.* enhanced those genetic algorithms with the objective of minimising the network power consumption, proposing in [46], two multiobjective algorithms, one of them enhanced with cognition techniques. Fukushima *et al.* [47] proposed a heuristic for virtual topology design, lightpath provisioning and routing which aims at maximising the throughput and minimising the number of employed fibre amplifiers. Din [48] proposed a heuristic and a genetic algorithm to solve the topology design and the rate of the lightpaths in mixed-line-rate (MLR) WDM networks with the objective of minimising the cost of the transceivers. Table 2.2 summarises these techniques.

Table 2.2: Summary of heuristics and meta-heuristics that solve the topology design subproblem.

Authors	*Subproblems*	*Technique*	*Objective*
Ramaswami and Siravajan [15]	1 – 2	Heuristic based on placing logical links according to some design criteria	Four algorithms: • Congestion minimisation • Delay minimisation • Active wavelength minimisation • Meeting degree constraints

Continued on next page

Table 2.2 – *Continued from previous page*

Authors	*Subproblems*	*Technique*	*Objective*
Zhang and Acampora [38]	1 – 2	Greedy algorithm	Maximises the sum of one-optical-hop traffic to minimize congestion
Banerjee *et al*. [32]	1	Link elimination through matching scheme	Minimises maximum carried traffic by a lightpath
Sengezer and Karasan [39]	(1 – 3) + 2	Tabu and greedy search	Maximises transported traffic while minimizing number of transceivers, considering physical impairments
Asghar *et al*. [28]	1 – 2 – 3	Multi- weighted graph combined with a Pareto optimal algorithm	Minimises O/E/O conversions and employed lightpahts
Pavon-Marino *et al*. [40]	1 – 3	Traffic dominance based heuristic	Optimises network costs minimizing the number of required transceivers
Mukherjee *et al*. [14]	1 – 3	Simulated Annealing and fow deviation	Two algorithms: • Minimise congestion • Minimise packet delay
Saha *et al*. [41]	1 – 3	Genetic Algorithm	Congestion minimisation
Gazen and Ersoy [42]	1	Genetic Algorithm	Virtual Topology Design
Ghose *et al*. [43]	(1 – 3) + 2	Genetic Algorithm	Delay minimisation
Durán *et al*. [27], [44], [45]	1 – 2 – 3	Multiobjective genetic algorithm	Congestion, resource utilisation and delay minimisation

Continued on next page

Table 2.2 – *Continued from previous page*

Authors	*Subproblems*	*Technique*	*Objective*
Fernández *et al*. [46]	1 – 3	Multiobjective genetic algorithms	Power minimisation, one enhanced with cognition techniques
Fukushima *et al*. [47]	1 – 2 – 3	Greedy algorithm	Heuristic which maximises throughput and minimises fibre amplifiers
Din [48]	1	Heuristic and genetic algorithm	Minimise cost of transceivers

Lastly, studies can be found in literature which reconfigure static logical topologies. Given the variable nature of traffic, designing a static topology may cause network inefficiencies or traffic losses. The reconfiguration is accomplished by setting up new lightpaths or changing and removing existing lightpaths [49]. The objective of reconfiguration is to achieve improvements in the efficiency and reliability of the network while optimising aspects as the resource usage.

Table 2.3: Virtual topology reconfiguration proposals.

Authors	*Reconfiguration Stage*	*Algorithm*	*Objective*
Zhang *et al*. [50]	Offline Reconfiguration	Multi-stage decision-making process and prediction-based heuristic	Minimise average hop count
Chen *et al*. [37]	1 – 2 – 3	ILP	Reduces CAPEX minimising the number of optical transceivers
Baldine and Rouskas [51]	Offline Reconfiguration	Multi-stage decision-making process	Select rewarding and cost functions to achieve the desired performance

Continued on next page

Table 2.3 – *Continued from previous page*

Authors	*Reconfiguration Stage*	*Algorithm*	*Objective*
Ricciato *et al*. [52]	Offline Reconfiguration	MILP	Minimise cost
Ohsita *et al*. [53]	Online Reconfiguration	Multi-stage reconfiguration based on traffic prediction	Limit the changing lightpaths at each stage
Gençata and Mukherjee [54]	Online Reconfiguration	Load-based lightpath addition or deletion	Minimise the number of changes
Melidis *et al*. [55]	Online Reconfiguration	Load-based lightpath addition or deletion	Minimise the power consumption and reduce the number of required reconfigurations
Durán *et al*. [44]	Offline Redesign	Genetic Algorithm	Minimise number of changes
Fernández *et al*. presented in [56]	Online Redesign	Cognitive and traffic prediction-based reconfiguration algorithm and transition planning	Minimise instabilities
Banerjee and Mukherjee [26]	Single-step Migration	ILP	Minimise of number Wavelength-Routing Switch configurations
Takagi *et al*. [57]	Step-by-step Migration	Migration heuristics in which only one ligthpath changes at each migration step	Maximise network availability

The WDM network reconfiguration consists of three steps [49], the design of a reconfiguration policy which decides whether the reconfiguration should be performed, the selection of a new topology according to an optimisation criterion and the migration to the new topology.

There are two main events that trigger the reconfiguration of a network, which are a change in the traffic pattern or a change in the network resources, for example, for the addition of new network equipment, the deletion due to network maintenance or the failure of network equipment. Reconfiguration policies can be classified as offline policies and online policies.

Offline policies are designed using traffic estimation techniques before its implementations in the network. Zhang *et al.* [50] propose a multi-stage decision-making process formulation and a prediction-based heuristic for offline reconfiguration. Baldine and Rouskas [51] also proposed a multi-stage decision process for network reconfiguration which focuses on appropriately selecting rewarding and cost functions to achieve the desired performance. Finally, Ricciato *et al.* [52] proposed a MILP formulation for network reconfiguration that assumes that the operator knows the network traffic behaviour in advance.

Ohsita *et al.* [53] proposed an online reconfiguration policy that divides the reconfiguration process in various stages and predicts the traffic using the traffic matrices of past stages. In this manner, the algorithm limits the number of lightpaths that change at each stage. Gençata and Mukherjee proposed in [54] an algorithm to reconfigure a virtual topology, adding or deleting lightpaths according to the lightpath loads at the end of an observation period, minimising the number of changes. Similarly, in [55], Melidis *et al.* proposed an online policy that minimises the power consumption and reduces the number of required reconfigurations. In this case, a third threshold is added: if a lightpath is overloaded but the carried traffic does not exceed the activation threshold, new traffic demands will not be routed through these lightpaths but no additional lightpath will be created.

Another option to react against a traffic change or network failure is redesigning the virtual topology. However, since reconfiguring the topology may cause instabilities and, consequently, packet delay or loss, the design methods employed when reconfiguration is allowed tend to include mechanisms to minimise the number of added and/or deleted lightpaths and, consequently, instabilities. Durán *et al.* [44] presented a proposal in which the number of changed lightpaths and, consequently, the changes between the previous and the reconfigured network are minimised. Fernández *et al.* presented in [56] an algorithm that proactively reconfigures the virtual topology using cognitive techniques and traffic prediction and also plans a transition sequence that minimises the possible instabilities.

Finally, once a new topology is designed, a migration between the old topology and the new topology must be perform. The objective is to reduce the instabilities and packet delay and the packet loss rate. We can find two approaches to the migration phase: the single-step migration, in which the traffic migrates from one topology to another in just one step. Banerjee and Mukherjee proposed in [26] an ILP that minimises the number Wavelength-Routing Switch configurations required to change from the existing to the new topology. On the contrary, some studies approach the migration phase using a step-by-step migration technique. In [57], Takagi *et al.* proposed algorithms in which the basic change unit is the lightpath, i.e., only one lightpath changes from one configuration to another, in order to maximise the network availability. A summary of the reconfiguration methods can be seen in Table 2.3.

2.1.1.2 The Routing and Wavelength Assignment Problem

After the lightpaths to be established in the virtual topology, they have to be embedded in the physical topology. This process implies allocating to each lightpath composing the designed virtual topology a route, or set of fibres to be traversed, and an available wavelength which has not been assigned to other lightpath traversing all or part of the fibres in the route. This second subproblem is known as the Routing and Wavelength Assignment (RWA) problem. Some of the methods that solved the topology subproblem also addressed the RWA problem [15], [27], [28], [31], [36], [37], [38], [39], [43], [44], [45], [47] . However, there are methods that solve the RWA subproblem independently.

This subproblem can be solved using ILP formulations, as the proposed by Ramaswami and Sivarajan in [58]. However, Chlamtac *et al.* proved this problem to be NP-Hard [59] and, therefore, its computational complexity increases exponentially with the network size. Consequently, it is often solved using heuristics and meta-heuristics since this kind of approaches simplifies the solving process.

The existence of wavelength converters in the network is an important aspect to consider when solving the RWA problem. In the absence of wavelength converters, the allocated wavelength to a lightpath must be the same throughout the route. However, if the nodes of the network can be equipped with wavelength converters, additional design decisions must be solved, such as the number and position of the converters or the range of wavelengths they can convert. Stern and Bala proposed in [60] an ILP formulation that can be applied to a wavelength-convertible network, which solves the routing problem. Chu *et al.* solved the converter placement problem in [61]. More information on the RWA problem-solving under wavelength conversion can be found in [62]. However, converters increment the network cost and complexity, so the common approach is to solve the RWA problem in the absence of this element.

It is common to solve the RWA problem by separately finding a route and then an available wavelength to be allocated to the lightpath. In this manner, the routing subproblem can be solved utilizing a pre-computed list of paths between the source and destination nodes. On the other hand, the wavelength allocation problem can be solved attending to different design criteria, as minimising the number of active wavelengths or the energy consumption.

The routing problem is frequently solved using one of these heuristics:

1. **Fixed Routing (FR)**: This is the most straightforward method and consists in assigning always the same route to the same pair of source-destination nodes, which means that only one route for each pair is pre-calculated. The route is usually calculated as the shortest-path route in terms of hops or total delay using methods as Dijkstra's algorithm [62].

2. **Fixed-Alternate Routing (FAR)**: In this technique, each node of the network maintains a routing table containing pre-calculated routes to each destination node. These routes are frequently sorted in increasing order of length, i.e., the first route is the shortest-path route, followed by the second shortest-path route, etc. Consequently, when a request arrives, the algorithm tries the routes following the order in the routing table, until finding the first available route.

3. **Adaptive Routing (AR)**: The routes are calculated according to the network state and

reordered accordingly [63].

On the other hand, the wavelength assignment problem can be solved using one of the following techniques:

1. **First Fit (FF)**: In this assignment scheme, wavelengths are numbered and checked from the lower-numbered to the highest-numbered wavelength, selecting the first available one.

2. **Most Used (MU)**: This scheme attempts to allocate the wavelength which has been employed more times in the network.

3. **Least Used (LU)**: Similar to the previous method, this method selects the least used wavelength in the network.

4. **Random**: The scheme computes the set of available wavelengths and randomly selects one from this set.

Chlamtac *et al*. [59] proposed a heuristic in which routes are ordered from the longest to the shortest path. In that order, the algorithm assigns an available wavelength utilising the FF scheme. Banerjee and Mukherjee [64] proposed a method which also divides the RWA problem into two steps, solving the routing problem through an ILP formulation which minimises the number of lightpaths sharing a link. Authors showed that the wavelength allocation problem is equivalent to a graph colouring problem and used the solving methods for that kind of problem.

Stern and Bala [60] proposed a non linear formulation for joint RWA problem-solving which minimises the number of active wavelengths and routes. In [65], Deylamsalehi *et al*. proposed a MILP formulation for solving the RWA problem that aims at minimising the electricity cost and the produced emissions. Since the MILP formulation will not solve the problem in polynomial time when the objective network is large, authors accompanied their proposal with a logistic regression model to solve the RWA problem minimising the electricity cost and the produced emissions.

Christodoulopoulos *et al*. [66] proposed a RWA algorithm which minimises the maximum network resources in use. The algorithm first precomputes the possible paths in a network, solves the static RWA problem and, if the problem is infeasible, if tries iterative rounding and fixing techniques or increases the number of possible wavelengths until a result is found. This algorithm was further extended to render it impairment aware, so that it introduces the physical impairments as constraints of their formulation.

Another technique for jointly solving the RWA problems is using a wavelength graph as in [31], [67], [68]. This technique consists in creating copies of the physical topology for each available wavelength. In order to enable wavelength conversion, a link can be added between layers through the nodes with this capacity. This links can be assigned a larger weight in order to avoid wavelength conversion. Initially, any wavelength can be utilised when establishing a lightpath between nodes. Therefore, a shortest path algorithm can be applied, resulting in the route and wavelength to use at each fibre. This route is removed from the wavelength graphs so that they can be reused in following searches.

The different proposals to solve the RWA problem are summarised in Table 2.4.

Authors	*RWA solving strategy*	*Technique*	*Objective*
Ramaswami and Siravajan [58]	Joint RWA	ILP	Maximise routed connections
Chlamtac *et al*. [59]	R + W	Routes ordered in decreasing length order + FF	Maximise unused wavelengths
Banerjee and Mukherjee [64]	R + WA	ILP + graph coloring algorithms	Minimises required wavelengths
Stern and Bala [60]	Joint RWA	NLP	Minimises active wavelengths and routes
Deylamsalehi *et al*. [65]	Joint RWA	MILP and logistic regression model	Minimises electricity costs and produced emissions
Christodoulopoulos *et al*. [66]	Joint RWA	Heuristic + LP for RWA	Minimises network resources in use
Cinkler *et al*. [31]	Joint RWA	Wavelength graph	Minimise number of hops
Chatterjee *et al*. [67]	Joint RWA	Wavelength graph	Minimise blocking rate
Zhou *et al*. [68]	Joint RWA	Wavelength graph	Minimise blocking rate

Table 2.4: Summary of proposals to solve the RWA problem.

2.1.1.3 The Routing Subproblem

The final step is routing the traffic over the lightpaths which were designed solving the first subproblem and embedded in the physical topology solving the second subproblem. Some proposals that addressed the topology subproblem also solved the routing subproblem [14], [15], [27], [28], [31], [32], [33], [34], [35], [36], [37], [39], [40], [41], [43], [44], [45], [46], [47]. However, the routing can be solved independently.

There are two possibilities for carrying the traffic: the first one is routing all the traffic between the source and destination nodes using a single route or through multiple routes.

Furthermore, some traffic requests may require less bandwidth than the total capacity of the lightpath. Assigning a lightpath to carry this single traffic flow would be highly inefficient since the unoccupied bandwidth would be misused. Consequently, it is common to carry or groom multiple low-speed connections or flows into a high-capacity lightpath. In this manner, the network throughput, i.e., the amount of traffic successfully carried by the network is maximised, and the network cost is optimised. This technique is known as traffic grooming [69].

When we consider static traffic demands, the traffic grooming subproblem can be considered an optimisation problem and, therefore, can be solved using an ILP formulation as the presented in [69], [70]. However, the traffic grooming problem has been shown to be NP-Hard [71], [72], [73] and thus, this kind of formulations will not be able to solve the traffic grooming problem in polynomial time when the network size increases. Therefore, there are in literature traffic grooming solving methods based on heuristics, as the ones presented in [74] and [75].

2.1.1.4 Survivable WRON

Given the amount of traffic that optical networks carry, due to the increasing number of connected users and the apparition of new applications and services, a failure of the equipment or the fibres composing the network can cause the disruption of one or more established lightpaths and, consequently, a dramatic loss of information. Therefore, it is important to provide fault-recovery schemes to ensure the survivability of the connections.

Fault-recovery can be performed in the electrical domain. In this domain, protection schemes will generally aim at rerouting the affected traffic using existing lightpaths with spare capacity. Fault-recovery mechanisms in the optical layer reroute the traffic affected by a lightpath disruption through a new lightpath. The mechanisms can be classified into two types: protection and restoration. In protection, backup resources as routes and wavelengths are precomputed and reserved in advance for all or some lightpaths [76]. In restoration, however, a new route and wavelength are dynamically discovered and employed to transport the traffic affected by a connection interruption [77]. Some advantages of dynamic restoration schemes are the efficient use of network resources since they do not reserve backup resources in advance and the provided resilience against different types of failures. However, this sort of schemes cannot guarantee the recovery of interrupted connections, as protection schemes do. Furthermore, protection schemes shorten the reaction time to failure [12].

Depending on the network topology, protection schemes can be classified as ring protection and mesh protection. The mesh protection schemes can be further classified as:

1. **Path protection**: This sort of schemes provides end-to-end protection to a path. Both

primary and backup paths must be link-disjoint to avoid disruptions in both paths if a single link fails. This kind of scheme is known for their efficient use of backup resources and better end-to-end propagation delay respect other protection schemes [12]. These schemes can be also classified as:

(a) **Dedicated protection**: the backup resources reserved for a primary lightpath cannot be shared by other lightpaths. Monti *et al.* [78] proposed a heuristic for lightpath provisioning with dedicated path protection which minimises the energy consumption. Zang *et al.* [79] proposed an ILP for solving the RWA problem which aims at minimising the active wavelengths in the links and provides dedicated-path protection.

(b) **Shared protection**: the backup bandwidth can be shared by different primary lightpaths if the primary lightpaths sharing the backup resources are link-disjoint. Therefore, lightpaths sharing primary resources, i.e., traversing the same link, must have totally disjoint backup lightpaths [80]. An example of shared-protection schemes can be found in the proposal of Ou *et al.* [81], where authors developed a backtracking-based heuristic for primary and shared-path backup lightpaths, which computes $k-$shortest paths between source and destination nodes as primary lightpaths, as well as a backup route for each primary lightpath. Once a feasible solution is found, authors employ a second heuristic to optimise the solution and find the solution that consumes fewer resources. Zang *et al.* [79] proposed an ILP for lightpath provisioning with shared-path protection, that minimises the total number of wavelengths.

2. **Link protection**: In this sort of schemes, each link of the primary lightpath has allocated backup resources, i.e., backup links and wavelengths. If a link fails, the scheme selects a link and a wavelength and reroutes the traffic through those resources, only around the failing link. These schemes provide better protection-switching time than path protection schemes [12]. Link protection schemes can also be divided into dedicated and shared protection. Ramamurthy *et al.* proposed in [77] ILP models for both shared and dedicated link-based protection which minimise the total consumed capacity.

3. **Sub-path protection**: Is a method half-way between the path and link protection techniques. In these schemes, the network is divided into segments, and each segment is protected separately. The network can also be divided into domains, each composed of various segments. In the latter case, protection lightpaths for each segment cannot employ resources allocated to backup lightpaths of other segments. Ou *et al.* [82] proposed an ILP formulation and a heuristic to provide this kind of protection while minimising the resource consumption.

Dynamic restoration reacts only upon a network failure and employs the available network resources to provide a backup lightpath to a disrupted connection [77]. Restoration can also be classified as:

1. **Path restoration**: If a failure happens, the origin and destination nodes of the connection are notified about the failure and independently find an end-to-end backup route and wavelength. This scheme is employed by Mohan *et al.* in [83].

2. **Link restoration**: In this scheme, the adjacent nodes of the failing link dynamically find an alternative route around the failing link. Shenai *et al.* [84] proposed an algorithm for link-restoration that, for a set of links which satisfy a threshold condition, as a given maximum occupied capacity, computes and reserves backup resources for all connections traversing the link.

3. **Sub-path restoration**: When a link fails, the event is detected by the upstream node of the affected link and it finds a backup route from itself to the destination node. Wang *et al.* implemented and compared in [85] the performance of this restoration scheme and the performance of path and link restoration schemes in an IP-over-WDM network.

Table 2.5 summarises the reviewed protection strategies and proposals that implement those protection schemes.

2.1.2 Dynamic WRON

When the traffic pattern is dynamic, lightpaths are established only when the network receives a connection requests and released after some lightpath-holding time. In this scenario, the RWA problem must be solved in real-time, hence requiring fast algorithms which determine the route and the available wavelength between source and destination in a short amount of time or block the connection requests if there are not available resources.

The preferred methods to solve the RWA problem in dynamic WRON scenarios would be based on heuristics since other kinds of mathematical formulations would not be able to solve the problem in a reduced amount of time, as these scenarios require.

Depending on the entity performing the RWA methods, we could find centralised or distributed RWA algorithms. In centralised RWA, a node of the network known as the control node holds the updated and complete network state information. With this information, the node is responsible for deciding which route and wavelength to assign to each connection request coming from other nodes of the network. After that, the control node sends configuration messages to the nodes involved in the connection with the information they required to configure the resources. Once the resources are configured, the node control sends a message to the requesting nodes to use the established lightpath. The control node also tears down lightpaths and free resources when this kind of requests arrives.

Centralised dynamic WRON architectures present two main problems: the failure of the controller may cause new lightpaths to not being established or old lightpaths to not being released. To avoid this problem, a backup control node can be added. The other problem is that centralised architectures present scalability issues, since the larger the topology is, the more requests the controller receives, which could cause a bottleneck if the node is unable to process them.

In distributed WRON architectures, however, every node of the network is responsible for the management of the resources required in the lightpath set up process, as well as the release of said resources, once the lightpath is torn down. The collaboration between nodes allows for more flexible and scalable networks since it avoids the possible bottlenecks that may appear when a central node executes all the tasks. It also favours resilience, since in case a node fails, the others can continue establishing and releasing lightpaths, and cuts down the delays due to the communication between the controller and the nodes of the network. Nevertheless,

Authors	*Protection strategy*	*Technique*	*Objective*
Monti *et al*. [78]	Dedicated path protection	Heuristic	Minimise power consumption
Zang *et al*. [79]	Dedicated path protection	ILP	Minimise number of wavelengths
Ou *et al*. [64]	Shared path protection	Backtracking algorithm	Minimises consumed resources
Zang *et al*. [79]	Shared path protection	ILP	Minimises total number of wavelengths
Ramamurthy *et al*. [77]	Shared and dedicated link protection	ILP	Minimises resource consumption
Ou *et al*. [82]	Sub-path protection	ILP and Heuristic	Minimises resource consumption
Mohan *et al*. [83]	Path restoration	Heuristic	Maximise the recoverability of connections
Shenai *et al*. [84]	Link restoration	Heuristic	Meet restoration efficiency requirements while reducing capacity requirements

Table 2.5: Summary of protection proposals in survivable WRONs.

these scenarios lead to a slower lightpath establishment process. Furthermore, the nodes will possibly work with not updated network state information, so they will not be able to find the optimal solution to the RWA problem.

Depending on the network architecture, i.e., centralised or distributed, the RWA problem can be solved employing different approaches. In centralised WRON, for instance, the RWA problem can be solved either in a joint manner or separately, solving first the routing problem and then the wavelength assignment problem or vice versa. If the routing problem is solved in the first place, the proposed techniques are similar to the ones shown for the static case, so we can find Fixed Routing (FR), Fixed Alternate Routing (FAR) and Adaptive Routing (AR).

In FR, one route between each pair of source-destination nodes is precalculated, normally looking for the shortest path in terms of hops or delay. We can find proposals using this routing method in [36], [86], [87], [88], [89], [90].

FAR is a variation of FR in which several routes between each pair of source-destination nodes are pre-calculated. These routes are normally disjoint, i.e., they do not share any fibre, and are also ordered from the shortest path in terms of hops to the longest one. This is the proposed method to solve the routing problem in [58], [86], [88].

Finally, AR also pre-calculates a set of routes between each source-destination pair, and chooses the best route or calculates new ones according to the network state. The first approach is used in algorithms as Least Congested Path (LCP) [91] or Fixed-Paths Least-Congestion (FPLC) [92]. Proposals based on the second technique, i.e., the calculation of new routes, are found in [63],[89], [93], [94], [95], [96].

The techniques for solving the wavelength assignment problem in static WRON can also be applied in the dynamic scenario. Consequently, we can find the First Fit technique in [36], [63], [95], [97], [98], Random in [86], [87]; while [63], [64] utilise Most Used and Least Used is employed in [63].

Furthermore, the RWA problem in dynamic scenarios can be solved in a joint manner as in [99], [100]. Of special interest is the proposal of Mokhtar and Azizoglu, Aur Exhaustive [63]. Upon a request arrival, the method considers the available network resources at the moment and computes the shortest path for each available wavelength. Then, the method compares the resulting routes and chooses the shortest of the calculated routes, and the associated wavelength.

In distributed architectures, algorithms differ from the centralised schemes in which it is the nodes of the network who are actually responsible for finding a route and a wavelength to assign to a connection request, instead of a control element. In this kind of architectures, nodes are unable to find the optimal solution to the RWA problem since they do not have all the network state information. Hence, RWA algorithms in distributed dynamic WRON can be divided in two classes, according to the network state information the nodes manage: global network state information, if nodes store the information of the whole network, which may not be entirely reliable since it may not be updated information, or local network information, in which each node only knows the state of their own links. For example, Pavon-Marino and Bueno-Delgado presented in [101] a heuristic that solves the distributed RWA problem considering the occupation of the add/drop ports of the Reconfigurable Add/Drop Multiplexer (ROADMs). To perform the algorithm, nodes store in their Traffic Engineering Database updated information of the fibre topology.

2.1.3 From WRONs to EONs

The appearance of bandwidth-consuming services as high-definition video distribution or real-time video communications, paired with the ever-increasing connected devices, dictated the evolution to new optical transport networks that would satisfy the increasing and demanding user's requirements.

In response to the increasing bandwidth demand, significant innovations in optical communication systems, the advance in optical amplification or the appearance of new modulation formats enabled the long-distance Dense Wavelength-Division Multiplexed (DWDM) transmission, which offers a per-channel bandwidth of 100 Gb/s [102]. This transmission technology not only offers increased channel bandwidth but also augmented optical reach, i.e., the signal is able to travel longer distances before requiring an O/E/O regeneration. Yet, there are still some drawbacks associated with the granularity in DWDM networks. For instance, in a DWDM network, analogously to WDM networks, full-wavelength capacity is allocated to any connection between two nodes. This implies that, when the traffic demand is below the lightpath capacity, the spare capacity is wasted. Contrarily, if a traffic demand is higher than the connection capacity, a number of wavelengths whose combined capacity can satisfy the traffic demand can be allocated to the connection. If there are adjacent wavelengths, then spectrum guard-bands should be added, causing an inefficient use of the bandwidth. To address these problems, proposals as Optical Packet Switching (OPS) or Optical Burst Switching were introduced.

In OPS [103], information is divided into packets, and the packet-switching operations occur in the optical domain. This technology allows for a more efficient usage of network resources since the capacity is occupied only during the packet transmission. However, this architecture requires the existence of buffers or memories to implement store-and-forward operations, as in IP routers. To date, no optical equivalent to Random Access Memory (RAM) exists and, therefore, "optical buffers" are implemented by means of Fibre Delay Lines (FDL).

In OBS [104], packets sharing similar characteristics are aggregated in the edge node and the burst is transmitted afterwards. Before the burst transmission, the edge node would send a control packet to set up the connection. This packet includes information as the source and destination nodes, the offset or time difference between the transmission of the control packet and the data payload and optionally the burst length. The nodes of the network electronically process this control packet and utilise the information to determine to which node they must transmit the burst, for how long and how much bandwidth they must reserve, and also how they should configure their switches. Still, as in the previous proposal, the enabling technologies are still immature.

The interest of the scientific community in OPS and OBS has decreased over the years, given that these proposals rely on still immature or non-existent technology. For this reason, a new solution must be proposed to address the problem of the ever-increasing traffic volume. The advances on techniques like optical Orthogonal Frequency Division Multiplexing (OFDM), Nyquist-WDM or the Optical Arbitrary Waveform Generation (OAWG), in conjunction with the development of devices like the Bandwidth-Variable (BV) Transponder and the BV-Wavelength Optical Cross-Connect (BV-OXC) [18], [19], set the path for the proposal of a new optical transport network architecture that is spectrum efficient and scalable, the Elastic Optical Networks (EON), also known as Flexible Optical Networks.

In the following section, we will explain into detail this new optical transport technology and the main advances with respect to WRONs.

2.2 EON

Elastic Optical Networks address the flexibility issue present in WDM and DWDM networks by allocating custom-size bandwidth to channels [102]. Some early studies on flexible optical networks studied gridless scenarios in which a portion or slice of spectrum of variable size was assigned to a request [105], [106], [107]. However, the most common approach to the spectrum allocation in flexible optical networks considers migrating from from the fixed frequency grid employed by WDM and DWDM to a flexible one, which allows for the allocation of multiple consecutive spectrum slots of fixed width.

The new frequency grid divides the spectrum into frequency slots (FS) described by the central frequency and the slot width. The set of nominal frequencies is given by the expression $f = 193.1 + n \times 0.00625$ THz, where n is an integer number, and the slot width is 12.5 GHz, [19], although granularities of 6.25 are being studied [108]. Compared to the fixed WDM grid, where the channel spacing can vary from 12.5 GHz to 100 GHz [20], the flexible grid or flexgrid provides finer granularity. Furthermore, in fixed WDM grid the connection is allowed to occupy only one FS, while flexgrid allows the allocation of multiple FS to adequate the assigned bandwidth to the requested capacity [19]. A comparison of the bandwidth assignment in fixed WDM and flexgrid is shown in Figure 2.2.

The migration to a new frequency grid is combined with a node architecture change, in which Bandwidth Variable Transponders (BV-T) and Bandwidth Variable Cross Connects (BV-OXCs) are employed. BV-T are employed to dynamically adjust the bandwidth by adapting the modulation format and the transmission bit rate. Depending on the lightpath distance, these devices can employ spectrally efficient modulation formats, like 16 or 64 Quadrature Amplitude Modulation (QAM), or less efficient although more robust ones, like binary phase-shift keying (BPSK) or quadrature phase-shift keying (QPSK) [109]. On the other hand, BV-Cross Connects (BV-WXC) allocate a cross-connection with the corresponding spectrum to create an end-to-end optical path of appropriate size [109], [110]. With these elements, EON networks are able to create channels which can contract or expand according to the bandwidth requirements of the request [102].

EONs are characterised by the following features [109], [111], [112]:

1. **Bandwidth Segmentation:** EONs allocate just the necessary amount of bandwidth to satisfy the traffic request. This means that, if a connection only requires partial bandwidth, EONs are able to divide the spectrum and allocate the needed bandwidth, in contrast to WRON, where full wavelength capacity is allocated to each connection. In this manner, EONs avoid the stranded bandwidth problem, i.e., when a connection is allocated full capacity but the traffic demand is lower and, therefore, cannot completely fill the allocated bandwidth [112].

2. **Super-wavelength accommodation (super-channel formation)**: In WRON, traffic demands higher than wavelength capacity would be accommodated in various lightpaths. If the chosen channels where adjacent, additional guard-bands for switching purposes would be added, leading to an inefficient use of bandwidth. EON, on the other hand, can modulate and multiplex groups of optical channels at a source node and transmit and

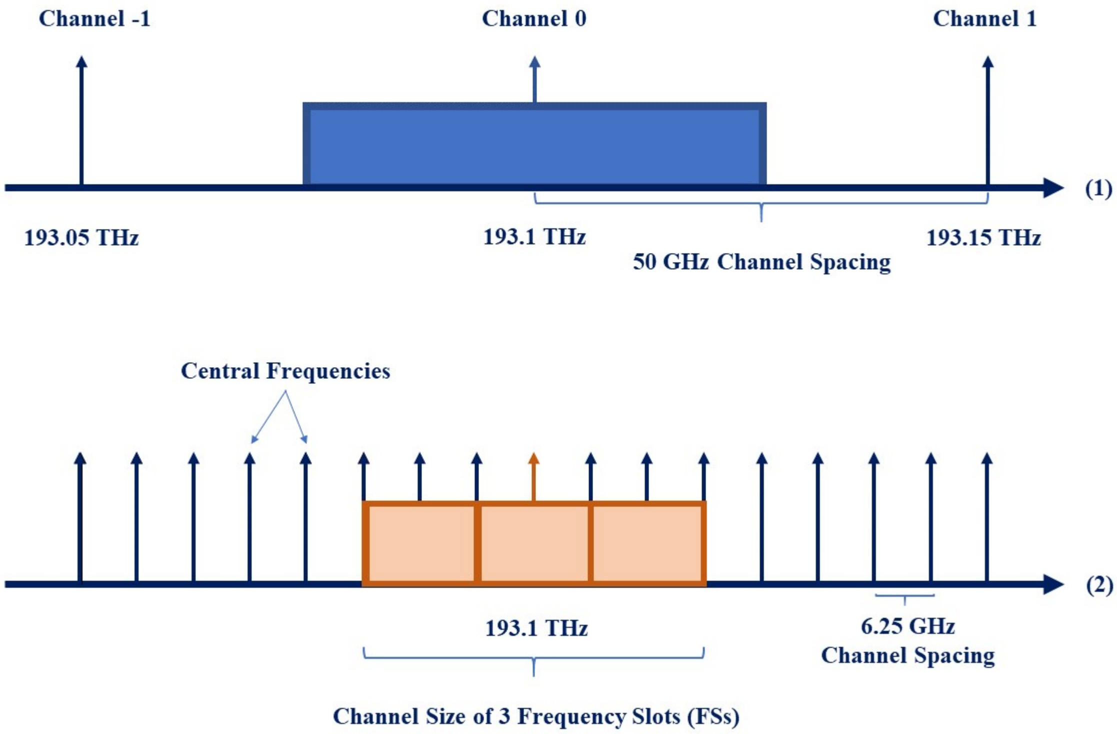


Figure 2.2: Channel comparison between Fixed DWDM Grid with 50 GHz channel spacing (1) and Flexgrid with 6.25 GHz spacing between Central Frequencies (2).

route them together until arriving to the destination node. Consequently, traffic demands greater than wavelength capacity can be accommodated in tailor-made super-channels, making a more efficient use of the spectrum since super-wavelength accommodation reduces the introduction of guard-bands. This feature does not eliminate, however, the requirement of adding guard-bands between two adjacent super-channels.

3. **Aggregation:** EON is able to aggregate multiple requests to be transmitted over a single super-channel, hence saving utilised spectrum.

4. **Bandwidth Variation:** Since the capacity demand of an established path can vary with time, EON is able to dynamically adjust the allocated spectrum to a connection.

5. **Efficient multiple data rate accommodation:** The flexible assignment of spectrum enables the possibility of accommodating mixed data-bit rates in the optical domain in contrast to WRON, where accommodating low bit rate signals can lead to the stranding of the optical bandwidth, due to the excess of frequency spacing.

6. **Reach-adaptable line rate:** The ability to vary the employed modulation formats and the number of subcarriers enables EONs to support line rates adapted to the optical reach, as well as the dynamic expansion or contraction of the allocated bandwidth to a connection.

7. **Energy Saving:** When the carried traffic decreases, EONs are able to turn off some subcarriers, hence reducing the energy consumption.

8. **Network virtualisation:** It is possible to virtualise the network by creating virtual links that can be supported by the subcarriers.

Adding flexibility to the optical transport network promises higher spectrum efficiency compared to WDM, but also poses new challenges in the network optimisation. One of these issues is the optimisation of the connection establishment. Since EON allocates portions of spectrum to a connection, instead of full wavelength capacity, the RWA problem transforms now in the Routing and Spectrum Assignment (RSA) problem, i.e., deciding which portion of spectrum and route should be allocated to a connection, considering two key conditions: the bandwidth that the connection occupies must be the same throughout the whole route, restriction referred to as the spectrum continuity constraint, and the bandwidth must be contiguously allocated, condition known as the spectrum contiguity constraint. In the following subsection we will focus on the RSA problem.

2.2.1 The RSA problem

While in WRON the RWA problem must be solved to allocate a route and a wavelength to a connection, in EON an analogous problem must be solved, only that it is a portion of spectrum, instead of a wavelength, the resource to be allocated to a connection. Hence, the basic problem to solve when facing the network design phase, i.e., when allocating network resources to a connection request is the Routing and Spectrum Assignment (RSA) problem. In this case, the network receives a connection request with an associated bandwidth demand. The problem is finding a set of contiguous FSs that satisfies the demanded capacity. If there are not enough contiguous slots along the chosen path and the contiguity constraint cannot be satisfied, then it is possible to break the connection into smaller demands, where each new demand would require less contiguous FS. Furthermore, the continuity constraint must be fulfilled, in the same manner as in the RWA in the absence of wavelength converters, i.e., the same FSs must be allocated at each link composing the path [109].

Elastic networks, however, not only bring flexibility in terms of allocated spectrum but also offer other flexibility degrees as the power level or the modulation format. When the latter area is to be taken into account, then the problem is referred to as the Routing, Modulation Level, and Spectrum Allocation (RMLSA) problem.

2.2.2 The Static RSA problem

The RSA problem can be jointly solved using mathematical methods like ILP and MILP, as in RWA. These methods will optimally solve the problem but, just as in the RWA case, they could lead to high computational complexity, particularly when the network is large, since the RSA problem is shown to be NP-Hard [109], [110], [113]. Therefore, these methods are more suitable to solve the offline RSA problem, in which the traffic matrix is known in advance. For example, Klinkowsky and Walkowiak proposed in [114] an ILP formulation for solving the joint RSA problem that aims at minimising the number of FSs allocated to at least one connection. Christodoulopoulos *et al.* [110] proposed an algorithm which precalculates *k* paths between each source-destination pair and then applies an ILP model to solve the joint RSA problem which finds the path and the starting frequency of the allocated bandwidth, minimising the total used spectrum. Wang *et al.* presented in [115] an ILP formulation that jointly solves the RSA problem, minimising the maximum subcarrier index in all the fibres, as well as the total allocated subcarriers over the fibres of the network. In [116], Cai *et al.* presented an ILP formulation which jointly solves the RSA problem and minimises the maximum FS index employed in the network. Miyagawa *et al.* [117] proposed two ILP models for static EON in intra-data centre networks, the first aiming at minimising the number of utilised FSs and the second aiming at maximising the number of served traffic requests under the given number of FSs. These methods are summarised in Table 2.6.

Many studies also tackle the joint static RSA problem proposing heuristics, that will be able to find a solution to the problem in polynomial time. This is the case for Klinkowsky and Walkowiak, who also proposed in [114] a heuristic which minimises the maximum FS index used in the network. The heuristic examines each candidate path for all the demands, in decreasing order of demanded FSs, and selects the path for which there is a set of FSs that satisfy the traffic demand and the index of the initial FS is the smallest between the initial FSs indexes of the candidate paths. Cai *et al.* also proposed a greedy algorithm for joint RSA problem-solving in [116], based on spectrum window, i.e., a window or set of available FSs, whose size can vary according to the traffic demand. Hence, the algorithm calculates the hop-length of the shortest path between each source-destination pair of nodes. Then, for each demand, the algorithm creates a plane or layer for each spectrum-window. This layer contains a virtual topology with the links in which the spectrum window is available. Finally, for each layer, the algorithm computes the shortest path between source and destination and selects the shortest path. If no path is selected, a new FS is added, and the algorithm repeats the process. Finally, Wang *et al.* [113] presented two heuristics to solve the RSA problem aiming at minimising the maximum subcarrier index, called Shortest Path with Maximum Spectrum

Authors	*RSA solving strategy*	*Technique*	*Objective*
Klinkowsky and Walkowiak *et al*. [114]	Joint RSA	ILP	Minimises the allocated FSs
Christodoulopoulos *et al*. [110]	Joint RSA	ILP	Minimise used spectrum
Wang *et al*. [115]	Joint RSA	ILP	Minimises maximum FS index and allocated FSs over the fibres of the network
Cai *et al*. [116]	Joint RSA	ILP	Minimises maximum FS index employed in the network
Miyagawa *et al*. [117]	Joint RSA	ILP	Two objectives: • Minimises number of utilised FSs • Maximises number of served traffic requests

Table 2.6: Summary of static RSA techniques that propose a linear programming formulation.

Reuse (SPSR) and Balanced Load Spectrum Allocation (BLSA). In the former, requests are sorted in decreasing order of demanded FSs and, for each request, allocates the shortest path and the lowest-indexed consecutive FSs available. The same spectrum slots allocated to a given request can be reused in a different one if the paths are link-disjoint. BLSA is a three-stage heuristic that first computes $k-$ shortest paths for each source-destination node pair, then checks which of the computed paths minimises the maximum fibre load and finally allocates the lowest-indexed consecutive FSs. The techniques are summarised in Table 2.7.

As in WRONs, the RSA problem can be solved as a subproblem of the Virtual Topology Design (VTD). The VTD problem comprises the selection of lightpaths to be established, the allocation of network resources solving the RSA problem and the routing of the traffic through the established lightpaths. Zhao *et al.* [118] propose an ILP to solve the topology design and the resource allocation problems in EON, with the objective of minimising the maximum used FS index on any link of the topology. The proposal includes a list scheduling heuristic that reduces the request blocking and the bandwidth blocking compared to first fit based heuristics. Yu *et al.* [119] proposed a MILP formulation and a heuristic to solve the topology design and network resource allocation problems, minimising the power consumption. Velasco *et al.* [120] propose an ILP formulation that solves the topology design as an RMSA problem, minimising the capital expenditures (CAPEX) of the network.

Authors	*RSA solving strategy*	*Technique*	*Objective*
Klinkowsky and Walkowiak *et al.* [114]	Joint RSA	Path Shorting and selection of lowest indexed FS	Minimises the allocated FSs
Cai *et al.* [116]	Joint RSA	Greedy algorithm	Minimises maximum FS index employed in the network
Wang *et al.* [115]	Joint RSA	SP+Spectrum reuse and balanced load spectrum allocation	Minimises maximum FS index and allocated FSs over the fibres of the network

Table 2.7: Heuristics to solve the RSA problem.

2.2.3 The Dynamic RSA problem

In dynamic scenarios, upon a connection request, the network should be able to provision a traffic demand with an available portion of spectrum and a route in a brief period of time. Since the RSA problem is NP-Hard, methods as ILP are not particularly suitable to solve the problem in these scenarios, since they will not solve the problem in polynomial time. Hence, it is very common to find proposals based on heuristics and meta-heuristics, to solve the dynamic RSA problem. These methods can be divided into one-step RSA and two step-RSA.

In one-step RSA, the routing and the spectrum assignment are jointly solved employing just one step. Wan *et al*. [121] proposed in two heuristics that jointly solve the RSA problem. The Spectrum-Constraint Path Vector Searching Algorithm (SPV) builds a decision tree whose route is the source node and whose leaves are adjacent nodes in the path whose connecting link has enough available to satisfy the bandwidth demand, including the guard-band. If there is enough spectrum, the algorithm adds the node to the decision link and repeats the process between this node and the following hop in the path. Finally, it selects the path with enough available spectrum and minimum cost. Additionally, authors presented a modified version of Dijkstra's Shortest Path (Modified Shortest Path, MSA), in which the algorithm computes the shortest path between source and destination and checks each link to calculate the aggregated available spectrum along the whole path. In this manner, the algorithm is able to verify that the same consecutive FSs are available in all the links composing the path. At the same time, the algorithm checks if the portions of available spectrum satisfy the bandwidth and guard demands. Salani *et al*. [122] presented an ILP to solve the RSA in one step, aiming at minimising the number of transceivers and the number of FSs in use. If multiple modulation formats are included, then the solution includes reach constraints and becomes the Routing, Modulation and Spectrum Assignment (RMSA) problem. Furthermore, the ILP is enhanced with machine learning techniques to include Quality of Transmission (QoT) estimation in the solution. Leiva *et al*. [123] proposed a Dynamic Graph Coloring algorithm that jointly solves the RSA problem. For each FS in the spectrum, the algorithm builds sub-graphs that include the links with enough available FSs to satisfy the traffic demand, assuming that the first FS in the available set is the checked FS. When the sub-graphs are built, the algorithm looks for the shortest path in terms of number of hops and assigns the path and the available FSs.

On the other hand, the RSA problem can be addressed by breaking it up into the routing and the spectrum allocation problems and solving them separately, in a similar approach as the RWA problem.

The routing problem can be addressed through two different approaches. The first tactic would not consider the elastic characteristics of EONs. In this case, analogous algorithms to those employed to solve the RWA problem can be adopted. Therefore, we can employ Fixed Routing or Fixed Alternate Routing as in [124], Adaptive Routing like Alyatama *et al.* employed in [125], or Least Congested Routing, in which the algorithm selects the path among a set of predetermined routes between the source-destination pair, with more FSs available, i.e., the least congested path [12], [109].

The second tactic, on the other hand, would account for the elastic features of EONs. Single path routing in the RSA approach can lead to spectrum fragmentation, i.e., the introduction of gaps, or not utilised spectrum, which is a frequent issue in dynamic scenarios. This problem may produce connection blocking since the remaining sets of contiguous FSs may not be enough to allocate the connection, although there might be enough overall spectrum. Hence, to overcome this issue, we can employ routing approaches that account for this issue as multi-path or spectrum splitting routing [126], [127], [128] in which the request is split into two or more paths, provided that the consecutive available slots of the paths satisfy the traffic demand of the request.

Finally, the spectrum allocation problem can be solved through one of the following algorithms:

1. **First Fit (FF)**: In this scheme, the FSs are indexed and a list of the available and utilised

FSs is maintained. The algorithm precalculates k-shortest paths between the source and destination nodes and sorts it in increasing length order. Then, it searches for a set of contiguous FSs that satisfies the traffic demand, also in ascending index order, i.e., aiming at allocating the lowest-indexed FSs first. If the algorithm finds spectrum to allocate to the demand, it stores the assigned FSs in the not available FSs list. When the connection is released, the slots return to the available slot list. This policy is employed in [129], [130], [131].

2. **Random Fit (RF)**: This scheme was proposed in [130] and it randomly selects spectrum portions among the list of available FSs. These portions must be big enough to satisfy the traffic demand and must be the same in all the links conforming the first found route

3. **Last Fit**: Similar to FF in the functioning, this policy, however, attempts at allocating the highest indexed FSs to a lightpath [132].

4. **Lowest Starting Slot (LSS)**: presented in [133], the policy tries to allocate the first set of available FSs that satisfy the traffic request. The policy examines the available paths between the source and destination nodes, and the available slots from the ones with lower index to the ones with higher index. The policy assigns the path with the lowest-indexed available slots among the candidate paths.

5. **First-Last-Exact Fit (FLEF)**: This policy [134] separates connections into two groups: non-disjoint and disjoint. Disjoint requests are solved using First-Exact Fit which, similarly to FF, tries to assign the first (and thus the lowest-indexed) set of FS which exactly adapt to the traffic demand, or assigns the lower indexed FS if no exact fit is found. On the other hand, non-disjoint requests are solved using Last-Exact Fit, which attempts at allocating the highest-indexed FSs that exactly fit the traffic demand. If no exact fit is found, allocates the first, higher-indexed available slots. In this manner, the number of contiguous slots is maximised, and so the policy reduces the blocking probability.

2.2.4 Issues related to the performance of RSA

There are aspects related to EONs, as the fragmentation, survivability and traffic grooming issues, that may impact the performance of the RSA algorithms. In this subsection we will briefly describe them and their effects on the performance of RSA.

Fragmentation: Since EONs assign contiguous FSs to the connection requests that adjust the demanded bandwidth, a dynamic set up and tear down of lightpaths can cause available FSs to be isolated between them. This condition is known as fragmentation and complicates the employment of the isolated FSs in upcoming connections [109].

Fragmentation can be managed through the RSA algorithms employed to provision a connection. For example, proposals in [135], [136], [137] employ the multipath transmission, which divides a request into various, smaller connections and transmits them through different paths. Moura *et al.* [138] proposed a heuristic based on multigraph, a graph where vertices can have various edges. In their proposal, the vertices are the OXC of the network and there are as many edges connecting the OXCs as FSs in the spectrum of each link. Using this grapth, authors calculate the number of FSs required to satisfy the traffic demand and propose a heuristic which selects the available consecutive FSs which satisfy the demand and reduce the overall power consumption and bandwidth blocking, according to a cost model proposed by the authors. Moreover, a partition approach can be employed. This technique makes partitions out of the spectrum and classifies lightpaths, both according to some criteria. In this manner, the technique can dedicate each partition to one sort of lightpath, as in [134]. Lastly, Waldman *et al*. proposed a deadlock-avoidance technique [139] that aims at reducing fragmentation by only assigning network resources if the allocated link, after reserving resources, is fully utilised or if the available spectrum resources are enough to accommodate another traffic request. Bórquez-Paredes *et al*. [140] compared this strategy to other greedy techniques as first fit and last fit and showed that the deadlock-avoidance strategy was able to reduce fragmentation and bandwidth blocking. Nevertheless, a new type of blocking due to the restricting criteria to accept connection requests raised with this technique.

Additionally, fragmentation can be addressed through an operation called defragmentation, in which the existing connections and allocated spectrum are periodically reconfigured. In this manner, the misuse of spectrum resources and the bandwidth rejection, i.e., the rejection or blocking of incoming requests because of the inexistence of enough consecutive FSs to fulfil the traffic request, are avoided [19], [109]. Dá *et al*. [141] proposed two meta-heuristics based on Ant Colony Optimisation and Genetic Algorithms that aim at reducing the request blockage by deciding the best set of lightpaths to be proactively rerouted. Furthermore, there are various defragmentation techniques, as the hop-tuning, the make-before-brake technique, and the push-and-pull approach [19], [142], that aim at reducing the misuse of spectrum. The hop-tuning approach [143] keeps the physical route of the lightpath but moves the allocated slots to other, available slots. The push-and-pull technique [144] changes only the allocated slots to a connection, by first increasing the allocated resources to the connection, then pushing the central frequency so that it is moved as near as possible to the side of the adjacent lightpath and finally reconfiguring the allocated resources to reduce them to the original number of assigned slots. Finally, the make-before-break technique [145] provisions a new connection between the source and destination nodes of the lightpath to be defragmented. The routes of the old and new lightpaths are link-disjoint. The traffic is shifted from the original connection to the new lightpath and then the original lightpath is torn down. A comprehensive survey about fragmentation can be found in [142].

Traffic Grooming: Traditionally employed in WRON, traffic grooming consists in aggregating low-speed connection requests into a higher capacity traffic flow (e.g. a lightpath) to improve the spectrum utilisation. In EON this technique was introduced because (i) it allowed to make a better use of the transponder capacity, given the limitations in slicing that BV-T presented in their early stages [134] and (ii) it allowed to improve the use of the spectrum, since electrically aggregating low-speed connection into a higher capacity traffic flow reduced the introduction of guard-bands between channels [109].

Traffic grooming can be performed electrically by employing electrical subcarrier multiplexing and switching [146], [147]. However, it requires additional O/E/O conversions and switching requirements at the intermediate nodes, incrementing the energy consumption [147], [148], [149]. Furthermore, in order to overcome the limitations of BVTs, researchers developed the Sliceable BVT, a device capable of supporting different modulation formats, bit rates, transmission distances and sliceability [109],[147], [150]. Employing these devices, traffic grooming can be partially performed at the optical layer, by aggregating in the optical layer different low capacity connections into one BVT and switch them as an optical tunnel or group of optical paths, where a guard-band to separate the different services inside a network should be added [147], [148], [151].

Optical grooming can be planned offline, i.e., for static traffic. For example, Zhang *et al.* [148] proposed an ILP formulation and a heuristic to perform optical grooming with the possibility of minimising either the consumed spectrum or the number of employed transponders. It can also be performed under dynamic traffic, as the proposal by Khodashenas *et al.* [152], a heuristic that solves the RSA problem with traffic grooming to minimise the spectrum and transmitter usage in the network. Furthermore, traffic grooming can be performed considering aspects as fragmentation or survivability. A survey on traffic grooming in EONs can be found in [147].

Survivability: As in WRON, a connection disruption in EON can cause the loss of an incredible amount of data, as well as affect thousands of users. Hence, it is important to provide fault-management mechanisms that minimise the effects of a failure in the network. EON's fault-management techniques can be classified as protection and restoration. In protection, backup lightpaths are precomputed before a failure event. They can be dedicated, if the backup lightpath only protects a primary connection, as in the proposed offline RSA algorithms by Klinkowski *et al.* [153], or shared, where the backup lightpath can protect various primary lightpaths, provided they are link-disjoint as in the proposals by Shao *et al.* [154] or Wang *et al.* [155].

The second class of fault-management techniques is restoration. This approach searches resources for a new lightpath when a failure happens, employing the available resources at the moment of the failure. Since sometimes it is not possible to allocate the full capacity of the primary connection to the backup lightpath, approaches as the bitrate squeezing used in [156], [157], in which just part of the capacity is recovered, or the multipath transmission employed in [157], in which the original capacity is split among multiple connections, are explored.

2.3 Conclusions

The increasing traffic that transport networks must carry and the apparition of new services demanded new technologies which closed the gap between the capacity of optical fibre and the actual transmission capacity of electronic equipment. WDM closed this gap by allowing the transmission of multiple channels at electronic speeds over the same physical links. These channels are composed of a set of fibres or route and a wavelength and are called lightpaths. Moreover, the set of lightpaths established over a physical network topology is called Virtual Topology. The Virtual Topology Design is a highly complex problem and, in consequence, can be solved in one step or divided into various subproblems: Topology design, Routing and Wavelength Assignment (RWA) for embedding the design topology, and Traffic Grooming. We have explained the main methods to solve these subproblems. In dynamic scenarios, on the other hand, lightpaths are provisioned and set up upon request arrival and tear down after a given holding time. In this type of scenario, the RWA problem becomes the dynamic RWA problem. Therefore, we have reviewed the most important proposals to solve the RWA problem dynamically.

Nevertheless, the increasing traffic required more spectrum efficient routing techniques. Some technological breakthroughs as the apparition of new modulation formats, the BV-

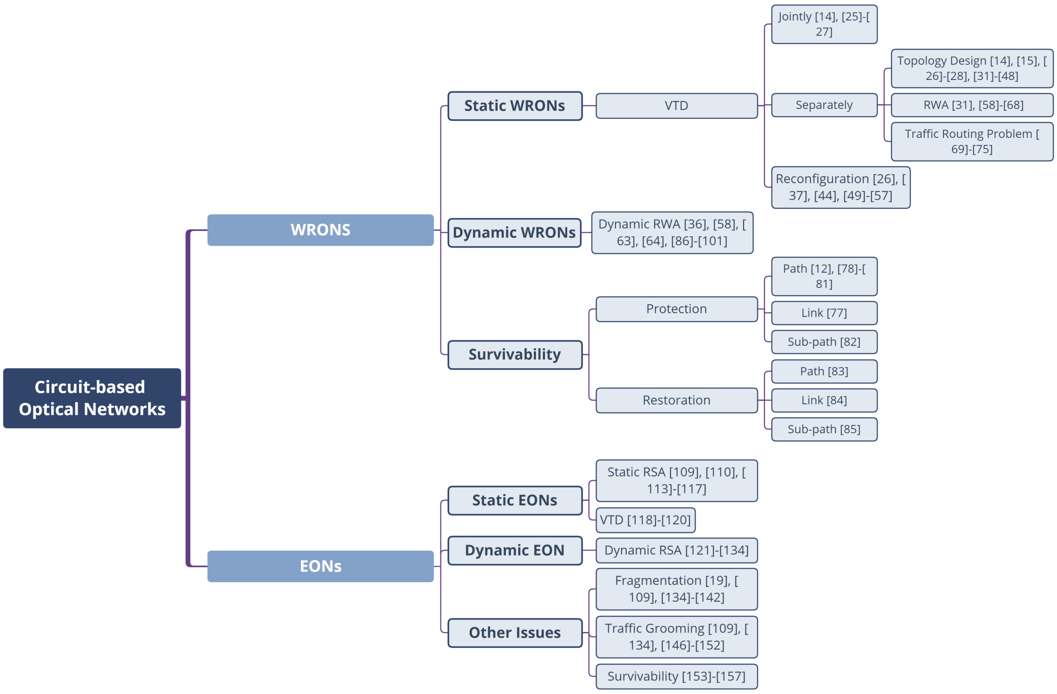


Figure 2.3: Summary of the chapter.

Transponder and the WXC, combined with the adoption of a new frequency grid that divided the spectrum into slots described by their central frequency and width and with a smaller channel spacing favoured the apparition of Elastic Optical Networks.

One of the most interesting features of EONs is their ability to provision portions of spectrum to the connections, instead of full wavelength capacity. Therefore, EONs are able to provision just the required capacity, increasing the spectrum efficiency. In this kind of networks, the RWA problem becomes the Routing and Spectrum Assignment Problem in its basic form. Moreover, other flexibility parameters like the modulation level, can be considered during the routing and spectrum assignment problem. In that case, the problem is known as the Route, Modulation Level and Spectrum Assignment (RMLSA) problem. We have also reviewed the most important methods to solve both the static and the dynamic RSA problem and some issues related to EONs that can affect the performance of the RSA algorithms.

In the next Chapter, two sets of RSA algorithms to solve the dynamic, centralised RSA problem are introduced. The first set combines different flexibility degrees regarding the assignment of the spectrum and the possibility of splitting the request into multiple sub-lightpaths with traditional routing and spectrum assignment methods as shortest path and first fit [62]. The second set combines the same flexibility degrees with first fit and a new spectrum assignment method named Best Gap (BG). We will study the performance of the proposed methods in terms of blocking rate and analyse the benefits of introducing different flexibility degrees in the RSA algorithms.

Chapter 3

Exploiting Different Types of Flexibility in EONs

Optical networks are the perfect candidate to deploy metro and transport networks thanks to their offered high capacity, but also to their dynamicity, flexibility, and reliability [12]. Wavelength-Routed Optical networks (WRON), which we introduced in detail in Chapter 2, appeared to solve the gap between the fibre and the capacity of electronic devices, by enabling the possibility of establishing multiple connections over the same physical network, by using WDM. To establish a connection in this kind of network, it is necessary to solve the routing and wavelength assignment (RWA) problem. Nevertheless, current WRONs use the ITU-T fixed channels and, therefore, they allocate to each connection full grid slot capacity. Consequently, this technology is not able to allocate just the required capacity to satisfy the actual traffic requests, which leads to inefficient use of fibre bandwidth.

One of the emerging network technologies which aims at addressing the inefficient use of the spectrum is the Elastic Optical Network (EON) [102]. This network architecture, which was also introduced in Chapter 2, allocates a portion of the spectrum adapted to the actual traffic request, transporting the traffic on multiple low-rate subcarriers. In this manner, EONs can provide sub-wavelength granularity to low-traffic requests, or create super-channels to transport high-rate demands.

In this kind of architecture, the RWA problem becomes the routing and spectrum assignment problem (RSA). In Chapter 2 we have reviewed some of the most common techniques proposed in the literature to solve this problem. The problem can be solved for static networks or in dynamic ones. Classical routing methods as shortest path, or spectrum assignment techniques as first fit can be employed to solve the RSA problem [131]. However, elastic networks allows the proposal of more flexible routing and spectrum assignment techniques, like the split-spectrum approach [126], [127], in which the request is divided into multiple "sub-lightpaths" or defragmentation techniques [19], [109], which replace existing connections to increase the network efficiency. Most of the spectrum assignment methods proposed in the literature divide the spectrum into slots and assign just the number of slots that satisfies the traffic request.

In this Chapter, we present four dynamic, centralised RSA algorithms, which combine two degrees of flexibility using the traditional $k-$shortest paths and first fit techniques. Then, we propose a flexible spectrum assignment technique called Best Gap, which addresses the problems raised when flexibility techniques are combined with traditional, non-flexible RSA techniques. The rest of the Chapter is structured as follows: Section 3.1 present the four proposed RSA algorithms which combine two different levels of flexibility with with the well-known RSA algorithms $k-$shortest paths and first fit, and a performance comparison of the algorithms in terms of the blocking ratio. Section 3.2 presents the Best Gap spectrum assignment technique and four RSA algorithms which combine the proposed levels of flexibility with $k-$shortest paths and Best Gap. The section also presents a comparison study to show the benefits that can be achieved when the flexibility of EONs is conveniently exploited with proper RSA algorithms. Finally, Section 3.3 presents the conclusions of this Chapter.

3.1 RSA Algorithms

We propose different dynamic RSA algorithms which consider diverse types of flexibility on two well-known RSA methods: $k-$shortest paths and first fit.

One of the main characteristics of EONs is the possibility of assigning the portion of bandwidth that exactly satisfies the traffic request. If the demanded traffic is higher than the frequency slot, it can be accommodated in various slots, creating a super-channel. Adjacent super-channels must be separated by a guard-band, in order to avoid interferences between them. The most common approach to assign bandwidth is to consider the spectrum divided into Frequency Slots (FSs) of a given width and assign, to each traffic demand, the required number of slots that satisfies the requested bandwidth. However, dividing the available spectrum into slots may be inefficient since the allocated bandwidth may not adjust exactly to the traffic request and, in consequence, part of the spectrum might be misused. Considering that, we would like to compare two types of flexibility regarding the consideration of the spectrum (Figure 3.1):

- **Flexgrid**: Considers the spectrum divided into slots. Consequently, when a traffic request arrives at the network, the algorithm will search a route and a set of available FSs which satisfy the traffic demand. Traditional flexgrid defines the set of central frequencies of the assignment as $f = 193.1 + n \cdot 0.00625$ THz, where n is an integer number, and a slot width of 12.5 GHz [19], although granularities of 6.25 GHz have also been considered [108]. We want to study the performance of EONs with different slot granularities. Consequently, we consider slot widths of $12.5, 25, 50$ and 100 GHz.

- **Gridless**: This approach does not consider the spectrum to be divided into FSs. Therefore, upon a traffic request arrival, the algorithms implementing this approach look for a route and assign the exact portion or slice of spectrum which satisfies the bandwidth demand [105], [106], [107].

The second class of flexibility is associated with the consecutiveness of the allocated spectrum. In EONs, the contiguity and continuity of spectrum, in the absence of waveband conversion must be fulfilled in the spectrum assignment process. This means that a set of contiguous FSs which satisfy the bandwidth demand should be allocated to the request and that these should be the same throughout the fibres composing the assigned route. If we consider a gridless scenario, we need to find a slice of available spectrum whose size satisfies the requested demand, and whose initial and final frequencies are the same along the complete

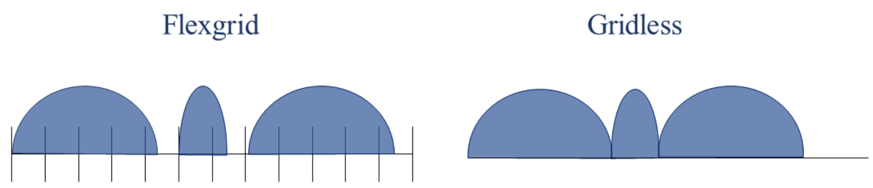


Figure 3.1: Example of Flexgrid and Gridless spectrum.

route. However, if not enough available consecutive FSs or big enough slice is found, a request could be split into "sub-lightpaths", smaller demands requiring less consecutive FSs or a smaller portion of spectrum. Consequently, depending on the allowance to break a request into small sub-lightpaths, we define the following types of flexibility:

- **Joint Spectrum**: This method allocates the required capacity in one single superchannel, to which assigns a monolithic portion of spectrum or a set of consecutive FSs, depending on the grid implementation.
- **Disjoint Spectrum**: This technique allows the splitting of the required capacity into sub-lightpaths with different allocated bandwidths. Traffic grooming mechanisms are implemented at the edges of the lightpaths so that the demanded capacity can be divided at the source node and merged at the destination node.

Therefore, we have combined these two types of flexibility to propose four RSA algorithms: Joint Spectrum Flexgrid (JSF), Disjoint Spectrum Flexgrid (DSF), Joint Spectrum Gridless (JSG) and Disjoint Spectrum Gridless (DSG) [158]. These methods solve separately the routing and assignment problem. The $k-$shortest paths heuristic was chosen to solve the route allocation problem, while the spectrum allocation problem was solved employing the First Fit heuristic [62]. The following subsections explain each algorithm in more detail.

3.1.1 Joint Spectrum Flexgrid (JSF)

The first proposed RSA algorithm combines the Joint Spectrum technique and the Flexgrid approach to solve the RSA problem, which is shown in Algorithm 1. Upon a traffic request, the algorithm receives as inputs the source and destination nodes, the requested bandwidth, and connection holding time. Then, the algorithm solves the RSA problem in the following manner:

1. Calculates the $k-$shortest paths between the source and destination nodes and sorts them in increasing order of hop length.
2. For each path:
   - 2.1. Sorts available slices in the route in a matrix in increasing order of index, i.e., from the lowest to the highest frequencies.
   - 2.2. Calculates the total number of slots which satisfy the bandwidth request.
   - 2.3. For each set of FSs:

2.3.1. Checks if the number of available FSs is equal or greater than the requested FSs.

2.3.2. If an available set is found, allocates the required FSs and establishes the connection. When the holding time is finished, the algorithm tears down the connection and releases the resources. End the algorithm

2.3.3. Otherwise, checks the next set of FSs.

3. If the algorithm is not able to assign a set of contiguous FSs after checking all the computed paths, the request is blocked.

In EONs, a guard-band between two consecutive channels must be included to avoid interference. Therefore, our algorithm computes the number of required slots as:

$$S = \left\lceil \frac{B + G}{T} \right\rceil, \tag{3.1}$$

where S represents the required number of FSs, B is the requested bandwidth in Hz, G is the size of the guard-band in Hz and T is the width of the frequency slot in Hz.

Algorithm 1 Joint Spectrum Flexgrid (JSF)

```
procedure JSF(origin, destination, bandwidth, lpHoldingTime, slotSize, guardbandSize)
    establishedConnection ← false
    paths ← kShortestPaths(origin, destination)
    for i=0, i < size(paths), i++ do
        fibres ← getFibres(paths[i])
        occupiedFrequencies ← getOccupiedSlots(fibres)
        availableSlots ← getAvailableSlots(occupiedFrequencies)
        demandedSlots ← (bandwidth + guardbandSize)/slotSize
        allocatedSlots ←
            findSuitableSetOfSlots(availableSlots, demandedSlots)
        if size(allocatedSlots) ≠ 0 then
            establishConnection(paths[i], allocatedSlots, lpHoldingTime)
            establishedConnection ← true
            break
    if establishedConnection = false then
        blockConnection(origin, destination, bandwidth)
```

3.1.2 Disjoint Spectrum Flexgrid (DSF)

The second proposed algorithm combines the Disjoint Spectrum technique and the Flexgrid approach to solve the RSA problem. Therefore, it splits a traffic demand into multiple sub-lightpaths that are not contiguous in the spectrum, separated from other connections by a guard-band, if it is not able to find a set of contiguous FSs capable to transport the requested bandwidth. The proposal, which is shown in Algorithm 2 performs the following tasks:

1. Calculates the k- shortest paths between the source and destination nodes and sorts them in increasing order of hop length.

2. For each path:

   2.1. Calculates and sorts the sets of available FS in the route in a matrix in increasing order of index, i.e., from the lowest to the highest frequencies.

   2.2. Computes the number of required FSs.

   2.3. For each set:

   2.3.1. Checks if the number of available FSs in the set is equal or greater than the required FSs.

   2.3.1.1. If an available set of proper size is found, stops the search, allocates the required FSs and establishes the sub-lightpath. When the holding time is finished, the algorithm tears down the sub-lightpath and release the resources. End the algorithm.

   2.3.1.2. If an available set of FSs is found, but the total bandwidth is insufficient to meet the bandwidth requests, reserves the available FSs, updates the remaining bandwidth that requires allocation and continues the search until all the demanded traffic is allocated or all the available sets of FSs are checked.

3. If the algorithm is not able to find enough sets of FSs to satisfy the traffic request after checking all the computed paths, the reserved resources are released, and the request is blocked.

For each established connection a guard-band is added at the last assigned slot, as in the JSF method. Therefore, the allocated bandwidth to the sub-lightpath i can be calculated as:

$$B_i = S_i \cdot T - G, \tag{3.2}$$

where B_i is the allocated bandwidth to the sub-lightpath i, S_i is the number of FS allocated to the sub-lightpath i, T is the width of the FS and G is the guard-band size. B_i, T and G are measured in Hz. Consequently, for each established sub-lightapth, the remaining bandwidth B_r to be allocated is updated according to the expression:

$$B_r = B - \sum_{j=1}^{i} B_j \tag{3.3}$$

3.1.3 Joint Spectrum Gridless (JSG)

This RSA algorithm is similar to the JSF method, but it considers the spectrum as a block and does not divide it in slots. Therefore, the spectrum assignment problem consists in finding the slice of spectrum which satisfies the requested bandwidth. When a traffic request arrives at the network, the algorithm stores the source and destination nodes, the requested bandwidth and set up time. The algorithm solves the RSA problem in the following manner:

1. Calculates the k- shortest paths between the source and destination nodes and sorts them in increasing order of hop length.

2. For each path:

Algorithm 2 Disjoint Spectrum Flexgrid (DSF)

```
procedure
DSF(origin, destination, bandwidth, lpHoldingTime, slotSize, guardbandSize)
    remainingCapacity ← bandwidth
    paths ← kShortestPaths(origin, destination)
    for i=0, i < size(paths), i++ do
        search ← true
        while search = true do
            fibres ← getFibres(paths[i])
            occupiedFrequencies ← getOccupiedSlots(fibres)
            availableSlots ← getAvailableSlots(occupiedFrequencies)
            demandedSlots ← (bandwidth + guardbandSize)/slotSize
            allocatedSlots ←
                findSuitableSetOfSlots(availableSlots, demandedSlots)
            if size(allocatedSlots) ≠ 0 then
                allocatedCapacity ←
                    calculateAllocatedCapacity(guardBand, allocatedSlots)
                remainingCapacity ← remainingCapacity − allocatedCapacity
                reservedSlotsAndPathMatrix ← [allocatedSlots, paths[i]]
                if remainingCapacity = 0 then
                    search = false
            else
                search = false
    if remainingCapacity ≠ 0 then
        for i=0, i < size(reservedSlotsAndPathMatrix), i++ do
            releaseResources(reservedSlotsAndPathMatrix[i])
            blockConnection(origin, destination, bandwidth)
    else
        for i=0, i < size(reservedSlotsAndPathMatrix), i++ do
            establishConnection(reservedSlotsAndPathMatrix[i])
```

2.1. Calculates and sorts available slices in the route in a matrix in increasing order of index, i.e., from the lowest to the highest frequencies.

2.2. For each slice:

2.2.1. Checks if the slice is equal or greater than the requested bandwidth.

2.2.1.1. If an available block is found, the algorithm stops the search, allocates the required spectrum and establishes the connection. When the set up time is finished, the algorithm tears down the connection and releases the resources. End the algorithm.

2.2.1.2. Otherwise, checks the next spectrum slice.

3. If the algorithm is not able to assign a a slice of spectrum after checking all the computed paths, the request is blocked.

Algorithm 3 shows the pseudocode for the Joint Spectrum Gridless RSA algorithm.

Algorithm 3 Joint Spectrum Gridless (JSG)

```
procedure JSG(origin, destination, bandwidth, lpHoldingTime, guardbandSize)
    establishedConnection ← false
    paths ← kShortestPaths(origin, destination)
    for i=0, i < size(paths), i++ do
        fibres ← getFibres(paths[i])
        occupiedFrequencies ← getOccupiedBandwidth(fibres)
        availableSlices ← getAvailableSlices(occupiedFrequencies)
        demandedCapacity ← bandwidth + guardband
        allocatedBandwidth ←
            findSuitableSlice(availableSlices, demandedCapacity)
        if size(allocatedBandwidth) ≠ 0 then
            establishConnection(paths[i], allocatedBandwidth, lpHoldingTime)
            establishedConnection ← true
            break
    if establishedConnection = false then
        blockConnection(origin, destination, bandwidth)
```

Since a guard-band between two consecutive channels must be included to avoid interference, our algorithm computes the required spectrum as

$$S = B + G, \tag{3.4}$$

where S is the size of the allocated portion of spectrum, B is the requested bandwidth and G is the size of the guard-band, all measured in Hz.

3.1.4 Disjoint Spectrum Gridless (DSG)

Lastly, the fourth proposed method, shown in Algorithm 4, works in a similar manner to DSF, but considering the gridless approach and, consequently, assigning slices of spectrum to each sub-lightpath. Therefore, upon a traffic request, the algorithm performs the following actions:

1. Calculates the k- shortest paths between the source and destination nodes and sorts them in increasing order of hop length.
2. For each path:
   2.1. Calculates and sorts available slices in the matrix in increasing order of index, i.e., from the lowest frequencies to the highest ones.
   2.2. For each slice:
      2.2.1. Checks if the slice size is greater or equal to the requested bandwidth.
         2.2.1.1. If an available slice of proper size is found, stops the search, allocates the slice and establishes the sub-lightpath. When the holding time is finished, the algorithm tears down the sub-lightpath and releases the resources. End the algorithm.
         2.2.1.2. If a slice is found, but the size is insufficient to meet the requested bandwidth, reserves the available frequencies, updates the remaining bandwidth that requires allocation and continues the search until all the demanded traffic is allocated or all the available slices are checked.
3. If the algorithm is not able to find enough slices to satisfy the traffic request after checking all the computed paths, the reserved resources are released, and the request is blocked.

Again, in the gridless techniques, a guard-band between adjacent sub-lightpaths is added to avoid interference. Therefore, the actual bandwidth allocated to the sub-lightpath i can be calculated as

$$B_i = S_i - G, \tag{3.5}$$

where B_i is the allocated bandwidth to the sub-lightpath, S_i is the size of the allocated portion of spectrum and G is the guard-band size, all measured in Hz. Therefore, the remaining bandwidth B_r to be allocated after reserving resources for the sub-lightpath i is updated according to the expression:

$$B_r = B - \sum_{j=1}^{i} B_j \tag{3.6}$$

3.1.5 Performance Comparison

In this subsection we evaluate the performance of the proposed algorithms in terms of blocking ratio and execution times. To that aim, we have implemented a flexible optical network simulator using the C++ based, discrete event simulator OMNeT++ [159] (see Appendix A). We have chosen the 14−node NSFNet physical topology for this study, where we assumed that the cable connecting two nodes of the network consists of two unidirectional fibres, one for each direction. We set the capacity of each fibre in 4 THz.

The lightpath requests arrive at the network following a Poisson process, while the source and destination nodes of each request are randomly selected using a uniform distribution $\mathcal{U}(0, N-1)$, where $N = 14$ represents the number of nodes. Moreover, the requested traffic for each lightpath is also randomly generated using a uniform distribution $\mathcal{U}(Bw_{min}, Bw_{max})$ where

Algorithm 4 Disjoint Spectrum Gridless (DSG)

```
procedure DSG(origin, destination, bandwidth, lpHoldingTime, guardbandSize)
    remainingCapacity ← bandwidth
    paths ← kShortestPaths(origin, destination)
    for i=0, i < size(paths), i++ do
        search ← true
        fibres ← getFibres(paths[i])
        while search = true do
            occupiedFrequencies ← getOccupiedSlots(fibres)
            availableSlices ← getAvailableSlices(occupiedFrequencies)
            demandedBandwidth ← bandwidth + guardbandSize
            allocatedBandwidth ←
                findSuitableSlices(availableSlices, demandedCapacity)
            if size(allocatedBandwidth) ≠ 0 then
                allocatedCapacity ←
                    calculateAllocatedCapacity(guardBand, allocatedBandwidth)
                remainingCapacity ← remainingCapacity − allocatedCapacity
                reservedBandwidthAndPathMatrix ← [allocatedBandwidth, paths[i]]
                if remainingCapacity = 0 then
                    search = false
            else
                search = false
    if remainingCapacity ≠ 0 then
        for i=0, i < size(reservedBandwidthAndPathMatrix), i++ do
            releaseResources(reservedBandwidthAndPathMatrix[i])
            blockConnection(origin, destination, bandwidth)
    else
        for i=0, i < size(reservedBandwidthAndPathMatrix), i++ do
            establishConnection(reservedBandwidthAndPathMatrix[i][0])
```

Bw_{min} = 1 GHz and Bw_{max} = 300 GHz. The holding time for each connection is calculated using the exponential distribution:

$$exponential(0, averageLightpathHoldingTime). \tag{3.7}$$

Finally, the frequency in which the requests arrive at the network is calculated using an exponential distribution

$$exponential(avRequestInterval, 0), \tag{3.8}$$

where

$$avRequestInterval = \frac{averageLightpathHoldingTime}{load \cdot (nodes - 1)} \cdot \frac{Bw_{max} - Bw_{min}}{2 \cdot Bw_{max}} \tag{3.9}$$

and $0.1 \leq load \leq 0.9$ in normalised Erlangs.

We added a guard-band of size 10 GHz between adjacent connections in the four schemes. For the schemes implementing the flexgrid spectrum approach, the guard-band was accommodated inside the last slot of each established superchannel. Furthermore, in these schemes we explored the results for different granularities, and hence the FS width could take the values 12.5, 25, 50 and 100 GHz, being the 12.5 GHz width the most common size employed in the studies of Elastic Optical Networks. In the gridless methods, the guard-band is also accommodated at the end of each superchannel. The algorithms pre-compute $k-$shortest paths. Simulations for $k = 1, 3$ and 5, i.e., for different numbers of k paths between each pair of nodes, were performed. The results are plotted in average with 95% confidence intervals.

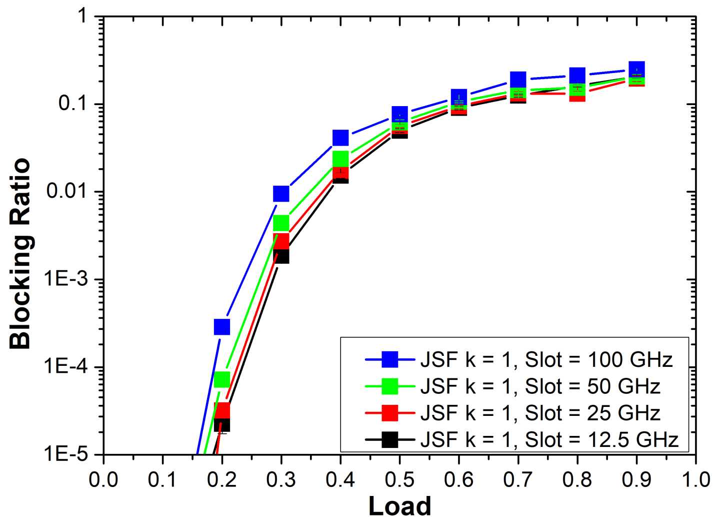


Figure 3.2: Blocking ratio for the JSF algorithm when $k = 1$, for different slot granularities.

Figure 3.2 shows the blocking ratio for all the possible values of FS width and $k = 1$, i.e., when the algorithm checks only the shortest path. Results show that the largest slot width is the configuration which obtains the highest blocking rate, due to the lack of precision in the bandwidth assignment offered by large FSs. Results show that the best performance is achieved when the slot width is fixed in 12.5 GHz, and for low network loads can be approximately a

78% lower than the blocking ratio of JSF for a 100 GHz slot width. With regard to the other possible values of slot width, the second-best performance is achieved by the second-smallest FS width, i.e., 25 GHz, so the third-best performance is achieved when the FS has a width of 50 GHz. Therefore, smaller slot sizes achieve better results, as they make more efficient use of the spectrum.

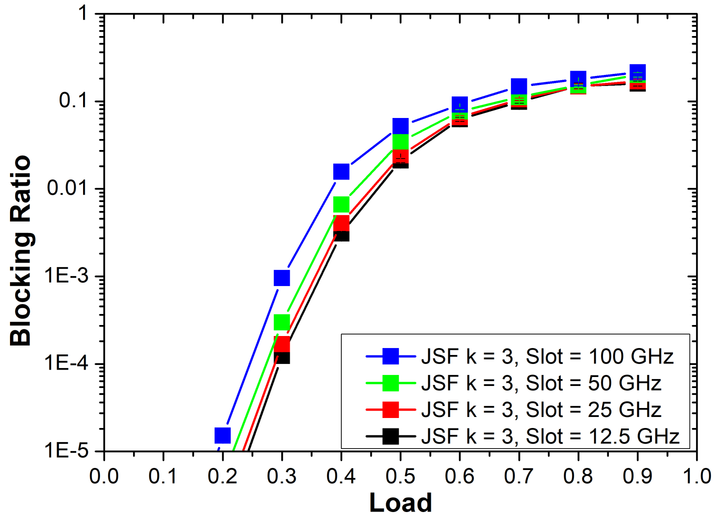


Figure 3.3: Blocking ratio for the JSF algorithm when $k = 3$, for different slot granularities.

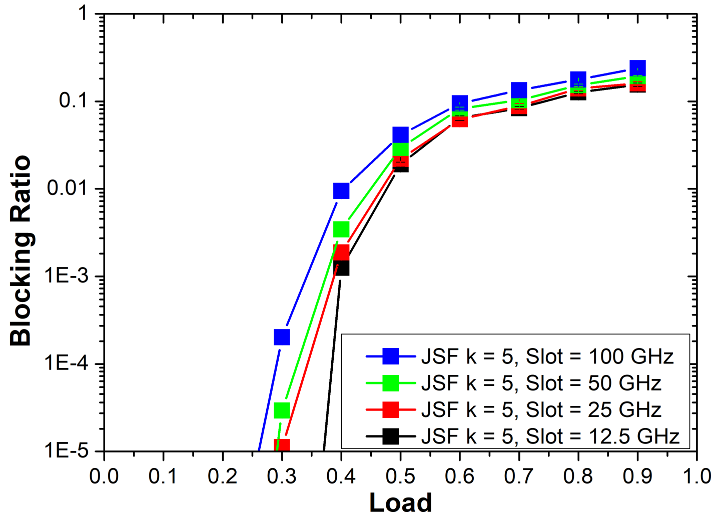


Figure 3.4: Blocking ratio for the JSF algorithm when $k = 5$, for different slot granularities.

If we increase the possible number of paths to 3 and 5, the best performance is obtained with a width of 12.5 GHz as shown in Figures 3.3 and 3.4 respectively. This result was expected given that, with a smaller slot size, the spectrum allocation is performed in a more precise manner. Furthermore, the increment of the number of possible paths which can be assigned to a connection also causes an increment of the probability of finding a path with available bandwidth and, therefore, the blocking ratio decreases. We can observe this tendency in Figure 3.3 and, particularly, in Figure 3.4, where the blocking ratio is close to 0 for loads lower than 0.4 and a slot size of 12.5 GHz. Figure 3.5 shows that JSF with $T = 12.5$ GHz and $k = 5$ obtains lower blocking ratio compared to JSF with the same slot size and lower number of k, which confirms that allowing for a higher number of possible routes between the source and the destination decreases the blocking ratio in this kind of scheme.

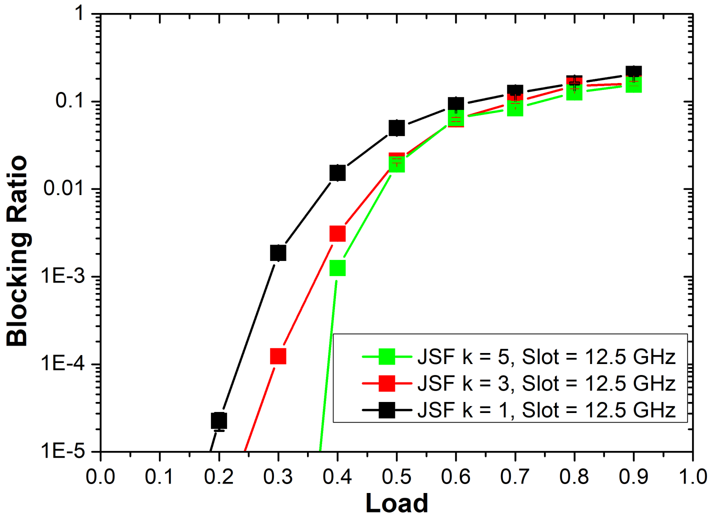


Figure 3.5: Blocking ratio for the JSF algorithm when $k = 1, 3, 5$ and $T = 12.5$ GHz.

Next, we present the results for the DSF scheme, which assumes that the spectrum is divided into slots, and splits, if necessary, the traffic request into multiple sub-lightpaths, if there is not a set of contiguous FSs which satisfies the requested bandwidth. Although initially it could be thought that splitting the request into multiple sub-lightpaths can minimise the blocking rate, it is also important to consider the inefficiency in the spectrum utilisation in which this kind of scheme incurs since they have to add a guard-band to each newly established connection. We can see in 3.6 the blocking ratio achieved by this scheme for all the slot width granularities when $k = 1$. Figure 3.6 shows that the best performing size are 25 and 50 GHz. It can be observed that the scheme with slot size of 12.5 GHz, the size which achieved better results in JSF, is now the width value achieving the worst behaviour in terms of blocking ratio. Given the very narrow size of the slot, the scheme is able to split the capacity into many sub-lightpaths, but also wastes spectrum in allocating guard-bands to the new connections. A medium slot width, on the other hand, is able to achieve a good trade-off between the number of established sub-lightpaths and the misuse spectrum, reducing the blocking rate, as Figure

3.6 shows.

Moreover, increasing the number of possible paths also decreases the blocking rate, as happens when using JSF. This behaviour can be observed in Figures 3.7 and 3.8, which show the results for $k = 3$ and $k = 5$ respectively. In both cases, the best results are achieved when the 50 GHz slot size is employed. The 100 GHz slot size is able to improve the results of the 25 GHz slot size for high network loads when $k = 3$, and totally when $k = 5$. These results suggest a trade-off between slot size and guard-bands: small slot widths increase the precision of the bandwidth allocation, in DSF also implies a higher number of guard-bands, and therefore, the use of the spectrum. However, bigger sizes of slots offer less precise bandwidth allocation but also allows for the establishment of fewer connections and, consequently, the scheme employs less bandwidth to allocate guard-bands.

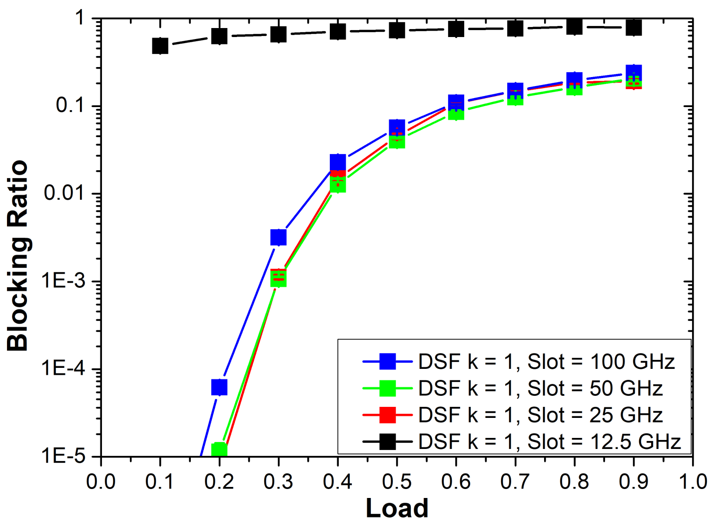


Figure 3.6: Blocking ratio for the DSF algorithm when $k = 1$, for different slot granularities.

Lastly, Figure 3.9 shows the performance comparison of DSF when the slot width is 50 GHz for all possible values of k. We can observe that allowing more paths also increases the possibility of establishing enough sub-lightpaths to satisfy the traffic request, hence reducing the blocking ratio.

We now present the results obtained by JSG and DSG, which follow the gridless approach and, in consequence, assign a spectrum slice whose size is equal or the closest possible to the demanded bandwidth plus the guard-band.

Figure 3.10 shows the blocking ratio achieved by JSG for all values of k. The higher the number of possible paths is, the higher is the probability of finding a route which a spectrum block whose size is sufficient to meet the traffic request. Therefore, the blocking ratio obtained when $k = 5$ is lower than the obtained with $k = 1$ or 3.

This behaviour can also be observed for DSG in Figure 3.11. However, this scheme establishes more connections since it splits a traffic request into as many sub-lightpaths of different allocated bandwidths as required to satisfy the demanded traffic. Therefore, it also

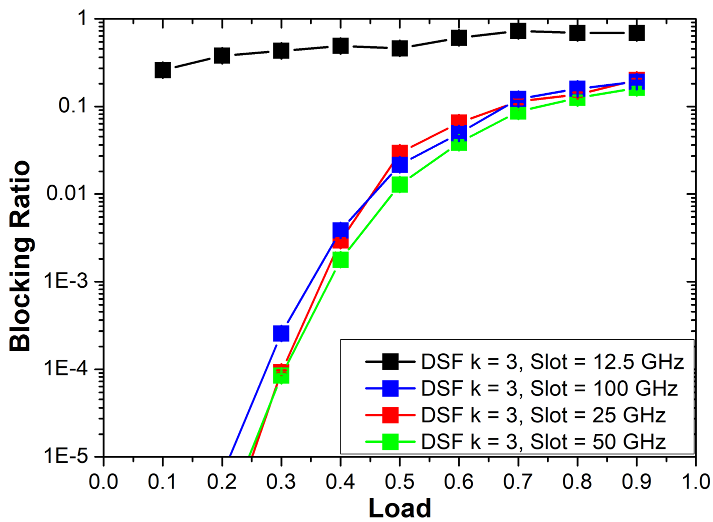


Figure 3.7: Blocking ratio for the DSF algorithm when $k = 3$, for different slot granularities.

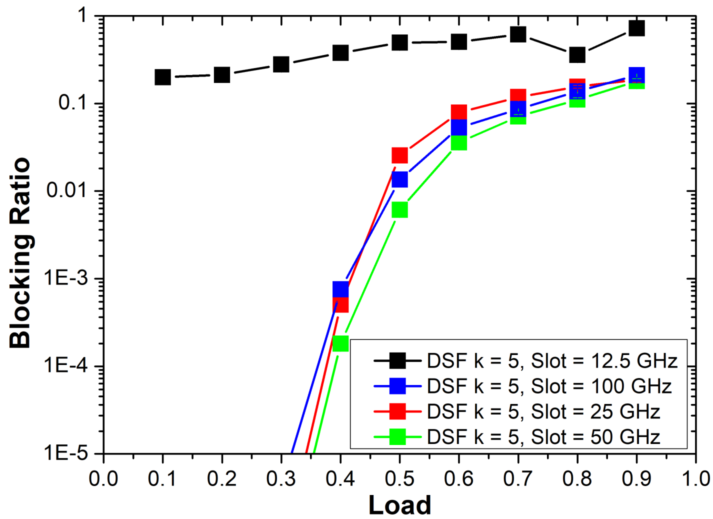


Figure 3.8: Blocking ratio for the DSF algorithm when $k = 5$, for different slot granularities.

allocates part of the spectrum to create guard-bands, leading to inefficient use of the spectrum, as in the case of DSF. In consequence, although the blocking ratio is better for the lowest network loads than the obtained using the JSG method, the inefficiency in the spectrum utilisation leads to higher blocking ratio for the highest network loads.

Lastly, we compare the performance of the different proposed methods. For this aim, we choose, for each scheme, the value of k and the slot size which present the better performance

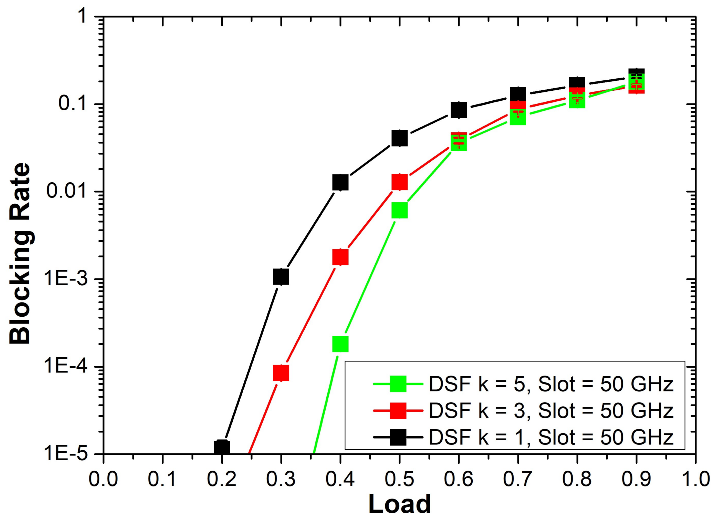


Figure 3.9: Blocking ratio for the DSF algorithm when $k = 1, 3, 5$ and $T = 50$ GHz.

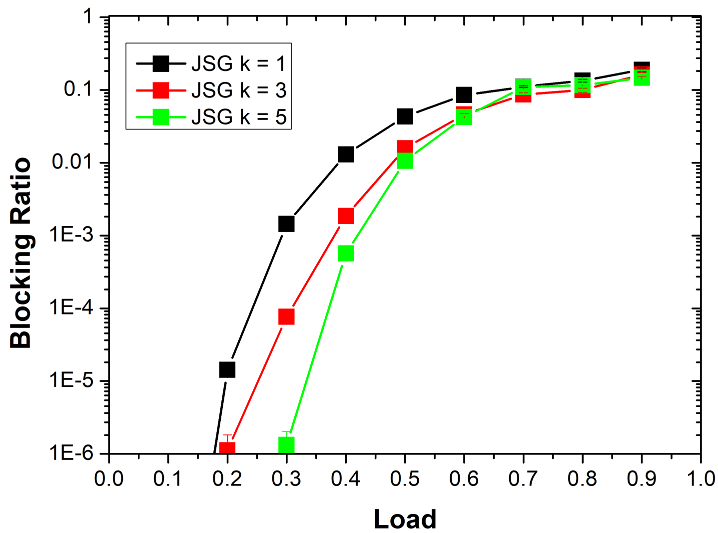


Figure 3.10: Blocking ratio for the JSG algorithm when $k = 1, 3, 5$.

in terms of blocking ratio.

Figure 3.12 shows the blocking ratio of all the schemes in their best performing configuration. It can be seen that the lowest blocking ratio is achieved by DSF with a slot size of 50 GHz. Note that DSF with a slot size of 50 GHz is the configuration of a classic WRON, although in this case the split of the request into multiple sub-lightpaths is allowed. The DSG scheme, which is the more flexible method in terms of the spectrum allocation and sub-lightpath formation is the worst performing scheme, i.e., the method which leads to the highest blocking ratio. The result, therefore, suggests that allowing the splitting of the request into

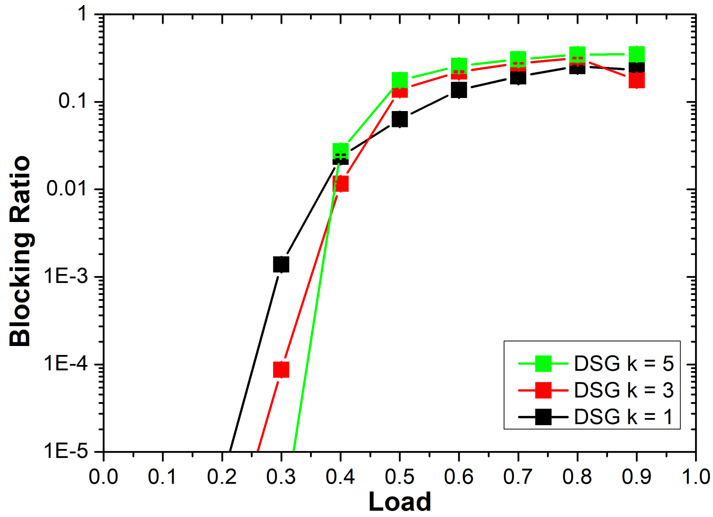


Figure 3.11: Blocking ratio for the DSG algorithm when $k = 1, 3, 5$.

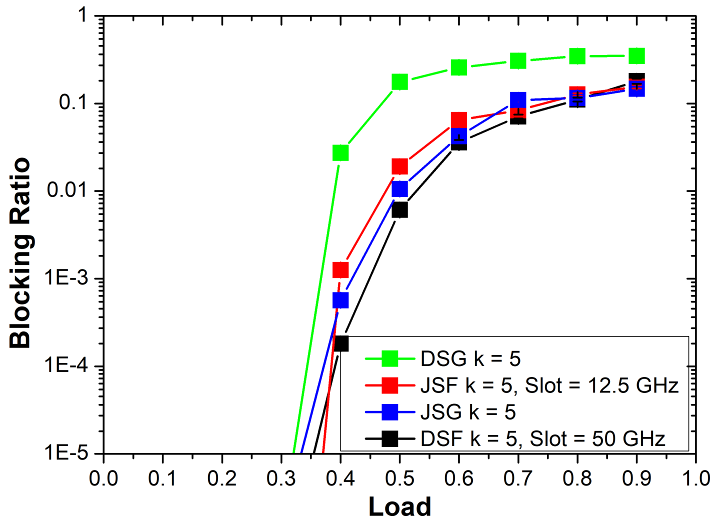


Figure 3.12: Blocking ratio obtained by the schemes in their best performing configurations.

multiple sub-lightpaths can lead to significant improvements in the blocking ratio. However, it is important to properly select the slot size since using narrow slot widths, or implementing the gridless approach, can lead to high fragmentation and inefficient use of the spectrum and higher blocking ratio. Furthermore, the disjoint methods also require more transmitters and receivers to establish all the required methods, hence increasing the complexity and the capital and operational costs of the network.

If we reduce the allowed flexibility and no sub-lightpaths can be established, the use of the gridless approach can improve the efficiency of the spectrum allocation, hence producing better results than the JSF scheme. This behaviour can be seen in Figure 3.12, where the JSG obtains lower blocking ratio than its flexgrid counterpart.

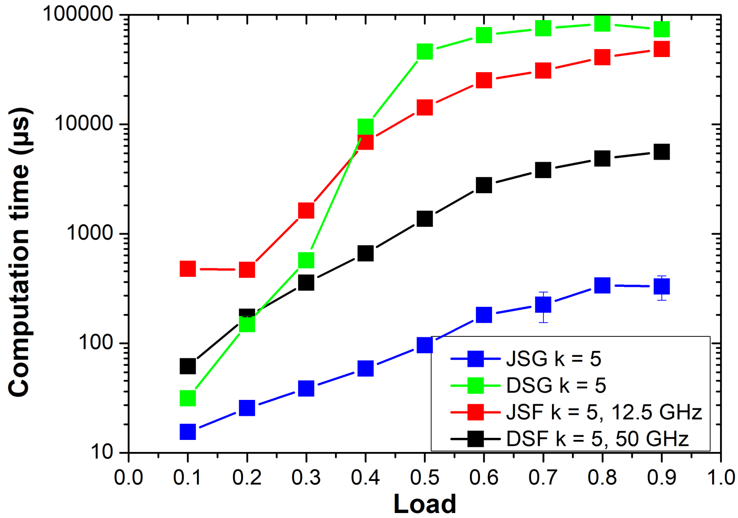


Figure 3.13: Computational times obtained by the schemes in their best performing configurations.

Figure 3.13 shows the computation times of the four methods in their best performing configuration in terms of blocking ratio. JSG is also the algorithm which requires less computation time to perform its tasks. JSF and DSG present, on the other hand, a large computational time, which grows with the network load. Therefore, they are not suitable methods to be deployed in a dynamic scenario since this kind of network requires really fast algorithms.

In conclusion, we have compared two types of flexibility to implement four RSA algorithms, which can consider the spectrum divided into slots or as a unified piece of bandwidth, and which can split the request into multiple sub-lightpaths or just establish one connection to which allocate a set of contiguous FSs or a slice of the spectrum. Employing split spectrum techniques can bring benefits in terms of reducing the blocking ratio of the network. However, it is important to combine them with an appropriate slot size since a narrow slot or the absence of slots, i.e., allocating just the sufficient amount of the spectrum which satisfies the traffic request, may lead to a misuse of the spectrum due to the guard-band establishment and a higher blocking ratio. Moreover, we have seen that the most flexible scheme, i.e., DSG, is the method which obtains worst results in terms of blocking ratio. Therefore, combining high flexibility with traditional RSA methods like $k-$shortest paths and first fit increases the complexity of the algorithm and the network costs but does not reduce the blocking ratio compared to algorithms that implement less-flexible approaches like JSF.

In the next section, we present a spectrum assignment technique which does not make use of the first fit approach to solve the spectrum allocation problem. Results will show that, using this algorithm, the network is capable of efficiently exploiting the flexibility, reducing the blocking ratio.

3.2 The Best Gap (BG) Spectrum Assignment

The RSA algorithms presented in the previous section combined different flexibility levels with regard to the consideration of the spectrum, as a sequence of slots or as a spectrum slice, and the possibility of dividing the bandwidth demanded by a traffic request over multiple sub-lightpaths, with classical RSA algorithms like $k-$shortest paths and first fit. However, results show that incrementing the flexibility does not entail a reduction of the blocking ratio when applied to those RSA algorithms. Furthermore, results also show the importance of carefully selecting the level of flexibility to be applied and, in case of considering the spectrum as a sequence of slots, the necessity of selecting the adequate slot width.

In this section, we propose a spectrum allocation technique called Best Gap which, combined with the $k-$shortest paths, exploits better the flexibility of EONs, achieving better performance in terms of blocking ratio than $k-$shortest paths and first fit.

3.2.1 Best Gap Technique

The previously proposed methods assign the bandwidth employing the first fit technique, i.e., they allocated the first set of contiguous FSs or the first slice of the spectrum which satisfies the traffic demand. However, this technique could lead to a bandwidth blocking situation. For example, let us have only one available route between the source and destination nodes, which has two sets of five and three FSs, where the four-slot sized set is the one with lower index. An example of this configuration can be seen in Figure 3.14. If a traffic request demanding three FSs arrives at the network, following the first fit technique, our proposals allocate three FSs belonging to the first available set of slots, i.e., the set of size four, as shown in Figure 3.14a. If a new traffic request demanding four slots arrives, this request is blocked since there are not sufficient contiguous FSs to satisfy the demanded traffic.

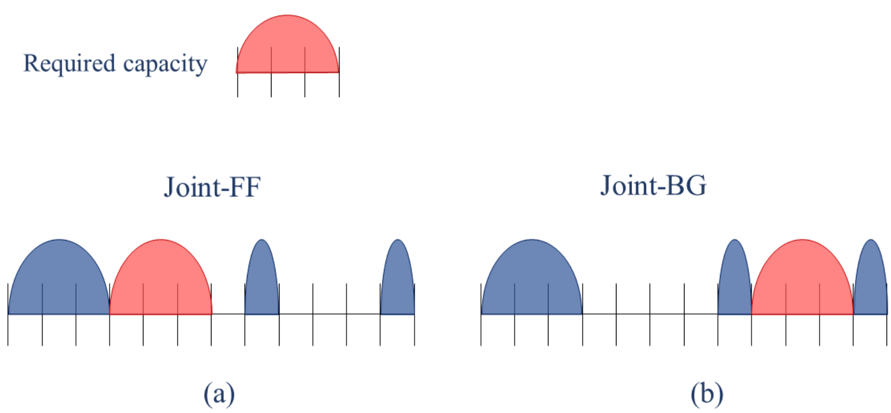


Figure 3.14: Example of resource allocation using Joint Flexgrid-First Fit and Joint Flexgrid-Best Gap. For simplicity, guard-bands are not considered in this example.

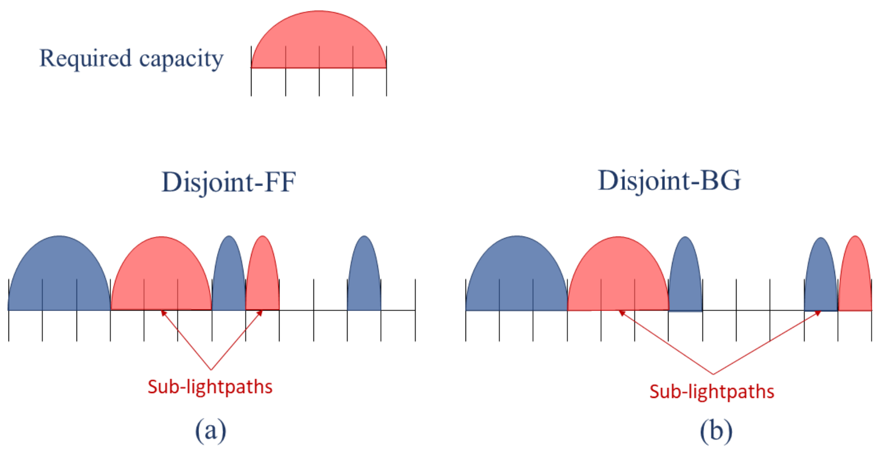


Figure 3.15: Example of resource allocation using Disjoint Flexgrid-First Fit and Disjoint Flexgrid-Best Gap. For simplicity, guard-bands are not considered in this example.

The Best Gap (BG) technique, on the other hand, addresses this problem by checking the sizes of the available sets of contiguous FSs in the route and allocating FSs from the set whose size is the closest to the number of FSs that satisfies the traffic demand. In the example of Figure 3.14, the Best Gap technique tracks the existence of two available sets composed of four and three available slots, respectively. When the three-slot traffic demand arrives at the network, the algorithm allocates the three available slots belonging to the three-slot size set, although they have a larger index, as shown in Figure 3.14b. In this manner, when the four-slot traffic demand arrives, it can be allocated to the available four-slot size set.

First fit and Best Gap can be combined with the proposed levels of flexibility to develop four new RSA algorithms: JSF-BG, DSF-BG, JSG-BG, and DSG-BG. Their functioning is very similar to their first fit counterparts since the only difference is how they allocate the spectrum resources. The Joint Spectrum techniques performs the following tasks:

1. Calculate the k- shortest paths between the source and destination nodes and sorts them in increasing order of hop length.

2. For each path:

   2.1 Calculate and sort sets of available FSs or available slices in decreasing size order.

   2.2 For each set or slice:

      2.21 If the size of the set or slice does not satisfy the demanded traffic:

         2.211 If a previous set or slice was checked and its size satisfied the demanded traffic, allocate corresponding frequencies of the previous set or slice, establish sub-lightpath and, after holding time is over, tear down the sub-lightpath. End the algorithm.

         2.212 Otherwise, stop the search in this route.

      2.22 If the size of the set or slice is equal to the demanded traffic plus the guard-band, reserve current frequencies, establish lightpath and, after holding time is over, tear down the sub-lightpath. End the algorithm.

2.23 If the size of the set or slice is bigger than the demanded traffic plus the guard-band, check next set or slice and repeat from step 2.21

3. If the algorithms are not able to assign the requested bandwidth after checking all the computed paths, the request is blocked.

The Disjoint Spectrum techniques can also be combined with BG. If a DS method cannot find enough available consecutive spectrum, either sets of FSs or spectrum slices, to allocate the demanded bandwidth to a single super-channel, it is allowed to split the demand traffic into various sub-lightpaths. In consequence, if the algorithm must split the traffic over multiple sub-lightpaths, it means that there is not a set of FSs or slice that best adapts to the demanded traffic, i.e., there is not a "best gap". Therefore, the methods compute the available sets of FSs or spectrum slices, sort them in decreasing size order, allocate the first sequence of available FSs or the first available spectrum slice, update the remaining bandwidth to be allocated, and search the most adapted set of FSs or slice that meets the requirements or assign the first portion of available spectrum. Figure 3.15 shows two examples of resource allocation using Disjoint Flexgrid combined with First Fit and Best Gap respectively. Considering just one possible route with three sets of available slots of sizes two, three and two respectively and an upcoming traffic request of four slots, Disjoint Flexgrid First Fit splits the demanded traffic into two sub-lightpaths, assigning the first set of size two and two slots of the second set, of size three, as Figure 3.15a shows. However, Disjoint Flexgrid Best Gap allocates the first set of available slots so that two other FSs need to be allocated in order to satisfy the requested traffic. since there are two sets of available FSs, one of size three and the other of size two, and the latter is more adjusted to the remaining traffic to be allocated, the algorithm selects the two-sized set, as shown in Figure 3.15b. Hence, the methods using Best Gap perform in the following manner:

1. Calculate the k- shortest paths between the source and destination nodes and sorts them in increasing order of hop length.

2. For each path:

   2.1. Calculate and sort sets of available FSs or available slices in decreasing size order.

   2.2. For each set or slice:

   2.2.1 If the size of the set or slice does not satisfy the demanded traffic:

   2.2.11 If a previous set or slice was checked and its size satisfied the demanded traffic, allocate corresponding frequencies of the previous set or slice, establish sub-lightpath and, after holding time is over, tear down the sub-lightpath.

   2.2.12 Otherwise, reserve current set or slice and update the remaining spectrum that needs allocation. Then, check following set or slice and continue with the frequency allocation.

   2.2.2 If the size of the set or slice is equal to the demanded traffic plus the guard-band, reserve current frequencies, establish sub-lightpath and, after holding time is over, tear down the sub-lightpath. End the algorithm.

   2.2.3 If the size of the set or slice is bigger than the demanded traffic plus the guard-band, check next set or slice and repeat from step 2.2.1

3. If the algorithms are not able to assign the requested bandwidth after checking all the computed paths, release the reserved resources and block the request.

3.2.2 Best Gap Results

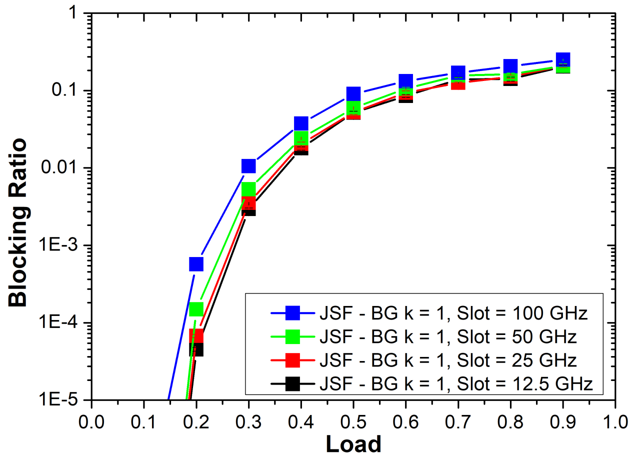
We want to compare the performance of the proposed RSA algorithm when they are combined with the $k-$shortest paths and first fit methods and when they are combined with the BG technique. Figures 3.16a, 3.16b and 3.16c show the behaviour of JSF-BG when $k = 1, 3$ and 5 respectively. As in the JSF method, the configuration which employs a slot size of 12.5 GHz achieves the best performance in terms of blocking ratio since it is the slot width which offers the greatest precision during the spectrum allocation, compared to other tested values. Furthermore, JSF-BG with $k = 3$ obtains better results than JSF-BG with $k = 1$, while the $k = 5$ configuration outperforms the other two, as happened with the original JSF method. Employing a small slot size and increasing the number of possible paths between the source and destination nodes help to reduce the blocking ratio.

If we observe Figures 3.17a, 3.17b and 3.17c, which show the blocking ratio for DSF-BG when $k = 1, 3$ and 5, respectively, we can observe that the best performance is achieved when the slot size is 12.5 GHz. If we compare this results with the results shown in 3.6, 3.7 and 3.8 we can see that, in the original DSF, there was a trade-off between the size of the slot and the number of connections since more flexibility implied more established connections and more guard-bands, leading to an inefficient use of the spectrum. The BG technique, on the other hand, finds the most adapted set of free FSs. Therefore, it reduces the number of connections into which the request is splitted and makes better use of the spectrum compared to the original DSF proposal. In consequence, using efficient spectrum assignment techniques is key to fully exploit the flexibility of EONs.

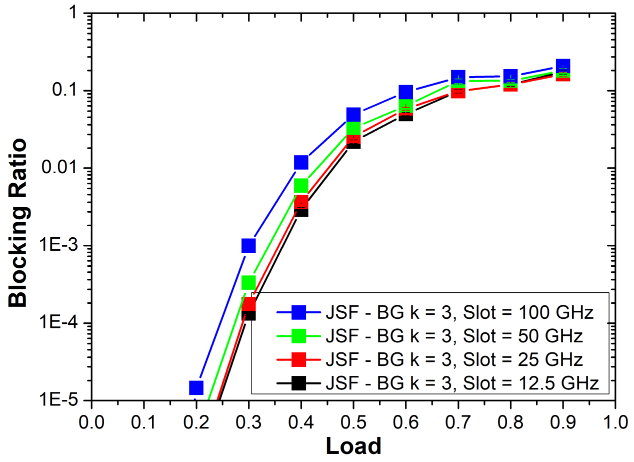
As in the DSF technique, increasing the number of paths between the source and destination nodes and, therefore, increasing the number of possible routes in which allocate sub-lightpaths also decreases the blocking ratio. Consequently, DSF-BG when $k = 5$ and the slot size is 12.5 GHz outperforms all the other possible configurations of DSF-BG.

Figures 3.18a and 3.18b show the blocking ratio achieved by JSG and DSG. This figures show that enabling BG also helps to improve the performance of JSG and DSG But, again, its influence is more evident in the most flexible scheme, i.e., in the DSG method, which clearly improves its performance compared to the original DSG results shown in Figure 3.11. As in the case of DSF-BG, DSG-BG makes better use of the spectrum and, in consequence, helps to improve the behaviour in terms of blocking ratio.

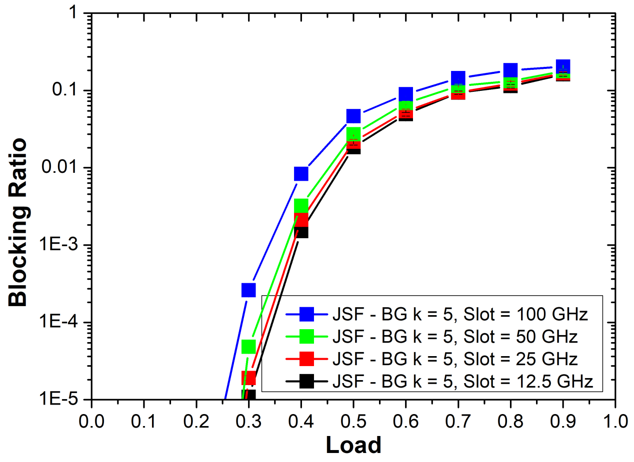
The impact of BG can be better seen in Figure 3.19, which shows the blocking ratio of the best performing configurations of all the proposed algorithms. In this figure can be observed that BG helps to improve the results compared to FF. For example, DSG-BG achieves an improvement of the blocking ratio compared to DSG in almost four orders of magnitude. It is also noticeable that the DSG scheme, combined with the first fit spectrum allocation technique, obtains the worst blocking ratio of all the proposed methods, up to three orders of magnitude higher than DSG-BG for some network loads. BG also helps to improve the behaviour of DSF, decreasing the blocking ratio up to one order of magnitude. However, the less flexible methods, i.e. JSF and JSG do not obtain great benefits using BG since their blocking ratio are similar or only slightly better when the BG technique is employed. Moreover, it can be seen that using BG allows to better exploit the flexibility, because combining BG with gridless or



(a) $k = 1$

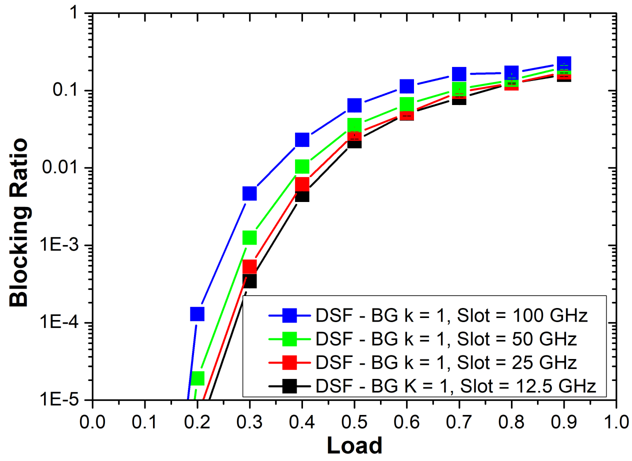


(b) $k = 3$

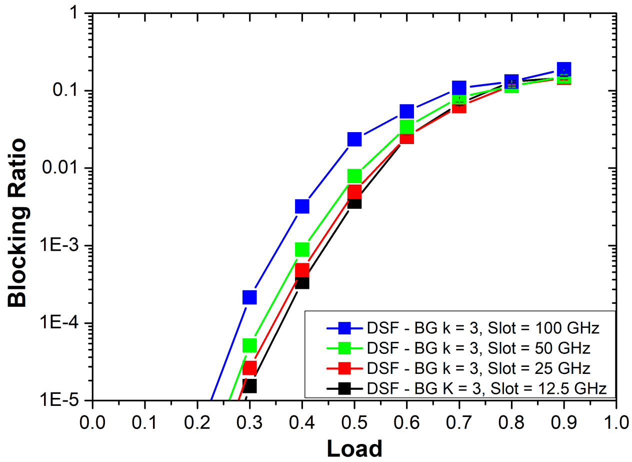


(c) $k = 5$

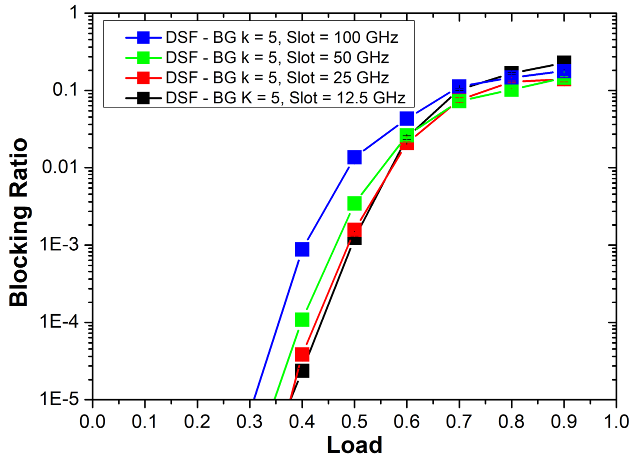
Figure 3.16: Blocking ratio achieved by JSF-BG when $k = 1, 3$ and 5 respectively.



(a) $k = 1$

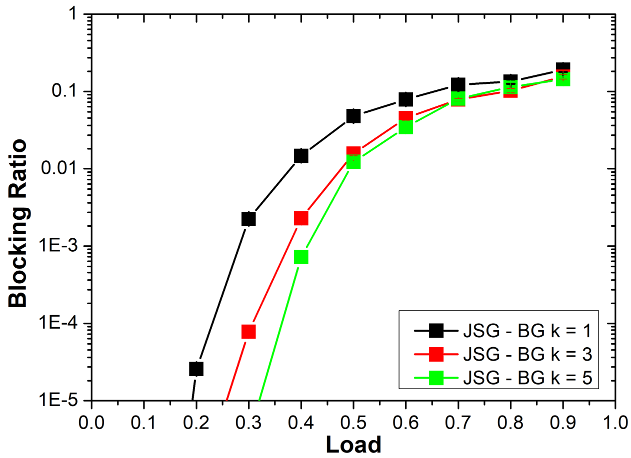


(b) $k = 3$

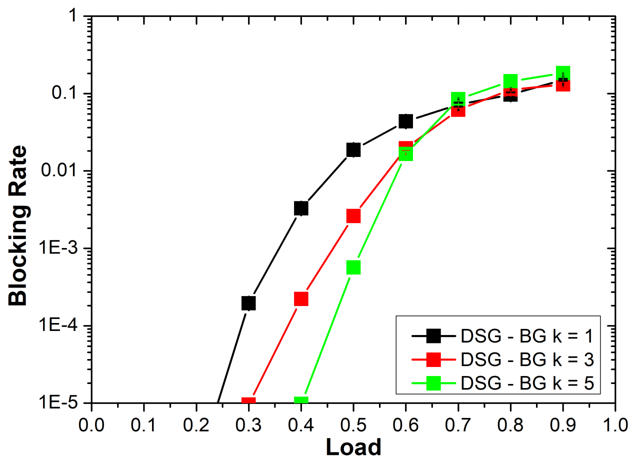


(c) $k = 5$

Figure 3.17: Blocking ratio achieved by DSF-BG when $k = 1, 3$ and 5 respectively.



(a) JSG



(b) DSG

Figure 3.18: Blocking ratio achieved by JSG and DSG when $k = 1, 3$ and 5.

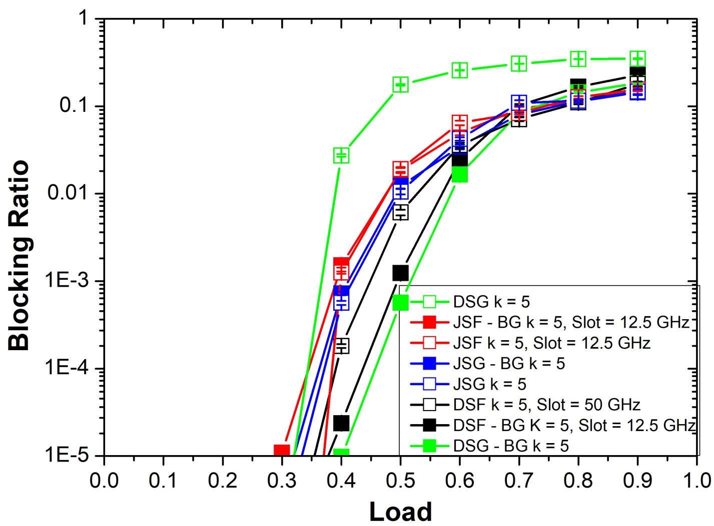


Figure 3.19: Blocking ratio for the best performing configuration of the proposed RSA algorithms.

disjoint traffic implies a reduction of the blocking ratio. For example, if we compare the most and least flexible methods, i.e., DSG-BG and JSF, we can observe that DSG-BG achieves a blocking ratio two orders of magnitude lower than the blocking ratio obtained by JSF.

If we observe the computational times of the methods, which are shown in Figure 3.20, we can observe that applying the BG technique to the DSG helps to reduce the computational time required to solve the RSA problem. In the case of DSF, the computational time using BG is significantly higher than the computational time using FF. This is due to the fact that the best configuration of DSF-BG employs slots of 12.5 GHz of size, whilst DSF with First Fit uses slots of size 50 GHz, reducing the number of elements or blocks that must be checked and, in consequence, the computational time compared to DSF-BG. This technique, on the other hand, slightly increases the computational time for JSF-BG and JSG, although they are still feasible in a dynamic network.

3.3 Conclusions

Elastic Optical Networks are a specially promising technology since they exploit the capacity of the fibre by assigning to each connection request the exact or nearly exact bandwidth that satisfies the demanded traffic. In this manner, the spectrum is used more efficiently and more traffic can be carried.

In these kinds of networks, the routing and wavelength assignment (RWA) problem is transformed into the routing and spectrum assignment (RSA) problem. The routing problem can be solved using traditional routing techniques as $k-$shortest paths, while the spectrum assignment problem can be solved using strategies as first fit. However, this kind of technology allows exploring new techniques and strategies and flexibility levels for solving the RSA

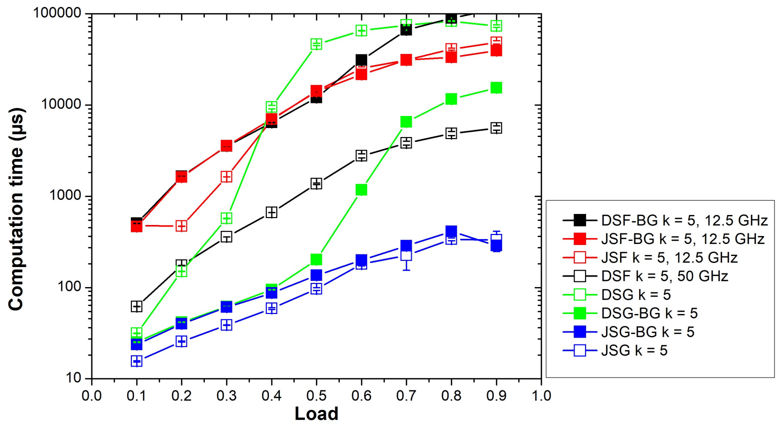


Figure 3.20: Computational time for the best performing configuration of the proposed RSA algorithms.

problem.

In this Chapter, we have combined two degrees of flexibility to propose new RSA strategies. The first flexibility degree is to consider the spectrum divided into slots, like traditionally considered in most of the studies on EON, or to consider the spectrum as a block and assign a spectrum slice of size adjusted to the requested frequency. The second flexibility degree consists in allocating the requested bandwidth in one lightpath or allowing the split of the request into multiple sub-lightpaths, with different allocated bandwidth. Combining both flexibility levels we have proposed the JSF, DSF, JSG, and DSG algorithms. Results showed that combining the highest levels of flexibility with First Fit does not improve the performance of the network in terms of blocking ratio. In conclusion, when $k-$shortest paths and first fit are used as RSA algorithms, it is more effective to split the request into multiple sub-lightpaths to reduce the blocking ratio, instead of following the gridless approach and allocate spectrum slices. Consequently, new spectrum assignment techniques must be proposed to more efficiently exploit the flexibility of EONs.

To address this problem, we propose the Best Gap technique, a spectrum allocation method which searches the most adapted set of consecutive FSs or spectrum slice, in terms of size, to the requested traffic. We have proposed four new RSA algorithms: JSF-BG, DSF-BG, JSG-BG, and DSG-BG. The use of BG improves the blocking ratio compared to First Fit. Furthermore, it helps to better exploit the flexibility, since the most flexible methods, i.e., DSF and DSG noticeably improve their performance compared with the same methods when the first fit technique is adopted.

To conclude, EONs require efficient RSA methods to show their full potential. Our spectrum assignment proposal, Best Gap, is and efficient technique capable of exploiting the network flexibility and improve its performance in terms of blocking ratio, compared to other classical spectrum assignment algorithms as first fit.

Chapter 4

NFV, SDN and MEC

The increasing number of connected users and devices, as well as the appearance of new applications and network services, have pushed the evolution of optical networks and favoured the appearance of technologies as WRON or EON. However, emerging paradigms and applications as Cloud Networking, Big Data, Industry 4.0, Tactile Internet or Social Networking are demanding flexibility, adaptability, and ubiquitous access to the new networks.

Furthermore, 5G, whose backbone is expected to be based on optical technologies, promises to bring new features like multi-tenancy, low latency services, high capacity, resource virtualisation or high-speed communications. In order to achieve these features, operators must face profound architectural changes in their networks.

Moreover, the appearance of new computation and networking paradigms may facilitate the adaptation of communication networks to the new demands and the increasing traffic, while helping operators to reduce the investments and the capital and operational costs.

In this chapter, the Network Function Virtualisation (NFV) paradigm, the technology that promises to reduce the management complexity and the network costs by deploying network functions as virtual appliances, is reviewed. The chapter also describes the architecture, the main building blocks and the most important design problems. Furthermore, two technologies related to NFV are briefly introduced: Software Defined Networking and Multi-access Edge Computing, reviewing their structure and main features.

4.1 NFV Overview

Network Function Virtualisation is a network architecture paradigm emerged from the collaboration between industry and the European Telecommunications Standards Institute [1], with the aim of reducing the number of hardware appliances that populate current networks. In order to deploy new services, operators perform operations called Network Functions (NFs) on associated traffic. This NFs cover a variety of processes like Network Address Translator (NAT), Firewall (FW), Traffic Monitor (TM) Wide Area Network (WAN) optimizer, Intrusion Detection and Protection (IDP) systems, proxies, or load-balancers [160]. These NFs are chained, i.e., they are connected following a certain order to achieve the desired network functionality. Hence, the NFs are essential for the correct performance of the network.

Commonly, NFs are deployed as proprietary hardware appliances called middleboxes. Each middlebox performs only one function and does not allow to perform more operations.

Furthermore, a middlebox is independently provisioned for peak loads and usually, middleboxes are managed separately. Additionally, they are expensive and their life cycle is short. Therefore, any time operators deploy a new service, they must acquire a number of new hardware appliances and manually integrate them in the network. As a consequence, operators incur in high Capital (CapEx) and Operational (OpEx) expenditures any time they deploy and operate a new service, with little revenue.

Network Functions Virtualisation (NFVs) aims to solve the aforementioned shortcomings by using standard IT virtualisation techniques [161]. This networking paradigm proposes to deploy NFs as virtual appliances called virtual network functions (VNF). VNFs are hosted by commodity servers, which could be located in data centres, network nodes or even end-user premises [161]. Compared to current practices, NFV introduces the following major differences [162], [2]:

- **Software and Hardware Decoupling**: In the traditional approach, NF are integrated software and hardware entities. The virtualisation approach separates software from hardware and leverages the possibility of an independent evolution of both parts.
- **Flexible Deployment of NFs**: If a pool of hardware resources is installed, the virtualization of NFs enables the possibility of automatically deploying functions on this pool of resources. Furthermore, the virtualization approach also leverages the resource reallocation and sharing.
- **Dynamic Operation**: The virtualisation approach allows the network operators to dynamically scale the NF performance according to the current network conditions.

With the advent and deployment of NFV, not only can operators benefit from reduced equipment costs, network flexibility, and faster service deployment cycle, but also from multi-version and multi-tenancy network appliances, which allow sharing resources across services and customer bases and from the introduction of varied eco-systems [161]. However, there are some technical requirements to be considered during the deployment of an NFV infrastructure [162]:

- **Performance**: Migrating from network functions implemented in dedicated hardware appliances to virtualised appliances may degrade some performance parameters as latency or throughput. Therefore, aspects as the performance of the deployed hardware platforms and the state of the network must be taken into account during the VNF deployment stage, in order to minimise the performance degradation.
- **Manageability and Scalability**: The NFV infrastructure must be capable of creating and placing VNFs at the required time and location, allocate and scale hardware resources, and choose and connect the VNFs to create a service chain. The manager entity should also be able to make the best utilisation of resources and be able to detect and manage any failure in the VNF infrastructure.
- **Security**: The deployment of a NVF environment brings new security concerns, due to the utilisation of third-party infrastructures, as data centres, new software elements as orchestrators and hypervisors, or the possibility of deploying software components from different vendors may introduce new vulnerability threads to the infrastructure that should be taken into consideration during the design stage.

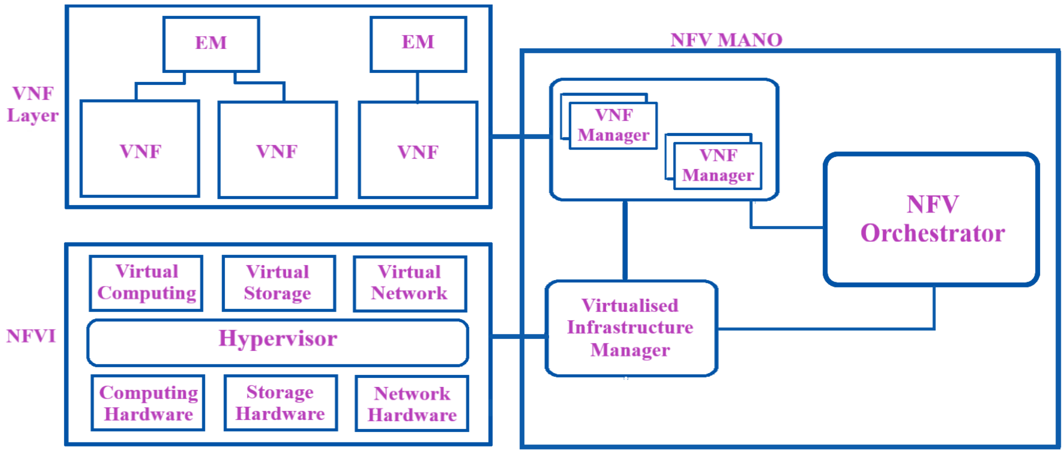


Figure 4.1: ETSI NFV Reference Architecture [1],[2].

- **Reliability and Stability**: Moving from dedicated hardware appliances to virtual appliances instantiated at prone-error hardware platforms may affect the performance of the services. It is important to deploy resilience and fault-management methods to ensure that the service level agreements and the reliability are guaranteed. Furthermore, migration should be performed so that the service continuity is not affected.

The following subsection introduces the ETSI NFV reference architecture and the NFV technical requirements.

4.1.1 NFV Reference Architecture

Figure 4.1 depicts the ETSI NFV reference architecture. The NFV architecture is divided into three key segments: Network Function Virtualisation Infrastructure (NFVI), NFV Management and Orchestration (NFV MANO) and Virtual Network Functions (VNFs).

The NFVI [1], [2], [163] is the set of hardware and software resources that composes the environment in which to establish, execute and manage Virtual Network Functions (VNFs). The computing resources are assumed to be Commercial-Off-The-Shelf hardware, whereas the storage resources can be either shared Network Attached Storage (NATs) or the storage devices inside the COTS server. The physical infrastructure of the NFV can be geographically distributed among different NFV Points of Presence (NFV-PoP or PoP). Consequently, the network interconnecting those PoPs would be part of the NFVI, distinguishing between [2]:

- **NFV-PoP Network**: The network which connects the computing and storage elements in an NFVI, including switching and routing for external communication.

- **Transport Network**: The network connecting different NFV-PoPs and the network which connects the NFV-PoP with other network elements which do not belong to an NFV-PoP. This network can be owned by one or different network operators.

The physical infrastructure provides the processing, storage, and connectivity to the VNFs through the Virtualisation Layer or hypervisor [2]. This layer is responsible for abstracting the physical resources into virtual resources, providing these virtual resources to the VNFs and allowing the software that implements VNFs to make use of them, so that VNFs can be executed. NFV MANO [2], [164] is the element responsible for managing the NFVI resources and orchestrating the allocation of the resources necessary for the correct performance of the VNFs. Therefore, MANO manages the lifecycle of VNFs and physical resources and orchestrate hardware resources [1] among other tasks. The NFV MANO is composed of the following functional identities:

- **Virtualised Infrastructure Manager (VIM)**: This block is responsible for the control and management of the storage, computational, and network resources of the NFVI.
- **VNF Manager (VNFM)**: This block is responsible for the management of the VNF lifecycle. Among other functions, the lifecycle management would include operations like VNF instantiation, scaling (increase or reduction of the VNF capacity), update and upgrade of the VNFs, and release. One VNFM entity can manage multiple VNF instances. However, each VNF instance is managed by only one VNFM entity.
- **NFV Orchestrator (NFVO)**: This block is responsible for the NFVI resource orchestration. Therefore, this block would allocate and release resources to the VNFs through multiple VIMs. Furthermore, this identity manages the lifecycle of the Network Services, being responsible for instantiating, scaling, updating and releasing Network Services, among other functions.

Finally, VNFs are the software deployment of the physical network functions. Each VNF would be managed by a functional block named Element Manager, responsible for tasks as configuration, accounting or security management of the VNFs. An EM may manage one or various VNFs in an NFV system. The set of Element Managers is called Element Manager System (EMS). In the next subsection we will explain in a little bit more detail the VNFs and the main research challenges.

4.1.2 Virtual Network Functions

Any service offered by a network operator has a Service Chain (SC) associated with it. An SC is a concatenation of NFs or, if the NFV paradigm is applied to the network, a set of VNFs which must be traversed in a specific order. When deploying a new service, operators must make decisions regarding the following aspects of the VNF deployment: placement, chaining, scheduling, migration, and orchestration.

The VNF-placement problem is the process for which operators decide the number of instances of the VNFs shall be created and which NFV-PoP hosts them. These NFV-PoPs can be Data Centres (DC), the Central Office (CO) or the nodes of the network. After placing the VNFs, it is also necessary to decide which instances are going to be part of the SC and the routes to connect each VNF to the following one in the SC. Furthermore, the chosen VNFs must be connected between them, so network resources must be allocated to the connections. This is known as the VNF-chaining problem.

The VNF-scheduling problem englobes two design aspects. The first one is scheduling the VNFs required to provide a service. This aspect is commonly solved in conjunction with the VNF-placement problem [1]. The second aspect is finding the most adequate time slot to perform a given task or VNF on a traffic flow, since it can impact the resource scaling decisions. For example, assigning new traffic to an already active VNF instance may require the operators to allocate more computing resources to this VNF to maintain the Service Level Agreement (SLA) of the service. If that were not possible, it could even cause the rejection of the service request. Whereas allocating this traffic to another, less loaded, VNF instance may avoid the computing resource scaling and a possible service request rejection [165].

When the VNF-placement, chaining, and network resource allocation are solved jointly, the problem is commonly known as the VNF-orchestration problem [166].

Finally, the VNF-migration problem must be solved when VNFs migrate from one location to another. This event can be triggered due to hardware maintenance or to keep some performance requirements as load balance. In case of migration, the VNF state must also migrate to the new location.

The VNF-placement and chaining problems have raised great interest in the scientific community. Consequently, we can find studies which may address different aspects of the placement and chaining processes, such as the resource allocation, the energy consumption, the load balancing, the latency or the blocking probability. It is also studied in different networks and network segments, such as Data Centre Networks (DCN), the metro/core networks or the access network. In the next subsection, we will cover some of the existing techniques in the literature that handle the VNF-placement and chaining problem for static scenarios.

4.1.2.1 VNF-Placement and Chaining Problem in Static Scenarios

The VNF-placement and chaining problems can be solved in static scenarios where the traffic matrix, i.e., the number of service requests are known in advance. In this kind of scenarios, optimal solutions can be found using mathematical formulations such as ILP or MILP. Furthermore, the problems can be solved aiming at optimising different parameters or fulfilling diverse key performance indicators. Consequently, we can find studies aiming at the minimisation of resource consumption, energy consumption or to ensure that the latency requirements are fulfilled.

There are several examples of VNF-placement studies that aim at finding an optimal solution through the development of mathematical models. Moens and Turck [167] presented an ILP formulation for solving the VNF-placement and chaining problems in hybrid and totally virtualised scenarios. The model aims at minimising the computational resource consumption and ensures that the network capacity is not exceeded and that the corresponding latency restrictions associated with each service are met.

In [168], Lin *et al.* considered the NFV use case Link Level VNFs [169], in which traffic flows that are routed through a given set of links must also traverse a certain set of VNFs, and proposed a MILP formulation that, taking as inputs the set of end-to-end requests and the physical substrate network with the associated link and node capacities, solves the VNF-placement and chaining problem minimising the resource consumption.

Bari *et al.* presented in [166] an ILP problem which decides the optimal number and placement of VNFs required to serve a given number of service connection requests, minimising the cost of the network in terms of deployment, energy consumption, and traffic forwarding costs. This study was further extended in [170] to include the minimisation of network resource fragmentation. Similarly, Wang *et al.* [171] proposed an ILP formulation to solve the VNF-placement and chaining problems in a SDN network. The proposal aims at minimising the network resource consumption, delay, CapEx and OpEx. The proposal does not consider, however, the impact of restricted computing resources on the VNF-placement and chaining.

Zeng *et al.* proposed in [172] a MILP formulation to solve the VNF-placement and chaining in an inter-DC EON, with the objective of minimising the overall cost of the network, which the authors modeled as the sum of the cost of the VNF deployment, the cost of the spectrum and the cost of the IT resources.

Luizelli *et al.* [173] proposed a math-heuristic method to solve the VNF-placement problem in the backbone network to reduce the overall network consumption, taking into account the computing and bandwidth constraints. The method is composed of two stages: A first stage in which authors use an ILP formulation to find a feasible solution to the VNF-placement problem and a second stage in which authors, taking as the starting point the feasible solution obtained in the first stage, use the Variable Neighbour Search approach to find a set of NFV-PoP that improves the placement of the VNFs obtained in the first stage.

In [174], Carpio *et al.* proposed an ILP formulation to solve the VNF-placement problem with the objective of optimizing the load balance in the network by making use of the concept replication. Authors distinguish VNFs as replicable and no replicable. If VNFs are not replicable, they are hosted in DCs, whereas the other class of VNFs can be replicated and hosted at smaller servers located at the network nodes. Replicas can be implemented as many times as required to find the optimum load balancing.

Other studies focus on the impact of the service latency requirements in the VNF-placement and chaining. For example, Savi *et al.* [7] studied the latency costs of consolidating multiple VNF instances in the same host. The authors identified two factors: the scaling latency cost and the context switching costs. The first one is due to the size of the VNFs since if a VNF requires more than one CPU core to handle the arriving traffic, a load balancer is required to balance traffic between CPUs, which adds a new layer in the architecture which may lead to performance penalties. The second one is due to the resource sharing among VNFs, since save/load context operations are required, which adds additional latency costs. In order to minimise the impact of these processing costs in a NFV-enabled network, authors proposed an ILP formulation for VNF consolidation which takes as inputs the physical network topology, the SCs to be established and optimally decides the placement of each VNF minimising the number of NFV-enabled active nodes, so that the latency constraint associated with each SC and the capacity constraints of nodes are and links are met. Results show that increasing the number of established SCs in the network leads to a higher context switching cost, whereas it does not impact the upscaling costs.

Jemaa *et al.* addressed the VNF-placement problem in inter-DC networks [175]. They proposed a MILP that aims at minimising the computational resources at the edge cloudlet (cloud environment closer to the end-user) and the central cloud as well as the QoS violations in terms of latency requirements. For real-time requirements, authors introduced two latency parameters: the latency the traffic incur when traversing a virtualization layer, i.e., the latency introduced by the Virtual Machine Management, and the VNF processing delay, both modelled as M/M/1 queues. Furthermore, authors also modelled the link delay between the cloudlet and the central cloud as an $M/G/\infty$ queue. In conclusion, authors not only solve the VNF-placement problem but also the computing resource allocation that minimise the desired objectives while meeting the latency requirements.

In [176], Bhamare *et al*. studied the optimal VNF-placement in multicloud environments and proposed an ILP formulation to solve the problem with the objective of minimising the latency due to VNF processing and inter-DC propagation, and the inter-cloud traffic. Their proposal models the inter-DC links as M/D/1 queues and the servers as M/M/1 queues.

Table 4.1: Mathematical formulations for solving the VNF-placement and chaining problems in a static scenario.

Authors	*Design Problem*	*Formulation*	*Optimisation Objective*
Moens and Turck [167]	VNF-placement and chaining	ILP	Minimise the computing resources
Lin *et al*. [168]	VNF-placement and chaining	MILP	Minimise the resource consumption
Bari *et al*. [166], [170]	VNF-placement and chaining	ILP	Minimise the cost of network. Extended to optimise the resource fragmentation
Wang *et al*. [171]	VNF-placement and chaining	ILP	Minimise the network resource consumption, delay, CapEx and OpEx
Luizelli *et al*. [173]	VNF-placement	ILP + heuristic	Reduce the overall network consumption
Carpio *et al*. [174]	VNF-placement	ILP	Optimise the load balance in the network
Savi *et al*. [7]	VNF-placement	ILP	Minimise the number of NFV-enabled active nodes and ensure that the latency constraints are met
Jemaa *et al*. [175]	VNF-placement	MILP	Minimise the computational resources employed at the edge cloudlet and the central cloud as well as the QoS violations in terms of latency requirements

Continued on next page

Table 4.1 – *Continued from previous page*

Authors	*Design Problem*	*Formulation*	*Optimisation Objective*
Bhamare *et al.* [176]	VNF-placement	ILP	Minimise the latency due to VNF processing and inter-DC propagation, and the inter-cloud traffic
Alleg *et al.* [177]	VNF-placement and chaining	MIQCP	Maximise the request acceptance rate, minimise the resource consumption and ensure that the latency requirements are fulfilled
Marotta *et al.* [178]	VNF-placement	BIP	Minimise the energy consumption while meeting the SC latency requirements
Cho *et al.* [179]	VNF-placement	ILP	Minimise the network latency
Arouk *et al.* [180]	VNF-chaining	ILP	Minimise the resource utilisation costs ensuring that the latency constraints are met

Alleg *et al.* [177] studied the VNF-placement and chaining problems considering the relationship between allocated computing resources assigned to a VNF and the expected associated latency. Hence, the solutions provided are delay-aware and meet the SC latency constraints. Authors proposed a Mixed Integer Quadratically Constrained Program (MIQCP) which solves the VNF-placement problem and flexibly allocates resources to the VNFs with the objective of maximising the request acceptance rate, minimising the resource consumption while ensuring that the latency requirements are fulfilled, considering that the VNF processing latency is linear. Comparing to the scenario in which processing delays are not considered, the network achieves a better resource utilization under the delay-aware scenario and a higher acceptance rate. Neither restricted computing resources nor the network technology or topology are considered in this proposal.

In [178], Marotta *et al.* proposed a Binary Integer Programming (BIP) model enhanced with robust optimisation which solves the VNF-placement problem in a DC, aiming at minimising the energy consumption while meeting the SC latency requirements. Cho *et al.* [179] also studied the VNF-placement in Cloud DC but focusing on the latency introduced by the network components. The authors consider three possible VNF-location scenarios which introduce different latency costs due to the network components: when consecutive VNFs in a chain are instantiated in different VM in the same server, when two consecutive VNFs are instantiated at different servers connected to the same switch and when two consecutive VNFs are instantiated at different servers not connected through the same switch, since diverse network elements are involved in the transmission of the traffic between consecutive functions in the three identified scenarios. Taking into consideration these scenarios, authors modelled the latency and proposed an ILP formulation that decides the optimal VNF-placement that minimises the network latency.

Arouk *et al*. presented in [180] an ILP formulation for solving the VNF-chaining problem for 5G networks, when VNFs are hosted by cloud environments. The model makes use of the 5G C-RAN concept, in which traditional Base Stations are divided into Remote Radio Units (RRU) and Base Band Units (BBU). BBUs perform network functions that can be virtualised and hosted in cloud environments. The proposed method aims at minimising the resource utilisation costs while meeting the latency requirements, but does not address the acceptance rate of the network.

Table 4.1 shows a summary of the different proposals that solve the VNF-placement and chaining problem using mathematical formulations in a static scenario.

Although the previous proposals are able to find an optimal solution to the VNF-placement and chaining problems, they cannot find a solution in polynomial time, since both problems are proved to be NP-Hard [170]. This issue can become a problem when the network size is large since it requires large computational time to find a feasible solution to the VNF-placement and chaining problems. Therefore, it is common to find proposals based on heuristics and meta-heuristics, which are able to find a solution to the problems in polynomial time.

Bari *et al*. [166], [170] complemented their ILP formulation with a heuristic that aims at reducing the cost of the network. Authors proposed the creation of a multi-stage graph, in which the first and last stages contain the source and destination nodes, and the stage i, where $i \in [1, s+1]$ with s being the number of stages, contains the $\text{VNF}_{(i-1)}$ of the service chain and the possible locations in which can be instantiated. A heuristic based on the Viterbi algorithm is then applied to solve the VNF-placement and chaining that minimises the cost of the network.

Wang *et al*. [171] proposed a framework called JoraNFV, composed of a one-hop scheduling algorithm that solves the VNF-scheduling problem, i.e., selects the instance of the following VNF in the SC that should be employed to minimise the bandwidth and delay costs and a multipath greedy algorithm to solve the placement and chaining problems. The framework aims at reducing the resource consumption, delay and network costs.

Chi *et al*. [181] studied the VNF-placement problem in DCNs, focusing on the optimization of inter-server traffic and computation resource consumption. In their study, the authors proposed a heuristic to solve the problem using the bin packing technique. For each set of root and three connecting nodes, the algorithm composes a set of VNFs that can be created, starting at the connecting nodes and finishing with the root node. Then, if there are enough computational resources, the VNFs are instantiated.

Carpio *et al*. [174] accompanied their ILP formulation with a Genetic Algorithm (GA) and a heuristic to find solutions to the VNF-placement problem based on the replication concept, which reduces the network costs. The proposed GA is divided into three sub-algorithms which solve the routing problem, the resource allocation and finally the resource replication. The first sub-algorithm finds a set of feasible paths between source and destination and computes the network costs. The output is employed by the second sub-algorithm to solve the resource allocation problem, i.e., to create VNF instances in the order required by the SC, and searches the placement and route which produces the lowest network cost after routing the traffic. Finally, the remaining paths are employed by the third sub-algorithm to place VNF replicas. The algorithm creates replicas until the network cost cannot be improved. The proposed heuristic is called Random Fit Placement Algorithm and considers all the feasible solutions to the ILP formulation. The algorithm randomly chooses one solution and places the VNFs. Then, the algorithm searches the paths traversing the VNFs in the correct order and chooses a number of feasible paths equal to the number of allowed VNF replicas. Finally, the algorithm randomly chooses one of the paths and returns the network cost and the traversed nodes.

Bhamare *et al.* also proposed a greedy algorithm to solve the VNF-placement problem in [176]. The method was further enhanced with a technique called Affinity-Based Allocation approach (ABA) heuristic to solve the problem in polynomial time. The greedy algorithm determines the number of instances of the VNFs required to attend the requests and places them in the clouds, considering that some of them may need to be located either at edge-clouds or core-clouds depending on Service Level Agreement requirements. Then, the algorithm allocates the user requests, ensuring that enough VNF instances exist in the cloud in which the request is assigned and that the delay restrictions are also met. The placement part is enhanced with the affinity-based approach, for which VNFs with higher traffic between them should be instantiated closer in the network.

In [182], Nguyen *et al.* proposed two offline heuristics to solve the VNF-placement and the routing problem, minimising the cost of the network. In their proposals, authors categorized the nodes of the networks according to their ability to connect to other nodes, the available computational resources or the prices of the resources and follow two possible strategies: assigning a low-ranked node to a VNF with high computational resource demands (Max-Min Resource heuristic), or assigning low-ranked nodes to low-demanding VNFs in terms of computational requirements (Min-Min Resource Heuristic). When the placement is finished, the routing between the nodes hosting the VNFs in the chain is chosen using the Shortest Path heuristic.

Marotta *et al.* proposed in [178] a heuristic to solve the VNF-placement problem in a DC. Authors tried to minimise the energy consumption by reducing the number of active servers which host VNF instances. The problem of the solution is that reducing the number of active NFV-enabled nodes increases the overall latency. Hence, authors concluded that there must be a balance between reducing the active VNF nodes and the latency constraints.

Cho *et al.* accompanied their ILP formulation in [179] with a heuristic called VNF-Low Latency Placement, which solves the VNF-placement while minimising latency. The approach followed by the authors is to establish the $\text{VNF}_{(i-1)}$ of an SC at the same physical node where the VNF_i of the chain is instantiated if the node has enough computation and network resources. If it is not possible due to lack of resources, the $\text{VNF}_{(i-1)}$ is placed at the node with lower network latency.

Khebbache *et al.* proposed in [183] a genetic algorithm based on the non-dominating sorting technique, which solves the VNF-chaining problem minimising the servers in use and the link resource utilisation. Their algorithm creates a set of initial individuals, which are solutions to the VNF-chaining problem. Each individual is represented by a chromosome, which is an array of size N, where N is the total number of servers in the network. Each position has an integer value, which represents the number of VNFs that the server can host. Therefore, the solution is the number of VNF instances created at each server in the network. These individuals are created using the first fit heuristic and sorted in increasing order of cost. Then, individuals are mutated, choosing two random individuals, a crossover point and interchanging the chromosomes, and mutated, by randomly changing the values of the chromosome. The algorithm returns the best results in terms of non-dominance and diversity.

Arouk *et al.* also presented in [180] a Multi-Objective Placement (MOP) algorithm for solving the VNF-placement and chaining problem in 5G networks deploying C-RAN architecture with virtualised BBUs. The algorithm divides the nodes of the clouds into Eligible Regions and, for each VNF, finds the corresponding Eligible Region in terms of latency requirements. This step avoids instantiating all the VNFs at the edge, which may cause problems when trying to establish new chains if the traffic of the network increases. Then, the algorithm looks for the Candidate Nodes that have enough computational resources to host the VNF. Finally, the algorithm chooses the host node among the Candidate Nodes, according to the chosen target objective, i.e., to balance the load, to maximise the virtualized BBUs or to minimise the active NFV-enabled nodes, etc. If no node is found in the eligible region, the algorithm looks for a Candidate Node in the region immediately below to the corresponding region.

Agarwal *et al.* proposed a method for solving the VNF-placement and CPU allocation jointly in 5G scenarios, so that the latency is minimised [184]. The authors consider the propagation delay and the processing delay. The latter is calculated modelling the VNFs as M/M/1 queues. The method decouples both problems and solves them sequentially, so first solves the VNF-placement by using a confidence-based heuristic, i.e., authors place the VNF, compute a confidence score of the locations and choose the one with higher confidence score. Then, authors solve the CPU allocation problem.

Table 4.2 shows the presented heuristics for solving the VNF-placement and chaining problems in a static scenario.

In the present section, we have reviewed several proposals which study the VNF-placement and chaining problem in scenarios where the traffic matrix is known in advance. However, realistic scenarios should consider the time-varying nature of traffic. Consequently, we will review some proposals in the literature which solve the same problems in dynamic scenarios.

4.1.2.2 The VNF-Placement and Chaining Problem in Dynamic Scenarios

The previous studies solve the VNF-placement and/or chaining problem on static scenarios where the matrices of service requests are known in advance. However, there are multiple studies in the literature which address the same problems from a dynamic point of view. In this kind of scenarios, the service requests arrive on real time. Therefore, the SC provisioning occurs when the service request arrives at the network, which means that the decisions regarding the placement and chaining, i.e., creating and assigning computing resources and locations to new instances of VNFs, the chaining and the allocation of network resources must be taken when the connection request arrives, with the currently available network and computing resources. Consequently, the methods required to solve the VNF-placement and chaining problems must be able to solve the problem in a very short period of time.

We can find proposals in the literature which solve the VNF-placement and chaining problems by means of mathematical models. For example, Ghaznavi *et al.* [185] presented the elastic VNF-placement problem and proposed a mathematical model that solves the problem

Authors	*Design Problem*	*Optimisation Objective*
Bari *et al.* [166], [170]	VNF-placement and chaining	Heuristic to reduce the cost of network
Wang *et al.* [171]	VNF-placement, scheduling and chaining	Framework JoraNFV, that reduces the network resource consumption, delay and costs
Chi *et al.* [181]	VNF-placement	Heuristic which optimises the inter-server traffic and computation resource consumption
Carpio *et al.* [174]	VNF-placement	Genetic algorithm which optimises the load balance in the network
Bhamare *et al.* [176]	VNF-placement	Heuristic which reduces the latency due to VNF processing and inter-DC propagation
Nguyen *et al.* [182]	VNF-placement	Heuristics which aim at minimising the cost of the network
Marotta *et al.* [178]	VNF-placement	Heuristic to reduce the energy consumption and meet the SC latency requirements
Cho *et al.* [179]	VNF-placement	Heuristic which minimises the network latency
Khebbache *et al.* [183]	VNF-chaining	Genetic algorithm to minimise the active number of servers and the link resource utilisation
Arouk *et al.* [180]	VNF-placement and chaining	Multi-Objective Placement algorithm that maximises: • the load balance • the virtualised BBUs or minimises the active NFV-enabled nodes
Agarwal *et al.* [184]	VNF-placement	Heuristic which minimises latency

Table 4.2: Heuristics for solving the VNF-placement and chaining problems in static scenarios.

minimising the operational costs.

Cziva *et al.* [186] proposed a method to dynamically solve the VNF-placement at the edge network considering the user demands, the network dynamicity, and the user mobility to achieve the latency-optimal location of the VNFs. This method acts in two stages: first, authors solve statically the optimal VNF-placement by means of an ILP formulation. Then, they apply a scheduler that triggers a re-evaluation of the VNF-placement, by choosing the optimal stopping time t which, in this case, is the time in which the cumulative latency violations is the closest to the maximum latency violation tolerated by the system. In this manner, the scheduler reduces the number of times the re-evaluation is triggered and, in consequence, the migration costs generated when VNF must be migrated.

In [187], Rankothge *et al.* proposed a set of ILP equations to solve two different aspects of the VNF-placement problem: the provisioning of new VNFs and the scaling of existing VNFs, in cloud environments. The set of ILP formulations aim at minimising the required resources in terms of active servers, the number of links and link utilization when creating new VNF instances and minimising the number of changes while guaranteeing that the requirements due to traffic changes are satisfied when scaling existing VNF instances.

Authors	*Design Problem*	*Technique*	*Optimisation Objective*
Ghaznavi *et al.* [185]	Elastic VNF-placement	Mathematical Model	Minimises the operational costs
Cziva *et al.* [186]	VNF-placement	ILP + re-evaluation	Minimises the migration costs
Rankothge *et al.* [187]	VNF-placement	ILP	Minimises the required resources in terms of servers, number of links and link optimisation

Table 4.3: Mathematical formulations for solving the dynamic VNF-placement and chaining problems in dynamic scenarios.

A summary of the proposals which implement mathematical formulations to solve the dynamic VNF-placement and chaining problems is shown in Table 4.3.

Although mathematical models can be proposed to solve the dynamic VNF-placement and chaining problems, these are not the most adequate methods to employ in dynamic scenarios since the VNF-placement and chaining are NP-Hard problems [170] and, therefore, a mathematical model would not be able to solve the problem in polynomial time. For this reason, the most common approach to solve the problems is the proposal of heuristics and meta-heuristics.

Ghaznavi *et al.* [185] proposed a heuristic for solving the elastic VNF-placement problem in DC-networks called Simple Lazy Facility Location. The heuristic aims at minimising the operational costs of the network. Upon a connection request, the algorithm assigns the traffic to an existing VNF with minimum transport cost and, for each node of the network, calculates the migration and installation transport potential, i.e., the difference in the transport cost of the chosen VNF at the current node and the cost if the VNF migrates to another node or the cost of creating a new VNF in the node. Then, the algorithm computes the best migration and installation potentials and selects the best option, i.e., leaving the traffic to the assigned VNF, migrating to another node or creating a new instance of the VNF. When a connection is released, the algorithm optimises the VNF-placement by deciding if the VNF to which the demand was allocated should migrate to another node or removed from the network. The algorithm computes the difference in costs before and after migrating the VNF to another node and the cost before and after removing the VNF. Lastly, the algorithm selects the option which minimises the costs.

In [182], Nguyen *et al.* complemented the proposed offline heuristics with an online heuristic to solve the VNF-placement and the routing problems, which aims at maximising the acceptance ratio. The heuristic computes the shortest path between origin and destination and then locates the VNFs at the nodes in the route one by one.

Rankothge *et al.* complemented their ILP in [187] with a genetic algorithm which finds optimal or near-to-optimal solutions to the VNF-placement problem in cloud environments, reducing the required computing time. Authors assumed that a connection request may specify the required VNFs and the interconnectivity between them, which authors called policy. Therefore, the algorithm creates populations of individuals, in which individuals are full solutions to the VNF-placement problem. The full solutions are composed of partial solutions, which contain the servers considered to place the VNFs and the paths considered to route the traffic according to the different policies. Then, the algorithm computes the fitness of the solutions and creates a new population by applying crossover and mutation operations. In crossover, the algorithm randomly selects two individuals from the set and a partial solution. Then checks if the first partial solution can be applied to the second partial solution. If it can be applied, the solutions are interchanged. In the mutation operation, the algorithm either can change the placement of the VNFs or the paths. If the placement is change, the algorithm randomly selects a partial solution and tries to move all the VNFs to one, different server, and computes new paths. If the mutation operation changes the path, then it randomly selects a partial solution and a VNF and changes the path between the selected VNF and the following VNF in the chain.

Beck *et al.* addressed the dynamic SC provisioning in [188] and proposed a heuristic to solve the problem with the objective of maximising the acceptance ratio. For each incoming SC request, the algorithm determines the set of VNFs that must be instantiated. Then, it randomly selects a node of the network for creating the first VNF, then selects the next VNF in the chain and tries to allocate it in a node with sufficient network and computing resources. The process is repeated until the SC is provisioned. If the algorithm is not able to allocate a VNF at one point, reverses the last decision and considers other allocation options.

Zeng *et al.* complemented their static MILP formulation in [172] with a greedy algorithm to solve the VNF-placement problem in an inter-DC EON. The proposal jointly finds the location of the required VNFs and allocates the required spectrum resources and route to establish the SCs.

Wang *et al.* studied the dynamic VNF-placement in DCs [189]. Authors proposed an online method which aims at minimising the operational and deployment costs. The method computes the total number of VNF instances required at a certain time slot to establish the SCs and serve the requested traffic. Then, authors proposed an algorithm which solves the initial placement of the computed number of VNF instances assuming that the served traffic is equal to the maximum flow which the system can support. Finally, authors proposed a heuristic to solve the final number and placement of the VNF instances. The algorithm employs the obtained initial VNF placement, decides whether the initial placement have enough instances to serve the SC or new ones must be created, and puts the instances which have not been employed to create the chain at idle state. Finally, the algorithm calculates the number of time slots in which the instances can remain idle before been removed from the system, as a function of the operational and deployment costs. The study is extended in [190] to consider traffic fluctuations and inter-DC bandwidth limitations, so that the authors slightly modified their method to only solve the required number of VNF instances at a certain time slot, and proposed an additional step which locates each VNF instance minimising the total congestion.

López *et al.* [191] studied the impact on the number of accepted requests, latency and resource consumption of different VNF-placement and chaining heuristics. Authors proposed four heuristics based on greedy algorithms which search the placement which either introduces minimum latency between the source and destination nodes, maximises the resource usage, i.e., uses the hosts with larger available computing and network resources, minimises the overall delay by placing the VNFs at the most central nodes first or jointly optimises the latency and the resource consumption.

Otokura *et al.* proposed in [192] a genetic algorithm-based method to dynamically solve the VNF-placement problem minimising the delay and the number of active CPU cores. The individuals, or solutions to the VNF-placement problem, contain the physical servers, the virtual machines created at each server and the VNF type and instance created at each VM. The algorithm computes the fitness of each individual and measures the behaviour in terms of delay and core utilisation, or in terms of the number of delay violations. Individuals are mutated to create new offspring and populations, but authors do not employ the crossover operation. Furthermore, authors proposed a method called Evolvable VNF Placement, which periodically changes the fitness objective of the genetic algorithm to enhance its performance and accelerate the evolution process. Authors consider two contributions to the delay: the propagation delay and the processing delay. The processing delay is modelled as a M/M/1 queue.

There are proposals that focus on the VNF-placement and chaining problems in metro/core and access network, closer to the end-user, essential to meet the most stringent latency requirements, as Savi *et al.* shown in [8]. In this work, authors studied VNF-placement and chaining problems at the edge network and metro/core network, when latency-sensitive services are to be offered by a network operator. In this case, operators must choose between the "cheap" solution, which would be centralising all the VNFs in a DC, at the risk of degrading the performance of the network in terms of latency constraints fulfilment, or placing the VNFs at the network edge or the metro/access network nodes, closer to the end-user. In this case, Central Offices and the nodes of the network would be the potential hosts of the VNF instances. Authors proposed a heuristic to solve the VNF-placement problem in an edge network with latency-sensitive SCs, considering the physical topology, the bandwidth of the links and the capacity of the nodes. In the proposal, the SCs firstly try to employ existing VNFs in the network or create new ones in active NFV nodes if the VNFs do not have enough available capacity. If the established SC does not meet the delay requirements, the resources are released and VNFs are placed in inactive NFV nodes, i.e., nodes which have not hosted VNFs before, on the shortest latency path. The result provides the position of the VNF instances so that the SC is established, the latency requirements are met, and the capacity constraints are fulfilled, and showed that for those services with restrictive latency requirements, VNFs should be located closer to the end-user.

In [193], Askari *et al*. proposed an algorithm for dynamic VNF-orchestration in metro networks, which adjusts the location of the VNFs to the network state to ensure that the latency threshold of the different SCs are met. Authors consider the propagation delay, the O/E/O conversion, the Forward Error Correction (FEC) and the context switching delay as the main contributors for the overall latency. The algorithm first tries to use active VNFs in the network. If it does not find active VNFs with enough computational resources, it tries to allocate them in the nodes conforming the shortest path between source and destination. Finally, once the VNFs are placed, the algorithm checks if the latency requirements are met. If not, the algorithm tries to minimise the delay by calculating the longest virtual link delay and placing the VNFs hosted at the end points of that link at the adjacent virtual nodes.

Lastly, Pedreno-Manresa *et al*. introduced a VNF-placement and chaining problem-solving algorithm in [9], [10], which considers rapid time-varying traffic, Quality of Service (QoS) and Quality of Experience (QoE) expectations in 5G-access scenarios. The authors presented a heuristic that dynamically places the SC, ensuring that the computing resources and the network bandwidth requirements are met, while minimising the blocking probability. Their heuristic aims at utilising available VNF instances located at the local node to which the requesting user is connected or creating new ones if there are enough computational resources. If it is not possible, but there are enough network resources to connect to the Central Office, the algorithm aims at employing existing VNFs or creating new ones at this node. If the operation fails due to lack of network or computing resources, the connection is blocked.

Table 4.4: Heuristics and meta-heuristics for solving the VNF-placement and chaining problems in dynamic scenarios.

Authors	*Design Problem*	*Technique*	*Optimisation Objective*
Ghaznavi *et al*. [185]	VNF-placement	Simple Lazy Facility Location heuristic	Minimises the operational costs
Nguyen *et al*. [182]	VNF-placement and routing	Shortest Path + VNF-placement at nodes of the path	Maximises the acceptance ratio

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Table 4.4 – *Continued from previous page*

Authors	*Design Problem*	*Technique*	*Optimisation Objective*
Rankothge *et al.* [187]	VNF-placement	Genetic Algorithm	Minimises the required resources in terms of servers, number of links and link optimisation
Beck *et al.* [188]	VNF-placement and chaining	Backtracking algorithm	Maximises the established connections
Zeng *et al.* [172]	VNF-placement	Greedy algorithm	Minimises the overall cost of the network
Wang *et al.* [189], [190]	VNF-placement	Bin-packing (pre-planning) + heuristic for single SC placement	Minimise the provisioning cost
López *et al.* [191]	VNF-placement and chaining	Greedy algorithm	Four objectives: • Minimises introduced latency • Maximises resource usage • Minimises overall delay • Optimises latency and resource consumption
Otokura *et al.* [192]	VNF-placement	Genetic Algorithm	Minimises the delay and the active CPU cores
Savi *et al.* [8]	VNF-placement and chaining	Heuristic	Meet the latency and the capacity constraints
Askari *et al.* [193]	VNF-placement and chaining	Heuristic	Meet the latency constraints

Continued on next page

Table 4.4 – *Continued from previous page*

Authors	*Design Problem*	*Technique*	*Optimisation Objective*
Pedreno-Manresa *et al*. [9], [10]	VNF-placement and chaining	Heuristic	Guarantee and acceptable Quality of Service and Experience

The proposals that implement heuristics and meta-heuristics to solve the VNF-placement and chaining in dynamic scenarios are summarised in Table 4.4.

We have seen the importance of the VNF-placement and chaining and the interest that these problems have raised in the scientific community. The problems can be solved in static and dynamic scenarios, and several efforts have been presented which aim the problems separately or jointly, using mathematical formulations as ILP or MILP, or heuristic approaches which try to find a solution in less computational time that the optimal mathematical formulations. In the next subsection we will introduce another important issue that affects NFV-environments: the survivability of VNFs.

4.1.2.3 Survivability in NFV

The VNF-placement and chaining problems are key design stages to establish a service connection optimising the network and computing resources and, therefore, the acceptance ratio and the operational and capital costs of the networks. Furthermore, it is important to provide mechanisms which protect the established connections from a potential failure. If a node, a VNF or a link in the network fails, the SCs traversing those nodes or links or employing the failing VNF will be disrupted, which may affect thousands of end-users and cause the loss of important amounts of data.

Fault-management techniques can be classified according to the element to which they provide protection. This can be the Service Chain, the individual VNFs or the path of the SC. If the SC is to be protected, then a backup SC is found, i.e., backup VNFs and network resources. In case of a failure, the traffic is rerouted through the backup SC, hence this kind of scheme provides end-to-end SC protection. Figure 4.2 shows an example of this kind of protection schemes. We can see that network resources are allocated between primary VNFs (blue arrows) and between backup VNFs (red arrows) if they are placed at different nodes. However, there are no network resources reserved to connect primary to backup VNFs and vice versa. Hence, if a node hosting a primary VNF fails, the traffic necessarily has to traverse the entire backup SC.

On the other hand, VNFs can be protected individually, searching backup resources for each primary VNF. In case of failure, the SC employs the backup VNF which protects the failing primary one, but then returns to the working VNFs. Therefore, also network resources to connect the primary VNFs and the backup VNFs must be provided. An example of an individual VNF protection scheme for a primary SC composed of four VNFs can be seen in Figure 4.3. As shown in the figure, if node A fails, the traffic traverses the backup VNF_1 located at Node B, and then goes to the primary VNF_2 using the virtual link established between backup VNF_1 and primary VNF_2. If node B fails, then the traffic traverses the primary VNF_1, travels

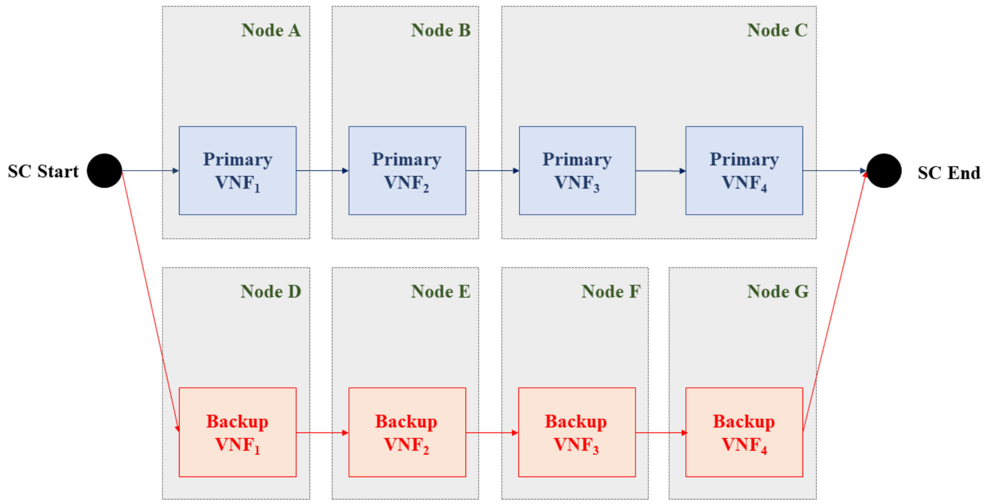


Figure 4.2: End-to-end SC protection scheme for a SC with four primary VNFs.

to the backup VNF_2, using the corresponding virtual link, then traverse the backup VNF_3 and travels to the primary VNF_4. Finally, if node C fails, the traffic travels from primary VNF_3 to the backup VNF_4 and arrives at the end point of the SC, using the corresponding virtual links.

Finally, network resilience may be the focus at the moment of providing protection to SCs. If that is the case, we can employ the link/path protection schemes developed for network protection, as shown in sections 2.1.1.4 and 2.2.4.

There are several studies in the literature that address the SC protection approach. Hmaity *et al.* proposed in [194] three ILP formulations to provide end-to-end SC protection. Each of these formulations implements one of the following protection schemes:

- **Path Protection**: In this case, the path of the backup SC must be link-disjoint with respect to the working path. However, the backup VNFs do not need to be in different nodes from the working VNFs. Furthermore, if no VNF protection is offered, the backup SC can employ the same VNF instances as the primary SC.

- **Node Protection**: In this case, the backup SC employs VNF instances located at different nodes with respect to the primary SC, i.e., the working and backup SC are node-disjoint.

- **Path and Node Protection**: Primary and backup SCs share neither VNF resources nor network resources, so they are link and node-disjoint.

Ye *et al.* proposed a method for SC embedding [195] in an inter-DC network, that aims at minimising the network resource consumption. The algorithm builds a decision tree containing the VNFs which can be combined, i.e., which can be hosted at the same cloud, and their neighbours, sorted in decreasing cost, or bandwidth consumption. In this manner, the algorithm solves first the location of the VNFs which consume more bandwidth, and then collocates the less bandwidth consuming VNFs. This algorithm is further enhanced to provide end-to-end SC protection, introducing the dedicated and shared schemes. In dedicated protection, a backup

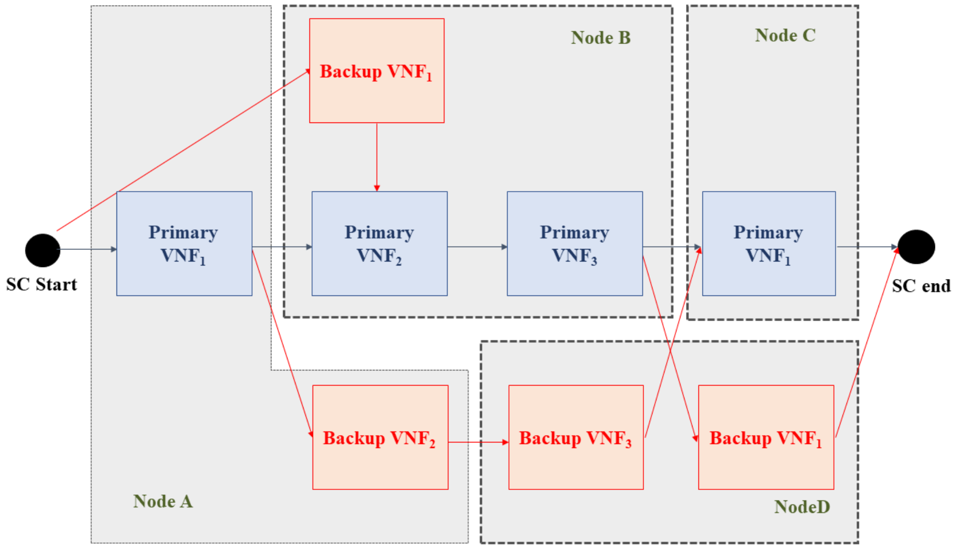


Figure 4.3: Individual VNF protection scheme for a SC with four primary VNFs.

SC protects only one working SC. Their proposal provisions initially a primary SC and creates a new virtual topology eliminating the nodes and links allocated to the primary SC and the computing and network resources allocated to other existing working and backup SCs. Then, the proposed algorithm is executed to find a backup SC. In shared protection, backup resources can be shared between the services whose primary SCs are totally node and path-disjoint. Therefore, the scheme implementations are similar to the dedicated approach but only backup resources, either computational or network ones, are removed from the new virtual topology if they protect SCs employing the same VNFs or routed through common physical links.

The individual VNF protection approach has also been covered in the literature. VNF protection can be shared when a backup VNF protects two primary VNFs located at different nodes, or dedicated, if a backup VNF protects only a primary VNF. Since not only computing resources but network resources to connect the primary and backup VNFs are required, the dedicated scheme requires great consumption of both kinds of resources. The shared scheme, on the other hand, is able to reduce the resource consumption, but may be insufficient to provide reliability in a multi-node or multi-VNF failure scenario. To address this problem, Fan *et al.* [196] proposed a heuristic for SC provisioning with VNF protection that aims at minimising the number of backup VNFs required to guarantee a certain network reliability degree, proposing a new protection scheme for multi-VNF failure, called Joint Protection. This scheme allocates enough computational resources to a backup VNF, so it is able to protect two primary VNFs if they fail at the same time. The algorithm computes the reliability of the network in terms of Mean Time Between Failures. Then, it selects the two less reliable primary VNFs, allocates them a backup VNF, and recomputes the total reliability of the network. The backup VNF is located at the node with higher available computing resources, and backup network resources are also provisioned. The algorithm repeats the process until achieving a certain reliability degree. Casazza *et al.* [197] proposed a greedy algorithm and a variable-neighbourhood search to solve the VNF-placement of the primary VNFs and protect them with a backup VNF.

The algorithms, however, do not perform VNF-chaining and, therefore, no network resources between primary VNFs or to connect them with the backup resources are reserved.

Beck *et al*. enhanced their algorithm in [188] adding path and node protection. In the path protection scheme, at each primary VNF provisioning iteration, a link-disjoint backup path is also computed. In the node protection scheme, at each VNF provisioning iteration, a backup VNF is created in a different node and network resources are reserved to connect the previous primary VNF with the backup VNF and the previous backup VNF with the new backup VNF.

Finally, some authors focus on the network resilience, proposing path protection schemes but not VNF protection schemes. Tomassilli *et al*. [198] proposed a link protection scheme for SC provisioning. Authors proposed an ILP and a decomposition model for shared and dedicated link protection which provisions an SC with their primary and backup, link-disjoint paths for each service request. Gao *et al*. [199] addressed the path protection issue by proposing an ILP formulation and a heuristic algorithm which solves the VNF-placement and chaining. In this case, multipath transmission is employed, so that the proposals calculate k paths between the hosting data centres of the VNFs and reserve the required capacity.

The reviewed proposals to address the survivability problem in NFV are shown in Table 4.5.

4.2 Technologies related to NFV: SDN and MEC

We have just discussed the NFV paradigm, which will bring flexibility and manageability to the networks while, at the same time, reducing their cost. We have briefly introduced the NFV architecture and its main components, and we have focussed on the main design problems of this kind of environments: placement, chaining, and survivability.

For this kind of networks to be implemented and develop their full potential, it is also necessary to introduce new network and computing technologies. In this subsection we will present two new technologies related to NFV: Software Defined Networking and Multi-access Edge Computing.

4.2.1 Software Defined Networking

Current networks present severe management difficulties: firstly, they present a high heterogeneity, i.e., routers, switches, and other network devices are provided by different manufacturers and vendors. Moreover, networks also present difficulties in the device management since they must be handled individually, commonly with vendor-specific commands. Furthermore, network devices are vertically integrated: the controllers responsible for deciding how to manage the traffic and the physical parts forwarding the traffic packets are integrated into the same device [200]. Consequently, techniques to facilitate the network management and configuration must be proposed.

SDN is a networking paradigm expected to facilitate the management and configuration and, consequently, the evolution of networks by decoupling the Data Plane and the Control Plane. In this manner, network devices composing the Data Plane would be mere Packet Forwarding Devices, while the Control Plane would be composed of centralized, software-based controllers, responsible for the management and configuration of the network devices.

Authors	*Protection strategy*	*Technique*	*Objective*
Hmaity *et al*. [194]	End-to-end SC protection	ILPs	Ensure SC resilience against node failure, link failure, and node and link failure
Ye *et al*. [195]	End-to-end SC protection	Heuristic	Minimises the network resource consumption
Fan *et al*. [196]	Individual VNF protection	Heuristic	Minimises the required backup VNFs to guarantee a certain network reliability degree
Casazza *et al*. [197]	Individual VNF protection	Heuristic	Achieves a trade-off between the resource availability and the server congestion
Beck *et al*. [188]	Path and individual VNF protection	Heuristic	Maximises the acceptance ratio
Tomassilli *et al*. [198]	SC Link protection	ILP and Heuristic	Minimises the bandwidth consumption
Gao *et al*. [199]	Path protection	ILP and Heuristic	Minimises the consumption of spectrum and computing resources

Table 4.5: Summary of protection proposals to address the NFV survivability problem.

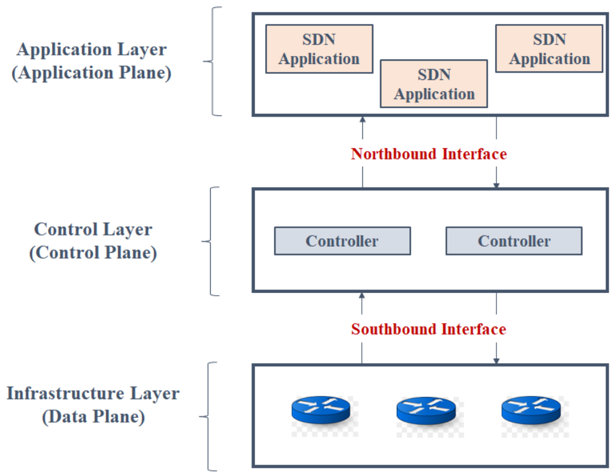


Figure 4.4: SDN Reference Architecture.

Figure 4.4 shows the SDN reference model. The first component (although at the bottom of the model) is the Infrastructure Layer. This layer is composed of all the forwarding devices in the Data Plane. These elements will be responsible for processing the packets according to the instructions they receive from a controller. The forwarding devices also collect statistics about the network status, temporarily store them and send them to the controller [201].

The second component is the Control Layer, i.e., the set of controllers responsible for managing the forwarding devices. This layer is responsible for indicating to the forwarding devices in the Infrastructure Layer how they should manage the packets. The controllers communicate with the forwarding devices through the Southbound Interface (SI), which defines the set of instructions that the controllers can use for the network infrastructure management.

The last functional block is the Application Layer. The layer is composed of SDN applications that may perform a variety of tasks, such as accessing the network status data, configuration, communication between controllers, etc., depending on the user requirements. In order to perform these tasks, the Application Layer communicates with the Control Layer, which is the layer responsible for providing these capabilities, through the Northbound Interface (NI), which usually is implemented as Application Programming Interfaces (APIs).

Whereas the NI is not standardized and is usually implemented as an API, there is a variety of efforts to implement the SI. For example, the IETF Forwarding and Control Element Separation proposed in 2010 the SDN architecture ForCES [202]. This protocol defines two elements called Forwarding Element (FE) and Control Element (CE). The FE is a logical entity that implements the ForCES protocol and is responsible for handling the packets, by using the underlying physical resources. The FE is composed of Logical Function Blocks (LFBs), which are functional elements controlled by the CE via the ForCES protocol. Through these functional blocks, the CE is able to control the FE configuration and the manner in which the FE handles the packages [202, 203]. But an even more popular SDN architecture is OpenFlow, the proposal coming from the Open Network Foundation (ONF).

The OpenFlow architecture is shown in Figure 4.5. The forwarding element in this architecture is the so-called OpenFlow Switch which implements one or multiple flow tables and securely communicates with the controller through an abstraction layer called OpenFlow

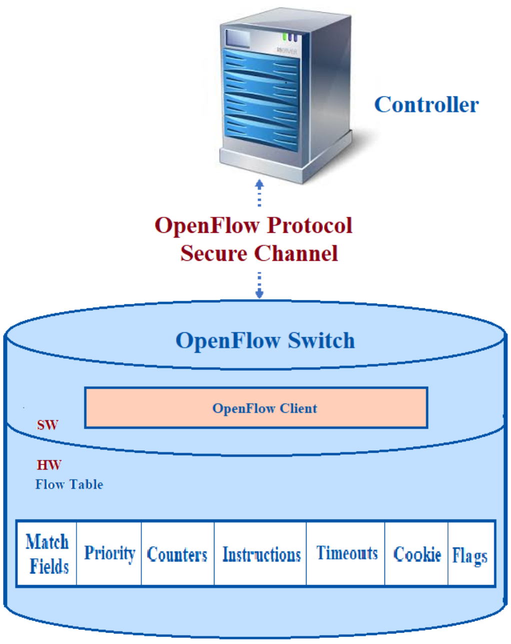


Figure 4.5: OpenFlow Architecture.

Client, using the OpenFlow protocol. The flow table consists of flow entries containing elements as the Matching Fields, Priority, Counters, Instructions, Timeouts, Cookie and Flags. The matching fields are contrasted against the packets and contain header and ingress port information mainly. The priority indicates the precedence of the flow entry. The counter is updated when a packet is matched. The instructions are the actions to be applied to the packet, while the timeout indicates the idle time before the flow expires. The cookie is chosen by the controller and may be used for flow modification or deletion requests, among other operations. Finally, the flag field is employed to modify the manner in which the flow is handled [204]. The OpenFlow switch also defines a table-miss flow entry to indicate how to manage those packets that do not match any entry of the flow table. Typical operations would be checking the next flow table or dropping the packet. Therefore, when a packet arrives at an OpenFlow switch, the header is extracted and compared to the matching fields of the flow table. If there are no matches, then the switch applies the instructions indicated by the table-miss flow entry. If the heather matches a matching field instead, the switch applies the corresponding set of instructions and updates the counter [204].

We can find a great variety of vendor-based implementations of the OpenFlow Switch as Open vSwitch [205], Pica8 [206] or Nettle [207], as well as the OpenFlow controllers, as NOX [208], POX [209] or OpenDaylight [210]. There are also many different applications of SDN as adapting routing, green networking or network virtualisation [201].

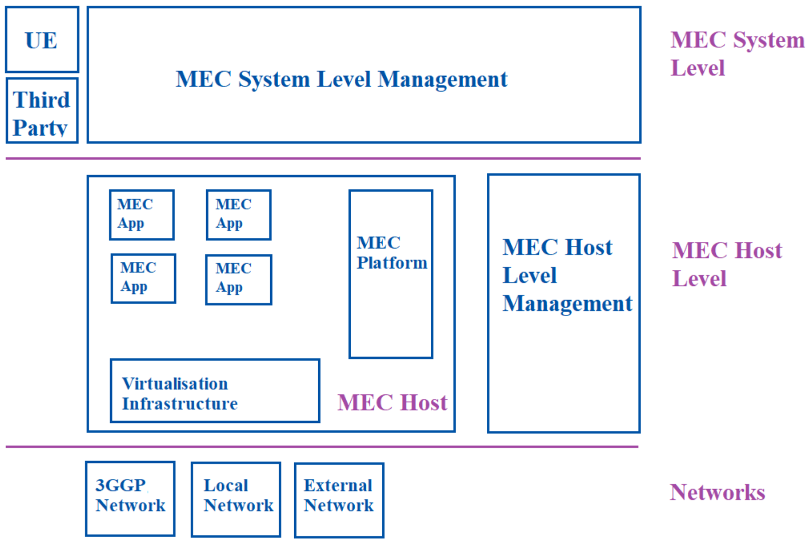


Figure 4.6: MEC Framework.

4.2.2 Multi-access Edge Computing

The ever-increasing number of connected users combined with the apparition of new services demanding stringent latency, bandwidth, Quality of Experience (QoE) and Quality of Service (QoS) requirements raised some challenges to networks that must overcome. To this purpose, communication networks and Information Technologies are converging, favouring the appearance of new capabilities that can be applied to networks [13]. This is the case of Mobile Edge Computing (MEC), which pushes the mobile-user data processing to the edge of the Radio Access Network, by running multi-vendor IT servers at the edge nodes. Consequently, an open, Cloud-Computing based environment is created at the network edge, which may overcome some shortcomings of user data processing at centralized Cloud-Computing, such as latency or bottlenecks in the core/backbone network [13], [211]. Since this trend can be extended to fixed access or WiFi networks, it was renamed as Multi-access Edge Computing in 2016 [211].

We can see a diagram of the MEC Framework as proposed by ETSI in [212] in Figure 4.6. The framework describes mainly the MEC System Level and the MEC Host Level. The MEC Host Level is composed of two blocks, the MEC Host and the MEC Host Level Management System. The MEC Host contains the MEC applications, the MEC Platform, and the Virtualisation Infrastructure. MEC Applications run on top of the Virtualisation Infrastructure and can interact with the MEC Platform to use and provide services. The MEC Platform is the entity which provides the core functionality necessary to run MEC applications operation. This entity also provides the Virtualisation Infrastructure with a set of routing rules collected from information provided by the applications, services and the MEC Platform Manager (not shown in the diagram). The element can also receive DNS records from the MEC Platform Manager and configure it accordingly. The Virtualisation Infrastructure provides the network, computing and storage resources for the correct functioning of applications [211],

[212]. Meanwhile, the MEC System Level offers an abstraction of the underlying MEC System and facilitates User Equipment (UE) and third-party applications to access the MEC System [211].

There are several use cases in which MEC can be exploited. For example, the increasing number of existing video services, such as home surveillance, requires networks to transport huge flows or video streaming traffic due to the traditional client-server architecture of video services, consuming high network capacity. Moving the analysis tasks closer to the end-users may reduce network congestion. Applications as IoT networks may benefit from MEC because, often times, IoT devices require the result of complex data processing operations to decide the response to a certain event or processing distributed computation information. Pushing these tasks to external servers, close to the IoT devices, helps to design simpler, less power-consuming IoT devices, which still can obtain the required data quickly thanks to the low latency that MEC can provide. And other use scenarios like healthcare, augmented reality, connected vehicle, mobile Big Data analysis, etc., can take great advantage of MEC [213], [214]. Finally, the upcoming broadband radio access technology 5G will require operators to transform their communication networks in order to adapt to the 5G stringent requirements and rapidly adapt to the new services and expected traffic. One of the most important performance parameters which 5G will aim to meet is extremely low latency. MEC will help to meet this requirement since the edge nodes of the radio access network will be able to host the necessary VNFs to deploy network services. Since the data processing will be closer to the end-user, so will reduce the overall service latency.

4.3 Conclusions

In this chapter we have reviewed NFV, MEC, and SDN, three computing and network paradigms that will redefine the design of future networks, helping to reduce the operational costs and management complexity, and that will be enabling technologies of future networks as 5G.

NFV is a network paradigm that aims at deploying network functions as virtual appliances, increasing their flexibility while reducing the management complexity and costs. We have discussed the NFV architecture and introduced its main elements. Furthermore, we have introduced the most common design problems that operators must face when deploying this kind of technology: the VNF-placement, chaining, and survivability. The VNF-placement and chaining can be addressed considering either static scenario, in which the service connection requests are known in advance, or a dynamic scenario, in which the problems must be solved when a connection request arrives at the network, with the computing and network resources available at the request reception time. Mathematical formulations to find the optimal solution to the placement and chaining, have been proposed in the literature, with diverse optimisation objectives as minimising the IT resource consumption, the network resource consumption, or the introduced latency. However, this kind of solution requires great computational time, particularly if the network size is large. Therefore, heuristics and meta-heuristics are proposed to find solutions to the problems in shorter computational time.

Although the placement and chaining are important design problems, it is also of great interest to provide NFV environments with fault-management mechanisms to protect established SCs from NFV and network failures. We have introduced the survivability problem in NFV environments and described the most important protection strategies that can be implemented: protection against node failure and protection against link failure. Depending on the protection approach, we can find proposals in the literature that provide end-to-end SC protection or individual VNF protection against node failure. Some proposals also combine the protection against node failure with the protection against link failure. Lastly, proposals can be found in the literature that address the survivability problem only against link failure.

Finally, we have also briefly discussed SDN and MEC, as enabling technologies for NFV and, in consequence, 5G. SDN is a network "softwarisation" trend that decouples the Data Plane and the Control Plane. In this manner, the Control Plane can be composed by controllers deployed as software appliances, while the devices composing the Data Plane would be mere packet forwarding devices. This decoupling eases the management and configuration of software devices. We have described the reference architecture of SDN, its main components and the most common implementations of the building components of SDN.

MEC, on the other hand, is a computation paradigm that provides the edge node of the network with cloud computing capabilities, by running multi-vendor servers at the edge nodes. In this manner, the data processing is pushed closer to the end-user, which can help to reduce the introduced latency [13]. We have reviewed the MEC framework and its building blocks. Finally, we have reviewed some use cases in which MEC can be exploited.

In the following Chapter, an algorithm to solve the VNF-placement and chaining problems in a 5G network with optical backhaul will be presented. This algorithm will solve the VNF-placement and chaining problems, considering restricted available computing and network resources, aiming at minimising the service blocking rate and the computing resource consumption.

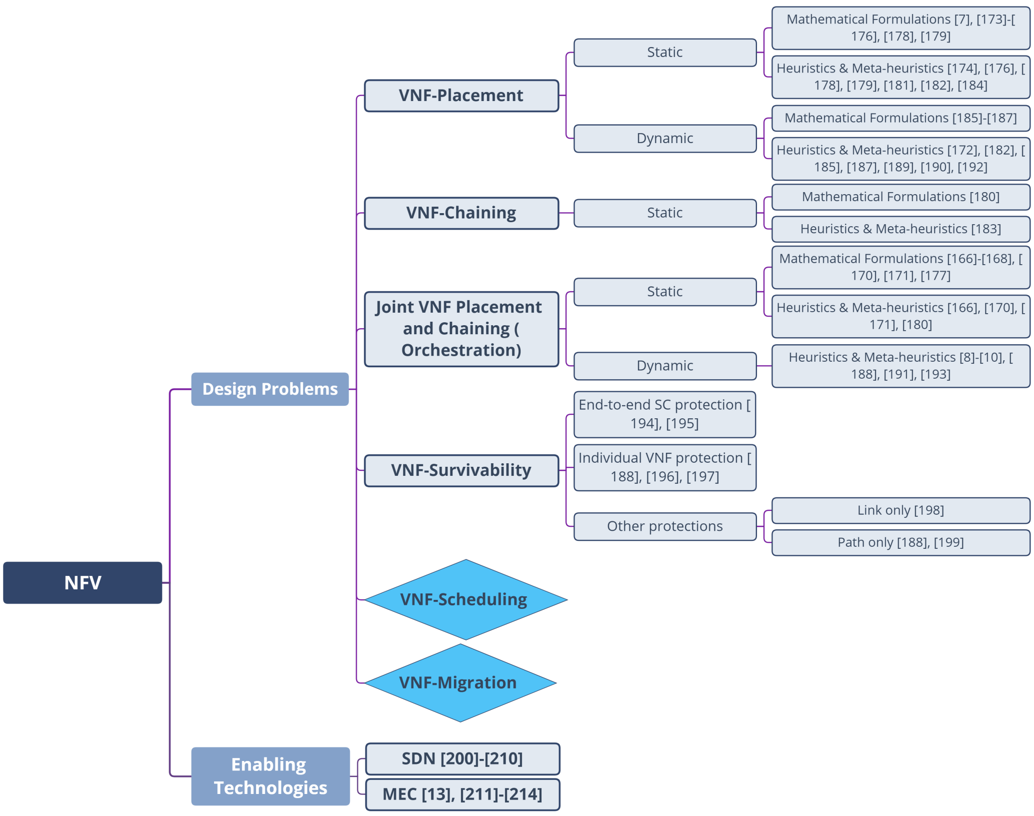


Figure 4.7: Summary of the chapter.

Chapter 5

Genetic Algorithm for Effective Service Mapping

In Chapter 4, we introduced NFV, one of the key technologies that will bring the necessary architectural changes to adapt to the new demands and services. This paradigm deploys network functions as virtual appliances, instead of the traditional proprietary hardware. In this manner, network operators can easily deploy new network services by creating instances of the virtual network functions (VNFs) at commodity servers, increasing the flexibility and manageability of the network and reducing costs, since no proprietary, vendor-specific hardware must be purchased.

In this kind of networks, service deployment is divided into two steps. The first one is to decide the number and location of the VNFs that must be instantiated over the network. This deployment step is known as VNF-placement. VNFs can be instantiated at Commercial-Off-The-Shelf (COTS) servers, located at data centres or the Central Office (CO) [7]. However, thanks to Multi-access Edge Computing, which provides computing and cloud capabilities to the edge nodes of the network, these nodes become a potential location for VNFs. In this manner, the data processing is pushed closer to the end-user and the latency is reduced [13]. In order to decide the location of the VNFs, parameters like the traffic patterns, energy efficiency, quality of service/experience (QoS/E), and the computing and network resource availability must be taken into account. The computing resource availability is of particular importance in 5G optical access network scenarios, in which VNFs can be located at the nodes of the network thanks to the MEC paradigm, hence reducing the latency, but whose computing capacities are low compared to the available resources present in data centres.

Once the VNF-placement is solved, the operators must create the required service chains (SCs) associated with each offered service. An SC is a set of VNFs that must be traversed in a certain order. Therefore, operators must select the most suitable VNFs to create the SCs, according to the VNF availability, the network resource availability and performance parameters like QoS or latency. This deployment stage is known as the VNF-chaining problem. A service blocking occurs if there are not sufficient computing or networking resources to instantiate and connect the VNFs which compose the requested SC. Consequently, the network technology, the network topology, and the network resource availability will have a great impact on the VNF-placement and chaining, and they must be taken into account during the design of NFV environments in order to minimise the service blocking ratio while meeting other 5G key performance parameters as the latency.

In Chapter 4 we have introduced the VNF-placement and chaining problems and reviewed some of the available studies that address these design stages. The reviewed studies may address just one of the problems at the time or try to solve both problems jointly. The latter case is known as VNF-orchestration or VNF-mapping. These studies aim at reducing the computing and/or network resource consumption, reducing the number of active VNF-enabled nodes, minimising the energy consumption, meeting the latency requirements or minimising the service blocking ratio.

In this chapter, we propose GASM (Genetic Algorithm for effective Service Mapping), a genetic algorithm that solves the VNF-placement and chaining problems in a 5G network with optical backhaul. We consider a network composed of 5G-nodes that are equipped with MEC resources and, in consequence, can host instances of VNFs. These nodes are connected to a CO by dedicated optical links, i.e., forming a star topology. The CO is also equipped with IT resources, hence enabled to host VNFs. The objective of GASM is minimising the service blocking ratio and the computing resource consumption, hence reducing the energy consumption and the operation expenses (OpEx). Moreover, our method considers limited available computing and network resources. The 5G-nodes can be traditional macro and micro-stations, but they can also implement the C-RAN technology, which divides the traditional Base Stations into two entities, the Remote Radio Heads, implementing basic Layer−1 functions, and Base Band Units (BBUs), which implement Layer−2 and Layer−3 operations. The advantage of BBUs is that they can be virtualised and hosted at different layers of the hierarchical aggregation network [215]. We will consider 5G-nodes implemented using C-RAN architecture. Therefore, 5G-nodes are composed of RRHs that are connected to an Access Central Office, which we call Access Office (AO). AOs are connected to the CO using point-to-point optical links, and both elements can host the virtualised Layer−2 and 3 functionality in the form of VNFs.

We initially consider a static scenario in which the service connection requests are known in advance. However, the service requests vary with time in real scenarios and statically planning this kind of networks may cause an increase of the service blocking ratio, if the number of VNFs is under-provisioned, or make inefficient use of the IT resources, if more VNFs than the necessary are created. Therefore, we propose a modification of our algorithm in order to be applied to dynamic scenarios in which the reconfiguration of the planning is allowed. Furthermore, we enhance the modified algorithm to include a learning step, with the objective of improving the performance of the algorithm. We call these algorithms GASM with reconfiguration and Evolutive GASM, respectively. These algorithms consider the operational time to be divided into time slots, and they solve the VNF-placement problem offline at the beginning of each slot, whereas the VNF-chaining problem is solved online using modifications of techniques already proposed in the literature.

The rest of the Chapter is structured as follows: In Section 5.1 we introduce the problem to be solved and the network scenario. Section 5.2 presents our proposal: GASM. In this section we describe the algorithm and compare its performance with other VNF-placement and chaining algorithms proposed in literature. In Section 5.3 we justify the necessity of allowing reconfigurations of the VNF-planning to properly design the VNF-placement and chaining in dynamic scenarios and present GASM with reconfiguration. This algorithm is further enhanced with a learning stage which improves its performance in terms of service blocking ratio. We

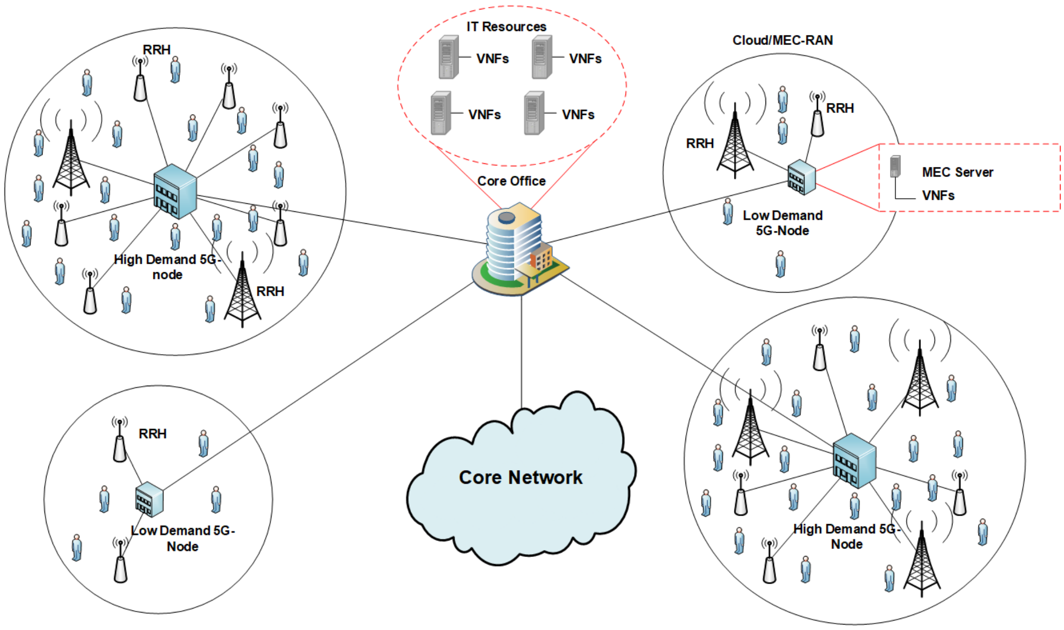


Figure 5.1: 5G access optical network scenario where 5G-nodes are connected to a CO using point-to-point optical links.

compare our proposals with the static planning with GASM and with online VNF-placement and chaining algorithms proposed in literature. Finally, we present some conclusions in Section 5.4.

5.1 Problem Statement

We aim at addressing the VNF-placement and chaining problems in a 5G network with optical star topology backhaul, with the objective of minimising the service blocking ratio and the computing resource consumption, considering limited IT and network resources. We assume that the 5G network is composed of 5G-nodes implementing the C-RAN architecture. Therefore, the nodes are composed of a number of RRHs connected to an AO, which, at the same time, is connected to a CO through dedicated optical links. An example of the architecture is shown in 5.1.

Some 5G nodes attend a higher number of average users, therefore we call them High-Demand 5G-nodes (HD-5G-nodes). The nodes which attend a lower number of users are called Low-Demand 5G-nodes (LD-5G-nodes). The 5G-nodes are connected to a Central Office (CO) with a dedicated optical link, composing a star topology network.

We assume that the nodes are equipped with MEC servers, hence they are supplied with computing and cloud capabilities, and C-RAN functionalities. HD-5G-nodes have more computing resources than LD-5G-nodes since they attend a higher number of average users. Furthermore, the CO is also equipped with computing resources. In this manner, the nodes of the network and the CO can host VNFs, however, their computing resources will be limited, compared to the available computing resources offered by data centres.

In this scenario, the nodes of the network receive service requests from their connected end-users. The total service requests that should be attended are known before the algorithm starts its operation, hence the algorithm works in a static scenario. The services have an associated SC composed of a set of VNFs which must be traversed in a certain order. In order to establish each requested connection, it is necessary to compute the number of instances of each VNF that must be created to serve them considering two factors: the computing resources with which each node of the network is equipped and the available network resources.

GASM solves the VNF-placement and chaining problem trying to minimise the service blocking ratio and the computing resource consumption, which implies less energy consumption and a reduction of network costs. Our method considers, furthermore, the limited available computing resources and the availability of network resources.

5.2 A Genetic Algorithm to Solve the Service Mapping Problem

In this section, we present a method to solve the VNF-mapping problem called Genetic Algorithm for Effective Service Mapping (GASM) [3]. Contrary to other proposals, which study the service mapping problem in inter-DC networks or generic core/metro networks, our proposal solves the VNF-placement and chaining problem in a 5G network with optical backhaul, to place the VNFs closer to the end-user and meet the 5G latency requirements. Furthermore, this kind of scenario presents a disadvantage in terms of available resources, since nodes are equipped with MEC capabilities, but the IT resources are limited compared to the IT resources offered in data centres. Furthermore, our algorithm aims at minimising the service blocking ratio and the computing resources usage, in contrast to other proposals in the literature focused on the VNF-placement and chaining in the access network optimising only one objective design.

5.2.1 Algorithm Overview

We propose a genetic algorithm to solve the VNF-placement and chaining problem in a 5G-network with point-to-point optical backhaul. Genetic algorithms are based on the mechanics of natural selection and evolution [216], and they are able to find close-to-optimal solutions to complex problems in reduced computational times. In consequence, they are commonly applied to solve search and optimization problems. Since the VNF-placement and chaining problems are NP-hard, a mathematical formulation cannot solve the problem in polynomial time. We avoid this problem by proposing a genetic algorithm.

5.2.1.1 Individuals and chromosome structure

In genetic algorithms, each solution in the space of all potential solutions, or search space, is called individual [216]. In GASM, an individual represents the potential solution to the VNF-placement problem. Individuals are described by their chromosomes, and a chromosome is composed of genes. In our proposal, a gene encodes the number of instances of a certain VNF which a given node must host.

Figure 5.2 shows an example of a chromosome in GASM. Our proposal works with n different VNFs, and we consider network composed of m nodes, $m - 1$ 5G-nodes plus a CO. Therefore, the first gene of the chromosome represents the number of instances of VNF_1 that

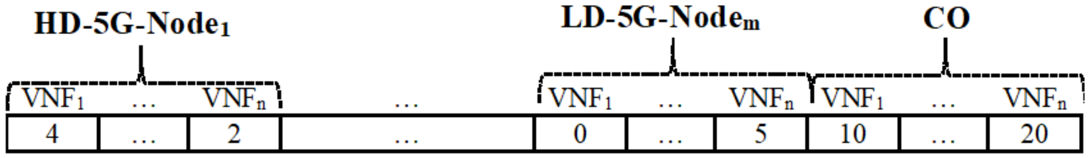


Figure 5.2: Representation of a chromosome.

$node_1$ must host. In the figure, it corresponds to 4 instances which must be hosted at HD-5G-$node_1$. The second gene, therefore, represents the number of instances of VNF_2 that $node_1$ should host. Therefore, $gene_n$ represents the number of instances of VNF_n to be hosted at $node_1$. If we follow the sequence, the gene $n + 1$ represents the instances of VNF_1 that must be created at $node_2$. In consequence the gene $((m - 1) \cdot n + i))$ represents the instances of VNF_i to be hosted by $node_m$.

5.2.1.2 Initial parent population construction

Our proposal is based on the classical genetic loop [216]. GASM creates an initial parent population composed of randomly generated individuals and two ad-hoc individuals. The mission of ad-hoc individuals is to enhance the performance of our proposal and speed up the process. We create these two individuals using VNF-placement and chaining heuristics proposed in the literature. We call the first ad-hoc individual "MEC-First" and it is based on the proposal by Pedreno-Manresa et al. [9], [10]. This heuristic starts the placement and chaining process at the local node to which the requesting user is connected. The algorithm tries to employ an existing VNF with available enough capacity. If it is not able to find an available VNF, it tries to create a new instance employing the remaining computing resources of the node. If the node cannot host more VNF instances and there are enough network resources between the node and the CO, the algorithm tries to repeat the same process at the CO, i.e., employs an existing VNF or tries to create a new one. Once in the CO, the algorithm is not able to search neither back at the local node nor at other nodes of the network. If the algorithm is capable of chaining the required VNFs and allocate network resources, the connection is established, otherwise is blocked. We proposed a second method inspired by the MEC-First heuristic, called CO-First [3], [4]. The main difference is that the chaining process starts at the CO. Therefore, the algorithm tries to employ existing VNF instances or to create new VNF instances at the CO first. If the algorithm is not able to continue the chaining process at the CO due to lack of resources, but there is enough available bandwidth, the algorithm continues the searching process at the local node. The idea behind this method is to reduce the number of active VNFs and, in consequence, the energy consumption.

5.2.1.3 Genetic evolution

When the initial parent population is completed, the individuals undergo two classical genetic operations, i.e., crossover and mutation, with the objective of constructing a descendant population composed of newly generated individuals, until achieving a certain descendant population size. In crossover, the algorithm randomly selects two individuals from the parent population and a crossover point. The algorithm then interchanges the second part of the chromosomes. The crossover pseudocode is shown in algorithm 5.

Algorithm 5 Crossover

```
procedure CROSSOVER(parentPopulation)
    parentA, parentB ← selectDifferentParents(parentPopulation)
    randomPoint ← random(0,size(parentA)
    newIndividual[0, randomPoint − 1] ← parentA[0, randomPoint − 1]
    newIndividual[randomPoint − 1, size(parentB)−1] ←
    parentB[randomPoint, size(parentB)−1]
    return newIndividual
```

The resulting individuals or offspring undergo then a mutation operation. In mutation, the algorithm randomly mutates each gene of the chromosome with a *mutationProbability*, which is user-defined. If the algorithm decides that a gene must be mutated, the new value of the gene is randomly generated, and the algorithm uses a uniform distribution between 0 and the maximum possible value for the gene, which is user-defined. The pseudocode for the mutation operation can be seen in algorithm 6.

Algorithm 6 Mutation

```
procedure MUTATION(individual, maxVNFperLocation, mutationProbability)
    gene ← 0
    while gene <size(individual) do
        if random(0, 1) < mutationProbability then
            individual[gene] ←random(0, maxVNFperLocation)
        gene ← gene + 1
    return individual
```

Once the individuals have undergone crossover and mutation, the algorithm verifies if the instances of the VNFs can be created at their corresponding hosting nodes of the network, as described by the chromosome. If the instantiation is possible, the individual is marked as valid, otherwise, it is discarded and a new individual is created with the crossover and mutation operations until the descendant population is completed.

Valid individuals then go through the translation stage. During the translation stage, the algorithm creates the VNF instances indicated by the chromosome of the individual at their corresponding locations. Then, the algorithm sorts the service connection requests according to a certain priority order to be determined by the network operator. Next, the algorithm tries to establish the SC associated with each request. Therefore, the algorithm checks which VNFs must be concatenated in order to establish the connection, and begins the chaining process using a variation of the MEC-First policy proposed in [9], [10]. Employing the modified MEC-First policy, the algorithm looks for the corresponding VNF instances at the local 5G-node to which the user is connected. If the created instances do not have enough processing capacity to deal with the traffic of the request, the algorithm does not try to create new instances at the local node. Instead, it tries to concatenate instances located at the CO if they have available processing capacity and there are enough available network resources to connect the local 5G-node and the CO. Once at the CO, the algorithm does not look for available instances of other VNF in the chain back at the local 5G-node or in other 5G-nodes. If the algorithm is not able to set up the SC either due to lack of VNFs with enough processing capacity or due to lack of network resources, the request is blocked.

5.2.1.4 Fitness calculation and individual selection

When the translation process is completed, the algorithm computes the fitness of the individuals. Fitness is measured in terms of service blocking ratio and percentage of active CPU cores in the network.

Once the algorithm has computed the fitness of the individuals, it chooses the best ones among the parent and the descendant populations to be the parents of the next one. To that aim, the algorithm selects the individuals with the best performance in terms of service blocking ratio. However, if two individuals are tied in this parameter, the algorithm chooses the individual with a lower percentage of active CPU cores.

The algorithm will repeat the evolution process a number of times, or generations, which is user-defined. At the end of the procedure, GASM returns the best individual, or VNF-placement configuration, in terms of service blocking ratio and CPU consumption found until that moment.

Algorithm 7 shows the pseudocode of our proposed algorithm GASM.

5.2.2 Simulation Study and Results

We have developed a network simulator using the C++ based discrete event simulator OMNeT++ [159], with the objective to test the performance of GASM (see Appendix A). Our simulator implements a 5G network with optical backhaul composed of 10 HD-5G-nodes and 10 LD-5G-nodes connected to a CO through dedicated optical links. Each link is composed of two optical fibres whose capacity is set to 10 Gb/s each.

Location	*Computational resources*
Central Office	100 CPU cores, 480 GB RAM and 27 TB HDD
HD-5G-node	16 CPU cores, 64 GB RAM and 10 TB HDD
LD-5G-node	8 CPU cores, 32 GB RAM and 7 TB HDD

Table 5.1: Hardware capabilities of the different 5G-nodes

We assumed that all nodes are equipped with MEC resources, hence they have computing capability to host VNFs. Since the HD-5G-nodes attend in average more users than the LD-5G-nodes, they are equipped with higher computing resources with respect to the LD-nodes. The CO also has IT resources and can host VNFs. The computing capabilities associated with each kind of node are shown in Table 5.1 and are the same of [3], [4], [7], [8], [9], [10].

We assumed that the network is managed by one network operator that offers three classes of network services: Voice over IP (VoIP), video streaming and web services. The users request one of those network services with a probability of 30%, 20% and 50% respectively, like in [9],

Algorithm 7 GASM

```
procedure GASM(trafficRequests, parentPopulationSize, descendantPopulationSize, numGenerations)
    solution ← ∅
    parentPopulation ← ∅
    parentPopulation ← generatedAdHocIndividuals
    while size(parentPopulation) < parentPopulationSize do
        parentPopulation ←checkFeasibility(generatedRandomIndividuals())
    i ← 0
    while i < numGenerations do
        descendantPopulation ← ∅
        checkPopulation ← ∅
        while size(descendantPopulation)< descendantPopulationSize do
            offspring ← crossover(parentPopulation)
            offspring ← mutation(offspring)
            descendantPopulation ←
                descendantPopulation∪checkFeasibility(offspring)
        checkPopulation ← parentPopulation ∪ descendantPopulation
        checkPopulationFitness ←
            fitnessEvaluation(checkPopulation, trafficRequest)
        checkPopulation, checkPopulationFitness ←
            selectFittestIndividuals(checkPopulation, checkPopulationFitness,
            size = parentPopulationSize)
        i ← i + 1
    solution ← selectFittestIndividual(checkPopulation, checkPopulationFitness,
    size = 1)
    return solution
```

Service	*Chained VNFs*	*Bandwidth*
VoIP	NAT-FW-TM-FW-NAT	64 kbps
Video	NAT-FW-TM-VOC-IDPS	4 Mbps
Web Services	NAT-FW-TM-WOC-IDPS	100 kbps

Table 5.2: Requirements of the deployed service chains. NAT: Network Address Translator, FW: Firewall, TM: Traffic Monitor, WOC: WAN Optimization Controller, VOC: Video Optimization Controller and IDPS: Intrusion Detection Prevention System [3], [4], [7], [8], [9], [10].

[10]. Each service has an associated SC and bandwidth, which are shown in Table 5.2. The employed resources are the same as the resources in studies [7], [8]. Furthermore, each VNF has some associated computing resource requirements and a maximum number of concurrent users. This requirements are shown in Table 5.3, and are the same as the requirements presented in [9], [10].

We defined a $parentPopulationSize$ of 5 individuals, a $descendantPopulationSize$ of 10 individuals and a $mutationProbability$ of 0.01. The chromosomes of the individuals were randomly created using a uniform distribution $\mathcal{U}(0, maxVNFperLocation)$, where $maxVNFperLocation$ was fixed in 10 for the CO, 4 for the HD-5G-node and 2 for the LD-5G-node.

We have also defined the input parameter $\bar{u}$, which represents the average connected users per HD-5G-node. At the beginning of each simulation, the average users connected to each HD-5G-node was randomly generated using a uniform distribution:

$$\mathcal{U}\left[0, 2 \cdot \bar{u}\right]. \tag{5.1}$$

The LD-5G-nodes attend on average 10% fewer users than HD-5G-nodes. In consequence, the number of connected users to each node of this class was randomly generated, at the beginning of each simulation, employing a uniform distribution:

$$\mathcal{U}\left[0, \frac{2 \cdot \bar{u}}{10}\right]. \tag{5.2}$$

We performed simulations for values of $\bar{u}$ between 500 and 8,500, with increments of 1,000 average users. For each scenario, GASM stopping criterion was set to 100 generation and 100 simulations with different traffic requests were performed. Results are plotted in average, with 95% confidence intervals. Other configurations have been tested, being the presented in this Thesis the configuration which offered the best performance.

Figure 5.3 shows a comparison of the service blocking ratio (SBR) achieved by MEC-First, CO-First and GASM. Results show that our proposal is able to achieve the same service blocking ratio than MEC-First, and improves the results obtained by CO-First. Furthermore, MEC-First and GASM are able to attend all the connection requests when $\bar{u} < 6500$. However, if we observe the CPU consumption shown in Figure 5.4, we can see that GASM is able to obtain the same service blocking ratio than MEC-First while employing less active CPU cores.

Service HW requirements	*# concurrent operations*
NAT CPU: 1 core, RAM: 1 GB, HDD: 2 GB	3000
FW CPU: 2 cores, RAM: 3 GB, HDD: 5 GB	2500
TM CPU: 1 core, RAM: 3 GB, HDD: 2 GB	2500
VOC CPU: 2 cores, RAM: 2 GB, HDD: 20 GB	1000
WOC CPU: 1 core, RAM: 2 GB, HDD: 10 GB	1500
IDPS CPU: 2 cores, RAM: 2 GB, HDD: 10 GB	2500

Table 5.3: Hardware requirements associated with the VNFs [7], [8], [9], [10], [3], [4]

Hence, GASM can find a VNF-placement which minimises the service blocking ratio and reduces the computing resource and energy consumption. If we compare the CPU consumption of GASM and CO-First, we can see that the latter method employs lower percentage of CPU. However, the algorithm reduces the computing resource consumption at the expense of worsening its behaviour with respect to the service blocking ratio.

We have prioritised the CPU consumption with respect to other computing resources like RAM or hard disk since the VNFs present high demand of CPU cores with respect to the number of CPU cores with which the CO and the nodes of the network are equipped. Nevertheless, we can see the RAM consumption of the three methods in Figure 5.5. This figure shows that MEC-First is the heuristic which makes higher consumption of memory resources. Therefore, it presents the same behaviour with respect to CPU consumption. Again, CO-First is the method which consumes fewer memory resources, but its performance in terms of service blocking ratio is also the worst. Hence, GASM, is able to reduce the memory consumption with respect to MEC-First while obtaining the same blocking ratio.

Finally, the hard disk consumption is shown in Figure 5.6. We can see that this computing resource is the less limiting of the three since the consumption does not reach the 1% for any of the studied methods. In this case, we observe that CO-First and GASM present the lower hard disk consumption for the lowest values of average users per HD-5G-node. Then, at medium values, it is MEC-First the best performing technique. However, MEC-First increases the consumption to become the worst-performing technique in this respect, as it did in RAM and CPU consumption. Again, GASM is able to outperform MEC in resource consumption, while CO-First is the less consuming method of the three studied techniques.

In conclusion, our proposal GASM presents a good trade-off between service blocking ratio and IT resource consumption, and it is able to achieve the same service blocking ratio than other VNF-placement and chaining methods proposed in literature, but reducing the consumption of the computing resources and, in consequence, the energy consumption and the operation expenses.

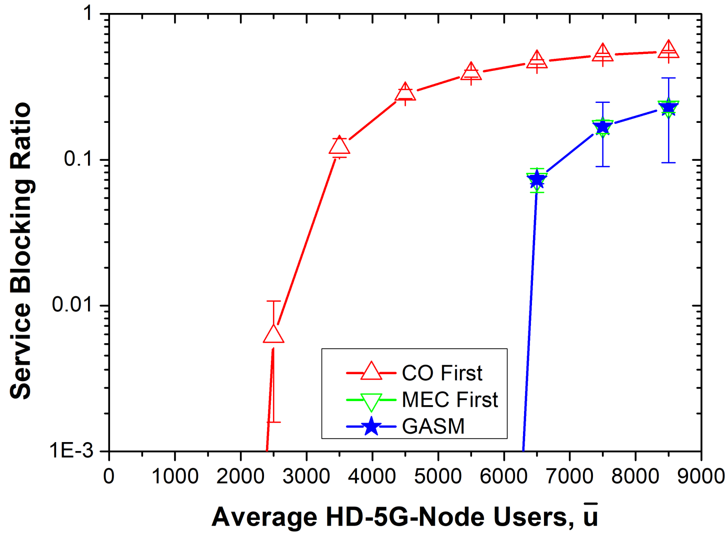


Figure 5.3: Service blocking ratio for MEC-First, CO-First and GASM [3].

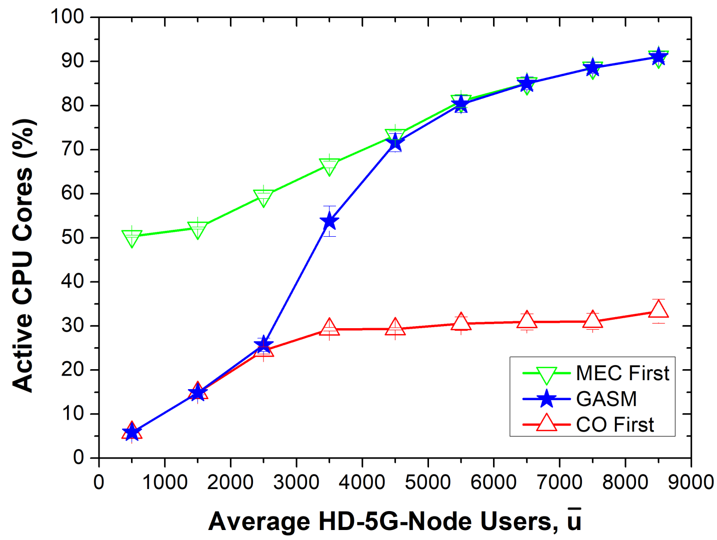


Figure 5.4: Percentage of active CPU cores for MEC-First, CO-First, and GASM [3].

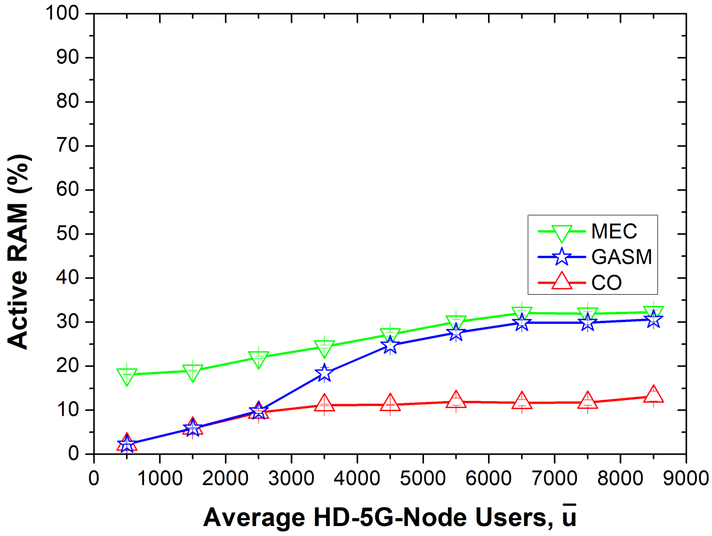


Figure 5.5: RAM consumption for MEC-First, CO-First and GASM

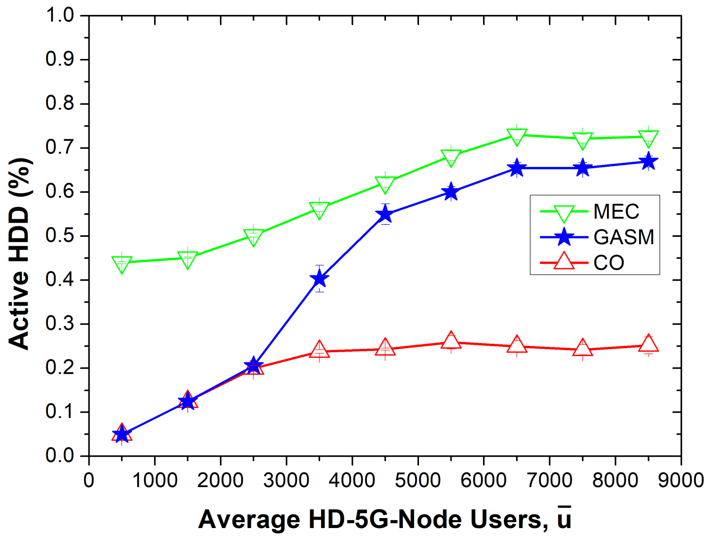


Figure 5.6: HDD consumption for MEC-First, CO-First and GASM

5.3 GASM in Reconfiguration Scenarios

In section 5.2 we have presented a genetic algorithm that solves the VNF-placement and chaining problem in a 5G networks with optical backhaul. This algorithm is able to design the service mapping in a static scenario, which means that the estimation of the services to be transported is known in advance.

However, in real networks, the service requests vary with time. In consequence, the VNF-placement and chaining problem can be solved online, i.e., developing a dynamic algorithm which designs the service mapping at the moment of receiving a service connection request, or offline with an algorithm which designs the service mapping using traffic estimators, leading to a static solution.

If the offline approach is adopted, network operators must decide whether to design the service mapping considering peak load periods, which may lead to inefficient use of the resources, or perform periodic reconfigurations on the service mapping based on traffic estimations which may improve the resource usage.

On the other hand, when the online approach is employed, the service mapping is performed when the service request arrives at the network, utilising the available resources at the moment. Although online approaches may present advantages with respect to the offline approaches, like better usage of resources, they are not necessary the most suitable approach for the design problems to be solved during the service mapping. For example, the chaining process cannot be solved based on traffic predictions since the network will discover the type of SC to be established only when the service request arrives. Hence, the online approach is more adequate to solve this kind of problems. However, if the VNF-placement is solved upon a request arrival, it would take seconds to set up the required VNFs, incurring in a delay which may affect the fulfilment of the associated latency to the service. Therefore, a static design with periodical planning could be a better approach to solve this kind of problem.

Therefore, we propose to combine the two strategies to solve the VNF-placement and chaining problems. On one hand, we employ GASM to plan the initial VNF placement at peak loads and perform a periodical reconfiguration based on traffic estimations. Moreover, we enhance GASM with a learning technique which can improve the behaviour of the algorithm in terms of service blocking ratio. On the other hand, we solve the VNF-chaining problem online, using the proposed modified version of the MEC-First method. We have compared the results obtained by the different algorithms in terms of the service blocking ratio and resource consumption of planning the VNF-mapping statically and allowing periodical reconfigurations.

5.3.1 Static planning for peak loads with GASM

As explained before, the VNF-placement and chaining in a 5G network with optical backhaul can be solved statically for peak loads, using a modified version of GASM [4]. The algorithm receives an estimation of the service requests that the network has to establish. The algorithm also receives as parameters the parent population size, the descendant population size and the number of generations which must be created. The performance of the algorithm is analogous to the proposed GASM in section 5.2, and is shown in algorithm 8.

The algorithm uses an estimation of the service requests arrived during the rush hour, which is calculated as:

$$U_i = k \cdot \overline{U_{5G-node_i}}, \tag{5.3}$$

Algorithm 8 GASM with Reconfiguration

```
procedure GASMReconf(trafficEstimation, parentPopulationSize, descendantPopulationSize, numGenerations)
    solution ← ∅
    parentPopulation ← ∅
    parentPopulation ← generatedAdHocIndividuals
    while size(parentPopulation)< parentPopulationSize do
        parentPopulation ←checkFeasibility(generatedRandomIndividuals())
    i ← 0
    while i < numGenerations do
        descendantPopulation ← ∅
        checkPopulation ← ∅
        while size(descendantPopulation)< descendantPopulationSize do
            offspring ← crossover(parentPopulation)
            offspring ← mutation(offspring)
            descendantPopulation ←
                descendantPopulation∪checkFeasibility(offspring)
        checkPopulation ← parentPopulation ∪ descendantPopulation
        checkPopulationFitness ←
            fitnessEvaluation(checkPopulation, trafficRequest)
        parentPopulation ←
            selectFittestIndividuals(checkPopulation, checkPopulationFitness,
            size = parentPopulationSize)
        i ← i + 1
    solution ← selectFittestIndividual(checkPopulation, checkPopulationFitness,
    size = 1)
    if solution ≠ currentlyEstablishedSolution then
        establishVNF(solution)
```

where U_i is the estimated number of users connected to 5G-node$_i$ and $\overline{U_{5G-node_i}}$ is the average number of connected users to the 5G-node$_i$, which is computed as indicated in Equations 5.1 and 5.2, depending whether it is an HD or an LD-5G-node. k is a scaling factor which can take different values to solve the initial VNF-placement for diverse peak loads.

5.3.2 Service Mapping Reconfiguration with GASM

Although GASM is able to supply a VNF-placement and chaining well-fitted for an estimated number of average users, this kind of planning is not adapted to time-varying traffic. Therefore, a rise in the number of connected users to the network can lead to an increment of the service blocking ratio, since there might not be enough provisioned VNFs to serve the higher-than-average requests. On the other hand, a decrease in the number of users can lead to inefficient use of computing and network resources, since more resources than necessary might have been reserved.

In this kind of scenario with time-varying traffic is convenient to perform periodical VNF-placement reconfigurations to improve the performance of the network in terms of service blocking ratio and resource usage. In this case, the operational time is divided into time slots and the VNF-placement algorithms are executed at the beginning of each time slot. The planning is performed based on traffic estimation, using a simple traffic estimator [4]:

$$U_i^{j+1} = U_i^j + \alpha \cdot \left(U_i^j - U_i^{j-1} \right), \tag{5.4}$$

where U_i^j represents the total number of connected users to node$_i$ in the current time slot, U_i^{j-1} represents the total number of connected users to node$_i$ in the previous time slot, U_i^{j+1} is the estimated number of connected users to node$_i$ during the following time slot and α is a scaling factor which represents the maximum variation in the number of users from a time slot to the following one. This scaling factor can be measured with traffic monitors the current time slot, and typically considers one time window, i.e., a day or a week. When the traffic is estimated, GASM performs the re-planning and provides a VNF-placement more adapted to the expected traffic of the following time slot.

The planning can be performed employing the GASM version shown in Algorithm 8, calculating $trafficEstimation$ with the Equation 5.4. However, the results of GASM can be improved by enhancing the algorithm with a simple learning technique. If the time slot size is defined with a sufficiently small granularity, then it is possible to assume that the number of traffic requests in the following time slot will be similar to the number of connected users to the previous one. In consequence, the provisioning of the VNFs between two consecutive time slots will not experience a significant variation. Hence, we can include the VNF-placement of time slot j as an initial solution to compute the VNF-placement of time slot $j+1$. This is done by incorporating the individual which codifies the placement of the previous slot as part of the initial parent population created by GASM. Therefore, the initial parent population includes the solution of the re-planning step for the previous time slot, two ad-hoc individuals and random individuals until completing the parent population size. We call this variation of our proposal Evolutive GASM (Evo-GASM) [4] and the operation is shown in Algorithm 9.

Algorithm 9 Evolutive GASM [4]

```
procedure EvoGASM(trafficEstimation, previousProvisioning, parentPopulationSize, descendantPopulationSize, numGenerations)
    solution ← ∅
    parentPopulation ← ∅
    parentPopulation ← previousProvisioning
    parentPopulation ← generatedAdHocIndividuals
    while size(parentPopulation)< parentPopulationSize do
        parentPopulation ←checkFeasibility(generatedRandomIndividuals())
    i ← 0
    while i < numGenerations do
        descendantPopulation ← ∅
        checkPopulation ← ∅
        while size(descendantPopulation)< descendantPopulationSize do
            offspring ← crossover(parentPopulation)
            offspring ← mutation(offspring)
            descendantPopulation ←
                descendantPopulation∪checkFeasibility(offspring)
        checkPopulation ← parentPopulation ∪ descendantPopulation
        checkPopulationFitness ←
            fitnessEvaluation(checkPopulation, trafficRequest)
        parentPopulation ←
            selectFittestIndividuals(checkPopulation, checkPopulationFitness,
            size = parentPopulationSize)
        i ← i + 1
    solution ← selectFittestIndividual(checkPopulation, checkPopulationFitness,
        size = 1)
    if solution ≠ currentlyEstablishedSolution then
        establishVNF(solution)
```

5.3.3 Simulation Scenario and Results

We have analysed the performance of GASM in a dynamic scenario using the same simulation settings described in subsection 5.2.2. Therefore, we assume a 5G network with 10 HD-5G-nodes and 10 LD-5G-nodes connected to a CO through dedicated optical links. We assume that the 5G-nodes are equipped with MEC resources and, in consequence, they are VNF-enabled nodes. The CO is also equipped with computing resources and can host instances of different VNFs. We assume that the computing resources with which the different nodes are equipped are the same as in the static scenario, shown in Table 5.1.

Like in the static scenario, we assume that the network is managed by one operator which offers VoIP, Video Streaming and Web searching services. Users connected to the network can request one of these services with $30, 20$ and 50% probability. The associated SCs and maximum number of concurrent users are shown in Table 5.2, whereas the hardware requirements of the VNFs are shown in Table 5.3.

The main difference between the simulation scenario with respect to the static simulation scenario is the traffic. Static traffic scenarios cannot be considered realistic since the transported traffic by a real network experiences variations with time. Therefore, we consider a dynamic scenario in which the number of connected users to the 5G-nodes varies with time according to the following equation [217]:

$$users_i\,(t) = \overline{users_i}\beta\,(t)\left[1 + \phi \sin\left(\frac{2 \cdot \pi \cdot t}{t_{variation}}\right)\right], \tag{5.5}$$

where $users_i$ represents the connected users to node i, while $\overline{users_i}$ represents the average number of connected users at the 5G-node i. $\beta(t)$ is a variable employed to introduce burstiness to the traffic and is randomly generated using a uniform distribution $\mathcal{U}\,[1-\epsilon, 1+\epsilon]$ every time that $users_i(t)$ is evaluated, where ϵ represents the level of traffic burstiness and is set to 10% (i.e. 0.1) in our simulation study. ϕ represents the traffic variability and can take the values $0.25, 0.5$ and 0.75. and $t_{variation}$ represents the variation period in seconds. In our study, we set $t_{variation} = 86,400$ s, i.e., one day.

The variable $\overline{users_i}$ is randomly generated at the beginning of each simulation using the same parameter $\bar{u}$ as in the static scenario, which represented the number of average users connected to the HD-5G-node. Therefore, $\overline{users_i}$ for the HD-5G-node is randomly generated using the uniform distribution:

$$\mathcal{U}\,[0, 2 \cdot \bar{u}]\,, \tag{5.6}$$

while in the case of the LD-5G-nodes, which will attend in average ten times fewer users than the HD-5G-nodes, this parameter is randomly generated using the following uniform distribution:

$$\mathcal{U}\left[0, \frac{2 \cdot \bar{u}}{10}\right]. \tag{5.7}$$

$\bar{u}$ takes values from 500 to $8,500$ users with increments of $1,000$ users. We repeat the simulation for each value of $\bar{u}$ 300 times with different traffics. At the beginning of each simulation, the network is planned for peak loads, and only in the reconfiguration scenario this planning is modified at the beginning of each time slot. We defined a simulation time of three days. We defined a $parentPopulationSize$ of 5 individuals, a $descendantPopulationSize$ of 10

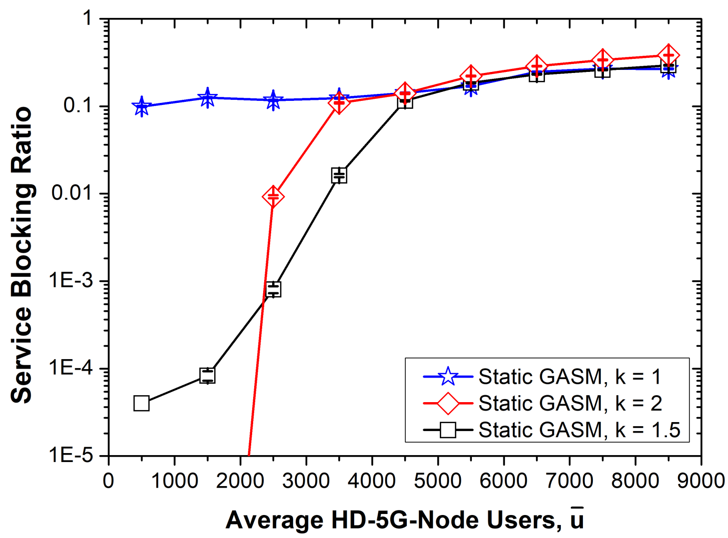


Figure 5.7: Service blocking ratio achieved for peak load plannification with GASM for different values of k and $\phi = 0.5$

individuals, and create 100 generations at the peak load planning stage, and 10 generations at the re-planning stage. The figures are plotted with 95% confidence interval.

5.3.3.1 Results of Static Configuration in Dynamic Scenarios

In this dynamic scenario, we have evaluated the performance of GASM (Algorithm 8) to statically plan the network, considering that the traffic is always equal to the peak value. The traffic peaks were estimated as described in section 5.3.1. We used the scaling factor k with values 1, 1.5 and 2. The planning is performed only at the beginning of each simulation and it remains unmodified throughout the three-day simulation.

Figure 5.7 shows the service blocking ratio for GASM when $\phi = 0.5$, while Figure 5.8 shows the percentage of active CPU cores. Figure 5.7 shows that the best results in terms of service blocking ratio are obtained when a scaling factor of $k = 1.5$ is employed. When $k = 1$, the number of connected users is under-estimated and the VNF configuration is not prepared to deal with the actual number of connected users. In consequence, the network presents a high value of service blocking ratio and makes this configuration infeasible to be used in a real network. On the other and, the number of users is over-estimated when $k = 2$ is used. In consequence, an unnecessary increment of the active CPU cores appears, as Figure 5.8 shows, which does not translate into an improvement of the service blocking ratio compared to the one obtained when $k = 1.5$. If we observe the consumption of RAM and HDD, shown in Figures, 5.9a and 5.9b respectively, the same conclusions can be extracted, i.e., under-estimating the number of connected users with a scaling factor of $k = 1$ leads to low consumption of the computing resources (either CPU cores, RAM or HDD) but also to poor results in terms of service blocking ratio. Selecting a scaling factor of $k = 1.5$ increases the computing resource consumption but also achieves the best results in terms of service blocking ratio. Finally, if

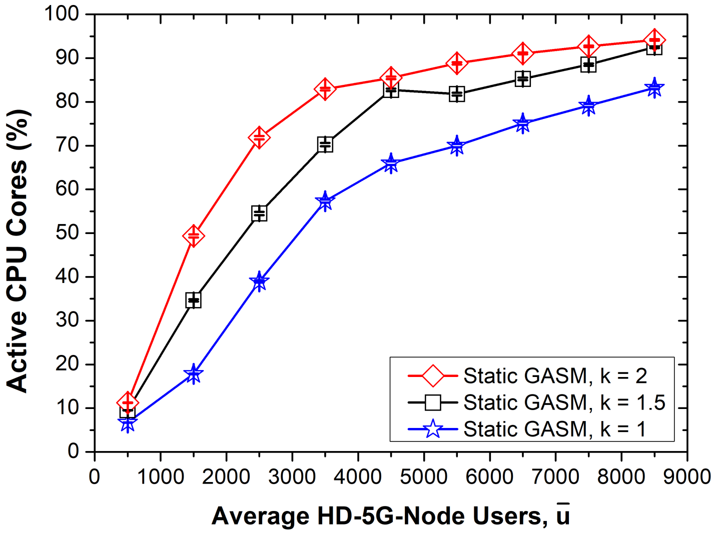


Figure 5.8: Active CPU Cores (%) achieved for peak load plannification with GASM for different values of k and $\phi = 0.5$

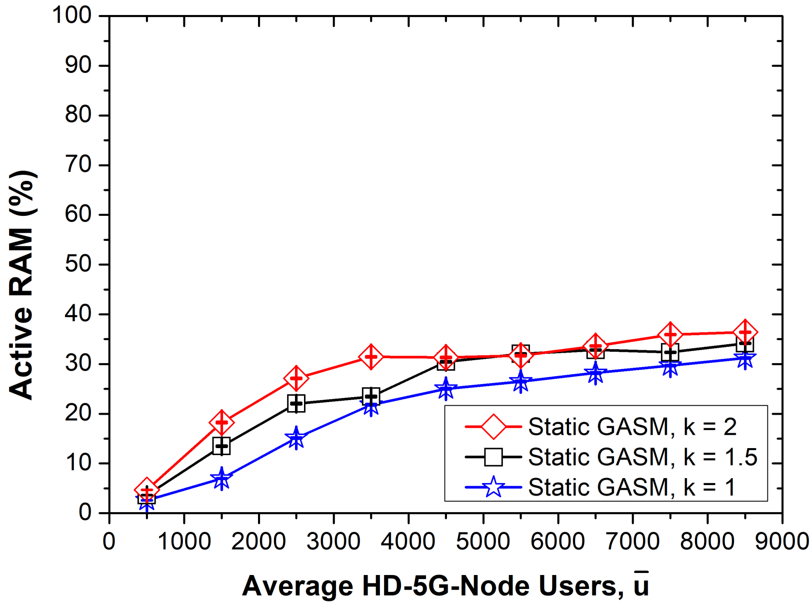
$k = 2$ the connected users are over-estimated, the computing resource consumption increases but the service blocking ratio is not improved.

Let us see what happens with different values of traffic variation. The service blocking ratio obtained by GASM when $k = 1, 1.5$ and 2 and $\phi = 0.25$ is shown in Figure 5.10. When $\phi = 0.25$, the scaling factor that obtains the best behaviour in terms of service blocking ratio is $k = 1.5$. When $k = 1$ the network cannot deal with the actual connected users, increasing the service blocking ratio, and $k = 2$ leads to an over-estimation of the connected users that does not translate into a better performance in terms of service blocking ratio compared to $k = 1$. If we increase the traffic variation to $\phi = 0.75$, we obtain the service blocking ratio results shown in Figure 5.11. In this case, incrementing the traffic variation affects the performance of GASM when $k = 1.5$ to the point of causing the blocking of service requests for low values of $\bar{u}$, as shown in Figure 5.11.

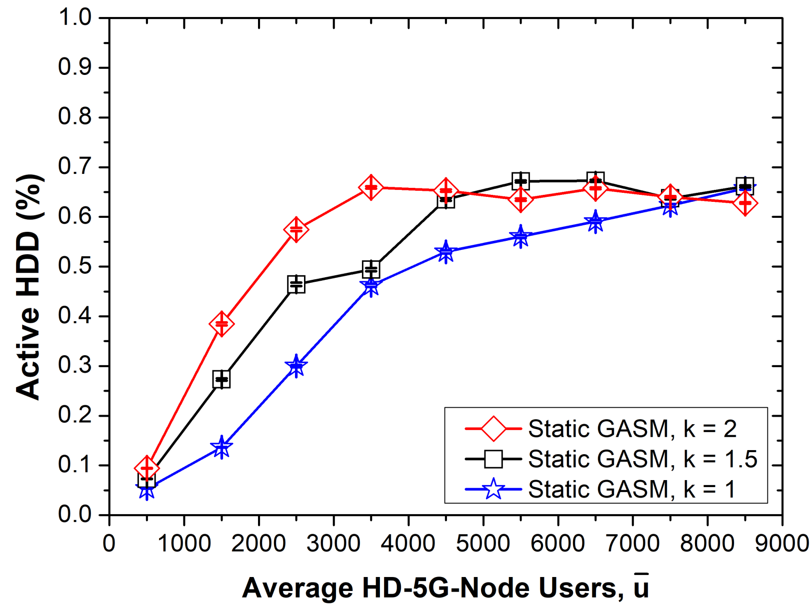
In conclusion, it is important to carefully select the scaling factor if a static planning for peak loads is to be implemented, since the traffic variation may affect the performance of the network. Results show that under-dimensioning leads to a bad performance in terms of service blocking ratio if the traffic variation is low. Over-dimensioning can achieve better results in terms of service blocking ratio, at the cost of increasing the computing resource consumption.

5.3.3.2 Enabling Reconfiguration in Dynamic Scenarios

In the previous subsection, we have seen the importance of selecting a good scaling factor to estimate the traffic when statically planning a network. In this subsection, we compare the results of statically solving the VNF-placement problem to the results obtained with our proposed algorithms GASM with reconfiguration and Evolutive GASM [4]. Furthermore, we also compare our results with the ones obtained when the VNF-placement and chaining are



(a) Active RAM (%)



(b) Active HDD (%)

Figure 5.9: RAM and HDD consumption (in (%)) for a peak-load planning with $k = 1, 1.5$ or 2 and $\phi = 0.5$.

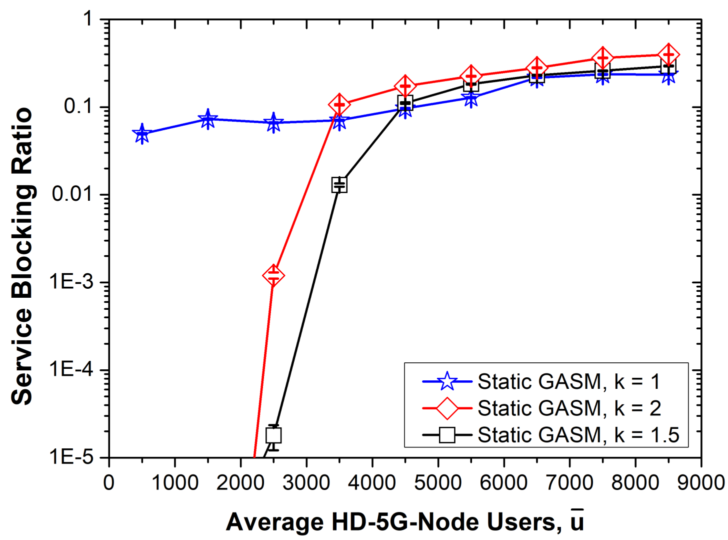


Figure 5.10: Service blocking ratio achieved when statically planning for peak loads using GASM with $k = 1, 1.5$ and 2 and $\phi = 0.25$.

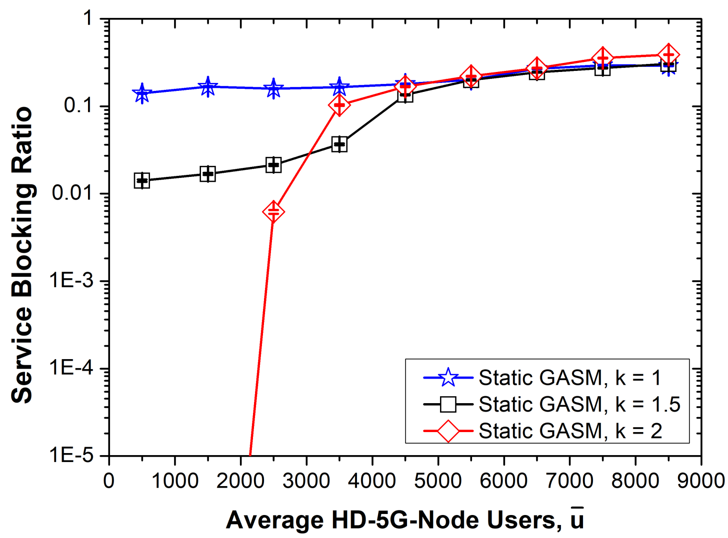


Figure 5.11: Service blocking ratio achieved for peak load plannification with GASM for different values of k and $\phi = 0.75$

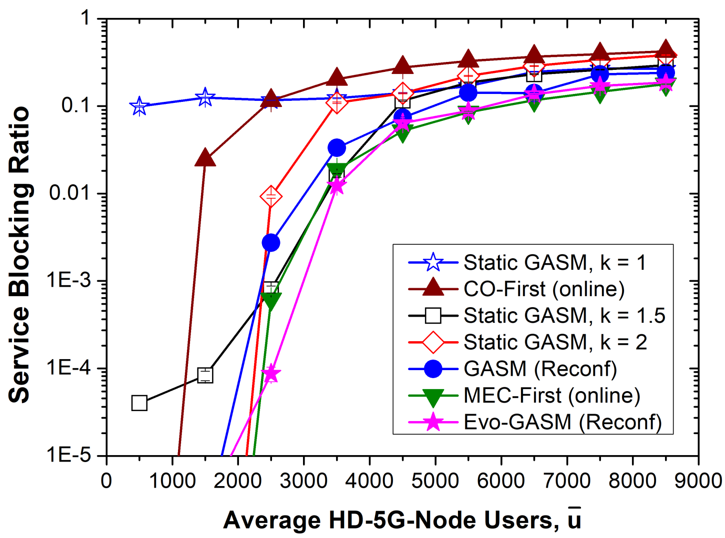


Figure 5.12: Service blocking ratio for the reconfiguration algorithms, the static algorithms and the online methods MEC-First and CO-First when $\phi = 0.5$

dynamically solved using the online methods MEC-First [9], [10] and CO-First.

In order to perform reconfigurations, we assume that time is divided into time slots whose duration is $900s$. This value was chosen since it offered the best results in terms of service blocking ratio and CPU core consumption. In order to test the reconfiguration algorithms, at the beginning of each simulation, the VNF-placement problem is solved for peak loads using GASM (Algorithm 8) with a value of $k = 2$. GASM evolves for 100 generations. Then, at the beginning of each time slot, GASM with reconfiguration or Evolutive GASM (Algorithms 8, 9), perform a reconfiguration of the VNF-placement using the traffic estimation computed using Equation 5.4. In this case, we configure the algorithms to evolve only for 10 generations to reduce the computational time, which must be lower than the time slot duration.

Figure 5.12 and 5.13 show the service blocking ratio and the CPU consumption obtained when planning with GASM for peak loads, allowing reconfiguration with GASM with reconfiguration and Evolutive GASM, and solving online the VNF-placement and chaining problems using MEC-First and CO-First when the traffic variation is set to $\phi = 0.5$. In this case, making a static planning causes a higher service blocking ratio than allowing a reconfiguration of the VNF-placement or online solving the service mapping with MEC-First. We can observe that GASM with $k = 2$ is one of the most CPU core-consuming algorithms while presenting one of the highest service blocking ratios, which confirms that over-dimensioning can lead to bad network performance and inefficient resource consumption. Although the performance of the static planning can be improved selecting other values of k, like 1.5, other planning algorithms like GASM with reconfiguration are able to outperform the static planning. Evolutive GASM is able to outperform MEC-First and GASM with $k = 1.5$ in terms of service blocking ratio in almost an order of magnitude, making a lower consumption of CPU cores. Moreover, Evolutive GASM improves the performance of GASM with reconfiguration in terms of service

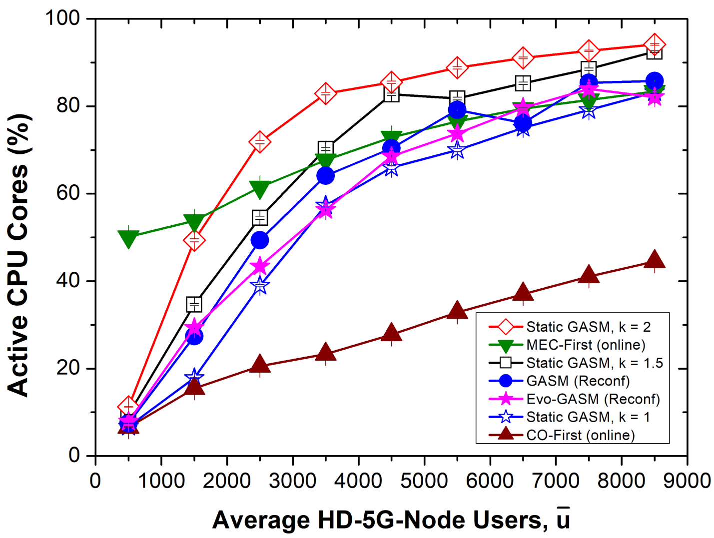
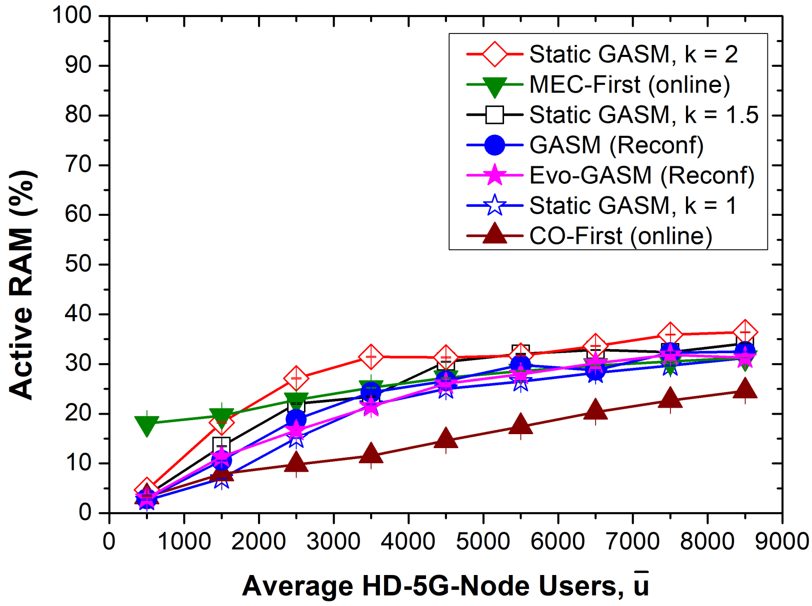


Figure 5.13: Active CPU cores (%) for the reconfiguration algorithms, the static algorithms and the online methods MEC-First and CO-First when $\phi = 0.5$

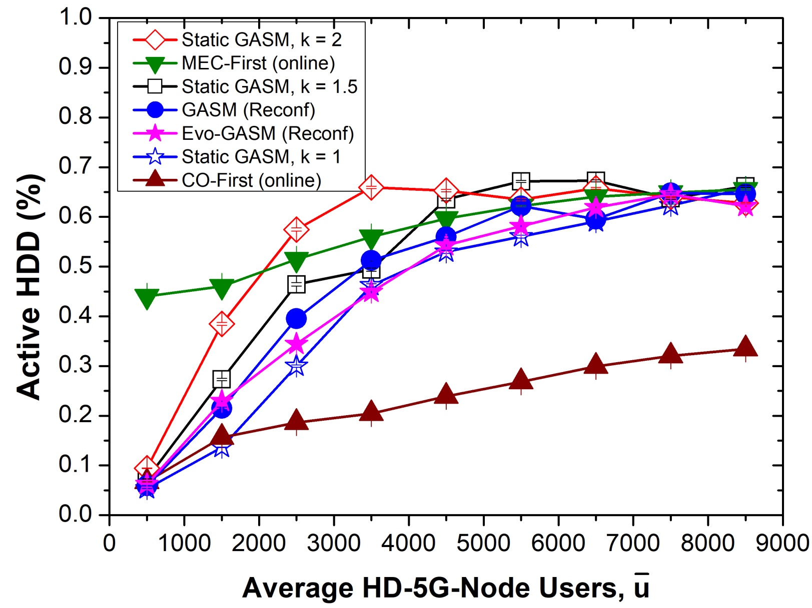
blocking ratio in almost two orders of magnitude. Furthermore, when compared to basic GASM when reconfiguration is allowed, the service blocking ratio is reduced in almost two orders of magnitude, proving the effectiveness of adding a learning stage to improve the behaviour of the algorithm. Evolutive GASM also makes a more effective use of the CPU cores, reducing the usage compared to GASM with reconfiguration and MEC-First almost a 10%. The same behaviour can be seen in the consumption of RAM and HDD, which are shown in Figures 5.14a and 5.14b respectively. Evolutive GASM outperforms MEC-First and GASM with reconfiguration making a lower use of the RAM and HDD up to 10% and 0.4% respectively.

Figures 5.15 and 5.16 show the service blocking ratio and the active CPU cores for $\phi = 0.25$. For low traffic variations, unless a proper scaling factor is selected, planning with GASM for peak loads leads to a reduction of the network performance in terms of service blocking ratio, as Figure 5.15. GASM with reconfiguration outperforms GASM when $k = 1$ and $k = 2$. Furthermore, the learning stage of Evolutive GASM helps to improve the performance with respect to GASM with reconfiguration, although not as noticeably as in the case of $\phi = 0.5$. Both GASM with reconfiguration and Evolutive GASM outperform CO-First, but do not improve the performance of MEC-First in terms of service blocking ratio, since this algorithm adapts very well to low traffic variations. However, GASM with reconfiguration and Evolutive GASM obtain similar results to MEC-First for medium to high values of average users per HD-5G-node reducing the CPU consumption, as shown in Figure 5.16. Similar results are obtained in terms of RAM and HDD consumption.

Finally, Figures 5.18 and 5.19 show the service blocking ratio and the percentage of active CPU cores when the traffic variation is set to $\phi = 0.75$. It can be observed, in Figure 5.18, that high traffic variations affect the performance of the network by increasing the service



(a) Active RAM (%)



(b) Active HDD (%)

Figure 5.14: RAM and HDD consumption (in (%)) for the reconfiguration algorithms, the static algorithms and the online methods MEC-First and CO-First when $\phi = 0.5$.

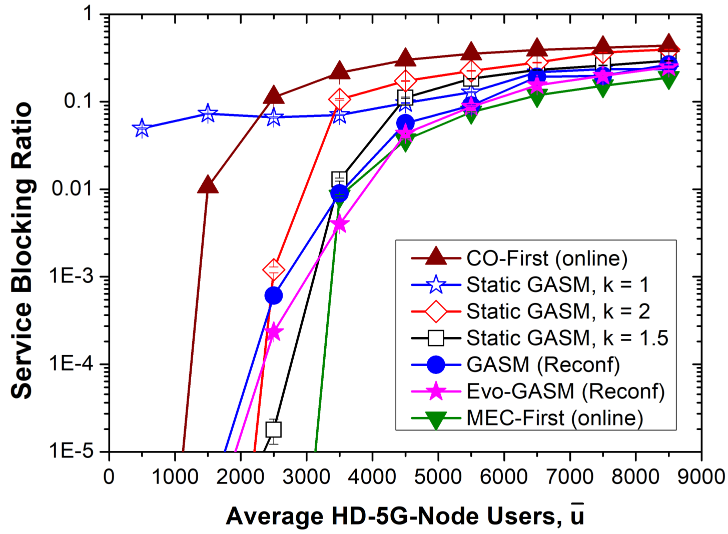


Figure 5.15: Service blocking ratio for the reconfiguration algorithms, the static algorithms and the online methods MEC-First and CO-First when ϕ = 0.25

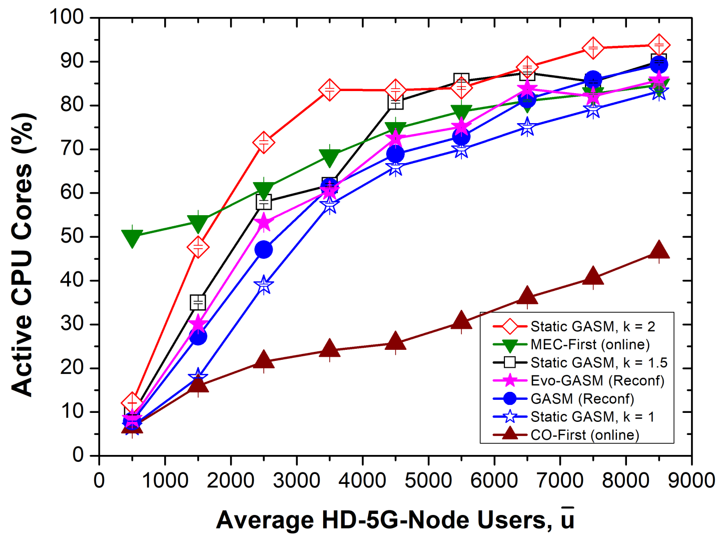


Figure 5.16: Active CPU Cores (%)

Figure 5.17: Service blocking ratio and CPU core consumption in (%) for the reconfiguration algorithms, the static algorithms and the online methods MEC-First and CO-First when ϕ = 0.25.

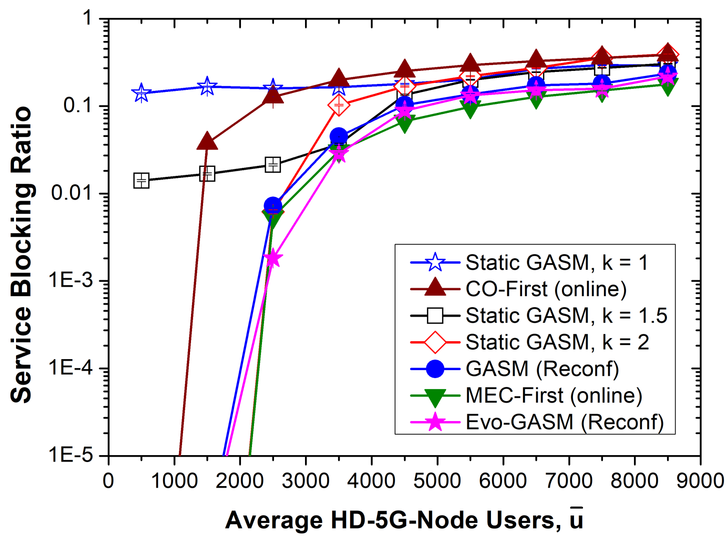


Figure 5.18: Service blocking ratio for the reconfiguration algorithms, the static algorithms and the online methods MEC-First and CO-First when $\phi = 0.75$.

blocking ratio for all the planning algorithms. Nevertheless, Figure 5.18 confirms that statically planning with GASM obtains the worst service blocking ratio for all traffic variation values. If reconfiguration is allowed, the performance of GASM with reconfiguration is similar to the performance of MEC-First while Evolutive GASM obtains the best results in terms of service blocking ratio. On the other hand, Evolutive GASM is able to obtain better service blocking ratio results consuming fewer CPU cores than MEC-First, as Figure 5.19 shows. Similar results are obtained in terms of RAM and HDD usage.

Lastly, we would like to compare the performance of the algorithms in terms of execution time. These values do not vary noticeably between different values of traffic variation, hence only the execution times obtained when $\phi = 0.5$ are shown.

Figure 5.21 shows the execution times of the compared algorithms. We can observe that the static planning algorithms require the highest computational times to execute the required tasks. However, time is not a limitation since the algorithms are not required to finish the execution in reduced periods of time. On the other hand, MEC-First and CO-First require really short computational times to serve the service requests, particularly compared with GASM with reconfiguration and Evolutive GASM. Nevertheless, these algorithms are able to perform the network planning in a period of time shorter than the time slot size, hence being feasible to be implemented in a dynamic scenario with planning reconfiguration with the time slot size used in the study [4].

In conclusion, NFV environments in which the traffic varies with time require proper planning algorithms able to correctly allocate computing resources both to the VNFs and network resources to the SCs to maximise the established service requests. In this kind of scenario, statically planning causes an inefficient usage of the computing resources. Allowing the execution of a periodical re-planning of the network with adequate algorithms can improve

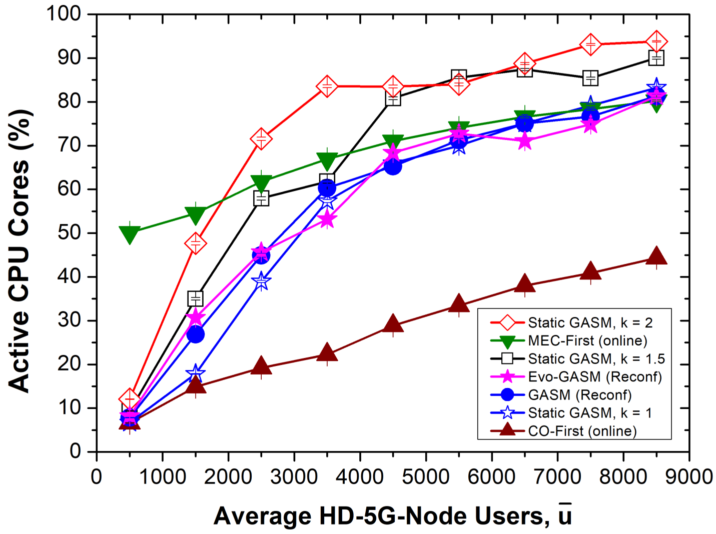


Figure 5.19: Active CPU cores (%) for the reconfiguration algorithms, the static algorithms and the online methods MEC-First and CO-First when ϕ = 0.75.

Figure 5.20: Service blocking ratio and Active CPU cores (in (%)) for for the reconfiguration algorithms, the static algorithms and the online methods MEC-First and CO-First when ϕ = 0.75.

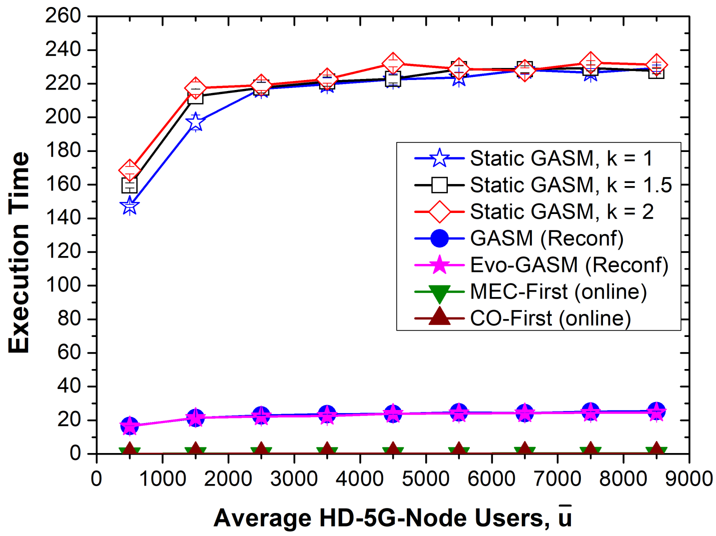


Figure 5.21: Execution times of the compared algorithms when ϕ = 0.5 [4].

the performance of the network in terms of service blocking ratio and computing resource consumption. In this subsection, we have compared the performance of our two proposals, GASM with reconfiguration and Evolutive GASM [4], with the results of statically planning the network for peak loads and with the online algorithms CO-First and MEC-First [9], [10]. Results show that Evolutive GASM obtains better results in terms of service blocking ratio and computing resource consumption, than static planning algorithms and other online algorithms proposed in literature, offering a good trade-off between resource consumption and service blocking ratio.

5.4 Conclusions

Network Function Virtualisation is a networking paradigm which aims at deploying network functions, like firewalls or packet inspectors, like software appliances. In this manner, networks can increase its flexibility and ease its management while reducing costs, since no more proprietary hardware appliances should be purchased and installed in order to deploy new services. This networking technology, in conjunction with other networking and computing technologies like SDN and MEC, are expected to enable the upcoming broadband communication technology 5G.

In this chapter, we have presented GASM (Genetic Algorithm for effective Service Mapping) a genetic algorithm which jointly solves the VNF-placement and chaining problems in a static 5G network with optical backhaul. Our algorithm initially solves the VNF-placement problem and then creates the necessary SCs to serve the connection requests arrived at the network. The algorithm aims at solving the design problem minimising the service blocking ratio and the active computing resources, and takes into consideration the available computing and network resources. We have compared our proposal with other VNF-placement and chaining algorithms proposed in literature and our results show that our algorithm offers a good trade-off between service blocking ratio and computing resource consumption, obtaining good results in service acceptance and improving the computing resource consumption with respect to other existing algorithms in literature.

However, the nature of the traffic in real networks is variable with time. In consequence, a static network planning can cause an inefficient performance of the network both in terms of service blocking ratio and resource consumption. In this kind of networks, it is necessary to implement planning algorithms which solve the service connection request online. This strategy is well suited to create SCs when the VNF instances are already deployed. Nevertheless, setting a VNF at the moment in which a service connection arrives at the network may take seconds or even minutes, incrementing the service set up time.

In consequence, we have proposed two strategies to reconfigure VNF-placement and chaining problems based on GASM, called GASM with reconfiguration and Evolutive GASM, which reconfigure the initial VNF-planning of the network. While GASM is similar to GASM, Evolutive GASM adds a learning stage which is able to improve the performance of the algorithm.

We have compared our proposals with the static planning using GASM and with online methods which solve the VNF-placement and chaining problems proposed in literature. Results show that our proposals are able to offer a good trade-off between service blocking ratio and computing resource consumption. Furthermore, adding a learning step allows Evolutive

GASM to outperform other methods proposed in literature in both the service blocking ratio and the IT resource consumption.

Chapter 6

Joint Solution of VNF Mapping and Virtual Topology Design

In Chapter 5, we presented GASM, a genetic algorithm for effective service mapping which solved the VNF-placement and chaining problems in static 5G networks, where the 5G-nodes of the network are equipped with MEC servers. This algorithm decides the best placement of the VNFs and establishes the required service chains, according to the requests, to minimise the service blocking ratio and the computing resource consumption. The algorithm was further modified to be applied in dynamic scenarios, where a periodical reconfiguration of the network planning is performed according to the traffic expected to arrive at the network. In both scenarios, the algorithm solves the planning of the network taking into account not only the restricted computing resources with which the nodes are equipped, but the limited network resources available, since the nodes of the network are supposed to be connected to a central office via dedicated optical links, forming a star topology.

Nevertheless, the star topology used as scenario to our proposal in Chapter 5 does not enable the efficient collaboration of the MEC nodes, as any connection between two MEC nodes must traverse the central office. Consequently, GASM was not able to fully exploit the MEC capacities of the nodes. Furthermore, the 5G optical backhaul can be built over other types of network topologies and optical technologies, e.g., the WDM-ring used in [215]. Hence, it is necessary to propose VNF-placement and chaining algorithms that are able to configure the network planning and operation in mesh topologies.

In this chapter, we propose GASM-VTD (Genetic Algorithm for effective Service Mapping with Virtual Topology Design), a genetic algorithm that addresses the problem of jointly solving the VNF-placement, chaining and the virtual topology design in a 5G network with optical backhaul, where the MEC nodes are connected via a WDM network. In this network, the benefits of enabling the collaboration between MEC nodes, to better exploit the cloud computing capabilities with which these kinds of nodes are equipped, are explored with a new VNF-chaining technique. This chaining scheme may construct SCs in which two consecutive VNFs are located at two different nodes of the network, requiring the establishment of a virtual link between them to transport the associated traffic from one VNF to the following one. Hence, the algorithm also designs the virtual topology which allows the establishment of the required virtual links, including the lightpaths which must be set up, assigning a route and a wavelength to each lightpath and transporting the traffic over the designed virtual topology using traffic grooming.

Later, we present a new version of GASM-VTD providing SC resilience against node failure. If a node fails, the SCs traversing that node may suffer a degradation of the Quality of Service (QoS) or even a disruption, which may affect thousands of end-users and cause the loss of large amounts of data. Hence, our proposal solves the individual VNF protection including the required connections (and allocated network resources) to ensure the transportation of traffic from the primary VNFs to the backup VNFs. We compare the performance of our proposals on different network scenarios, assuming limited and unlimited network resources. Furthermore, we compare our proposals with end-to-end SC protection strategies, which provide a complete backup SC to protect each working SC, based on proposals existing in the literature.

Finally, we present GASVIT, a new algorithm that solves the VNF-placement and chaining problems and the virtual topology design implementing a new chaining technique. The algorithm makes more efficient placement of the VNFs compared to the previous proposals by better exploiting the collaboration between MEC nodes. Four versions of GASVIT to provide individual VNF protection are proposed. We compare the performance of GASVIT and GASVIT with protection with GASM-VTD and its version with protection. Furthermore, since GASVIT works with any type of topology, a techno-economic study is conducted to compare different network topologies in terms of service blocking ratio and network costs.

The rest of this chapter is structured in the following manner: In Section 6.1, GASM-VTD is described and its performance in terms of service blocking ratio and computing resource consumption is presented. Section 6.2 presents the versions of GASM-VTD that integrate the different individual VNF-protection. Furthermore, protection schemes proposed in the literature [194] are presented and integrated into GASM-VTD, comparing the performance of the individual VNF protection and the end-to-end protection schemes. Section 6.3 presents GASVIT, the proposed versions of this algorithm that include protection techniques, the study of their performance compared to the performance of other methods. A techno-economic study that compares the behaviour of different network topologies in terms of service blocking ratio and network costs is also performed in this section. Finally, Section 6.4 concludes this chapter.

6.1 Genetic Algorithm for Service Mapping with Virtual Topology Design

In Chapter 5, we introduced GASM [3], [4], a genetic algorithm for effective service mapping which solves the VNF-placement and chaining problem in 5G networks with optical backhaul. The network was constructed over a star topology and its nodes were equipped with MEC server, thus being able to host VNFs. However, GASM is only able to use VNFs hosted at the local node at which the end-user is connected or the CO since any communication between MEC nodes implies traversing the CO, therefore consuming high bandwidth, increasing the latency and making the CO more complex. Consequently, GASM was not able to fully exploit the MEC capabilities of the 5G-nodes.

On the other hand, GASM was initially designed to solve the service mapping problem in 5G networks. However, 5G-nodes can be part of metro/core networks as in [215], [193]. Hence, it is necessary to adapt GASM to be able to solve the VNF-placement and chaining in other network topologies.

In this section, we present a version of GASM which is able to address these two aspects of the algorithm, called Genetic Algorithm for effective Service Mapping with Virtual Topology Design and embedding (GASM-VTD) [5]. Our proposal works with WDM networks that connect the 5G-nodes and a CO deploying different topologies. Therefore, a virtual link between two nodes of the network hosting two consecutive VNFs in an SC must be created to transport the traffic from one VNF to another. Since the nodes are connected through a WDM network, the algorithm establishes lightpaths, i.e., all-optical routes between the nodes, and electrically grooms the virtual links into the existing lightpaths, if they have enough available capacity, or creates new lightpaths otherwise, if there are sufficient network resources. Therefore, the algorithm:

- solves the VNF-placement problem.
- solves the VNF-chaining problem.
- solves the virtual topology design, including:
  - the connectivity problem, i.e., decide which lightpaths must be established.
  - the routing and wavelength assignment (RWA) problem for each lightpath.
  - the routing of traffic through the established lightpaths performing traffic grooming.

6.1.1 Algorithm Structure

As explained in Chapter 5, in genetic algorithms, each possible solution from the search space is an individual. Each individual is described by a chromosome, which in GASM-VTD represents the number of instances of a given VNFs that should be created at each hosting node of the network. The chromosome is analogous to the chromosome in GASM, and an example is shown in Figure 5.2. GASM-VTD creates an initial parent population composed of randomly generated individuals and two ad-hoc individuals, created using the MEC-First [9], [10] and CO-First [3], [4]. However, GASM-VTD does not take into account the bandwidth availability at the moment of deciding which VNF instances compose each SC.

Once the parent population is created, the composing individuals undergo the same genetic evolution loop as in GASM. The crossover operation is described in Algorithm 5. The offspring undergoes then the mutation operation described in Algorithm 6. After that, the individual is validated, i.e., GASM-VTD checks if the number of instances of the VNFs can be created at the corresponding hosting 5G-nodes, as the chromosome indicates. If the instantiation is possible, because there are enough available computing resources, then the individual is valid. Otherwise, it is discarded and a new one is generated using the crossover and mutation operations, until achieving a certain descendant population size, which is user-defined.

At this stage, the algorithm translates the chromosome and evaluates the fitness of the corresponding solution. For this process, GASM-VTD creates the instances of the VNFs according to the information of the chromosome. After that, the algorithm sorts the connection requests according to the operator's priority order (e.g., VoIP, video and web) and decides which of the VNF instances should be concatenated, according to their capacity availability only, thus not considering the bandwidth availability. We propose two versions of GASM-VTD, according to the chaining strategy:

1. **GASM-VTD-No-Collaborative**: This strategy only concatenates VNFs with available processing capacity located at the local 5G-node to which the requesting end-user is connected, and the CO. Once the strategy employs a VNF located at the CO, it does not search for available VNFs back at the local 5G-node. If the algorithm is not able to find an available VNF, the request is blocked.

2. **GASM-VTD-Collaborative**. This chaining strategy can use any VNF located at any node of the network. The strategy starts the chaining at the local node. If the algorithm is not able to find the corresponding VNF with enough capacity in that location, then tries to employ an available VNF located at the CO. If unable to concatenate a VNF, the algorithm continues the search starting with the nodes with larger computation capabilities and finishing with the nodes with fewer computation resources.

If the algorithm is not able to set up an SC due to a lack of VNF instances with enough available capacity to process the associated traffic, the request is blocked.

Once all the instances have been reserved for all the SCs required to establish the requested services, the algorithm starts with the virtual topology design process. If an SC contains two consecutive VNFs located at different nodes of the network, the algorithm creates a virtual link between them with enough capacity to transport the requested traffic. If there is an established lightpath between the hosting nodes with enough available capacity to create the virtual link required to transport the requested bandwidth, the algorithm grooms the traffic into this lightpath. If not, the algorithm tries to set up a new lightpath between the two nodes making use of the available network resources. GASM-VTD creates the lightpaths using the $k-$shortest paths and first fit strategies [62]. If the algorithm is not able to groom the virtual link into existing lightpaths and cannot establish new ones due to lack of network resources, the connection request is blocked and the reserved VNFs are released. Hence, at the end of this process a new virtual topology has been designed, solving the RWA problem to establish the required lightpaths and performing traffic grooming to transport the requested traffic over these lightpath.

The fitness of the individual is evaluated considering three parameters: the service blocking ratio, the percentage of active CPU cores and the percentage of used wavelengths, in that order. Then, the algorithm selects the fittest individuals, among the parent and descendant populations, to build the parent population of the following generation and repeats the process for a number of generations which is determined by the user. During the selection of the fittest individuals, the algorithm can find two individuals with the same score in terms of service blocking ratio. In that case, the algorithm selects the individual with the lowest percentage of active CPU cores. If the individuals are also tied in this parameter, the algorithm selects the individual with the lowest percentage of used wavelengths. At the end of the process, the algorithm provides the best solution which is composed of the VNF-placement, the established SCs, and the virtual topology.

6.1.2 Simulation Scenario and Settings

We tested the performance of GASM-VTD in a WDM-ring metro network conducting a simulation study using OMNeT++ [159] (see Apendix A). The objective is to compare the performance of GASM-VTD-Collaborative to the performance of GASM-VTD-No-Collaborative, GASM-VTD-Collaborative, MEC-First [9], [10], and CO-First [3], [4]. The

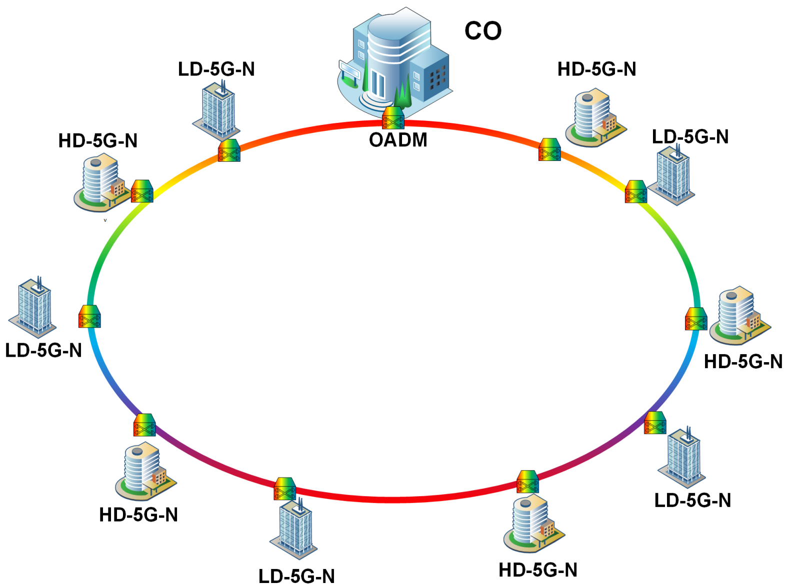


Figure 6.1: WDM-ring topology scenario [5].

network is composed of 5 HD-5G-nodes, 5 LD-5G-nodes, and a CO, as shown in 6.1. As explained in Chapter 5, the 5G-nodes are equipped with MEC capabilities, while the CO is also equipped with IT resources. Consequently, both kinds of nodes are able to host VNFs. However, HD-5G-nodes attend ten times more users on average than the LD-5G-nodes and, in consequence, they are equipped with larger MEC capabilities. The IT capabilities associated with each kind of node are shown in Table 6.1 [9], [10]. The IT capabilities are the same as the employed in Table 5.1 and are repeated in this chapter for the reader's convenience. We assumed that the nodes of the network are equipped with a set of transceivers and a reconfigurable optical add-drop modulator (ROADM). In this study, the network can employ 10 wavelengths at a 10 Gb/s rate.

We assumed that the network is managed by a network operator which offers VoIP, video streaming and web services. Each user can request one of these services with a probability of 30%, 20% or 50% respectively. The associated SC and demanded bandwidth are shown in Table 6.2 [7], [8], [3], [4], [5]. These requirements are the same as the shown in Table 5.2, and are repeated in this chapter for the reader's convenience.

Location	*Computational resources*
Central Office	100 CPU cores, 480 GB RAM and 27 TB HDD
HD-5G-Node	16 CPU cores, 64 GB RAM and 10 TB HDD
LD-5G-Node	8 CPU cores, 32 GB RAM and 7 TB HDD

Table 6.1: Hardware capabilities of the different 5G-nodes.

The IT resources and throughput associated with each VNF are shown in Table 6.3. In this case, the figures have been updated with respect to the values presented in Table 5.3, and the throughput is used instead of the number of concurrent operations as the capacity measure of the VNF.

Service	*Chained VNFs*	*Bandwidth*
VoIP	NAT-FW-TM-FW-NAT	64 kbps
Video	NAT-FW-TM-VOC-IDPS	4 Mbps
Web Services	NAT-FW-TM-WOC-IDPS	100 kbps

Table 6.2: Requirements of the deployed service chains. NAT: Network Address Translator, FW: Firewall, TM: Traffic Monitor, WOC: WAN Optimization Controller, VOC: Video Optimization Controller and IDPS: Intrusion Detection Prevention System [7], [8], [9], [10], [3], [4].

Service HW requirements	*Throughput*
NAT CPU: 2 core, RAM: 4 GB, HDD: 16 GB	2 Gb/s [218]
FW CPU: 2 cores, RAM: 4 GB, HDD: 16 GB	2 Gb/s [218]
TM CPU: 1 core, RAM: 2 GB, HDD: 16 GB	1 Gb/s [219]
VOC CPU: 2 cores, RAM: 4 GB, HDD: 2 GB	2 Gb/s*
WOC CPU: 1 core, RAM: 2 GB, HDD: 40 GB	0.5 Gb/s [220]
IDPS CPU: 1 cores, RAM: 2 GB, HDD: 8 GB	2 Gb/s [221]

Table 6.3: Hardware requirements associated with the VNFs [5]. *We assume that FW also includes NAT function, therefore the HW requirements are the same. Requirements for VOC are derived from the requirements of the other VNFs.

As we did in Chapter 5, we define the parameter $\bar{u}$ which represents the number of average users connected to an HD-5G-node. At the beginning of each simulation, the number of connected users to each HD-5G-node is randomly calculated using the uniform distribution:

$$\mathcal{U}\left[0, 2 \cdot \bar{u}\right]. \tag{6.1}$$

On the other hand, the LD-5G-nodes attend ten times fewer users on average than the HD-5G-nodes. Therefore, in each simulation, the number of connected users to each LD-5G-node is randomly generated using the uniform distribution:

$$\mathcal{U}\left[0, \frac{2 \cdot \bar{u}}{10}\right]. \tag{6.2}$$

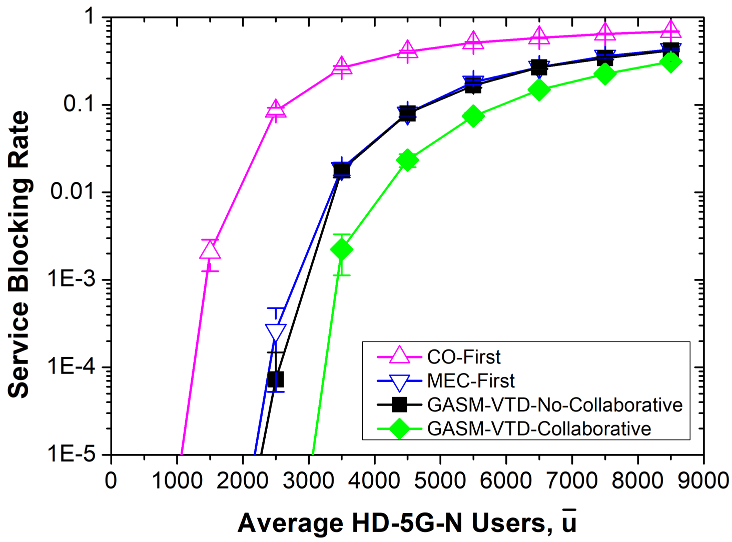


Figure 6.2: Service blocking ratio of GASM-VTD-Collaborative, GASM-VTD-No-Collaborative, MEC First, and CO-First in a WDM-ring 5G network [5].

The size of the parent population was set to 5 individuals, whereas the size of the descendant population was set to 10 individuals. The mutation probability was set to 0.02. We created 50 generations and repeated the simulation 900 times with different traffic demands. Results are shown on average, and are plotted with 95% confidence intervals.

6.1.3 Performance of GASM-VTD

The performance of the algorithm in terms of service blocking ratio is shown in Figure 6.2, whilst the percentage of CPU consumption of the algorithm is shown in Figure 6.3. We can observe that GASM-VTD-No-Collaborative achieves the same results in terms of service blocking ratio than MEC-First while improving the CPU resource consumption, particularly for the lowest values of $\bar{u}$, as Figure 6.3 shows [5].

Nevertheless, GASM-VTD-Collaborative, which exploits the collaboration between the nodes of the network, is able to outperform all the strategies compared in this study. In particular, the algorithm is able to support an average of $1,000$ users for the HD-5G-nodes and 100 users for the LD-5G-nodes more than GASM-VTD-No-Collaborative and MEC-First without causing service blockage. This algorithm presents a similar consumption of CPU core resources than GASM-VTD-No-Collaborative and MEC-First for low to medium values of $\bar{u}$. However, the algorithm obtains the highest consumption of CPU cores for the highest values of $\bar{u}$, as pictured in Figure 6.3 [5]. CO-First is the algorithm with the highest service blocking ratio and lowest IT resource consumption since it is not able to fully exploit the IT capabilities of the edge nodes.

In conclusion, allowing the collaboration between MEC nodes of a WDM network to solve the VNF-placement and chaining reduces the service blocking ratio while optimizing the number of active CPU cores.

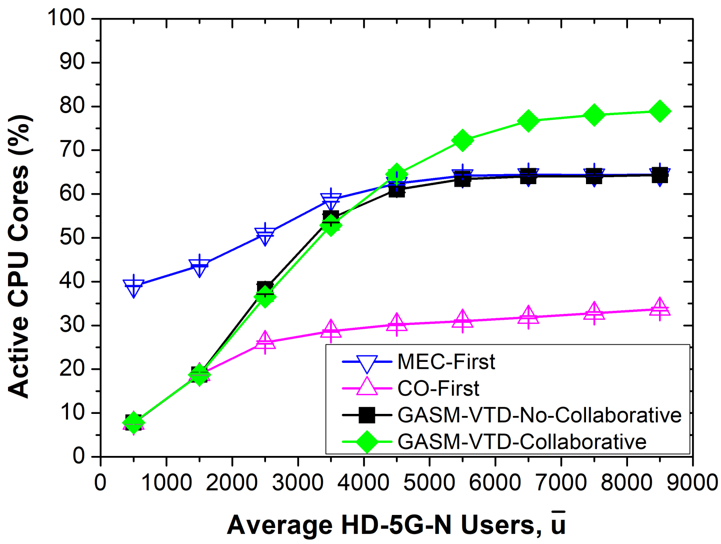


Figure 6.3: Percentage of CPU core consumption of GASM-VTD-Collaborative, GASM-VTD-No-Collaborative, MEC First and, CO-First in a WDM-ring 5G network [5].

6.2 Fault-management techniques to guarantee survivability in NFV environments

Results from the previous section have shown the importance of jointly solving the VNF-placement and chaining problems and the virtual topology design. Nevertheless, GASM-VTD does not address the survivability problem. If a VNF or a node fails, the SCs which concatenate the failing VNF or any VNF in the failing node will suffer QoS degradation or even a disruption. As a consequence, thousands of end-users can see their connection degraded or completely interrupted, and large amounts of data will be lost.

Hence, we extended GASM-VTD to include protection techniques that guarantee the resilience of the SCs in a single-node failure scenario. As showed in Chapter 4, the fault-management techniques can be classified according to the protected element. We can find SC protection techniques which provide a complete backup SC to protect a primary SC. In case of failure of one of the elements of the primary SC, the associated traffic would traverse the backup SC. Hence, this kind of technique provides end-to-end SC protection, as Figure 4.2 shows. Contrarily, there are techniques proposed in the literature which only provide individual VNF protection. In this kind of strategy, a backup VNF is provided for each primary VNF. If the primary VNF fails, the traffic will traverse the corresponding backup VNF and then the next elements of the initial primary SC, as shown in Figure 4.3.

On the other hand, the protection schemes can be dedicated or shared. In dedicated protection schemes, the backup element, which can be either a VNF or an SC, can protect only one primary element. Contrarily, in shared protection schemes the backup element can protect multiple primary elements. In the case of SC protection, a backup SC and its protected primary SCs cannot contain the same VNFs and the chains must be node-disjoint to avoid collision problems. In the case of individual VNF protection, a backup VNF cannot be employed as a primary VNFs, and can only protect multiple VNFs if they are node-disjoint between them and the backup VNF.

We present a version of GASM-VTD enriched with individual VNF protection, which solves the survivable VNF-placement and chaining problems and the virtual topology design, including the reservation of VNFs and the virtual links necessary to build the backup SCs. We have studied the impact of using dedicated and shared protection schemes, and analysed their performance in terms of service blocking ratio and computing resource consumption. Lastly, the performance of the proposed algorithm with individual VNF protection is compared to the performance of the algorithm with end-to-end protection schemes proposed in the literature.

6.2.1 Individual VNF protection schemes

When the individual VNF protection strategy is chosen, a backup VNF is assigned to each primary VNF employed in an SC. The primary VNF and its associated backup VNF must be hosted in different nodes of the network. Moreover, the corresponding virtual links between the primary VNFs and the backup VNFs must also be reserved to ensure that the traffic can traverse the backup VNF and be transported to the next primary VNF of the SC. We call these virtual links "backup virtual links". We showed an example of a primary SC with individual VNF protection in Figure 4.3, where the different cases in which a backup virtual link must be established were introduced.

The protection can be delivered either allocating dedicated protection resources to the primary VNFs or allocating shared resources between multiple primary VNFs. Moreover, we can allocate dedicated network resources to the virtual links between the primary and backup VNFs, or share those resources. Accordingly, we propose five variations of GASM-VTD [6]:

1. **GASM-VTD (NP):** This version of GASM-VTD does not provide individual VNF protection, allocating neither backup VNFs nor backup network resources. This scenario is equivalent to execute GASM-VTD-Collaborative.

2. **GASM-VTD (DV, DN):** This method allocates a dedicated backup VNF to each primary VNF. A primary VNF cannot be eligible to protect another primary VNF concatenated in any primary SC. The method also allocates dedicated network resources to establish the virtual links between the primary and backup nodes. Therefore, these network resources are not utilised to establish virtual links between primary and backup VNFs in any other established SC.

3. **GASM-VTD (DV, SN):** As in the previous version, the method provides dedicated VNF protection, so each backup VNF will only protect one primary VNF. However, the method shares the network resources allocated to backup virtual links between multiple SCs.

4. **GASM-VTD (SV, DN):** This method provides shared VNF protection and, thus, can use one single backup VNF to protect multiple primary VNFs. The primary VNFs cannot share the same location in order to avoid collision problems if a node fails. Furthermore, the primary and backup VNFs must be node-disjoint. The network resources allocated to backup virtual links are dedicated in this strategy, therefore they cannot be used to connect primary and backup VNFs in other SCs.

5. **GASM-VTD (SV, SN):** This method shares either the backup VNFs and the network resources.

6.2.2 Integrating VNF protection into GASM-VTD

We have proposed four variations of GASM-VTD that provide SC resilience by assigning backup VNFs to the designed primary VNFs and reserving network resources for the required backup virtual links.

The chromosome of the individuals in GASM-VTD with protection is analogous to the chromosome in GASM-VTD. Therefore, each gene indicates the number of instances of a certain VNF which should be created at a certain host.

The initial parent population in GASM-VTD with protection is composed of randomly generated individuals, which undergo the same crossover and mutation processes described in Chapter 5, Algorithms 5 and 6. The resulting offspring of each generation is validated checking if the required instances of each VNF can be created at every hosting node as the chromosome indicates. If the algorithm is unable to create the indicated instances due to lack of computing resources, the individual is discarded and a new one is created using the crossover and mutation operations. The process is repeated until achieving a user-defined population size.

After the population of valid individuals is completed, the algorithm starts the translation process. For each individual in the population, the algorithm translates it, i.e., creates the indicated instances of the VNFs at their corresponding hosts, which are assumed to remain idle until the algorithm is able to chain them in an SC, or reserve them as a backup VNF. The algorithm sorts the incoming service requests according to a certain operator's priority order. After that, the algorithm tries to serve each connection request by reserving first the VNFs to build the required primary SC and then the backup VNFs to protect the primary SC. The algorithm employs the GASM-VTD-Collaborative chaining policy introduced in Subsection 6.1.1. Hence, to construct the primary SC, it tries to chain VNFs with available capacity located at the local 5G-node. If no available instances of VNFs are found, the algorithm tries to find available VNF instances located at the CO. Again, if the algorithm is not able to find the required VNF at the CO, it searches at the 5G-nodes, starting with the nodes equipped with larger IT capabilities, and finishing with the nodes with fewer IT capabilities. If the algorithm cannot construct the SC, the service request is automatically blocked. Otherwise, the algorithm begins with the reservation of the backup VNFs.

After the primary SC is completed, the algorithm searches for backup VNFs to protect the primary VNFs in this SC. The VNFs already in use in any constructed primary SC cannot be utilised to protect another primary VNFs. In the same manner, a backup VNF cannot be chained in a primary SC. Furthermore, the primary VNF and its backup VNF must be hosted by different nodes, in order to provide node failure protection. If the dedicated VNF protection scheme is employed, then each backup VNF protects only one primary VNF. However, if the shared protection scheme is implemented, a backup VNF can protect multiple primary VNFs, provided that the hosting nodes are totally disjoint, i.e., two or more primary VNFs cannot be located at the same node, to avoid collision problems. The search strategy employed to find backup VNFs is highly similar to GASM-VTD-Collaborative, since the algorithm searches available VNFs at the CO, then at the nodes with larger computing resources and finishing with the nodes with fewer IT capabilities, avoiding the node at which the VNF to be protected is located. If the algorithm is not able to find a backup VNF for each VNF in the primary SC, the connection is blocked.

After constructing the primary SCs and allocating backup VNF resources the algorithm assigns network resources. If two consecutive VNFs of a primary SC are hosted by different nodes, the algorithm creates a virtual link between the nodes to connect them and establish the service connection. If a lightpath between the nodes exists, and it has enough available capacity to transport the associated traffic to the SC, then the algorithm uses it to establish the virtual link. Otherwise, the algorithm tries to establish a new lightpath between the two nodes, if there are sufficient available network resources. The algorithm uses the $k-$shortest paths and first fit policies to set up the required lightpaths. If the algorithm is able to assign the required network resources to the primary SC, it creates the required backup virtual links to connect the primary VNFs with their backup resources, and the consecutive backup VNFs hosted by different nodes which protect VNFs located at the same node. In this case, the lightpaths employed by the primary and backup VNFs are completely independent. Hence, a backup lightpath does not transport traffic associated with primary SCs. If the dedicated network resource scheme is employed, the connections between primary and backup VNFs and connections between backup VNFs are dedicated for each SC. Otherwise, these connections can be shared with other SCs. If the algorithm finds network resources for the primary and backup connections, it reserves the required bandwidth and establishes the connection. Otherwise, the service request is blocked.

For each individual in the population, the algorithm computes its fitness. As in GASM-VTD, the three selected fitness parameters are the service blocking ratio, the percentage of active CPU cores, and the percentage of used wavelengths. The algorithm selects the fittest individuals among the parent and the descendant populations to become the parents of the descendant population of the next generation. If two individuals obtain the same results in terms of service blocking ratio, the algorithm selects the one with better performance in terms of CPU core usage. If there is also a tie in this parameter, the individual with the lowest number of active wavelengths is selected. GASM-VTD with protection repeats the classical genetic loop for a number of user-defined generations. At the end of the process, the algorithm provides the best solution which is composed of the VNF-placement, the established SCs, their corresponding backup resources, and the designed virtual topology, including the primary and backup connections.

6.2.3 Simulation scenario and results

We performed a simulation study to compare the performance of the four versions of GASM-VTD with protection over a 5G WDM-ring network using the developed simulator in OMNeT++ [159]. We utilised the same network scenario described in Subsection 6.1.2. We assumed that the CO is equipped with IT resources and the 5G-nodes with MEC servers. The IT capabilities with which the nodes are equipped are shown in Table 6.1 [9], [10].

As in previous studies, we assume three different kinds of network services: VoIP, video streaming and web services. The end-user can request one of the services with 30%, 20% and 50% probability, respectively. Each network service has an associated SC and bandwidth requirements, which are shown in Table 6.2 [7], [8], [3], [4], [5].

Finally, each VNF has the associated CPU core, RAM, hard disk requirements, and throughput shown in Table 6.3.

We configured GASM-VTD with protection to create 50 generations, with an parent

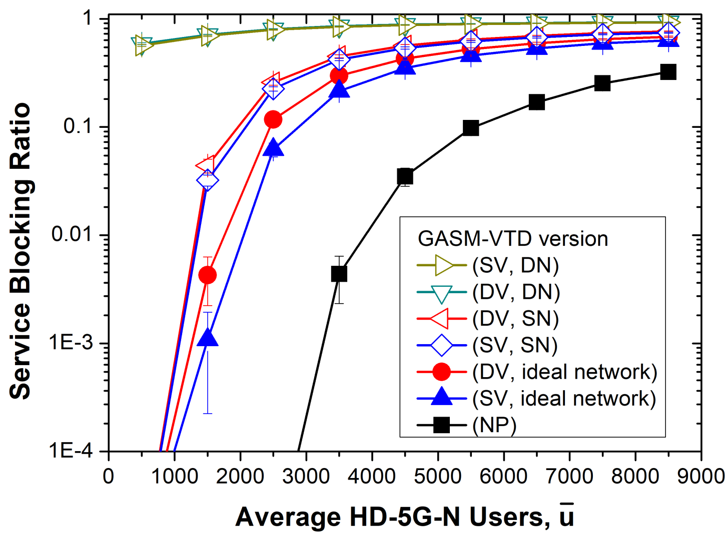


Figure 6.4: Service blocking ratio of GASM-VTD with the different protection techniques when the WDM network can use 10 wavelengths [6].

population size of 5 individuals, a descendant population size of 10 individuals and a mutation probability of 0.02. We performed 500 simulations, and the traffic requests are randomly generated at the beginning of each simulation. The algorithm randomly generates the number of connected users to each 5G-node according to the uniform distributions described in Equations 6.1 and 6.2. Furthermore, the network is able to employ either 10 or 20 wavelengths.

We compared the following variations of GASM-VTD:

- **GASM-VTD (NP).**
- **GASM-VTD (DV, ideal network):** In this protection scenario, the algorithm allocates dedicated backup VNF protection considering unlimited network resources.
- **GASM-VTD (SV, ideal network):** The algorithm assigns shared backup VNF resources and considers no restrictions in terms of transceivers and wavelength channels.
- **GASM-VTD (DV, DN).**
- **GASM-VTD (DV, SN).**
- **GASM-VTD (SV, DN).**
- **GASM-VTD (SV, SN).**

Figure 6.4 shows the service blocking ratio of GASM-VTD with the different protection strategies. Allocating backup resources requires more computing and network resource consumption. In consequence, it is not surprising that the service blocking ratio increases in the protection scenarios compared to the no protection case. However, we can observe that

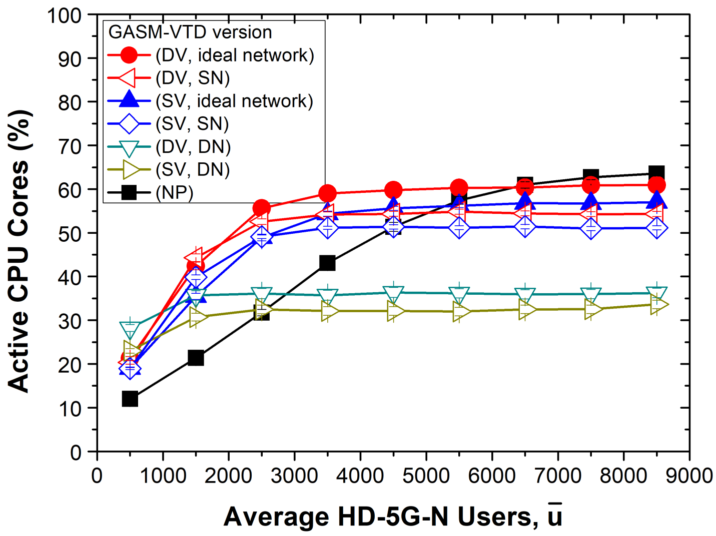


Figure 6.5: Percentage of CPU core consumption of GASM-VTD with the different protection techniques when the WDM network can use 10 wavelengths [6].

GASM-VTD (DV, ideal network) and GASM-VTD (SV, ideal network) achieve a significantly better service blocking ratio compared to the same schemes when the network resources are restricted to 10 wavelengths. That difference can be of an order of magnitude for low values of $\bar{u}$. Moreover, the protection schemes which employ dedicated network resources obtain a large service blocking ratio ($> 10^{-1}$), which makes them infeasible to be implemented in actual networks. Consequently, the availability of the network resources is a restricting factor that must be taken into account when solving the VNF-mapping. If the mapping is solved without designing the network (as previous studies do), the service blocking ratio will be much higher than expected. However, that problem can be avoided with GASM-VTD, which solves both the VNF-mapping and the virtual topology design.

Figure 6.5 shows the total CPU consumption of the primary and backup VNFs in terms of percentage of active CPU cores for GASM-VTD with the different protection schemes. We can observe that the no protection scheme is the least consuming method in terms of CPU cores. Moreover, the shared protection schemes are the strategies capable of making the best use of the CPU cores to reduce the service blocking ratio, since their results are lower compared to their dedicated counterparts. Lastly, if we compare the protection schemes observing the allocation method of the network resources (shared or dedicated), we can see that the methods with shared network resources make a higher consumption of CPU cores. This means that the availability of network resources becomes a limiting factor when solving the VNF-placement and chaining problems with VNF-protection since the network resources are consumed sooner than the computing resources. Hence, in the dedicated network schemes, there might be sufficient computing resources to allocate backup VNFs to the primary VNFs, but not enough network resources to establish the virtual links between the primary and the backup VNFs.

This behaviour can be observed in Figure 6.6. This figure shows the comparison of the

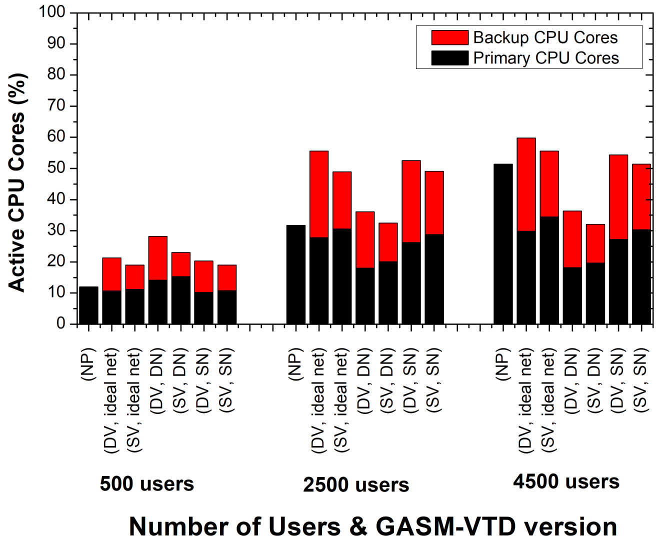


Figure 6.6: Comparison of the percentage of allocated CPU cores to the primary and backup VNFs, for the different protection schemes when the WDM network can use 10 wavelengths, for $\bar{u} = 500$, $\bar{u} = 2,500$ and $\bar{u} = 4,500$ [6].

percentage of CPU cores allocated to primary and backup VNFs, for the proposed protection schemes and three different values of the number of average users: $\bar{u} = 500$, $\bar{u} = 2,500$ and $\bar{u} = 4,500$. We can observe that the CPU core consumption increases with the number of average users in the network. However, this growth of the computing resource consumption is more significant between the $\bar{u} = 500$ and $\bar{u} = 2,500$ cases than between the $\bar{u} = 2,500$ and $\bar{u} = 4,500$ scenarios, particularly for the protection schemes. Since the number of users increases, also does the number of SCs which must be established and the network consumption. If the network resources are fully consumed, the algorithm is not able to establish the required lightpaths to set up the primary SCs and connect the primary VNFs with their backup resources. Hence, no more VNFs can be employed, neither as primary nor as backup VNFs, and the IT consumption does not increase. Nevertheless, if no protection is implemented, we can observe that the CPU consumption grows with the number of average users when the number of service requests increases, hence incrementing the number of required SCs and the number of active VNFs.

If we observe the percentage of active CPU cores for primary and backup VNFs shown in Figure 6.6, we can see that the shared-VNF policies employ fewer CPU cores than the dedicated-VNF policies, which is to be expected since the former are capable of allocating the same backup VNF to multiple primary VNFs. Since the shared-VNF protection policies aim at reusing backup VNF resources, they obtain a lower percentage of total allocated CPU cores, compared to their dedicated counterparts.

In conclusion, we can say that the network resources are the limiting factor which impacts the performance of the individual VNF protection schemes.

If we raise the number of possible wavelengths to 20, the performance of GASM-VTD

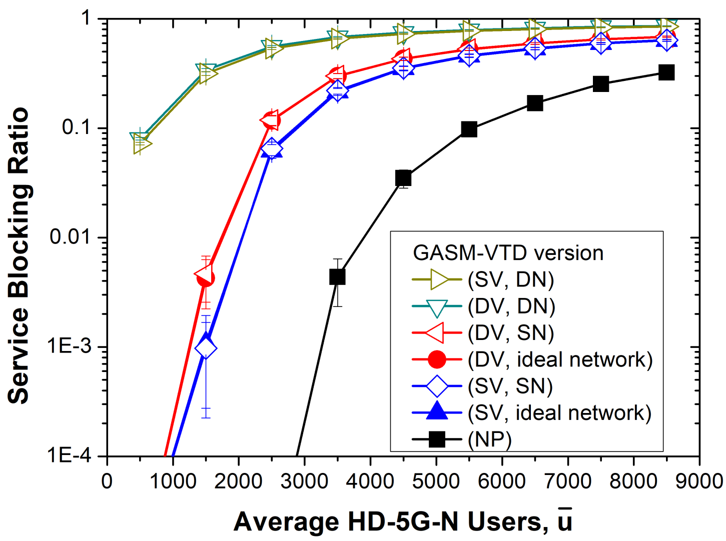


Figure 6.7: Service blocking ratio of GASM-VTD with the different protection techniques when the WDM network can use 20 wavelengths [6].

with the different protection techniques in terms of service blocking ratio improves, as can be seen in Figure 6.8. Actually, the implementations of the individual VNF protection schemes which employ shared network resources obtain the same service blocking ratio as the protection schemes applied in ideal network scenarios, i.e., with unlimited network resources. The protection schemes using dedicated network resources will require more active wavelengths to obtain service blocking ratio results closer to the results of GASM-VTD (DV, ideal network) and GASM-VTD (SV, ideal network) and make them feasible to be implemented in real networks. Consequently, we can improve the behaviour of the individual VNF protection schemes by incrementing the number of wavelength channels available in the network and, in consequence, the capital expenses of the network.

The CPU core consumption is also affected by the number of possible active wavelength. If this number grows to 20 possible wavelengths, the protection schemes which share the backup network resources obtain nearly the same resource consumption as the protection schemes performing in ideal network resource scenarios, which is obvious since the service blocking ratio is also almost equal. The protection schemes with dedicated backup network resources present a higher computing resource consumption, particularly for the lowest values of average users per HD-5G-node. Therefore, a higher value of active wavelengths in the network allows the different versions of GASM-VTD to establish more SCs since there are more available network resources to create the connections between the primary VNFs, and between the primary and the backup VNFs. In consequence, more instances of VNFs can be activated, either as primary or backup VNFs, increasing the CPU core consumption.

Lastly, we show in Figure 6.9 the percentage of CPU cores allocated to primary and backup VNFs for all the proposed protection schemes for three values of average number of connected users per HD-5G-node: $\bar{u} = 500, \bar{u} = 2,500$ and $\bar{u} = 4,500$. Results confirm the growth of the

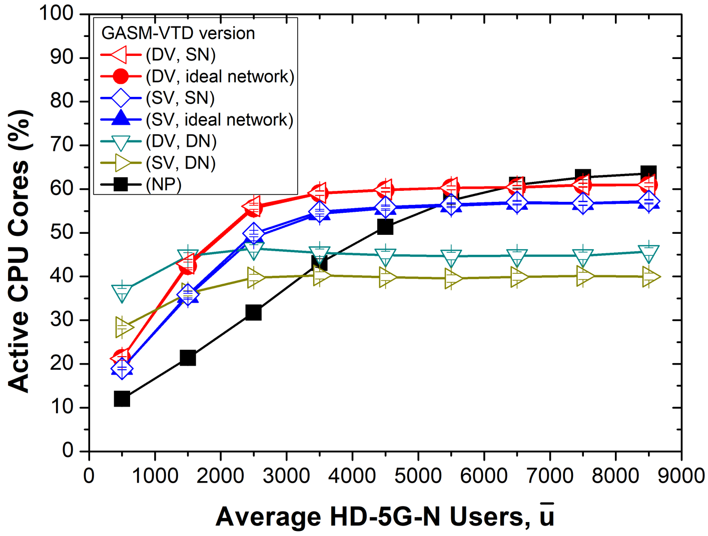


Figure 6.8: Percentage of CPU core consumption of GASM-VTD with the different protection techniques when the WDM network can use 20 wavelengths [6].

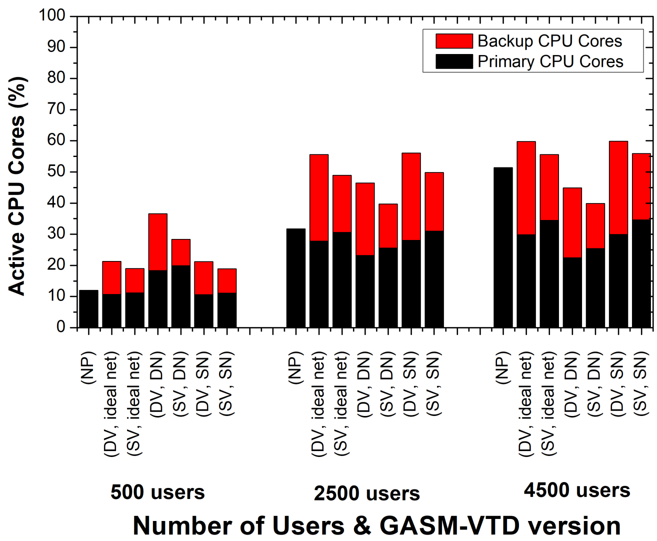


Figure 6.9: Comparison of the percentage of allocated CPU cores to the primary and backup VNFs, for the proposed protection schemes when the WDM network can use 20 wavelengths, for $\bar{u} = 500, \bar{u} = 2,500$ and $\bar{u} = 4,500$ [6].

CPU consumption, which is more noticeable for the protection schemes using shared network resources. Particularly, we can observe an increment of the CPU consumption for $\bar{u} = 2,500$ and $\bar{u} = 4,500$, compared with the results in the WDM network with 10 active wavelengths.

In conclusion, we have observed that the network resources are an important limiting factor to the behaviour of GASM-VTD with protection. In fact, it is the factor with the highest impact on the performance of our algorithm. Therefore, we have shown the importance of solving the VNF-placement, chaining, and protection problems and the virtual topology design jointly.

If enough network resources are available, we have seen that shared VNF-protection schemes, particularly with shared network resources, obtain the best results in terms of service blocking ratio and CPU consumption. However, we have proposed schemes that focus on protecting the VNF instances individually, while studies can be found in the literature that propose end-to-end protection schemes to guarantee the resilience of the SC. In the next section, we compare the individual VNF protection schemes with end-to-end protection strategies proposed in the literature.

6.2.4 Comparison between individual VNF protection and end-to-end SC protection schemes

The method proposed in this Thesis ensures protection against node failure by protecting each primary VNF individually, but there are different proposals in the literature that provisions a complete backup SC to protect a primary SC, like the study by Hmaity et al. [194]. In consequence, if any of the VNFs or their hosting node fails, the associated traffic traverses the backup SC completely, and will not make use of the primary resources, either computational or network resources, allocated to the primary SC. This kind of protection strategy is called end-to-end SC protection.

We would like to compare the performance of our proposed individual VNF protection schemes with the results obtained with an end-to-end SC protection scheme in terms of service blocking ratio and computing resource consumption. Therefore, we implemented four new versions of GASM-VTD that include protection schemes based on the proposal of Hmaity et al. [194]. These methods provide protection against node failure and provision a complete backup SC for each primary SC. The working and backup VNFs must be totally node-disjoint in order to avoid collision problems. For example, let us suppose a primary SC in which primary VNF_1 is hosted by Node A. The method cannot provide a backup SC in which any of the composing VNFs are hosted at Node A. Furthermore, if a VNF is chained in a primary SC, it is not eligible to compose any backup SC and vice versa. Moreover, since the protection backs up the SCs end-to-end, the algorithm does not reserve virtual links between primary and backup VNFs. Since the algorithm protects against node failure, the traffic associated with a primary SC and its corresponding backup SC can traverse the same physical links. We showed an example of end-to-end SC protection in Chapter 4, Figure 4.2.

As in the individual VNF protection schemes, the end-to-end SC protection methods can implement either dedicated or shared protection. In dedicated end-to-end SC protection, a backup SC can protect only one primary SC. However, the shared protection schemes allow sharing a backup SC between various primary SCs, provided that the primary SCs are node-disjoint with respect to the other primary SCs and the backup SC.

Lastly, the backup network resources can be also shared or dedicated. The end-to-end protection schemes must establish backup virtual links only between consecutive instances of

VNFs in a backup SC located at different nodes of the network. If the network resources are dedicated, the resources allocated to a backup SC are not allocated to another SC. However, if the network resources are shared, the same wavelength channels can be assigned to multiple backup VNFs, provided that the capacity constraints are met in case of failure.

Therefore, we propose four types of end-to-end SC protection schemes against node failure:

1. **GASM-VTD (DSC, DN):** This version provides dedicated end-to-end SC protection and dedicated backup resources. Hence, each provisioned backup SC can protect only one primary SC and its associated backup network resources cannot be shared with another backup SC.

2. **GASM-VTD (DSC, SN):** The version provides dedicated end-to-end SC protection and shared backup network resources. Consequently, each backup SC can protect only one primary SC. However, its associated backup network resources can be shared with the other backup SCs.

3. **GASM-VTD (SSC, DN):** This version provides shared end-to-end SC protection and dedicated backup resources, for which a backup SC can protect multiple primary SCs, but cannot share its network resources with the other backup SCs.

4. **GASM-VTD (SSC, SN):** Both the backup SC and its network resources are shared.

The algorithm GASM-VTD employs these protection schemes during the translation of the chromosome. After creating the instances of each VNF at the corresponding location that the chromosome indicates, GASM-VTD sorts the service requests according to a network operator's preferred priority and, for each request, it starts to select the VNF instances which will compose the required primary SC and the corresponding backup SC to establish the connection requests. When a primary SC is composed, the algorithm executes the protection schemes to provide an associated backup SC. The algorithm searches for the candidate VNFs to compose the backup SC at the CO, then the nodes with higher IT capabilities and finally with the nodes with fewer IT resources. If the algorithm is not able to provide a backup SC, the service request is blocked. Once the algorithm has allocated the VNF instances to the primary SCs and its associated backup SCs, it allocates network resources. If the algorithm is not capable of reserving network resources to a primary SC and its backup SC, the service request is blocked. Otherwise, the resources are allocated and the connection is established. The performance of GASM-VTD, other than including end-to-end SC protection schemes, is analogous to the performance described in Section 6.2.2.

We performed a comparison study of the individual VNF protection and the end-to-end SC protection schemes using the developed simulator in OMNeT++ [159]. The simulation scenario and settings are equal to the described in Section 6.2.3.

Figure 6.10 shows the service blocking ratio of GASM-VTD with end-to-end SC protection schemes when the network uses up to 10 wavelengths per fibre, compared to the end-to-end SC protection schemes executed considering an ideal network resource scenario, i.e., with unlimited network resources, and the no protection case. We can observe that the end-to-end protection techniques obtain a service blocking ratio higher than 10^{-1} even in ideal scenarios, which makes them not feasible to be implemented in real scenarios. Moreover, we can observe that the service blocking ratio of the protection schemes performed on realistic

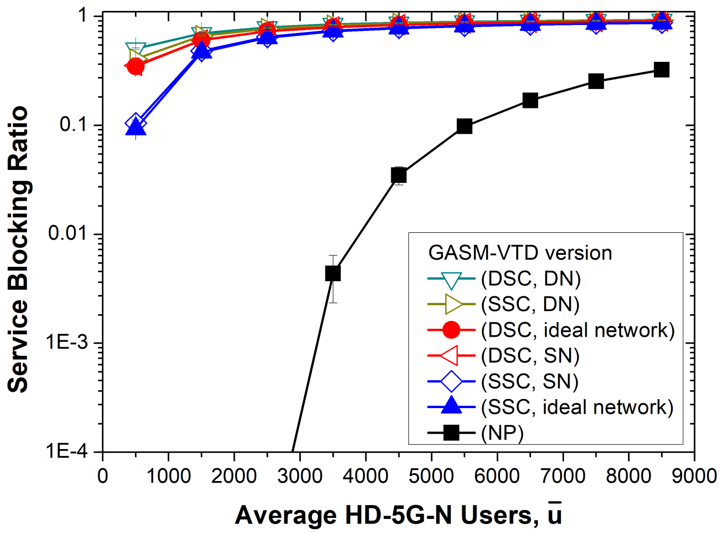


Figure 6.10: Service blocking ratio of GASM-VTD with end-to-end SC protection schemes when the WDM network can use 10 wavelengths.

network scenarios is quite close to the results of the same schemes performed on ideal network scenarios. These results suggest that end-to-end SC protection schemes require a large number of computing resources to establish the primary and backup VNFs.

If we increase the number of wavelengths to 20 (Figure 6.11), we observe that the achieved service blocking ratio of the end-to-end SC protection schemes is still close to or higher than 10^{-1}. The protection schemes, particularly the ones that share the backup network resources, achieve the same values of service blocking ratio than the protection schemes executed on ideal network resource scenarios. Therefore, incrementing the cost of the network by increasing the number of active wavelengths will not significantly benefit the performance of this kind of scheme.

We now compare the results of the end-to-end SC protection schemes and the individual VNF protection schemes. For that aim, we select the best performing protection schemes of each class in terms of service blocking ratio for the two possible network configurations, i.e., when the network can use either 10 or 20 wavelengths.

The results in terms of service blocking ratio are shown in Figure 6.12. As expected, the end-to-end SC protection schemes are the worst-performing schemes. Moreover, increasing the cost of the network by enabling the use of 20 wavelengths does not have an impact on the service blocking ratio of the scheme.

On the other hand, we can observe that the individual VNF protection schemes achieve a significantly better performance in terms of service blocking ratio compared to the end-to-end SC protection schemes, up to two orders of magnitude for the lowest values of average users per HD-5G-node. In the case of the individual VNF protection schemes, increasing the number of active wavelengths to 20 can improve the behaviour of the schemes up to an order of magnitude for the lowest values of $\bar{u}$ [6]. Therefore, an increment of the number of available wavelengths

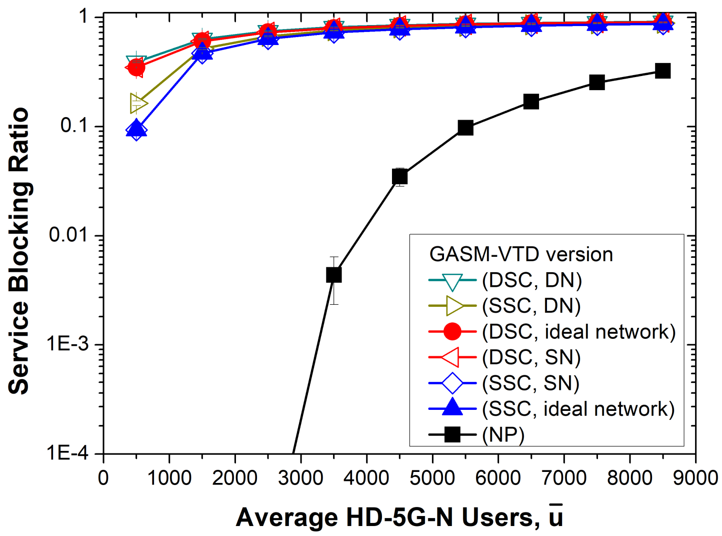


Figure 6.11: Service blocking ratio of the end-to-end SC protection schemes when the WDM network can use 20 wavelengths.

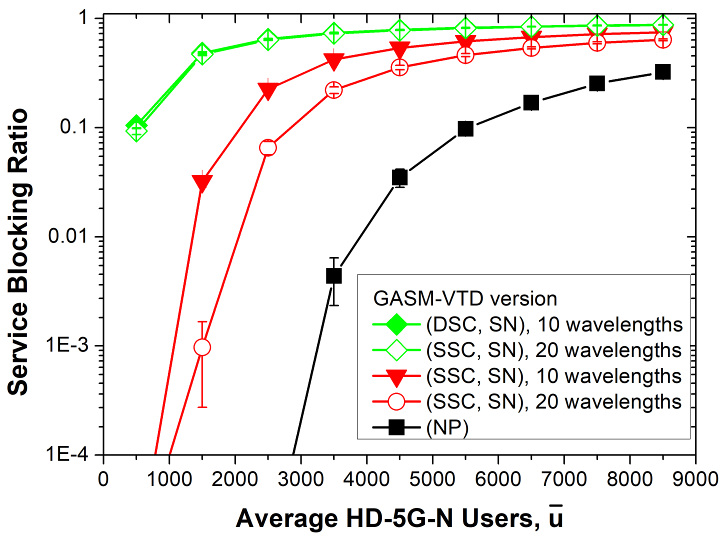


Figure 6.12: Service blocking ratio of the best performing configurations of end-to-end SC and individual VNF protection schemes when the WDM network can use 10 and 20 wavelengths.

can bring great benefits to the individual VNF protection techniques, whose performance is highly restricted by the availability of network resources [6]. Contrarily, increasing the capital expenditures of the network by augmenting the number of active wavelengths does not help to improve the performance of the end-to-end SC protection schemes, since they are highly restricted by the availability of computing resources.

In summary, the individual VNF protection schemes make better use of the computing resources and obtain a lower service blocking ratio compared to the end-to-end protection techniques. Therefore, the individual VNF protection technique will be used in the algorithm proposed in the next section to provide protection.

6.3 Efficiently solving the VNF-placement, chaining, virtual topology design and survivability problems on any kind of WDM-mesh network

We have proposed GASM-VTD to solve the VNF-placement and chaining problems and the the virtual topology design. Four variations of GASM-VTD have been proposed to provide SC protection in WDM networks. Here, we propose a new Genetic Algorithm for effective Service mapping and VIrtual Topology design (GASVIT) that is able to solve the VNF-placement, chaining and virtual topology design problems implementing a new chaining technique that is able to more efficiently exploit the collaboration between MEC nodes compared to the chaining technique proposed in GASM-VTD ([5], [6]) in the previous section. Then, GASVIT is modified to provide SC protection through the same individual VNF protection schemes as GASM-VTD. Finally, a techno-economic study is presented to compare the performance of the network in terms of cost and service blocking ratio when implemented using different physical topologies.

6.3.1 GASVIT

GASVIT is a genetic algorithm that solves the VNF-placement, chaining and virtual topology design problems in 5G networks with optical backhaul. In contrast to GASM-VTD, GASVIT achieves a more efficient distribution of the VNF instances thanks to the use of a new chaining technique.

Like in GASM-VTD, the solutions are described as individuals characterised by a chromosome composed of genes, in which each gene indicates the number of instances of a VNF that a certain node of the network must host. An example of chromosome can be seen in Figure 5.2. GASVIT creates an initial parent population composed of two ad-hoc individuals and randomly generated individuals. The ad-hoc individuals are created using the MEC-First [9], [10] and CO-First [3], [4] policies described in Chapter 5.

Once the initial parent population is created, its individuals undergo the same crossover and mutation operations described in Algorithms 5 and 6 of Chapter 5. After the offspring is created, it goes through a validation process in which GASVIT emulates the instantiation of the VNFs as indicated by the chromosome of the individual. If GASVIT is not able to create the indicated instances due to the lack of computing resources, the individual is discarded and a new one is created. The process is repeated until completing the desired size of the descendant population, which is a user-defined parameter.

The difference with GASM-VTD appears in the translation process of each individual. In this stage, GASVIT initially creates the VNF instances indicated by the chromosome. Then, it sorts the service connection requests arrived at the network, according to the preferred order determinded by a network operator, and starts to create the SCs required to serve each connection request. The chaining process proposed in GASVIT is different from those implemented in GASM and GASM-VTD, and it is able to better exploit the collaboration between the MEC nodes. The process performs the following operations:

1. Initially, GASVIT puts a token at the node to which the user is connected.
2. For each SC:
   - 2.1. GASVIT tries to concatenate a VNF, with enough available capacity to serve the requested traffic, located at the node with the token.
   - 2.2. If GASVIT cannot concatenate a VNF located at that node, it continues the search at the nodes located at one-hop distance in the physical topology from the node with the token. If no available VNFs are found at these nodes, GASVIT searches VNFs at the nodes located at two-hop distance from the node with the token. The process continues until GASVIT finds the available VNF or until exploring all the nodes of the network.
     - 2.2.1. If GASVIT finds an available VNF, it reserves resources and moves the token to the node in which the VNF is located. If the SC has been fully created, it continues with the following request. Otherwise, it tries to find the following VNF, starting from the step 2.1.
     - 2.2.2. If GASVIT does not find an available VNF, the request is blocked.

Once that all the non-blocked SCs have been constructed, GASVIT allocates network resources to each SC, in order to transport the traffic from one VNF to the following VNF. If two consecutive VNFs in the SC are located at different network nodes, GASVIT creates a virtual link between these nodes with enough capacity to transport the requested traffic. If a lightpath between the source and destination nodes with enough available capacity exists, the algorithm uses it to create this virtual link, performing traffic grooming. Otherwise, it tries to create a new lightpath, using the available network resources. The algorithm uses the $k-$ shortest paths and first fit techniques [62] to solve the resource allocation to the lightpaths. If GASVIT cannot allocate network resources to an SC, the associated service request is blocked.

When the individual is translated, GASVIT evaluates the fitness of the solution. The algorithm uses three fitness score parameters: the service blocking ratio, the percentage of active CPU cores and the percentage of used wavelengths. Then, among the individuals of the parent and the descendant population, the algorithm selects the best ones to be the parent population of the following generation. If two individuals are tied in service blocking ratio performance, GASVIT selects the one with the lowest percentage of active CPU cores. If the individuals are also tied in this parameter, it selects the one with the lowest percentage of used wavelengths. GASVIT repeats the genetic loop, i.e., crossover, mutation, validation, translation and fitness evaluation for a number of times, or generations, which is user-defined. The algorithm provides, at the end of the process, the best solution found, i.e., the VNF-placement, the set up SCs and the virtual topology design that achieves the lowest service blocking ratio and resource consumption.

6.3.2 Providing individual VNF protection with GASVIT

GASVIT has also been extended to incorporate the four individual VNF protection strategies against single node failure presented in Section 6.2.1. In these protection schemes, each VNF concatenated in a primary SC has an assigned backup VNF. In case of a node failure, the traffic travels to the corresponding VNF protecting the failing primary VNF, and then returns to the following primary VNFs, instead of traversing the entire backup SC. The protection strategies can utilise either shared or dedicated resources for both backup VNFs and/or backup network resources. Combining these approaches, we have developed five versions of GASVIT:

1. **GASVIT (NP)**: The basic version of GASVIT, with no protection strategies enabled.
2. **GASVIT (DV, DN)**: GASVIT with dedicated individual VNF protection and dedicated backup network resources.
3. **GASVIT (DV, SN)**: GASVIT with dedicated individual VNF protection and shared backup network resources.
4. **GASVIT (SV, DN)**: GASVIT with shared individual VNF protection and dedicated backup network resources.
5. **GASVIT (SV, SN)**: GASVIT with shared individual VNF protection and shared backup network resources.

The main difference between GASVIT and the versions of the algorithm that offer protection arises during the translation stage. Therefore, the chromosome structure and the crossover, mutation and validation processes are the same as in Subsection 6.3.1.

In the translation process, the algorithm creates the number of VNF instances at each node of the network as the chromosome indicates. Then, it sorts the arrived service connection requests and starts to provision each primary SC using the same procedure as GASVIT (NP), explained in Section 6.3.1. Once a primary SC is provisioned, i.e., it has not been blocked due to lack of available computing resources, the algorithm tries to reserve the corresponding backup resources. The algorithm cannot select as a backup VNF an instance that has been previously concatenated in a primary SC. Furthermore, the primary and backup VNFs must be hosted by different nodes. The algorithm selects dedicated or shared backup VNFs depending on the chosen protection strategy. The chaining strategy is similar to the strategy utilised to create primary SCs; however, the token is initially put at the node hosting the primary VNF to be protected and the search begins at the nodes located at one hop distance since primary and backup VNFs cannot be hosted by the same node. If the algorithm is unable to find the required backup VNF, the service request is blocked. Otherwise, it continues the provision of backup VNFs until protecting all the primary VNFs in the SC.

Once all the non-blocked SCs are constructed and the backup VNFs have been reserved, the algorithm allocates network resources. Similarly to GASVIT (NP), it starts by assigning network resources to the primary SC and then it allocates backup network resources, to connect the primary VNFs with their backup VNFs and ensure that the traffic can traverse the backup VNFs in case of node failure. As in the network resource allocation procedure, the algorithm tries to use existing lightpaths with available capacity to set up the backup virtual links. If no lightpaths are available, it tries to create new ones using the $k-$shortest paths and first fit techniques [62] for solving the RWA problem. The backup network resources can be shared or dedicated and traffic grooming is allowed, as in the primary network resources. It is important to note that the lightpaths used to provision primary and backup network resources are completely independent. If the algorithm allocates network resources for the primary SC and its backup VNFs, the service connection is set up; otherwise, it is blocked.

The fitness evaluation is performed as in GASVIT (NP) using the same three fitness parameters: service blocking ratio, percentage of active CPU cores and percentage of used wavelengths. When selecting the best individuals to be parents of the following generation, ties are also solved in the same manner, i.e., the individuals with the best service blocking ratio are selected. If two individuals are tied in this parameter, the one with the lowest percentage of active CPU cores is chosen. Finally, if the individuals are also tied in this parameter, the algorithm uses the one with the lowest percentage of used wavelengths. The loop is repeated for a number of generations determined by the user and, at the end of the process, GASVIT with protection returns the VNF-placement, the primary SCs, the corresponding backup VNFs, and the virtual topology design of the best individual found until that moment.

6.3.3 Simulation scenario and results

6.3.3.1 Performance of GASVIT with no protection

We initially compare the performance of GASVIT (NP) with other algorithms that do not exploit the collaboration between MEC nodes: GASM-VTD-No-Collaborative, MEC-First [9], [10], and CO-First [3], [4]. A simulation study using the OMNeT++ platform [159] was conducted. The test has been carried out considering a 5G network with an underlying WDM-ring topology, since this kind of topology is the most extended in metro networks. The network connects a CO, 5 HD-5G-nodes and 5 LD-5G-nodes. We assumed that the nodes of the network are equipped with a set of transceivers and a reconfigurable optical add-drop modulator (ROADM) instead of optical cross-connects, for the ring topology to be deployed in a cost effective manner [222]. Figure 6.1 shows the network topology utilised in this study. As in the previous studies, each physical connection in the physical topology is considered to be composed of two unidirectional fibres, each employing 10 wavelengths at a 10 Gb/s rate.

As in the previous studies, we consider that the CO is equipped with IT resources, while the 5G-nodes are equipped with MEC resources. The three types of nodes can host VNFs. Since HD-5G-nodes attends ten times more users on average than the LD-5G-nodes, they are equipped with larger MEC capabilities. The IT capabilities allocated to each kind of node are shown in Table 6.1 [9], [10].

Moreover, a network that is managed by a network operator which offers VoIP, video streaming and web services is assumed. Each user can request one of these services with a probability of 30%, 20% or 50% respectively. The associated SC and demanded bandwidth is shown in Table 6.2 [7], [8], [3], [4], [5].

Lastly, the IT resources and throughput of each VNF are shown in Table 6.3.

As in the simulation study described in Subsection 6.1.2, we define the parameter $\bar{u}$, i.e., the number of average users connected to an HD-5G-node. Assuming that HD-5G-nodes attend on average ten time more users than the LD-5G-nodes, the number of connected users to each HD-5G-node is randomly generated, at the beginning of each simulation, using the uniform distribution shown in Equation 6.1, whilst the number of connected users to each LD-5G-node

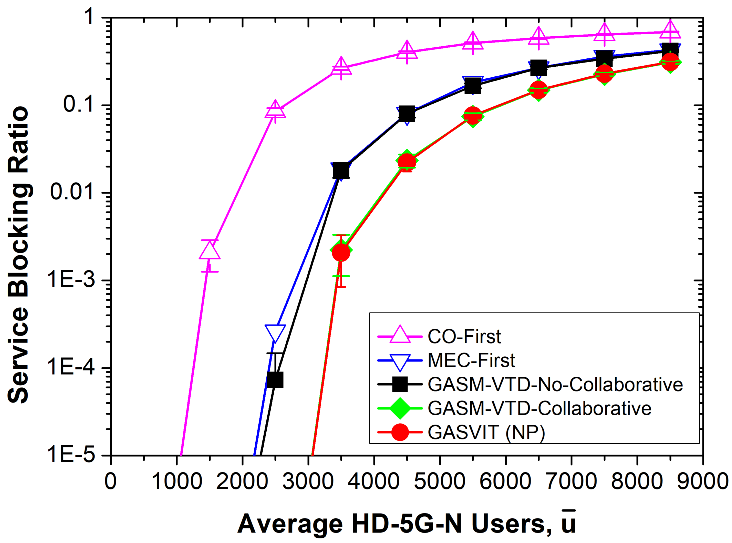


Figure 6.13: Service blocking ratio of GASVIT, GASM-VTD, MEC First, and CO-First when the WDM-ring 5G network can use 10 wavelengths.

is randomly generated using the uniform distribution shown in Equation 6.2.

The size of the parent population was set in 5 individuals, whereas the size of the descendant population was set to 10 individuals. The mutation probability was set to 0.02. We created 50 generations and repeated the simulation 500 times with different traffic demands. Results are plotted on average with 95% confidence intervals.

Figure 6.13 shows the service blocking ratio achieved by all the algorithms, whereas Figure 6.14 shows the percentage of CPU consumption. As in the previous section, when collaboration is enabled, the full potential of GASVIT and GASM-VTD is exploited. The proposals outperform the other techniques and achieves values of service blocking ratio more than two orders of magnitude lower than the non-collaborative techniques, for low values of average connected users. There are small differences between GASVIT and GASM-VTD because the network has enough resources to establish the required connections. However, in a more constrained scenario, e.g. when implementing protection, GASVIT clearly outperforms GASM-VTD. This behaviour will be shown in Figure 6.21.

In Figure 6.14, it can be observed that GASM-VTD-Collaborative and GASVIT uses the same percentage of CPU cores than GASM-VTD-No-Collaborative for low values of $\bar{u}$. However, GASM-VTD-Collaborative and GASVIT require a higher consumption of CPU cores for high values of $\bar{u}$ to lower the service blocking ratio.

Finally, Figure 6.15 shows the average number of hops in the physical topology of the SCs established by the different algorithms. We can consider the average number of hops as a measure of the propagation delay. We have just shown that there is little difference in terms of service blocking ration and IT resource consumption between GASVIT and GASM-VTD-Collaborative. However, Figure 6.15 shows that GASVIT establishes SCs that have a lower number of average hops than GASM-VTD-Collaborative (approximately one hop less

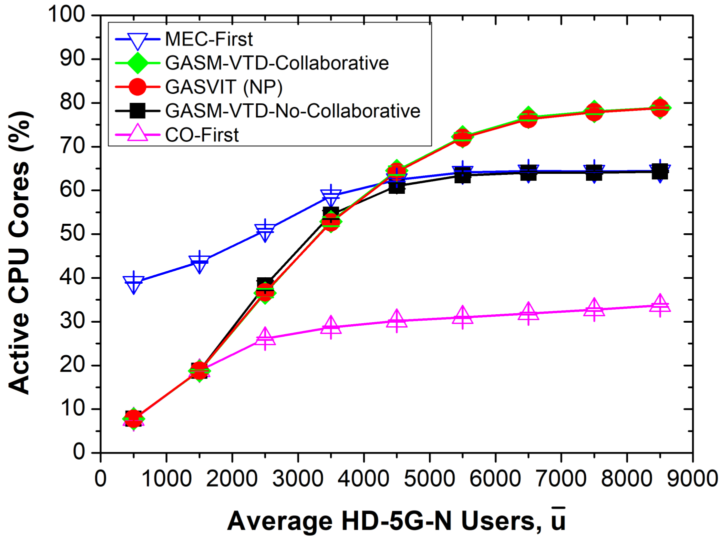


Figure 6.14: Percentage of CPU core consumption of GASVIT, GASM-VTD, MEC First, and CO-First when the WDM-ring 5G network can use 10 wavelengths.

for medium traffic loads) and, consequently, the SCs established using GASVIT have a lower end-to-end propagation delay. It is worth noting that the MEC-First, CO-First and GASM-VTD-No-Collaborative are the methods that obtain the lowest values of average hops per SC. Nevertheless, if we assume that the 5G network with metro WDM-ring backhaul considered in this study is deployed in a city with a diameter of 10 km and that the nodes are equidistant, the separation between nodes is less than 3 km (propagation delay lower than 0.015 ms). Consequently, the average propagation delay of the SCs for GASVIT would be 0.09 ms, widely meeting the 5G latency requirements (< 1 ms) [223].

Hence, GASVIT reduces the service blocking ratio because it makes a better use of the collaboration between MEC nodes. Moreover, the new chaining strategy proposed in GASVIT can improve the performance of the network in terms of service blocking ratio while not increasing the resource consumption.

6.3.3.2 Performance of GASVIT with protection

We now analyse the performance of the versions of GASVIT that provide individual VNF protection against node failure, introduced in Section 6.3.2. We compare their performance with the following versions of GASVIT:

- **GASVIT (NP)**: The version of GASVIT that provides no protection.
- **GASVIT (DN, ideal network)**: The version of GASVIT that provides dedicated VNF protection considering an ideal network scenario in which no restriction in the network resources is considered.

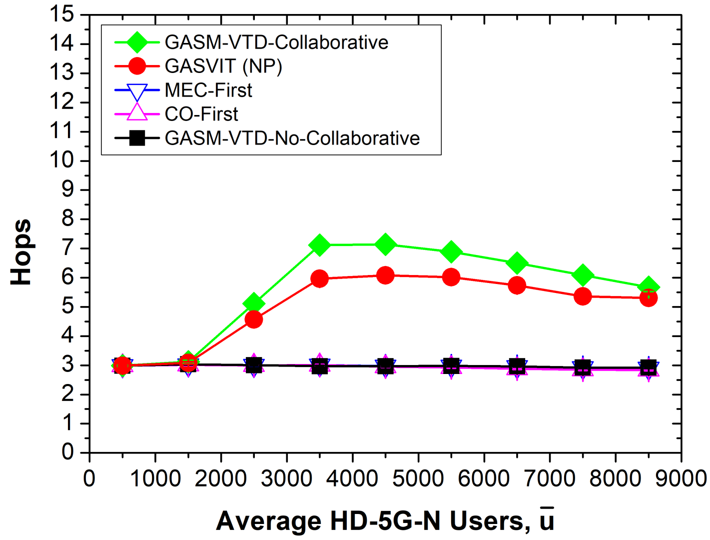


Figure 6.15: Average hops of the SCs established with GASVIT, GASM-VTD, MEC First, and CO-First when the WDM-ring 5G network can use 10 wavelengths.

- **GASVIT (SN, ideal network)**: The version of GASVIT that provides shared VNF protection considering an ideal network scenario in which no restriction in the network resources is considered.

Figure 6.16 shows the service blocking ratio obtained by the different versions of GASVIT with and without protection when the network works with up to 10 wavelengths. A degraded performance of the network appears when implementing protection schemes, compared to the no protection scenario, given that both backup computational and network resources must be reserved to provide protection. The higher service blocking ratio obtained by the versions with restricted network resources compared to the performance of the same versions with unlimited network resources shows the importance of considering the network design during the VNF-placement and chaining process, in order to avoid network collapse. On the other hand, we can observe that the service blocking ratio is much higher for the protection schemes using dedicated network resources, i.e., for GASVIT (DV, DN) and GASVIT (SV, DN), due to their high network resource consumption. Actually, their performance makes them infeasible to be implemented in real networks.

GASVIT (SV, SN), which utilises shared network resources, supports up to $1,000$ more users per HD-5G-node on average than its dedicated counterpart for the same service blocking ratio, given that they make more efficient use of the network resources. Furthermore, their performance is much closer to the performance of the protection schemes in ideal network scenarios, as Figure 6.16 shows. This performance can be further improved increasing the number of active wavelengths in the network, to the point of equalling the performance of the protection schemes in ideal scenarios, as can be seen in Figure 6.17, that shows the service blocking ratio of the various versions of GASVIT when the network uses up to 20 wavelengths. This improvement, however, is obtained at the expense of increasing the network cost.

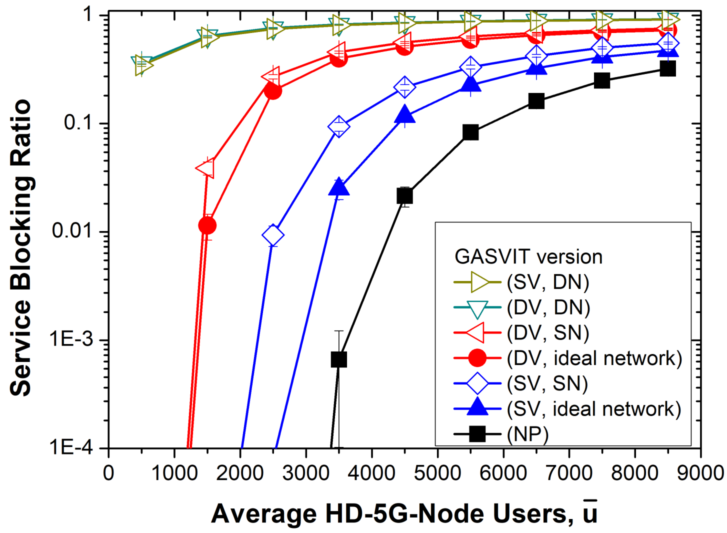


Figure 6.16: Service blocking ratio of GASVIT with protection when the network uses up to 10 wavelengths.

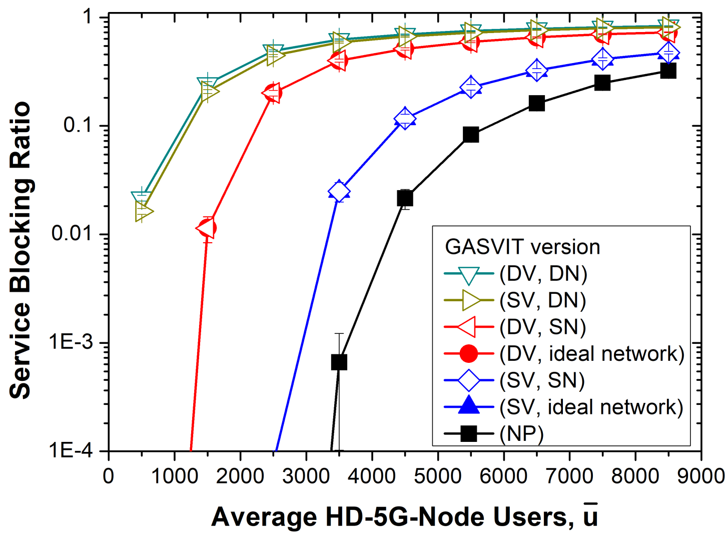


Figure 6.17: Service blocking ratio obtained by GASVIT with protection when the network uses up to 20 wavelengths.

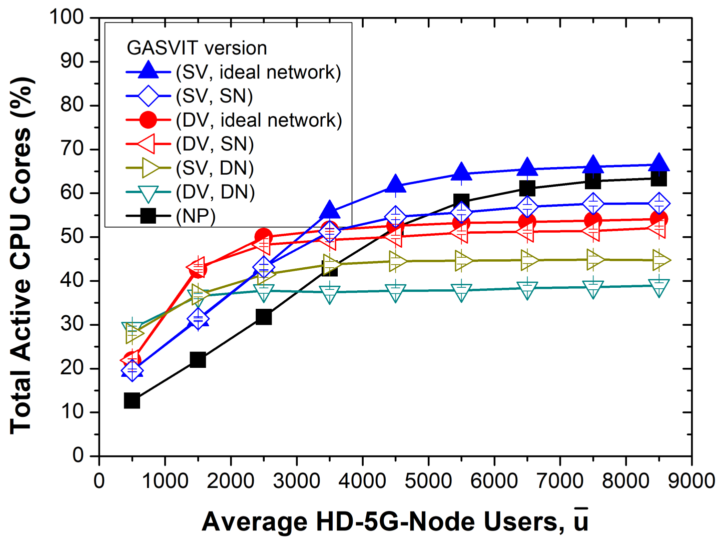


Figure 6.18: Percentage of the CPU cores employed by GASVIT with protection when the network uses up to 10 wavelengths.

Figure 6.18 shows the CPU consumption obtained by the different protection schemes when the network works with up to 10 wavelengths. As can be observed, GASVIT (NP) requires the use of the lowest percentage of CPU cores since it does not reserve computing capacity to provide protection. The protection schemes using dedicated network resources, i.e., GASVIT (DV, DN) and GASVIT (SV, DN), utilise less computational resources than the protection schemes implementing shared network resources. Since the strategies using dedicated network resources exhaust the network resources sooner, they are unable to create virtual links either between nodes hosting primary VNFs or to create new virtual links between nodes hosting primary and backup VNFs. On the other hand, GASVIT (DV, SN) and GASVIT (SV, SN), which use shared network resources, do not consume the network resources as quickly as their dedicated counterparts. Therefore, they are able to set up more primary and backup VNFs, improving the service blocking ratio at the expense of increasing the CPU core consumption.

If we compare the CPU consumption for the schemes using shared network resources when the network can use 10 or 20 wavelengths, shown in Figures 6.18 and 6.19 respectively, we can observe that the CPU consumption increases with the number of available network resources, until obtaining the same consumption as GASVIT(DV, ideal network) and GASVIT(SV, ideal network). Therefore, increasing the available network resources increases the cost, but it also improves the performance of GASVIT in terms of service blocking ratio.

Finally, Figure 6.20 shows a comparison of the percentage of CPU allocated to primary and backup VNFs, when the network is configured to use up to 10 wavelengths, for three different values of average users per HD-5G-node: $\bar{u} = 500, \bar{u} = 2,500$ and $\bar{u} = 4,500$. It can be observed that the percentage of CPU cores increases with the number of users. However, the increment is less significant between $\bar{u} = 2,500$ and $\bar{u} = 4,500$ for the versions of GASVIT implementing dedicated and shared network resources. This result shows again the impact of

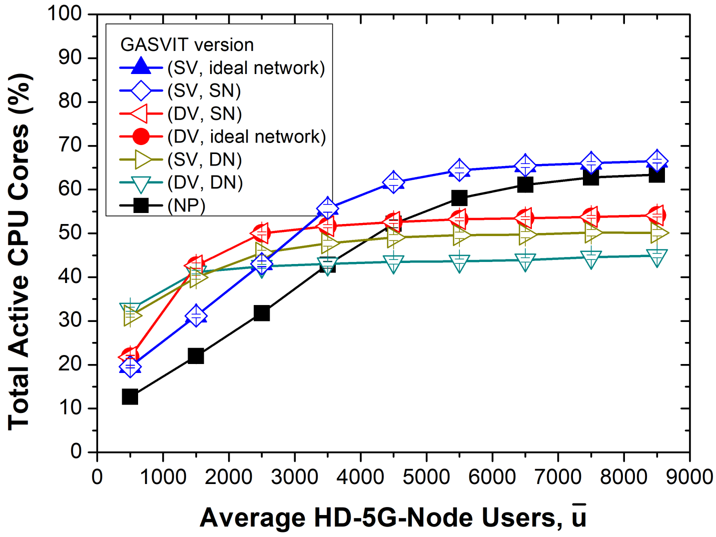


Figure 6.19: Percentage of the CPU cores employed by GASVIT with protection when the network uses up to 20 wavelengths.

the underlying network and the availability of the network resources in the performance of the protection schemes. If the algorithm is not able to reserve network resources for a given primary SC and its corresponding backup SC, it does not reserve the required computational resources, reducing the CPU core consumption.

Figure 6.21 shows a comparison of the best performing protection scheme implemented using GASVIT and the algorithm GASM-VTD proposed in Section 6.2.1 [6] in terms of reduction (in %) of the service blocking ratio and CPU core consumption. The figure compares the performance of GASVIT (SV, SN) with respect to GASM-VTD (SV, SN), when the network uses up to 10 wavelengths. GASVIT (SV, SN) achieves a noticeable reduction of the service blocking ratio, which can be more than a 90% for some values of average users per HD-5G-node. The CPU consumption shows a slight improvement for low values of $\bar{u}$ and an increment of the consumption when $\bar{u} > 3,500$. Therefore, thanks to the new chaining technique, GASVIT (SV, SN) achieves better behaviour in terms of service blocking ratio than GASM-VTD (SV, SN), at the cost of making a higher consumption of the CPU cores.

After analysing these results, we can conclude that GASVIT is able to outperform GASM-VTD. Moreover, when including protection, it is a must to use shared resources, since this approach obtains a significant improvement of the network performance, compared to the protection strategies which use dedicated backup resources.

6.3.3.3 Impact of deploying a 5G-WDM network using different WDM-mesh topologies. A techno-economic study

Since GASVIT operates on any kind of WDM-mesh topologies, this feature is utilised to perform a study of the impact of deploying different types of WDM-mesh topologies in 5G networks with optical backhaul, comparing their network capital expenditures (CAPEX) and

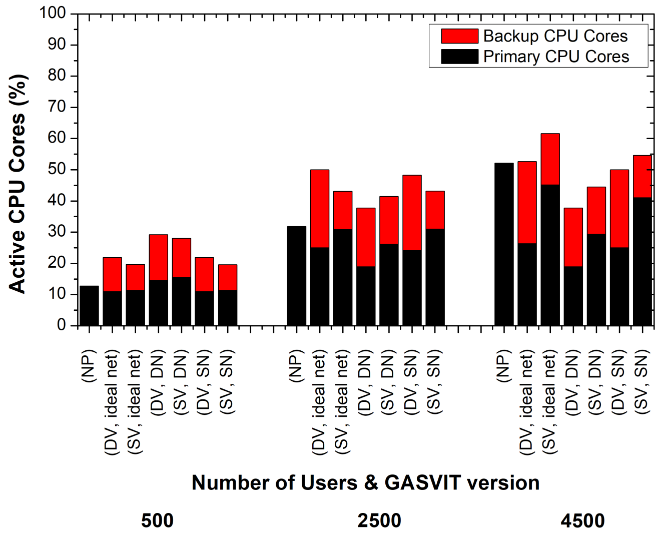


Figure 6.20: Percentage of CPU cores allocated to primary and backup VNFs for GASVIT with protection when the network uses up to 10 wavelengths.

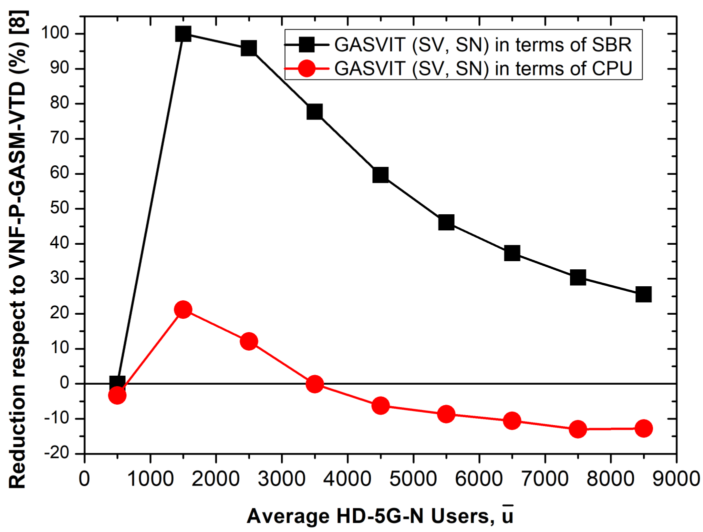
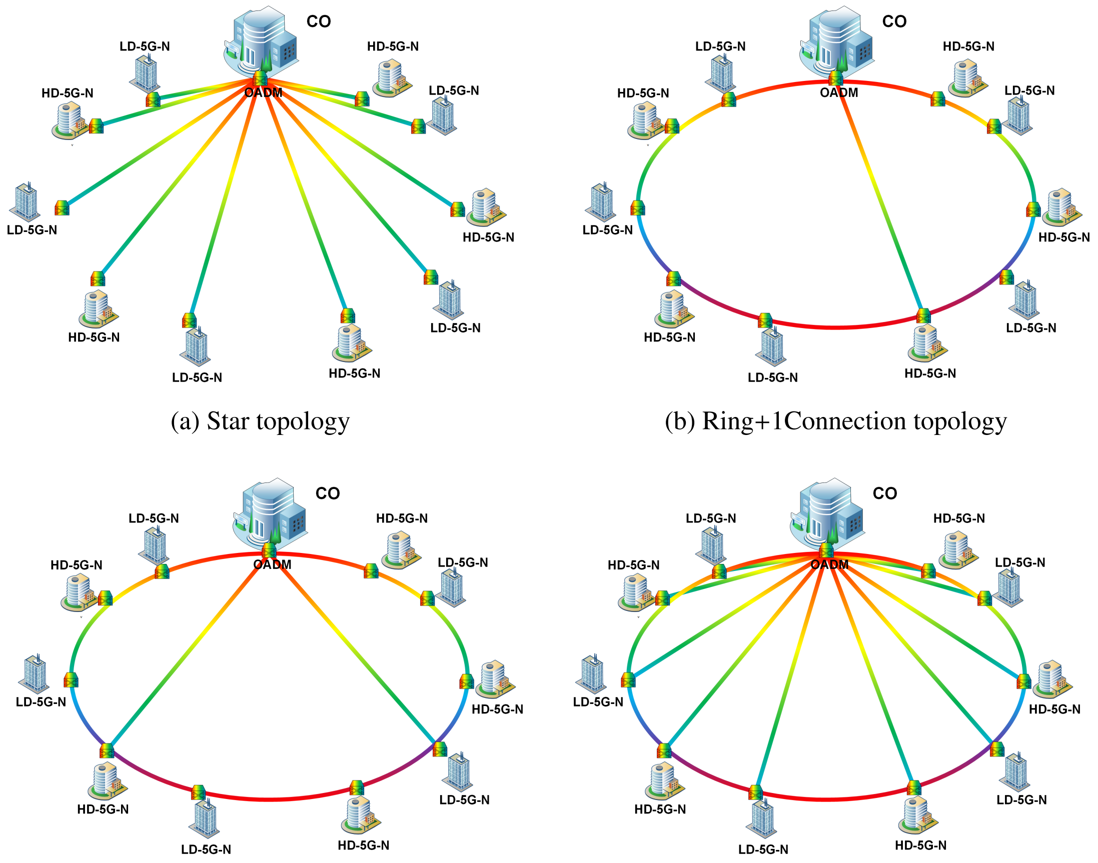


Figure 6.21: Reduction in terms of service blocking ratio and CPU core consumption obtained by GASVIT (SV, SN) compared to GASM-VTD, S-VNF & S-Net, when the network uses up to 10 wavelengths.



(a) Star topology (b) Ring+1Connection topology

(c) Ring+2Connections topology (d) Hybrid

Figure 6.22: Topologies compared in the techno-economic study.

the service blocking ratio.

Five different topologies have been compared: the WDM-ring topology deployed in our previous studies and four new topologies: a star topology since it was used in other studies in the literature [9], [10], and in the study presented in Chapter 5 and studies [3], [4], and three upgraded versions of the ring topology: a ring topology with an additional connection composed of two unidirectional fibres (Ring+1Connection), a ring with two additional connections (Ring+2Connections), and a hybrid topology which combines a ring and a star topologies (Hybrid). The four new topologies are shown in Figures 6.22a, 6.22b, 6.22c and 6.22d respectively.

We have considered that the nodes of all the topologies are equipped with OXC, assuming that the main contribution to the cost of an OXC is the Wavelength Selective Switch (WSS) [224]. Table 6.4 shows the number of WSS required to build the various types of OXCs that can be found at each topology. This table is built considering the cost model in [224]. On the other hand, Table 6.5 shows the number of WSS that each topology requires.

Moreover, Figure 6.23 shows the service blocking ratio reduction obtained by the different topologies compared to the topology that obtains the highest service blocking ratio, i.e., the star topology. As it can be seen in Table 6.5, the star topology requires the lowest number of WSS,

OXC Type	*WSS*
OXC2 (2 fibres)	8
OXC3 (3 fibres)	11
OXC4 (4 fibres)	14
OXC10 (10 fibres)	34

Table 6.4: Number of WSS required to build each type of OXC.

Topology	*OXC2*	*OXC3*	*OXC4*	*OXC10*	*Total # WSS*
Star	0	0	0	1	34
Ring	11	0	0	0	88
Ring+1C	9	2	0	0	94
Ring+2C	9	2	0	0	100
Hybrid	0	10	0	1	144

Table 6.5: Topology cost in terms of number of WSS.

however, it is also the worst behaving topology in terms of service blocking ratio, as Figure 6.23 shows. All the topologies present a significant reduction of the service blocking ratio compared to the star topology. Since the star topology is a centralised architecture, it cannot fully exploit the collaboration between nodes, because all the set up lightpaths must traverse the CO, increasing the network resource consumption. For this reason, it is essential to build 5G-WDM networks with topologies that enable the collaboration between nodes, if these are to be equipped with MEC resources and host VNFs, in order to take full advantage of their computing and store capacities.

The topology that presents the best balance between service blocking ratio performance and network cost is the ring topology. Additionally, this architecture can be implemented in a more cost-effective manner using the ROADMs proposed in [222], hence reducing the cost of the network. This topology achieves a service blocking ratio reduction higher than 50% for $\bar{u} \leq 4,500$.

Finally, better results can be obtained by upgrading the topology and adding more fibres. Actually, the addition of only one connection cuts down the service blocking ratio to its minimum value, as Figure 6.23 shows. With this addition, the network complexity and cost are not significantly increased with respect to the ring topology, and an improvement of the service blocking ratio higher than 50% for $\bar{u} \leq 5,500$ is achieved.

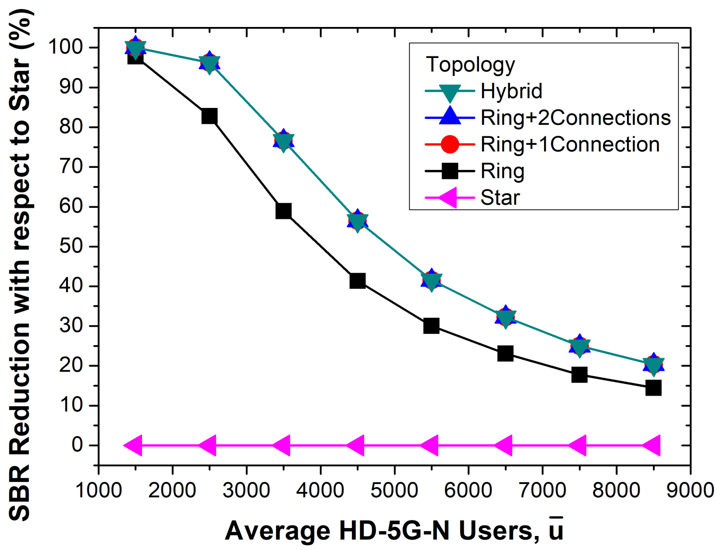


Figure 6.23: Reduction of the service blocking ratio obtained by the different network topologies.

6.4 Conclusions

We have studied the VNF-placement and provisioning in a 5G network with WDM backhaul. In this scenario, the 5G-nodes are equipped with MEC servers and, consequently, they can host VNFs. Hence, it is necessary to make proper planning of the network, both in terms of VNF location and virtual topology design of the optical network, to reduce the service blocking ratio and computing resource consumption. To this aim, we have proposed GASM-VTD, a genetic algorithm that solves the VNF-placement, chaining and the virtual topology design in 5G networks based on WDM optical technology. Our proposal provides the VNF-placement, the established chains and the virtual topology which minimises the service blocking ratio, and presented a chaining technique that explores the collaboration between the nodes of the network that are equipped with MEC resources.

Moreover, it is important to provide fault-management techniques which ensure the resilience of the established connections, to avoid the disruption of the network services and data loss. Thus, we have extended GASM-VTD to offer SC resilience, proposing the GASM-VTD algorithm. We have proposed four versions of the algorithm providing individual VNF protection and considering shared or dedicated backup VNF resources and shared or dedicated backup network resources. We have compared the performance of the four variations of GASM-VTD in terms of service blocking ratio and IT resource consumption to the performance of the algorithm in a no protection scenario and in an ideal network scenario in which the network resources are unlimited. Results showed the importance of considering the network resource availability during the VNF-placement, chaining and protection stages since it has a huge impact on the performance of this kind of scheme.

Furthermore, we have compared the performance of GASM-VTD with individual VNF protection with the performance of GASM-VTD with end-to-end SC protection, utilising end-to-end SC protection schemes based on the proposal by Hmaity et al. [194]. Results showed that the individual VNF protection schemes obtain better results in terms of service blocking ratio compared to the end-to-end protection strategies in the studied 5G-WDM network.

Moreover, we have presented GASVIT, a genetic algorithm that solves the VNF-placement, chaining and virtual topology design but implementing a new chaining technique that better exploits the collaboration between the MEC nodes of the network, making a more efficient placement of the VNF instances. Compared to other no-collaborative VNF-placement and chaining algorithms, GASVIT reduces the service blocking ratio and improves the performance of the network.

Since the initial version of GASVIT does not address the SC survivability problem, four new versions providing individual VNF protection are proposed. These versions are obtained by combining the shared and dedicated VNF and backup network resources. Results show the necessity of considering the underlying network when solving the VNF-placement and chaining problems since it impacts the overall performance of the network. Furthermore, it is almost mandatory to utilise shared backup VNF and network resources, since it reduces the service blocking ratio and makes more efficient consumption of the computing resources. Finally, GASVIT with protection outperforms GASM-VTD in terms of service blocking ratio since the implemented chaining strategy better capitalises on the collaboration between MEC nodes.

Finally, given that GASVIT can operate on any kind of WDM-mesh topology, a techno-economic study was conducted to compare the service blocking ratio and cost presented by 5G networks with optical backhaul and different topologies. Results show that the ring topology presents the best balance between cost and service blocking ratio compared to other topologies, although the performance can be improved by adding little upgrades, like including an extra connection, without adding excessive complexity to the network.

Chapter 7

Conclusions and Future Work

7.1 Conclusions

The appearance of new network services, as well as the ever-increasing network traffic and number of connected devices will push the evolution of current communication networks towards the Future Internet. Among other aspects, it is expected an evolution in the radio segment towards 5G, in the optical segment from WRONs to EONs, and in the control plane with the use of SDN and NFV and the incorporation of computing resources in the network using MEC.

In the area of optical networks, WRONs are evolving towards an optical technology capable of making more efficient use of the spectrum, in order to cope with the increasing traffic that networks must carry. Flexible or elastic optical networks (EONs) are able, among other features, to adapt the allocated bandwidth to the demanded capacity. In this kind of networks, establishing a lightpath requires the allocation of a slice of spectrum over a route from the source to the destination nodes. This design problem is known as the routing and spectrum assignment (RSA) problem. When solving this problem in a dynamic environment in which connection requests/releases arrive at the network in real-time, efficient RSA algorithms must be proposed to minimise the number of blocked connections and to solve the problem in a short period of time.

On the other hand, the stringent requirements that new 5G technologies aim at fulfilling require a deep change in the network architecture to increment its flexibility, manageability and adaptability, while reducing the capital and operation expenses of the network. For this reason, 5G technology is expected to rely on optical networks to be the base of their backhaul, given their flexibility and high capacity. Furthermore, other technologies as NFV, SDN and MEC are expected to enable future 5G networks.

However, the convergence of all these technologies to enable 5G poses extra challenges in terms of network orchestration. When NFV is implemented, it is necessary to plan the network according to the services to be deployed. In NFV environments, the planning is divided into two main phases: the VNF-placement, in which the number of instances and its location is decided, and the VNF-chaining in which the associated SC to an arrived service request is built, concatenating the corresponding VNF instances if they have available capacity to process the demanded traffic. Moreover, setting up an SC not only requires available VNFs, but also the allocation of network resources to transport the traffic from one VNF to another.

The resource allocation in the network is a complex problem that must not be overlooked. It is highly dependent on the topology and the optical technology, when an optical backhaul is deployed. The resource availability and allocation are different when a dedicated, point-to-point optical link connects two nodes of the network, compared to the case in which a WDM-ring connects the nodes of the network. Yet, the orchestration algorithms should be able to solve the network control when solving VNF-provisioning and VNF-chaining problems.

In this thesis, we have made contributions in two topics in order to evolve current networks towards the future Internet: RSA methods for EONs and algorithms to incorporate NFV into the control of current networks. In both topics, a deep analysis of the current State of the Art has been made and its conclusion have been presented in Chapter 2 and Chapter 4 of this thesis.

In the area of optical networks, we have presented two contributions. Firstly, we have studied the inclusion of different levels of flexibility in the solution of the RSA problem with two well-known RSA methods: $k-$shortest paths and first fit. In the first level of flexibility, the spectrum was either considered to be divided into small frequency slots (flexgrid), as the majority of studies on RSA algorithms do, or as a spectrum slice of continuous frequency (gridless). The second level of flexibility is related to the possibility of splitting a request into multiple sub-lightpaths or establish a single lightpath for each demand. Combining these two levels of flexibility with with first fit and $k-$shortest paths, four RSA algorithms were proposed: Joint Flexgrid Spectrum (JFS), Disjoint Flexgrid Spectrum (DFS), Joint Gridless Spectrum (JGS) and Disjoint Gridless Spectrum (DGS). Results have shown that, when $k-$shortest paths and first fit are used, more efficient use of the spectrum is made when allowing the splitting of the request into multiple sub-lightpaths than considering a gridless spectrum. Moreover, they have also shown that the inclusion of a high level of flexibility in networks does not necessary involve a reduction in the request blocking ratio. In fact, the most flexible approach, i.e., considering the gridless spectrum and the possibility of splitting the request into multiple sub-lightpaths, is the one with the highest blocking ratio.

The previous behaviour (contrary to expectations) appears because first fit is not the most suitable method for solving the spectrum assignment when using high levels of flexibility. Hence, a novel spectrum allocation technique called Best Gap has been proposed in this thesis. This new proposal searches for the most adapted portion of spectrum to the demanded traffic and can be combined with the levels of flexibility previously presented. Results from a simulation study have shown that the network can benefit from using high levels of flexibility by using $k-$shortest paths and Best Gap for solving the RSA problem. In fact, the flexible approaches are the ones that obtain the lowest values of blocking ratio, improving the network performance.

On the other hand, we have made different contributions to the integration of NFV in 5G networks with optical backhaul, where the network nodes are equipped with MEC resources. We have initially proposed a genetic algorithm for effective service mapping (GASM) with the objective of solving the VNF-placement and chaining problems in a 5G network with star topology backhaul. When comparing GASM with another technique previously proposed in the literature, GASM offers a good trade-off between service blocking ratio and computing resource consumption, achieving the same results in terms of service blocking ratio that the proposal in the literature, but reducing the IT resource consumption in terms of CPU cores, RAM and hard disk.

Then, GASM has been modified to perform a periodic reconfiguration of the network planning, i.e., the VNF-placement, in dynamic scenarios. Furthermore, a new version was proposed, called Evolutive GASM, which upgrades GASM by adding a learning technique. The proposals have been compared with a static planning using GASM and other methods from the literature modified to be use in a reconfigurable scenario. Results from this study have shown that performing a planning reconfiguration using Evolutive GASM improves the network performance in terms of service blocking ratio and resource consumption.

Then, a new algorithm was proposed to solve not only the VNF-placement and chaining problems but also the virtual topology design in 5G networks with WDM optical backhaul: GASM-VTD. Initially, we considered that MEC nodes are connected via a WDM-ring since it is the most extended topology in metro networks. The design of the virtual topology comprises deciding which lightpaths should be established, assigning them a route and a wavelength for each lightpath and finally deciding how to route the traffic over the established lightpaths performing traffic grooming. Two versions of the algorithm were proposed: one in which there is no collaboration between the MEC nodes and another that exploits this collaboration thanks to the use a chaining technique designed for that aim. The two versions of GASM-VTD have been compared with the proposals from the literature and results have shown that it is possible to reduce the service blocking ratio when exploiting the collaboration between MEC-nodes using our proposal.

In a second step, we have enhanced GASM-VTD proposing a new version that provides individual VNF protection using either dedicated or shared strategies for both computing and network resources. A simulation study has been conducted comparing the different alternatives and results showed that, thanks to the use of shared protection, it is possible to reduce the service blocking ratio compared with the other alternatives. Moreover, results also show that solving the VNF-placement and chaining problem with individual VNF protection without considering the optical connectivity between MEC nodes, like most of previous proposals do, can lead to unexpected (and worse) results. This problem can be sorted out by jointly solving the VNF-placement, VNF-chaining, VNF-protection, and virtual topology design with methods like GASM-VTD. Moreover, the individual VNF protection schemes have been compared with end-to-end SC protection strategies proposed in the literature. Results have shown that the end-to-end SC protection schemes required much more computing resources to reduce the service blocking ratio than the individual VNF protection used in our proposal.

In a third step, a new algorithm with the same objective than GASM-VTD but using a new chaining technique has been proposed: GASVIT. Thanks to the new chaining technique, GASVIT can exploit the collaboration between MEC nodes more efficiently than GASM-VTD, reducing the service blocking ratio, the resource utilisation and the propagation delay obtained with the latter. Then, the corresponding versions of GASVIT including individual VNF protection techniques have also been developed and compared. The version with shared protection in both VNF and network resources the one that obtains best results. Finally, since GASVIT can work with mesh topologies, we have presented a techno-economical study to evaluate the impact of using different network topologies for the WDM backhaul in terms of service blocking ratio and cost. The results have shown that the ring topology (i.e., the most extended topology in metro networks) presents the best balance in terms of cost and service blocking ratio, although little upgrades that do not highly increase the complexity of the network can positively impact the performance of the network.

7.2 Future work

New research topics emerge based on the results of this thesis. In the area of optical networks, the development of multicore fibres allows the use of space division multiplexing (SDM) in EONs/WRONs. In networks combining these two technologies, the RSA problems become the routing, spectrum and core assignment problem (RSCA). Therefore, the evaluation of different levels of flexibility in these networks and the proposal of new RSCA algorithms based on the Best Gap technique are suitable future lines of research.

Another straightforward research line is the inclusion of EON in the backhaul of the 5G networks and the development of new versions of GASVIT in order to adapt this algorithm to work over elastic optical networks.

Moreover, the state-of-the-art technology at the beginning of the thesis allowed to establish optical connections of 10 Gb/s. However, as it was to be expected, the technology has evolved and now the equipment allows to establish 25 Gb/s connections or connections with even higher capacity. It would be interesting to repeat the study with this new connection capacity, in order to see the impact of having more bandwidth in the service blocking ratio obtained by GASM and GASVIT.

Finally, another important aspect to be studied is the latency. We have assumed that pushing the data processing towards the edge nodes of the network, closer to the end-user, can help meeting the latency requirements in 5G. However, the design of control methods to solve the NFV problems taking into account latency is a promising line of research. A possible research line would be developing latency-aware chaining and protection strategies.

7.3 Publications

In this Section, we present the list of publications derived from this Thesis in chronological order:

- **L. Ruiz**, I. González, R. J. Durán, I. de Miguel, N. Merayo, J. C. Aguado, P. Fernández, R. M. Lorenzo, E. J. Abril, "Comparing Different Types of Flexibility when Solving the RSA Problem in EONs". *2017 International Conference on Computational Science and Computational Intelligence (CSCI)*, Las Vegas, NV, 2017, pp. 1356-1359.

- **L. Ruiz** and J. C. García, "Quantum arithmetic with the quantum Fourier transform", *Quantum Information Processing* 16.6 (2017): 152.

- **L. Ruiz**, R. J. Durán, I, De Miguel, P.S. Khodashenas, J.-J. Pedreño-Manresa, N. Merayo, J. C. Aguado, P. Pavón-Marino, S. Siddiqui, J. Mata, P. Fernández, R. M. Lorenzo, E. J. Abril, "Genetic Algorithm for Effective Service Mapping in the Optical Backhaul of 5G Networks", *2018 20th International Conference on Transparent Optical Networks (ICTON)*, Bucharest, 2018, pp. 1-4

- F. J. Moreno-Muro, R. Rumipamba-Zambrano, J. Perelló, P.Pavón-Marino, J. Solé-Pareta, R. Martínez, R. Casellas, R. Vilalta, R. Muñoz, J. Mata, **L. Ruiz**, N. Merayo, I. de Miguel, R. J. Durán, "Elastic Networks Thematic Network Results I: Planning and Control of Flex-Grid/SDM"*2018 20th International Conference on Transparent Optical Networks (ICTON)*, Bucharest, 2018, pp. 1-4

- **L. Ruiz**, R. J. Durán, I, De Miguel, P. S. Khodashenas, J.-J. Pedreño-Manresa, N. Merayo, J. C. Aguado, P. Pavón-Marino, S. Siddiqui, J. Mata, P. Fernández, R. M. Lorenzo, E. J. Abril, "A Genetic Algorithm for VNF Provisioning in NFV-Enabled Cloud/MEC RAN Architectures", *Applied Sciences* 8.12 (2018): 2614.

- **L. Ruiz**, R. J. Durán, I. de Miguel, N. Merayo, J. C. Aguado, P. Fernández, R. M. Lorenzo, E. J. Abril, "Joint VNF-Provisioning and Virtual Topology Design in 5G Optical Metro Networks", *2019 21st International Conference on Transparent Optical Networks (ICTON)*, Angers, France, 2019, pp. 1-4.

- **L. Ruiz**, R. J. Durán, I. de Miguel, N. Merayo, J. C. Aguado, P. Fernández, R. M. Lorenzo, E. J. Abril, "Design of VNF-Mapping with Node Protection in WDM Metro Networks", *10th EAI International Conference on Broadband Communications, Networks and Systems*, Xi'an, China, 2019, pp. 1-4.

- **L. Ruiz**, R. J. Durán, I. de Miguel, N. Merayo, J. C. Aguado, P. Fernández, R. M. Lorenzo, E. J. Abril, "Genetic Algorithm for Holistic VNF-Mapping and Virtual Topology Design", in Press, IEEE Access, 2020.

- **L. Ruiz**, R. J. Durán, I. de Miguel, N. Merayo, J. C. Aguado, P. Fernández, R. M. Lorenzo, E. J. Abril, "Comparison of Different Protection Schemes in the Design of VNF-Mapping with VNF Resiliency", Manuscript accepted as invited paper at 2020 21th International Conference on Transparent Optical Networks (ICTON).

Chapter 8

Conclusiones y Futuras Líneas de Investigación

8.1 Conclusiones

Tanto la aparición de nuevos servicios como el creciente tráfico y número de dispositivos conectados que las redes de comunicaciones actuales deben soportar, impulsarán su evolución hacia la Internet del Futuro. Entre otros aspectos, se espera que el segmento radio evolucione hacia la tecnología 5G, mientras que el segmento óptico lo hará desde las redes WRON a las redes EON. Finalmente, en el plano de control se espera que se incorporen nuevas tecnologías como SDN y NFV, mientras que en la red se integrarán recursos de computación mediante la tecnología MEC.

En el área de las redes ópticas, las redes WRON están evolucionando hacia una tecnología óptica que es capaz de hacer un uso más eficiente del espectro, con el objetivo de gestionar el tráfico creciente que las redes deben transportar. Las redes ópticas elásticas o flexibles son capaces de adaptar el ancho de banda asignado a la capacidad solicitada, entre otras características. En este tipo de redes, establecer una conexión o camino de luz requiere la asignación de una porción de espectro a lo largo de una ruta que una el origen y el destino. Este problema de diseño se conoce como problema de asignación de ruta y espectro (routing and spectrum assignment problem, RSA). Cuando este problema se debe resolver en entornos dinámicos en los que los establecimientos y las liberaciones de las conexiones se hacen en tiempo real, es necesario utilizar algoritmos RSA eficientes que minimicen el número de conexiones bloqueadas, y que sean capaces de resolver el problema en un periodo de tiempo corto.

Por otra parte, los exigentes requerimientos de la nueva tecnología 5G requieren un cambio profundo en la arquitectura de la red, con el objetivo de aumentar su flexibilidad y adapatabilidad, así como facilitar su gestión, a la vez que reducen los costes de la red. Por ello, se espera que 5G base sus redes de retorno en las redes ópticas, por su gran flexibilidad y capacidad. Además, se espera que otras tecnologías como NFV, SDN y MEC sean claves en el desarrollo de las redes 5G.

Sin embargo, la convergencia de estas tecnologías para permitir el desarrollo de 5G presenta desafíos extra en términos de orquestación de red. Cuando se implementa una red NFV, es necesario planificar la red de acuerdo con los servicios que serán desplegados. En este tipo de entornos, la planificación se divide en dos etapas: el emplazamiento de VNFs, en la que se decide el número de instancias y la localización de las VNFs, y la concatenación de VNFs, en la que se construye la SC asociada al servicio que se quiere establecer, eligiendo las instancias que deberá atravesar el tráfico asociado al servicio solicitado. Además, establecer una cadena no solo requiere VNFs disponibles, sino que necesita de recursos de red para transportar el tráfico de una VNF a otra. Este es un problema complejo que no puede ser obviado. Además, depende en gran medida en la topología de la red y en la tecnología óptica, cuando la red de retorno está construída sobre redes ópticas. La disponibilidad y asignación de recursos es diferente cuando los nodos están conectados con redes dedicadas punto a punto que cuando están conectados con redes WDM con topología en anillo. Por ese motivo, los algoritmos de orquestación de red deben ser capaces de resolver el control de red a la par que solucionan los problemas de emplazamiento y concatenación de VNFs.

En esta tesis se han hecho contribuciones en dos áreas con el objetivo de contribuir a la evolución de las redes de comunicación actuales hacia la Internet del Futuro: se han propuesto métodos RSA para redes ópticas elásticas y algoritmos para incorporar NFV en el control de las redes actuales. En ambos casos, se ha realizado un profundo análisis del estado del arte actual y sus conclusiones se han presentado en los capítulos 2 y 4 de esta tesis.

Se han presentado dos contribuciones en el área de las redes ópticas. En primer lugar, se ha estudiado la inclusión de diferentes niveles de flexibilidad en la resolución del problema RSA con dos conocidos métodos de asignación de ruta y espectro: $k-$shortest paths y first fit. En el primer nivel de flexibilidad, el espectro se considera o bien dividido en pequeños tramos (flexgrid), como en la mayoría de estudios sobre algoritmos RSA, o bien como una porción de espectro (gridless). El segundo nivel considera la posibilidad de dividir el tráfico solicitado entre varios caminos de luz o de establecer un único camino de luz que transporte todo el tráfico solicitado. Se han propuesto cuatro algoritmos RSA combinando ambos niveles de flexibilidad con los métodos $k-$shortest paths y first fit: Joint Flexgrid Spectrum (JFS), Disjoint Flexgrid Spectrum (DSF), Joint Spectrum Gridless (JSG) and Disjoint Spectrum Gridless (DSG). Los resultados de las simulaciones del comportamiento de estos algoritmos muestran que, cuando se emplean los métodos $k-$shortest paths y first fit, el espectro se utiliza de forma más eficiente si se permite dividir la solicitud de tráfico entre múltiples caminos de luz. Además, los resultados muestran que incluir grados altos de flexiblidad en la red no conllevan necesariamente una reducción de la probabilidad de bloqueo. En realidad, los métodos más flexibles, es decir, aquellos que consideran un espectro gridless y la posibilidad de establecer varios caminos de luz, son aquellos que obtienen una probabilidad de bloqueo más alta.

Este comportamiento (contrario a lo esperado) se da pues first fit no es el método más adecuado para resolver el problema RSA en redes elásticas con gran flexibilidad. Por este motivo, se propone una novedosa técnica de asignación de espectro llamada Best Gap. Esta técnica busca la porción de espectro disponible que mejor se adapta al tráfico demandado y se puede combinar con los niveles de flexibilidad presentados. Los resultados de las simulaciones que estudian el comportamiento de estos algoritmos muestran que la red se puede ver beneficiada cuando combina altos grados de flexibilidad con $k-$shortest paths y Best Gap para resolver el problema RSA. De hecho, los métodos más flexibles, en este caso, son los que obtienen mejores valores de probabilidad de bloqueo y, además, mejoran el comportamiento de la red comparado con los primeros métodos propuestos.

Por otro lado, se han realizado distintas contribuciones en el campo de la integración de la tecnología NFV en 5G con redes de retorno ópticas en las que los nodos están equipados con recursos MEC. Se ha propuesto inicialmente un algoritmo genético para el mapeo efectivo de servicios (GASM) con el objetivo de resolver el problema de emplazamiento y concatenación de VNFs en redes 5G cuya red de retorno está basada en una topología en estrella. En la comparación de GASM con otras técnicas propuestas en la literatura se muestra que GASM ofrece un buen equilibrio entre la probabilidad de bloqueo de servicios y el consumo de recursos computacionales, alcanzando el mismo comportamiento en términos de probabilidad de bloqueo del servicio que los métodos propuestos en la literatura pero reduciendo el consumo de recursos en términos de CPU, RAM y disco duro.

Posteriormente se ha modificado GASM para realizar reconfiguraciones periódicas en la planificación de la red, es decir, para modificar periódicamente el emplazamiento de VNFs, en escenarios dinámicos. Se propone una nueva vesión del algoritmo llamada Evolutive GASM que mejora a GASM añadiendo una técnica de aprendizaje. Se ha comparado la nueva propuesta con los resultados de realizar una planificación estática utilizando GASM, y con otros métodos propuestos en la literatura modificados para poder ser utilizados en escenarios reconfigurables. Los resultados de este estudio muestran que realizar replanificaciones periódicas con GASM mejora el comportamiento de la red en términos de probabilidad de bloqueo de servicio y de consumo de recursos.

Además, se ha propuesto un nuevo algoritmo que resuelve tanto el emplazamiento y la concatenación de VNFs como el diseño de la topología virtual en redes 5G con red de retorno basado en WDM: GASM-VTD. Inicialmente hemos considerado que los nodos MEC están conectados mediante una red WDM con topología en anillo, por ser la más desplegada en redes metro. El diseño de la topología virtual comprende decidir el número de caminos de luz que habrán de establecerse, asignarles una ruta y ancho de banda y decidir, finalmente, cómo encaminar el tráfico usando los caminos de luz establecidos. Se han propuesto dos versiones del algoritmo: una en la que no existe colaboración entre los nodos MEC de la red y otra en la que esta colaboración sí que existe, gracias a la implementación de una técnica de concatenado diseñada a tal efecto. Se han comparado ambas versiones de GASM-VTD con propuestas existentes en la literatura y los resultados muestran que es posible reducir la probabilidad de bloqueo cuando se explota la colaboración entre los nodos MEC, utilizando nuestra propuesta.

Este algoritmo ha sido mejorado proponiendo cuatro nuevas versiones que ofrecen protección individual de las VNFs empleando recursos tanto dedicados como compartidos, sea para los recursos computacionales que para los recursos de red. Se ha llevado a cabo una simulación para comparar las cuatro alternativas y los resultados muestran que es posible reducir la probabilidad de bloqueo de servicio, con respecto a otras alternativas, cuando se utilizan recursos de protección compartidos. De hecho, los resultados también muestran que resolver el emplazamiento y concatenación de VNFs con protección sin tener en cuenta la conectividad óptica entre nodos MEC, como hace la mayoría de estudios sobre el tema, puede conllevar resultados inesperados (y peores). Este problema se puede resolver solucionando conjuntamente el emplazamiento y concatenación de VNFs, la protección y el diseño de la topología virtual con métodos como GASM-VTD. Además se han comparado los esquemas de protección individual de VNFs con esquemas de protección de SCs extremo a extremo propuestos en la literatura. Los resultados muestran que los esquemas de protección extremo a extremo requieren más recursos computacionales para reducir la probabilidad de bloqueo de servicio comparado con los esquemas de protección individual de VNFs empleados en nuestra propuesta.

Por último, se ha propuesto un nuevo algoritmo que cumple con el mismo objetivo que GASM-VTD pero empleando una nueva técnica de concatenación: GASVIT. Gracias a esta nueva estrategia de encadenado, GASVIT puede explotar más eficientemente la colaboración entre los nodos MEC, comparado con GASM-VTD, reduciendo así tanto la probabilidad de bloqueo de servicio como el uso de recursos computacionales y el retardo de propagación. Se han propuesto y comparado las correspondientes versiones de GASVIT para implementar esquemas de protección individual de VNFs. La versión de GASVIT con protección que emplea recursos de protección compartidos tanto en VNFs como en recursos de red es la que obtiene los mejores resultados. Finalmente, dado que GASVIT puede trabajar sobre topologías en malla, se ha presentado un estudio tecno-económico que evalúa el impacto de usar diferentes topologías como red de retorno WDM en términos de probabilidad de bloqueo de servicio y coste. Los resultados muestran que la topología en anillo (la más extendida en redes metro) presenta el mejor equilibrio entre el coste y la probabilidad de bloqueo de servicio, aunque se pueden hacer pequeñas mejoras que no aumentan excesivamente la complejidad de la red pero que pueden impactar positivamente en el comportamiento de la red.

8.2 Futuras líneas de investiación

De los resultados de esta tesis pueden nacer nuevas líneas de investigación. En el área de las redes ópticas, el desarrollo de fibras multinúcleo permite el uso de la multiplexación por división de espacio (space division multiplexing, SDM) en redes EONs/WRONs. En las redes que combinan estas tecnologías, el problema RSA se transforma en el problema de asignación de ruta, espectro y núcleo (routing, spectrum and core assignment problem, RSCA). Por tanto, la evaluación de los distintos grados de flexibilidad en estas redes y la propuesta de nuevos algoritmos RSCA basados en la técnica Best Gap podría constituir una nueva e interesante línea de investigación.

Otra línea clara de investigación es la inclusión de las redes EON como redes de retorno de 5G y el desarrollo de nuevas versiones de GASVIT adaptadas para trabajar sobre este tipo de redes elásticas.

Además, el estado de la tecnología al comienzo de esta tesis permitía establecer conexiones ópticas a 10 Gb/s. Sin embargo, como era de esperar, la tecnología ha evolucionado, permitindo en la actualidad establecer conexiones a 25 Gb/s o mayores. Sería interesante repetir el estudio con esta nueva conexión de alta capacidad, para estudiar el impacto de tener mayor ancho de banda disponible en la probabilidad de bloqueo de servicio obtenido por GASM y GASVIT.

Por último, otro aspecto importante a estudiar es la latencia. Se ha asumido que llevar el procesamiento de los datos hacia los nodos de la red, más cerca del usuario final, puede ayudar a cumplir con los requerimientos de latencia de 5G. Sin embargo, el diseño de algoritmos de control que resuelvan los problemas de NFV considerando la latencia constituye una prometedora línea de investigación. Por tanto, un posible trabajo de investigación sería desarrollar técnicas de concatenación y protección que consideren la latencia del servicio.

8.3 Publicaciones

En esta sección se presenta la lista de publicaciones derivadas de esta tesis en orden cronológico:

- **L. Ruiz**, I. González, R. J. Durán, I. de Miguel, N. Merayo, J. C. Aguado, P. Fernández, R. M. Lorenzo, E. J. Abril, "Comparing Different Types of Flexibility when Solving the RSA Problem in EONs". *2017 International Conference on Computational Science and Computational Intelligence (CSCI)*, Las Vegas, NV, 2017, pp. 1356-1359.
- **L. Ruiz** and J. C. García, "Quantum arithmetic with the quantum Fourier transform", *Quantum Information Processing* 16.6 (2017): 152.
- **L. Ruiz**, R. J. Durán, I, De Miguel, P.S. Khodashenas, J.-J. Pedreño-Manresa, N. Merayo, J. C. Aguado, P. Pavón-Marino, S. Siddiqui, J. Mata, P. Fernández, R. M. Lorenzo, E. J. Abril, "Genetic Algorithm for Effective Service Mapping in the Optical Backhaul of 5G Networks", *2018 20th International Conference on Transparent Optical Networks (ICTON)*, Bucharest, 2018, pp. 1-4
- F. J. Moreno-Muro, R. Rumipamba-Zambrano, J. Perelló, P.Pavón-Marino, J. Solé-Pareta, R. Martínez, R. Casellas, R. Vilalta, R. Muñoz, J. Mata, **L. Ruiz**, N. Merayo, I. de Miguel, R. J. Durán, "Elastic Networks Thematic Network Results I: Planning and Control of Flex-Grid/SDM"*2018 20th International Conference on Transparent Optical Networks (ICTON)*, Bucharest, 2018, pp. 1-4
- **L. Ruiz**, R. J. Durán, I, De Miguel, P. S. Khodashenas, J.-J. Pedreño-Manresa, N. Merayo, J. C. Aguado, P. Pavón-Marino, S. Siddiqui, J. Mata, P. Fernández, R. M. Lorenzo, E. J. Abril, "A Genetic Algorithm for VNF Provisioning in NFV-Enabled Cloud/MEC RAN Architectures", *Applied Sciences* 8.12 (2018): 2614.
- **L. Ruiz**, R. J. Durán, I. de Miguel, N. Merayo, J. C. Aguado, P. Fernández, R. M. Lorenzo, E. J. Abril, "Joint VNF-Provisioning and Virtual Topology Design in 5G Optical Metro Networks", *2019 21st International Conference on Transparent Optical Networks (ICTON)*, Angers, France, 2019, pp. 1-4.
- **L. Ruiz**, R. J. Durán, I. de Miguel, N. Merayo, J. C. Aguado, P. Fernández, R. M. Lorenzo, E. J. Abril, "Design of VNF-Mapping with Node Protection in WDM Metro Networks", *10th EAI International Conference on Broadband Communications, Networks and Systems*, Xi'an, China, 2019, pp. 1-4.
- **L. Ruiz**, R. J. Durán, I. de Miguel, N. Merayo, J. C. Aguado, P. Fernández, R. M. Lorenzo, E. J. Abril, "Genetic Algorithm for Holistic VNF-Mapping and Virtual Topology Design", en edición, IEEE Access, 2020.
- **L. Ruiz**, R. J. Durán, I. de Miguel, N. Merayo, J. C. Aguado, P. Fernández, R. M. Lorenzo, E. J. Abril, "Comparison of Different Protection Schemes in the Design of VNF-Mapping with VNF Resiliency", Manuscrito aceptado como artículo invitado en al 2020 21th International Conference on Transparent Optical Networks (ICTON).

Appendix A

Developed Simulators using OMNeT++

A.1 Introduction

All the proposals presented in this thesis have been tested in two simulators, developed using OMNeT++ [159].

OMNeT++ is an object-oriented, C++ based, modular discrete event network simulation framework. The framework provides the required tools and infrastructure to model any kind of network and evaluate the performance of software systems [159].

The basic block in a model is the simple module, which encapsulates its basic functionality. Modules are written in C++, using the provided simulation libraries, and can have parameters to customise the behaviour of the module. Simple modules can be combined to create compound modules. The depth of the module nesting is not limited. Modules communicate with each other through messages, which can be sent directly from one module to another or using predefined paths described by gates and connections. Gates can be either input or output interfaces of a module, so an input interface is connected to an output interface of a different module, and vice versa. Finally, connections can be customised and assigned parameter values as bit rate, length, delay, etc.

The structure of the simulation model is defined by the user with the Network Description (NED) language. This language allows the declaration of simple modules, compound modules, and networks, typically. The declaration of simple modules includes sections as gates and parameters. In a similar manner, the compound modules are declared including sections as the simple modules of which they are composed, parameters, gates or connections. Finally, the networks are declared indicating the number and type of modules of the network and their connections.

Simulations in OMNeT++ can be run under graphical and command-line interfaces and different operating systems including Windows and Linux.

In this Thesis, we employed OMNeT++ due to its flexibility and the possibility of simulating different types of network architectures and technologies. Furthermore, its distribution is free for academic use. The employed version is OMNeT++ 5.0 since it was the most recent release at the beginning of this Thesis. The simulations have been run in two different types of servers equipped with 32 CPU AMD Opteron 6128 (8 cores) and 48 AMD

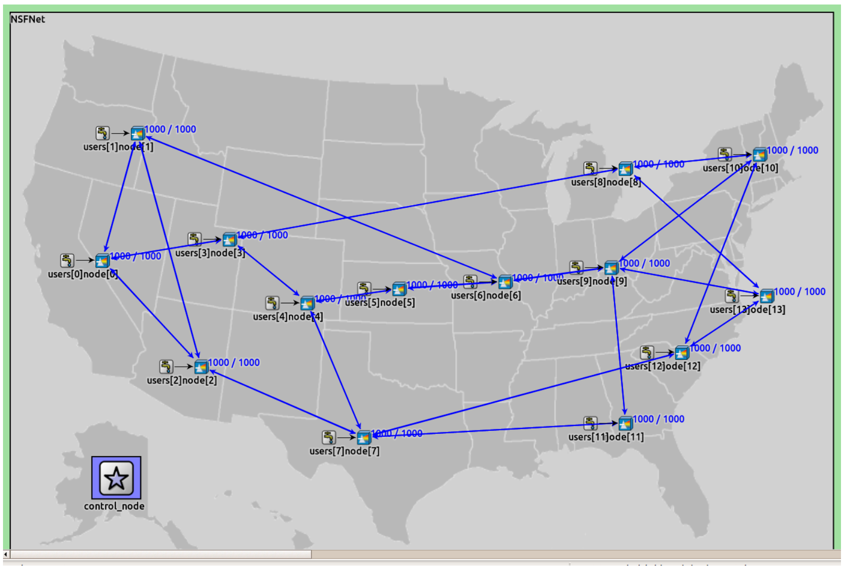


Figure A.1: NFSNet implemented in the EON simulator

Opteron 6127 (12 cores) and operating system Debian $4.9.88 - 1 + deb9u1$.

During the development of this thesis, we have constructed two OMNeT++ simulators: the NFV Simulator and the EON Simulator. In the first simulator, we implemented different 5G network scenarios and tested the proposed algorithms in this thesis to solve the VNF-placement, chaining and network resource allocation: GASM, GASM-VTD and GASVIT. The second simulator implements the 14-node NSFNet architecture and was used to test on an EON the performance of the RSA algorithms proposed in this Thesis.

A.2 EON Simulator

This simulator was developed to test different algorithms that solve the RSA problem in EONs on the 14-node NSFNet. The structure is shown in Figure A.1. The simulator is composed of a control node, a set of nodes and source blocks.

The source blocks generate random connection requests and send them to the corresponding node of the network. We can observe in A.1 that each node of a network is connected to one source module. When the request arrives at the node, it sends it to the control node, which will try to set up the connection solving the RSA problem. If the connection can be established, the control node will reserve the assigned resources and send a establishment message to the requesting node. The requesting node will establish a connection with the destination node. Once the holding time of the connection is met, the control node will release the resources and tear down the connection.

The structure of the control node is shown in Figure A.2. This is a compound module that contains the following simple modules:

- State: This module contains a table with up-to-date information on the network state, i.e., the number of transceivers, wavelengths, optical fibre state, established lightpaths, etc.

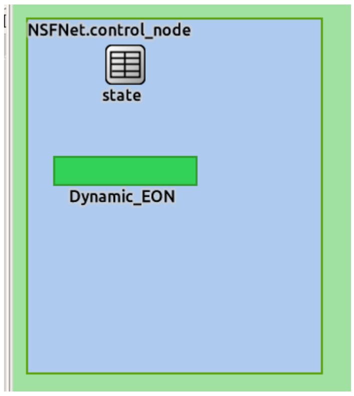


Figure A.2: Control node structure of the EON Simulator

- Dynamic_EON: This module contains the RSA algorithms that were implemented and tested in this simulator. It also contains the functionality to reserve network resources and release them when a connection is torn down.

Finally, we can observe in A.1 that the nodes of the network are connected to each other. We assume that the nodes are connected via two optical fibres, one for each direction, with a capacity of $4,000$ GHz.

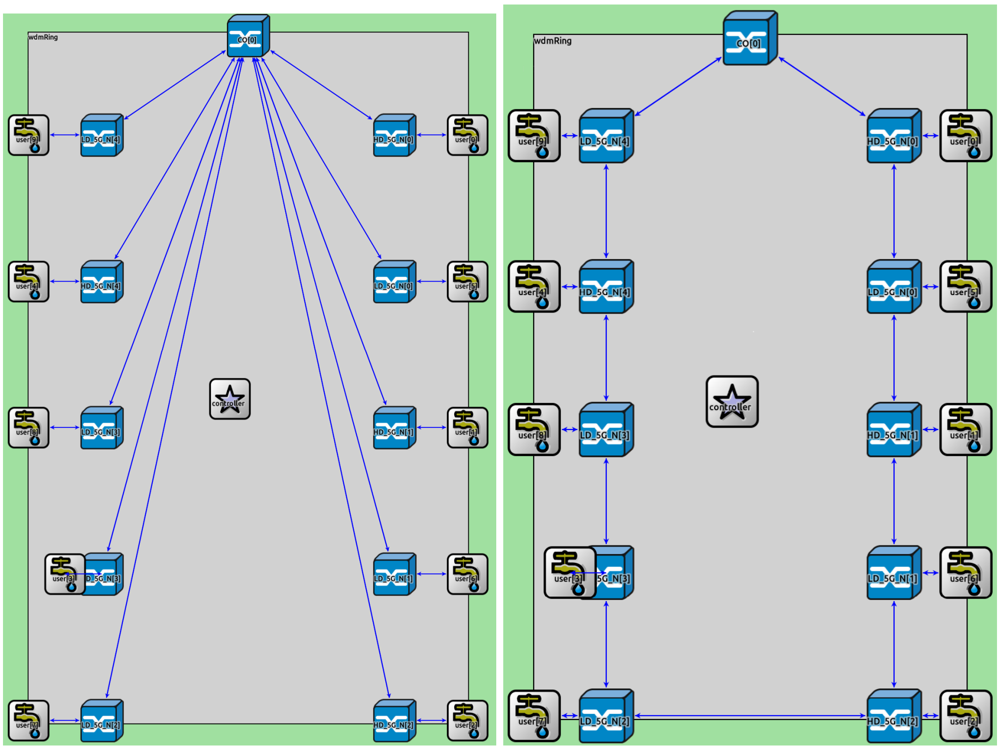
A.3 NFV Simulator

This simulator was developed to test the performance of algorithms proposed in this thesis to solve the VNF-placement, chaining and network resource allocation in 5G networks with optical backhaul: GASM, GASM-VTD and GASVIT. It implements two different centralised 5G network with optical backhaul scenarios, one in which the nodes are connected building a star topology and another in which the nodes build a ring topology. The structure is shown in Figures A.3a and A.3b.

The network is composed by a Controller, a Central Office and a number of HD-5G-nodes and LD-5G-nodes. The 5G-nodes are connected to a user block, responsible for randomly generating the number of users connected to the corresponding 5G-node. The 5G-nodes will send connection request messages to the Controller indicating the number of requests of each type received at each node. Although the Controller is not independent of the rest of the nodes of the network, it has been plotted separately and is not connected to any node to simplify the physical topology.

The Controller is shown in figure A.4. This compound module contains the following single modules:

- NetworkState: This module contains a table with up-to-date information on the state of the network, i.e., the active number of wavelengths, its state (active or inactive), the active lightpaths and their occupied capacity.
- VNFNodeState: This module contains two tables with up-to-date information on the state of the VNF nodes, i.e., the instantiated VNFs at each node and the available computing resources of each node of the network.



(a) Star topology (b) Ring topology

Figure A.3: Network topologies implemented in the GASM simulator.

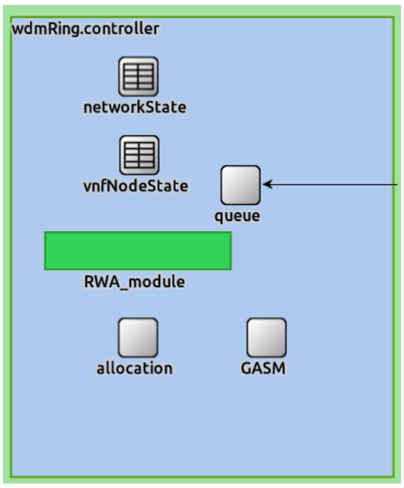


Figure A.4: Structure of the Controller module of GASM simulator.

- Queue: This module stores the connection requests and sorts it according to a certain network operator's preferred priority order.
- RWA_ module: Contains the RWA algorithms employed in the simulator.
- GASM: This block implements the genetic operations employed in the various versions of GASM, i.e., crossover, mutation, validation and translation.
- Allocation: This block receives the request queue and executes the GASM functionality, i.e., calls the methods implemented in GASM and solves the VNF-placement, chaining, and protection problems. This module also uses the RWA algorithms of the RWA_module to allocate network resources to the SCs that must be set up.

Therefore, the Controller is responsible for receiving and sorting the requests, solving the VNF-placement, chaining, and protection using the corresponding algorithm, allocating the resources, updating the network and node state information and releasing the connections and their allocated network and computing resources.

We implemented different topologies in which each physical link consists of two optical fibres. Lastly, Figure A.3a shows a star topology in which a point-to-point optical link with a capacity of 10 Gb/s connects each node of the network to the CO. Similarly, Figure A.3b shows a ring topology, the second scenario in which the algorithms have been tested. We have also assumed that the nodes in the ring topology are connected via an optical link. In this scenario the WDM technology is implemented. In consequence, the fibres support multiple wavelengths and, in consequence, channels, whose capacity is set to 10 Gb/s for each wavelength.

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