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Resilient Planning for Multi-Access Edge Computing in Sparsely Populated Areas

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***Abstract*—Resiliency (fault tolerance) is an important aspect in communication networks: a robust and well-planned network must have a strategy to face equipment failures. The planning of Multi-Access Edge Computing (MEC) systems should not only consider computing resources, but also the fiber connections to base stations (BSs) and to the WAN network gateway. This joint design is particularly important in sparsely populated areas (e.g., rural areas), as the distances are much longer than in urban environments. When solving the planning problem for these systems, reserving backup resources for both computing and networks is a must to ensure resiliency. In this paper, we propose and compare different strategies for the planning of resilient MEC networks assuming that there are backup resources for both MEC servers and fibers. The method provides protection against single-fiber failure or single-MEC node failure (with part or all the servers affected). The different approaches are evaluated in terms of cost and propagation delay from BSs to the primary and backup MEC servers. Results show the advantages of using edge technology instead of a centralized design, and they also suggest that is more convenient to jointly plan the main and backup MEC architecture than to deploy the backup resources over an existent infrastructure.**

Keywords— Multi-Access Edge Computing (MEC), resiliency, network planning, servers, optical networks, resource optimization.

I. INTRODUCTION

With the arising of fifth generation networks (5G) [1], and the rapid growth of Internet of things (IoT) technologies, the requirements for communication networks have become more stringent. New services such as virtual/augmented reality (AR/VR), autonomous vehicles, ultra-high-definition video streaming, and smart factories/cities, require very low transmission latency and high bandwidth to work properly. These two requirements (latency and bandwidth) may be hard to achieve in a cloud computing environment, due to the usually high distances between the end users and the cloud servers. Multi-Access Edge Computing (MEC) [2] is an architecture that brings the functionalities of cloud computing to the edge of the network. In MEC networks, servers are located at a short distance from the end users, in contrast to the classic cloud computing architecture, where servers are typically located at big and centralized data centers at large distances. Placing the servers at the edge of the network, significantly reduces the propagation latency. Furthermore, since the data does not have to travel long distances, the network is less congested, enabling a higher throughput.

In the planning of MEC networks, a problem inevitably arises, and it is the placement problem, which is about finding the optimal location for the servers and services in terms of an objective metric, such as cost or latency. Several works have dealt with the MEC server placement problem. Spinelli and Mancuso present in [3] a survey of them and study the required density of MEC hosts. Shao *et al.* [4] propose a learning-based framework integrating stochastic simulation, a neural network and a genetic algorithm in order to solve the placement problem considering uncertain BSs demands. The work done in [5] by Zhang *et al.* proposes an heuristic to achieve a cost-effective fog network design integrating micro data centers (MicroDC) and a Long-Reach Passive Optical Network (LRPON) to support delay-sensitive bandwidth-intensive services. In [6], Kasi *et. al.* propose to find the optimal locations of edge servers in order to balance workload and minimize access delay, using a genetic algorithm and local search optimization techniques, such as hill climbing and simulated annealing. In [7], we demonstrate the importance of solving the MEC planning problem in combination with the design of the fiber network that interconnects the BSs, MEC servers and WAN gateway.

However, new services do not only demand low latency solutions but also resilient infrastructures that continue working in case of failure. Therefore, resilience must be considered when solving the planning problem by including backup resources for the MEC servers, MEC nodes and fiber network. Lu *et al.* [8] formulate the robust server placement problem (RSP) in MEC environment and analyze the impact of simultaneous failures of several MEC nodes. However, based on the high mean time between failures (MTBF) of current technology, contingency plans are commonly designed for single fiber or single MEC node failures (with part or all the servers affected). Zhao and Dán [9] formulate the joint resilient planning and service placement problem with the objective of reducing energy consumption. Thiruvasagam *et al.* [10] propose a binary integer programming model based on multi-connectivity in 5G networks to optimally deploy network slices on top of MEC servers with the minimum cost and provide resiliency to the network against different kinds of failures. Nevertheless, these methods do not design the fiber network when solving the planning problem. In [11], Nag *et al.* propose a method referred to as dual homing, which consists of connecting a single remote node to two geographically separate metro/core nodes for dedicated protection in case of feeder fiber failure. The work of Barbosa *et al.* [12] studies the resiliency gap

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between an existing network topology and new network topologies designed to maximize its resilience considering different fiber budgets. They propose a multi-start greedy randomized method to generate network topologies, with a given fiber length budget, that are resilient to critical node failures. In this paper, we study the planning of MEC networks, including the server placement, the optical network deployment, and the inclusion of backup resources for both computing and the network to provide resiliency to the system. To the best of our knowledge, there are no published works dealing with all the mentioned issues.

II. GREENFIELD MEC RESILIENT NETWORK PLANNING

In this section, we present a scheme for deploying MEC resilient networks considering that there is not any prior deployment (i.e., greenfield scenario). In Section III, we compare the proposed method and other two approaches which perform brownfield planning by equipping the network with backup resources using the primary deployment designed with the two methods presented in [7]. All the approaches are evaluated under the following assumptions:

- MEC servers are placed in BSs. No other locations are allowed. A BS may host several MEC servers. From now on, a BS location which has at least one MEC server will be referred to as a MEC node.
- All the servers have the same characteristics.
- All the traffic (primary and backup) from a BS is served by MEC servers located in a single BS. The BS hosting primary resources is different than the one hosting backup resources, except for non-edge approach described in Section III.
- All connections will be performed using a point-to-point fiber cable without capacity constraints.
- If a BS is equipped with MEC servers, its associated users will be served by the servers located in that BS.
- All MEC nodes will be connected to a WAN gateway.

This approach defines an Integer Linear Programming (ILP) formulation which aims to minimize the deployment cost of a MEC network considering the capital expenditures (CAPEX) associated to the server placement and optical fiber deployment. This proposal jointly solves the planning of the main and backup network and assumes that each fiber link and MEC server have a dedicated replacement elsewhere.

Symbol	Meaning
$S_{\max}$	Maximum number of MEC servers in the network. It can be set to a huge value if there is no restriction on the number of servers
$S_{\min}$	Theoretical minimum number of MEC servers required
B	Number of BSs in the network
$U_{\max}$	Maximum number of simultaneous users (requiring MEC) that can be served by a MEC server (e.g., using the model in [3])
d_{ij}	Distance in km between BS$_i$ and BS$_j$
D_i	Distance in km between BS$_i$ and the WAN gateway
P_i	Population associated with BS$_i$
α_i	Fraction of population connected to BS$_i$ which simultaneously requires MEC services, $\alpha_i \in [0,1]$
C_{F}	Cost of the installation of one km of fiber cable
C_{S}	Cost of one MEC server
x_{ij}	Binary variable. x_{ij}=1 if the traffic from BS$_i$ requiring edge computing is served by servers located in BS$_j$, else 0
b_{ij}	Binary variable. b_{ij}=1 if the traffic from BS$_i$ requiring edge computing uses backup servers located in BS$_j$, else 0
y_i	Integer variable. Number of servers located in BS$_i$. $y_i \in [0, S_{\max}]$

TABLE 1. Model notations

Table TABLE 1 summarizes the notation used in the model. The variables (x_{ij}, b_{ij} and y_i), are the solutions of the problem. y_i is the number of servers located in BS$_i$ and x_{ij} is a binary variable that takes value one when the primary traffic (requiring edge computing) from BS$_i$ is served by the MEC servers located in BS$_j$ Therefore, if x_{ij} is one, an optical fiber cable must be laid between those two BSs. Similarly, if x_{ii} is one (which happens when y_i is greater than zero) an optical fiber cable connecting BS$_i$ and the WAN gateway must be deployed. The variable b_{ij} is like x_{ij} but it defines the backup links instead of the primary ones. The objective is to minimize the overall cost related to fiber deployment and servers. The cost of the fiber is obtained by multiplying its cost per kilometer by the kilometers of fiber required. We consider the fiber connections between each BS and its associated primary and backup MEC nodes, and the fiber connections between the MEC nodes and the WAN gateway. The total cost of the servers is the multiplication of the cost of one server by the amount of servers. The objective function includes all the mentioned components and is defined by equation (1). Thus, the proposed ILP formulation is as follows:

$$\min\left(C_{\mathrm{F}}\cdot\left(\sum_{i=1}^{B}\sum_{j=1}^{B}(x_{ij}+b_{ij})d_{ij}+\sum_{i=1}^{B}x_{ii}D_i\right)+C_{\mathrm{S}}\sum_{i=1}^{B}y_i\right) \quad (1)$$

subject to:

1) The maximum number of servers cannot be exceeded.

$$\sum_{i=1}^{B} y_i \leq S_{\max} \quad (2)$$

2) The traffic from any base station requiring MEC is only served by the MEC servers of one base station.

$$\sum_{j=1}^{B} x_{ij} = 1, \quad \forall i \in [1,B] \quad (3)$$

3) The traffic from any base station requiring MEC has backup computing resources in one and only one base station.

$$\sum_{j=1}^{B} b_{ij} = 1, \quad \forall i \in [1,B] \quad (4)$$

4) The total capacity of the servers located in BS$_j$ must be enough to serve all the workload assigned to this BS, including backup workload.

$$\sum_{i=1}^{B} \alpha_i P_i x_{ij} + \sum_{i=1}^{B} \alpha_i P_i b_{ij} \leqslant U_{\max}\, y_j, \quad \forall j \in [1,B] \quad (5)$$

5) If a base station is equipped with MEC servers, the traffic of that base station will be served by that base station.

$$\frac{y_i}{S_{\max}} \leqslant x_{ii}, \quad \forall i \in [1,B] \quad (6)$$

6) The backup computing resources must be located at a different BS than the primary ones.

$$b_{ij} + x_{ij} \leq 1 \quad \forall i,j \in [1,B] \qquad (7)$$

7) The backup computing resources must be located at a MEC node, and therefore, connected to the WAN gateway.

$$b_{ij} \leq x_{jj} \quad \forall i,j \in [1,B] \qquad (8)$$

III. CASE STUDY: DEPLOYMENT IN VALLADOLID PROVINCE

The proposed model has been tested assuming an implementation in the province of Valladolid, Spain. We employ a database with the location of 105 BSs in this province [13] and another database containing population data for each village in the province [14]. In this scenario the workload associated to each village is proportional to its population, similarly to the test environment we set in [7]. The workload has a mixed traffic profile composed by a 70% of video traffic, 15% of car traffic, 10% of smart factory and 5% of augmented/virtual reality, as described in [3]. A server is composed by 16 machines of 4 cores at 3.4 GHz, and each server can serve up to 75 simultaneous users ($U_{\max} = 75$) for that traffic profile. The cost of each server is set to 30,000 € and the cost of one kilometer of optical connection is set to 16,100 € (materials plus installation) [15]. To evaluate our proposal, we compare it against a network which does not deploy any backup resource [7]. Additionally, we have studied and compared the outcomes of two other deployment alternatives considering resiliency, as described below.

- *Resilience over an existing network (Brownfield dedicated protection):*

  This alternative solves the placement of backup resources considering that the primary network is already deployed. To implement this case, we first solve the non-resilient formulation of [7], and then, in a second phase, we apply the formulation of Section II, setting the values of x_{ij} as inputs to the system which are obtained in the first phase. This way, the primary network and MEC nodes are conserved and only backup fibers and additional MEC servers (in already established MEC nodes) are added to provide resiliency. The total cost of the whole system includes the cost of existing resources and of those added for protection.
- *Resilient non-edge approach with dedicated protection:*

  This model assumes a centralized approach with no edge computing, where all computing resources are hosted in the WAN gateway location. The BSs are connected to the servers located in the WAN gateway with direct fiber links. To provide resiliency, all computing resources must be deployed twice, thus doubling the cost. Although this approach deploys a smaller number of servers than the other approaches, it requires the deployment of more fibers and suffers from higher propagation delays between BSs and the servers as we will later show.

Fig. 1 compares the cost increase of each of the three models with respect to the MEC-based model without protection described in [7]. The model with the highest cost increase is the non-edge approach. This model increases the cost significantly more than the others because it requires a direct and dedicated fiber connection between each BS and the servers hosted at the WAN gateway. Furthermore, since we implement protection, each link has a backup, doubling the costs. The additional investment of the non-edge method in Fig. 1 decreases as the connected population increase because when the connected population grows, the number of servers required also grows, while the optical connections do not change, and since the increase in cost of this approach is essentially due to excess fiber, the percentage of additional investment decreases as the number of servers grows.

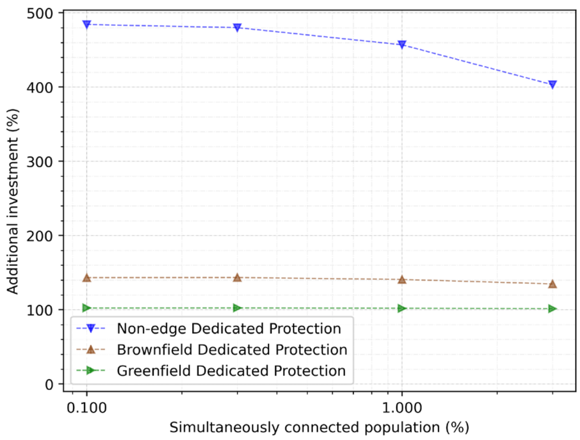

Fig. 1: Additional investment compared to a network without protection.

The greenfield scenario represents a smaller additional investment than the brownfield case, suggesting that it is more convenient to plan the whole network including the primary and backup resources, than to deploy the backup resources over an existent network. Although the addition of backup resources over a previously built network avoids the need to deploy new MEC nodes with their corresponding fibers to the WAN gateway, it implies deploying new backup links between each BS and the MEC node where its backup computing resources will be located, and these are typically longer links than those established when the primary and backup resources are jointly allocated (greenfield approach). For this reason, the brownfield approach results in a more expensive solution. Greenfield method allocates primary and backup resources jointly, thus it can find cheaper solutions.

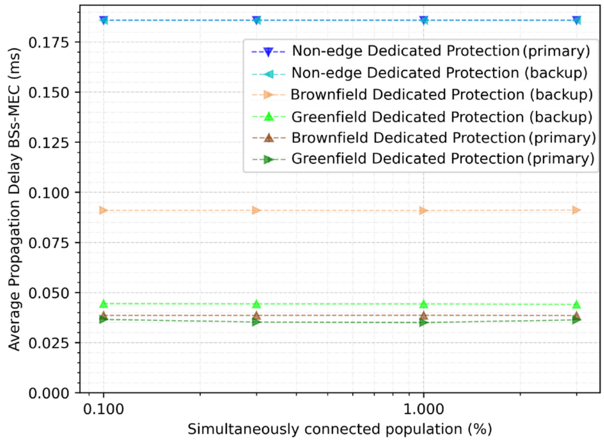

Fig. 2: Average propagation delay

Fig. 2 compares the average propagation delay from the BSs to their associated servers. The non-edge approach is the less convenient option, because all the BSs are connected to servers in the WAN gateway, increasing propagation delays. The primary and backup delays in that scenario are equal (assuming a best-case situation, although in practice primary and backup must use different paths). On the other hand, the greenfield approach leads to solutions with lower propagation delay. The difference is greater when comparing backup paths because the brownfield approach must deploy backup links from BSs towards already existing MEC nodes, which may translate in long links. The greenfield approach performs a joint selection of MEC nodes for primary and backup, and when doing this, the minimization of fiber costs in eq. (1) helps reducing delays. As for the average delay of primary paths, the greenfield approach also presents lower values because, to place backup resources, it deploys additional MEC nodes, and due to constraint (6) BSs with servers process their traffic locally, reducing the average delay.

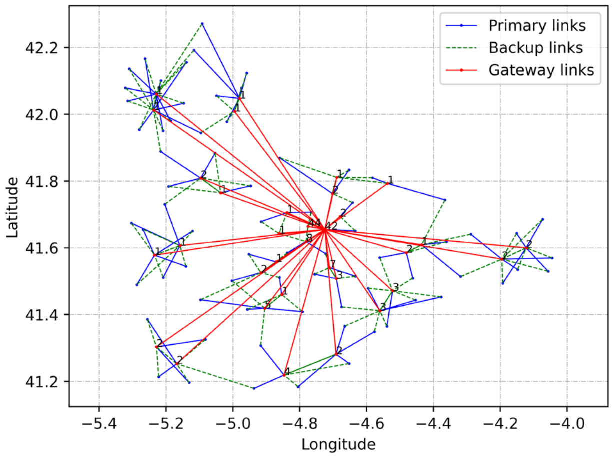

Fig. 3: MEC and network deployment for Valladolid province using the greenfield dedicated protection approach

Fig. 3 shows the results for Valladolid province using the greenfield approach. Red points on the map are MEC nodes, the numbers next to them represent the number of servers in each node. Each node has a fiber connection to the WAN gateway (red lines). Each BS without servers (blue points) has a primary fiber connection (blue lines) to a MEC node, and a backup link (green dashed line) to another MEC node. The obtained network has 33 MEC nodes, 153 servers and 2,639.63 km of fiber, where around 9.7% of the cost comes from servers and 90.3% from the fiber deployment.

IV. CONCLUSION

Achieving resiliency in MEC networks increases the deployment cost, but to different extents depending on the planning strategy. This paper concludes that the use of MEC technology allows huge reductions in both the cost and the propagation delay when compared with a centralized architecture. Two approaches have been proposed for MEC planning in sparsely populated areas: a greenfield and a brownfield approach. Both approaches determine which BSs should be equipped with how many MEC servers (thus becoming MEC nodes), which MEC nodes will serve each BS, and the required fiber network between BSs, MEC nodes and the WAN gateway. The study has also shown the advantages of the greenfield approach as it lowers the costs and propagation delays from BSs to MEC servers in both primary and backup paths. ILP models usually present scalability issues, for the studied case, the model works, but for bigger scenarios difficulties arise. To overcome this issue, heuristic and clustering methods are proposed as future works. Another future work is to consider and study changes of the network over time due to population variations.

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