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Optimizing road side units connectivity in intelligent transportation systems with optical network solutions ☆

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ABSTRACT

A fundamental component of Intelligent Transportation Systems (ITS) is connectivity. For connected vehicles to be aware of events occurring nearby, or even far from them, roadside infrastructure is essential. Roadside Units (RSUs) are electronic equipment placed along highways to provide connectivity and share data with vehicles, other RSUs, and networks. Connected vehicles require wireless communication with RSUs; however, depending on the complexity of tasks and the number of users, spectrum resources may be insufficient to handle all required communication between vehicles, RSUs and external networks. Since RSUs are stationary, optical fiber is an ideal technology for interconnecting them and linking them to the Internet and the cloud, providing reliable, high-performance connectivity, with low signal attenuation and high bandwidth. This paper proposes a model for deploying fiber networks to connect RSUs, with a focus on minimizing capital expenditures, including costs for civil works, cables, and devices, which are critical considerations given the large distances involved. Specifically, we consider and compare two established optical network technologies: point-to-point (PtP) and passive optical networks (PON). To support this comparison, we present and test two novel Integer Linear Programming (ILP) formulations: one for PtP and one for PON. Additionally, we introduce a genetic algorithm that improves upon a previously proposed heuristic, achieving near-optimal results comparable to the ILP formulation, while efficiently solving large-scale scenarios. The results show that the optimal choice between PtP and PON depends on the deployment area and density of RSUs.

Contents

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1. Introduction

Connected, cooperative, and automated mobility (CCAM) and Intelligent Transportation Systems (ITS) rely on high-performance communication infrastructures to support real-time services, enhance road safety, and accomodate growing data demands. These systems also help mitigate challenges such as accidents, congestion, and pollution [1]. Road Side Units (RSUs), which are fixed devices placed along roadways, are key components of ITS. They enable Vehicle-to-Infrastructure (V2I) communication with vehicles equipped with On-Board Units (OBUs), forming part of the broader Vehicle-to-Everything (V2X) environment. Their functionalities include traffic management, security, connectivity, and data collection. Typically, RSUs use Dedicated Short-Range Communication (DSRC) or Cellular V2X (C-V2X), and they connect to external networks via fiber-optic cables or wireless backhaul.

While V2X wireless technologies enable connectivity between vehicles and their environment, limited spectrum availability poses scalability challenges as service demands grow. According to a recent study [2], the current radio spectrum allocated for CCAM communications [3] suffices for low-complexity or low-demand services [4], which are prevalent today. However, future service demands may overwhelm wireless-only backhaul solutions. Thus, although V2I links support mobile users, RSUs themselves require high-speed, reliable communication with each other and with the core network.

Optical fiber, with its superior bandwidth, low latency, and high reliability, is a strong candidate for interconnecting RSUs and linking them to the network backhaul. Beyond capacity, fiber also offers sensing capabilities, such as seismic activity detection, intrusion detection, infrastructure health monitoring, and traffic measurement [5]. Thus, integrating wireless access with fiber backhaul, combines the flexibility of wireless with the performance of optical links. This hybrid model supports advanced use cases such as the Tactile Internet [6,7], enabling near-instantaneous communication, critical for vehicular safety and control in dynamic environments.

Many previous works have focused on urban scenarios, characterized by high infrastructure density and short distances. In contrast, rural or highway environments—where RSUs are more sparsely distributed—are frequently underexplored, and the cost implications of deploying optical fiber over long distances are often underestimated.

This paper addresses that gap by focusing on cost-efficient planning of optical access networks for RSUs, with capital expenditure (CAPEX) minimization as the main objective. Operational expenditures (OPEX), such as energy and maintenance, are also crucial—particularly in rural deployments. However, a thorough OPEX assessment requires a dedicated and more detailed analysis, which lies beyond the scope of this work. Therefore, we concentrate on CAPEX in this study.

We analyze two widely adopted architectures for the optical access segment: point-to-point (PtP) and passive optical networks (PON). For each, we introduce an Integer Linear Programming (ILP) formulation capable of computing optimal deployment solutions in small-scale scenarios. To address scalability in larger networks, we also propose a genetic algorithm as a complementary heuristic.

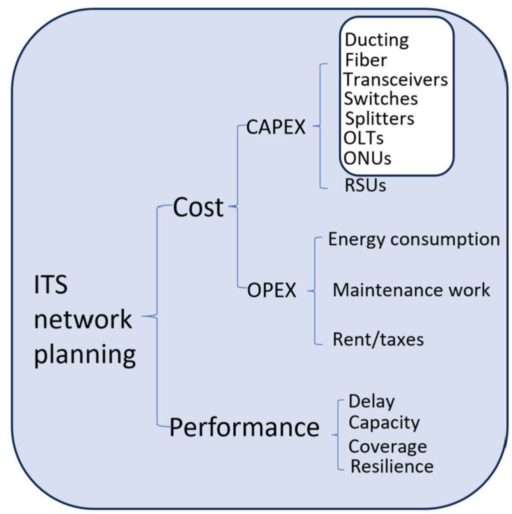


Fig. 1. ITS network planning optimization areas.

Compared to our previous work [8], which addressed the problem by relying on a basic heuristic and that was analyzed under limited testing conditions, the current approach introduces formal optimization, expands scenario coverage, and enables a more thorough performance comparison. Results show that the genetic algorithm consistently outperforms the earlier heuristic and achieves solutions close to ILP-optimal in small instances, while scaling to large deployments.

Fig. 1 presents a conceptual overview of the main objectives considered in ITS network planning. The planning process involves balancing cost and performance factors. Cost is divided into CAPEX, which includes expenses related to fiber, ducting, transceivers, splitters, PON-related devices (Optical Line Terminals –OLTs– and Optical Network Units –ONUs–), switches, and RSUs, and operational expenses (OPEX), which covers energy consumption, maintenance work, and rent or taxes. Performance metrics include delay, capacity, coverage, and resilience, all critical to ensuring an efficient and reliable ITS network deployment. The optimization objective of this work is highlighted in white in the figure. In our model, we assume that the RSUs are pre-deployed, so we focus solely on designing the access network behind them.

In the remaining of this paper, related works are analyzed in Section 2, highlighting both similarities and differences. Section 3 provides an overview of the two optical network architectures that we consider for deployment: PtP and PON. In Section 4, we model the environment, specifically the highway and road network as a graph, allowing us to process and simulate results using different techniques. Then, in Section 5, two ILP formulations aimed at minimizing the deployment costs of PtP and PON networks are presented. In Section 6, we present two alternative heuristics to address these optimization problems. The first heuristic is a recap of our previous work [8], and the second is a new genetic algorithm. The evaluation and comparison of the proposed solutions (ILP formulations and heuristic approaches) under different

Table 1
Related work and comparison with this proposal.

Proposal	Objective	Vehicular	Headers	Fiber planning	PON	PtP	Urban	Rural
Yao et al. [9]	Minimize delay	✓	×	×	×	×	✓	×
Massobrio et al. [11]	Optimize cost and QoS	✓	×	×	×	×	✓	×
Yu et al. [30]	Optimize delay and vehicles served	✓	×	×	×	×	✓	×
Lin et al. [12]	Minimize placement cost	✓	×	×	×	×	✓	×
Anzola et al. [2]	Minimize number of RSUs	✓	×	×	×	×	×	✓
Guo et al. [10]	Minimize delay	✓	×	×	✓	×	✓	✓
Vieira et al. [14]	Minimize latency	✓	×	×	×	✓	✓	✓
Rubin et al. [13]	Maximize throughput	✓	×	×	×	×	✓	×
Zukowski et al. [18]	Minimize the investment risk	×	×	✓	✓	×	×	✓
Hossen et al. [20]	Reduce energy consumption	✓	×	✓	×	✓	✓	×
Naeem et al. [17]	Minimize network cost	×	×	✓	✓	×	✓	✓
Peralta et al. [19]	Minimize fiber cost	✓	×	✓	✓	×	✓	✓
Ferreira et al. [15]	Experimentation platform	✓	×	✓	×	✓	✓	✓
SMLL [16]	Experimentation platform	✓	×	✓	×	✓	✓	×
Anzola et al. (BCF) [8]	Minimize network cost	✓	✓	✓	✓	✓	×	✓
This proposal	Minimize network cost	✓	✓	✓	✓	✓	✓	✓

scenarios are presented in Section 7. Conclusions and final remarks are offered in Section 8.

2. Related work

Many research works on communication infrastructures for ITS have explored the optimal deployment of RSUs, edge computing nodes, or 5G Micro Base Stations (gNB). Most of them assume that the backhaul network is already deployed, thus focusing on optimizing RSU placement considering objectives such as delay minimization [9,10], cost-efficiency [11,12], or coverage maximization. These strategies typically rely on heuristic or exact models for solving the RSU deployment problem under varying mobility or service demands. However, they do not address the design and cost implications of the supporting access and backhaul infrastructure, particularly those based on optical networks.

Some authors propose or assume fiber-based connectivity for RSUs. For instance, Rubin et al. [13] evaluate the impact of fiber links on system throughput in highway scenarios, and Vieira et al. [14] present a C-ITS architecture using either cellular or fiber connections between RSUs and the cloud. While these works demonstrate the technical benefits of optical backhaul, they omit a cost model or network topology design. Similarly, Guo et al. [10] investigate task offloading in Fiber-Wireless (FiWi) vehicular networks, but without explicitly optimizing or designing the optical layout.

Experimental platforms such as PASMO [15] and the Smart Mobility Living Lab [16] integrate fiber optics into real deployments over limited geographic areas. These testbeds offer V2X services, but due to their scale and scope, they do not require or propose formal network planning or optimization models.

Fiber network planning in residential or rural contexts has been addressed by some works. Naeem et al. [17] propose an Mixed Integer Linear Programming (MILP) model to reduce capital expenditure (CAPEX) in Fiber-to-the-Home (FTTH) networks. Zukowski et al. [18] focus on minimizing investment risk in rural FTTH strategies. Peralta et al. [19] develop a FiWi deployment using PON rings for Advanced Metering Infrastructure (AMI) and Vehicular Ad-hoc Networks (VANETs), considering a single optical line terminal (OLT). In a different approach, Hossen et al. [20] introduce a clustering hierarchy where RSUs act as gateways and connect via fiber, highlighting gains in energy efficiency and network lifetime of fiber-based vehicular networks. In this context, the benefits of fiber-based architectures such as high capacity, bidirectional communication, and long reach, have been widely acknowledged in the optical networking literature. Moreover, a recent survey by Arya et al. [21] highlights that passive optical networks (PON) and their next-generation variants (NG-PON) offer an attractive solution for integrated wired/wireless scenarios due to their flexibility, scalability, and energy efficiency. Optical fiber usage also allows to considerably improve energy consumption, better spectral usage, high data rate, and long reach transmission [22], which are crucial in rural deployments with long distances. Additionally, cybersecurity threats, such as denial-of-service attacks or remote hijacking, can severely impact both safety and reliability, highlighting the need for robust, multilayered protection mechanisms [23]. The use of optical fiber significantly reduces the feasibility of such attacks compared to wireless communication technologies.

In our previous work [8], we addressed the same backhaul planning problem using a cost function and a heuristic approach for selecting fiber routes and header locations. That study compared PON and PtP fiber layouts and considered deployment costs, but did not include a mathematical optimization model. The current proposal improves on that work by introducing an ILP formulation and a scalable genetic algorithm. Both urban and rural scenarios are supported, allowing a unified and scalable framework for CCAM infrastructure planning.

The reviewed papers related to network planning, together with the current proposal, are summarized in Table 1, which compares the most relevant literature across nine dimensions: objective, vehicular focus, header placement, fiber planning, PON/PtP use, and the geographical context (urban vs. rural). The first column in the table identifies the proposal's lead author, while the second outlines the main objective of the paper. The third column indicates whether the focus is on vehicular networks. Columns four and five address header placement and fiber planning, respectively. Analyses involving PON and PtP appear in columns six and seven, and the last two columns report the inclusion of urban and rural scenarios. To clarify, the 'Fiber planning' column indicates whether the work solves the fiber planning problem. Some papers consider a fiber optic network behind RSUs without explicitly designing it. In such cases, an '×' is placed in the 'Fiber planning' column, even if a '✓' appears under PtP or PON. As observed, none of the previous studies integrates all of these factors. Our work fills this gap by providing a holistic model that combines vehicular coverage needs with cost-effective, fiber-based network design strategies adapted to multiple topologies and regions.

Another line of research has explored hybrid optical access architectures that combine the advantages of PON and PtP links. For example, NG-PON2, as detailed in the tutorial overview [24], supports a hybrid architecture in which a TWDM-PON is complemented with optional PtP WDM overlays for flexible connectivity. This hybrid capability is formally specified in ITU-T Recommendation G.989.2 [25], and has been presented in surveys as an effective means to address limitations in reach, splitting, and bandwidth in next-generation PON deployments [26]. These hybrid approaches suggest promising directions for vehicular network planning, where combining the cost-effectiveness of PON with the flexibility of PtP links could enable more adaptive deployments. Although hybrid PtP–PON solutions provide an attractive compromise between cost efficiency and dedicated capacity [24–26], their analysis falls outside the scope of this work. Our objective is to present a clear comparison between the two fundamental architectures—PtP and PON—in terms of capital expenditures. Introducing hybrid overlays would significantly increase the parameter space and require additional assumptions regarding wavelength assignment, coexistence strategies, and equipment availability, which would blur the focus of our study. We therefore consider hybrid solutions as a promising direction for future work, once the baseline cost trade-offs between pure PtP and PON have been thoroughly established.

In addition to planning-oriented studies, recent research has also highlighted the role of software-defined networking (SDN) in vehicular environments. Zhang et al. [27] proposed an SDN-enabled load-balancing framework for vehicular edge computing over FiWi networks, emphasizing the importance of fiber backhaul in supporting delay-sensitive applications. Rodrigues et al. [28] investigated an SDN-controlled make-before-break handover scheme for C-V2X scenarios, demonstrating how centralized control can improve mobility management. Complementing these works, Nurkahfi et al. [29] provided a comprehensive survey on SDN for vehicular communications, covering both IEEE 802.11-based and C-V2X systems. While these contributions mainly address computation offloading, resource allocation and mobility support, they all implicitly rely on the presence of cost-efficient and well-dimensioned optical access infrastructures, which constitute the core focus of our study.

3. Optical network architectures

The objective of this paper is to determine the optimal approach for deploying optical access networks for connected vehicles. Specifically, the goal is to connect all RSUs to each other, to network headers, and to a WAN gateway, by means of optical fiber.

Network headers are facilities equipped with network devices that establish connections with nearby RSUs. Each network header is also linked to the WAN gateway via optical fiber, enabling communication with external networks. In this study, we assume that network headers can be installed at Potential Header Locations (PHLs), while the WAN gateway is positioned at a pre-determined strategic or central point in the deployment area, such as a city center or another convenient location, effectively serving as another PHL. However, it also includes a high-capacity router to manage communication with external networks.

Fig. 2 illustrates the network scheme considered in this paper. Initially, there is a set of RSUs, a set of PHLs, and a central point. The objective is to determine the most efficient and cost-effective way to deploy an optical network that connects each RSU to a header and each header to the WAN gateway, accounting for both connections and necessary devices. As shown in the figure, some PHLs are selected as headers, while others are not. Determining which PHLs to designate as headers is a critical part of the solution and will be explored in later sections.

For the optical network, we consider and analyze two architectural alternatives: Point to Point (PtP) and Passive Optical Network (PON). Both are existing approaches currently used in optical networking. In [8], we performed a preliminary comparative analysis of these architectures in the context of connected vehicle networks. Below, a brief description of PtP and PON is presented.

3.1. Point to point (PtP)

In this architecture, each connection between network headers and RSUs uses a dedicated fiber along the entire path. At both ends of the connection a Small Form-factor Pluggable (SFP) transceiver is required. At the headers, switches are deployed with enough ports to accommodate each connected RSU. The maximum distance between switches and RSUs is 40 km [31]. Fig. 3 shows a simplified illustration of the Point to Point architecture.

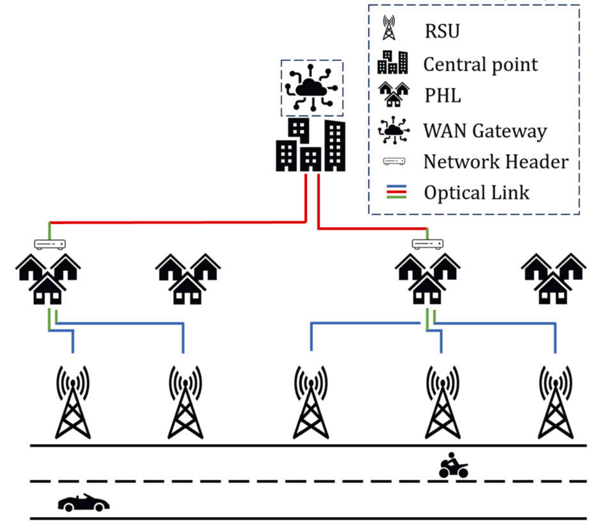


Fig. 2. Generic network scheme.

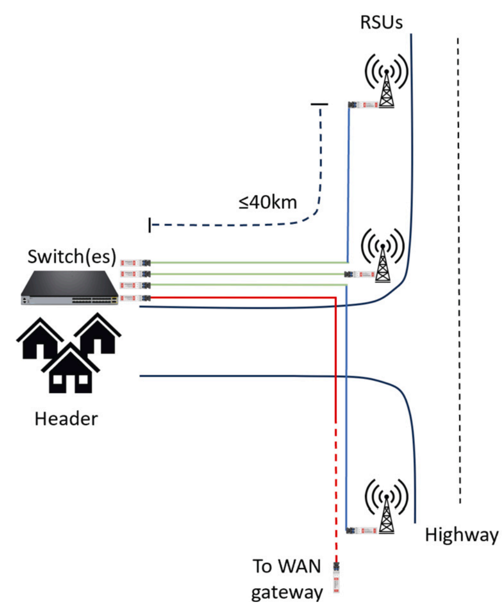


Fig. 3. Point to Point architecture.

3.2. Passive optical network (PON)

The second architectural alternative is the Passive Optical Network (PON). In this approach, both the equipment and the connections settings differ from PtP. PON employs Optical Line Terminals (OLTs) at the network headers, where individual OLT ports can be activated by enabling a transceiver and connected to an optical splitter. The splitter then distributes the signal to multiple RSUs. These splitters are positioned along the highway at the point nearest to the corresponding header following the path of the graph. At the RSUs, Optical Network Units (ONUs) are used (Fig. 4).

3.3. Trade-offs between PtP and PON architectures

Common to both architectures, within the headers, if multiple devices (OLTs for PON or switches for PtP) are needed, an aggregation switch must be included. Fig. 5 illustrates the general structure of a header, where an aggregation switch forwards traffic from the access devices (OLTs or switches). If a single device is sufficient for all RSUs connected to the header, the aggregation switch is unnecessary. In all cases,

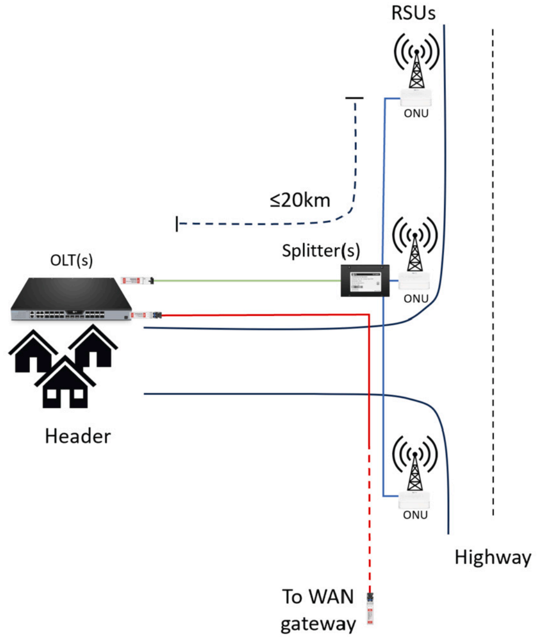


Fig. 4. Passive Optical Network architecture.

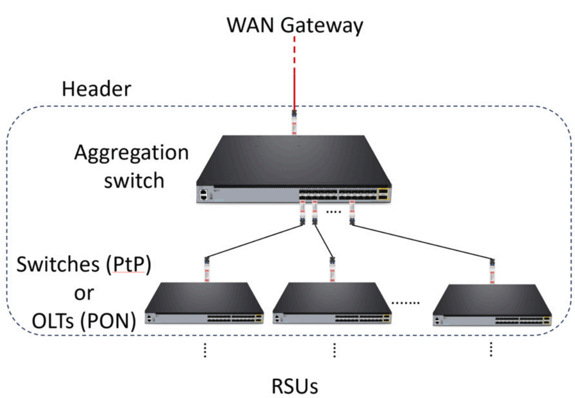


Fig. 5. Header structure.

a Point-to-Point connection must be established between the header and the WAN gateway, requiring a transceiver at each end.

The main difference of PON with PtP, is that a single optical fiber between the OLT and the splitter can serve multiple RSUs (up to the number of splitter ports). This shared fiber structure can reduce costs and simplify implementation. However, it also introduces two potential disadvantages. First, PON has a stricter distance limitation, as the maximum distance between the headers and RSUs is 20 km [32,31], compared to 40 km in the PtP architecture. Second, because the fiber is shared, the available bandwidth must also be distributed among RSUs, reducing the maximum traffic each RSU can handle. However, thanks to the dynamic nature of TDMA-based multiplexing in PON networks, in practice RSUs can obtain greater instantaneous bandwidth during traffic peaks, provided that other nodes are not fully utilising their allocated resources. This statistical allocation allows PON to adapt flexibly to bursty or peak traffic patterns, mitigating the limitations of average bandwidth distribution.

This illustrates the inherent trade-off between PtP and PON: PtP guarantees dedicated capacity at a higher cost, while PON leverages statistical multiplexing, which may potentially reduce deployment costs in exchange for sharing bandwidth. In addition, PON offers advantages in terms of scalability and energy efficiency, as a single feeder fiber and an OLT can serve multiple users, reducing both infrastructure complexity and operating expenses. While PtP provides guaranteed performance,

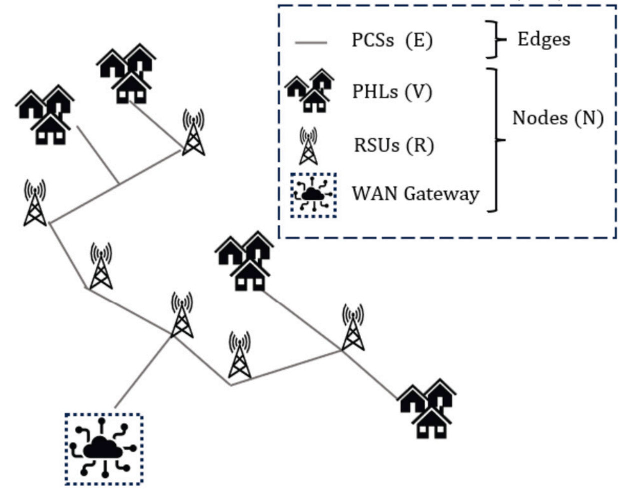


Fig. 6. Example model of the highway and road network with associated nodes and potential connection segments.

PON's dynamic bandwidth allocation mechanisms allow resources to be allocated flexibly based on real-time demand, which is particularly beneficial in scenarios with heterogeneous or bursty traffic patterns.

4. Modeling of the highway and road network as a graph

To model the environment, we represent the highway and road network as a graph $\mathcal{G}$, in which the set of RSUs is $\mathcal{R}$, the set of PHLs is $\mathcal{V}$, and the WAN gateway is W (with $W \in \mathcal{V}$). Together, RSUs and PHLs form the set of nodes $\mathcal{N}$. The potential connection segments (PCSs), which represent the possible optical fiber links between nodes, constitute the set of edges $\mathcal{E}$. We assume that ducts carrying optical cables, when required, follow the road infrastructure, so that all PCSs are aligned with highways or roads. The locations of all nodes ($\mathcal{N}$) and edges ($\mathcal{E}$) are assumed to be known beforehand. The objective is to determine which PHLs will be equipped as network headers and which edges will be selected as optical fiber connections.

The graph $\mathcal{G}$ is defined according to Equation (1),

$$\mathcal{G} = (\mathcal{N}, \mathcal{E}), \tag{1}$$

where

$$\mathcal{N} = \mathcal{R} \cup \mathcal{V}. \tag{2}$$

A graphical representation is shown in Fig. 6, where PHLs are interconnected with each other by edges (PCSs following highways or roads), with RSUs placed along these highways. We assume that each PHL j is connected exclusively to a single nearby highway via one edge, A_j. These edges form the set of access edges, $\mathcal{A} = \bigcup_j A_j$ with $\mathcal{A} \subset \mathcal{E}$.

To study the scenarios and evaluate different approaches, it is essential to determine the effective distance between pairs of points in the graph. For example, if an optical connection needs to be established between an RSU and a header, the required length of the corresponding cable and ducting must be known. The minimum distance d_{ij} between two nodes (RSUs or PHLs) i and j is defined as follows:

$$d_{ij} = \min_{p \in P_{ij}} \sum_{e \in p} l_e, \tag{3}$$

where P_{ij} is the set of all paths connecting i and j and l_e represents the length of edge e. As shown in Equation (3), the distance d_{ij} is the minimum sum of the lengths of the edges along any path between i and j. To compute these distances, the Dijkstra's algorithm is used for finding the shortest paths [33]. The shortest distance path between nodes i and j is denoted by p^*_{ij}.

Table 2
Notation of the ILP models (parameters and auxiliary –cost-related– variables).

Symbol	Meaning
R	Number of RSUs.
V	Number of PHLs.
E	Number of edges.
K	Number of cable types.
$\mathcal{A}$	Set of access edges (from a header to a highway/road).
l_e	Length of edge e.
p^*_{ij}	Shortest distance path between RSU i and PHL j.
d_{ij}	Distance between RSU i and PHL j (along path p^*_{ij}).
c_d	Cost of one kilometer of ducting.
C_d	Total cost of ducting.
f_k	Number of fibers within a k-type cable.
c_k	Cost of one kilometer of k-type cable.
C_c	Total cost of cable.
c_{tptp}	Cost of one PtP transceiver.
C_{tptp}	Total cost of PtP transceivers.
c_{tpon}	Cost of one PON transceiver.
C_{tpon}	Total cost of PON transceivers.
p_{sw}	Number of ports of one switch.
c_{sw}	Cost of one switch.
C_{sw}	Total cost of switches (PtP).
c_{ONU}	Cost of one ONU.
C_{ONU}	Total cost of ONUs (PON).
p_{sp}	Number of ports of one splitter.
c_{sp}	Cost of one splitter.
C_{sp}	Total cost of splitters (PON).
p_{OLT}	Number of ports of one OLT.
c_{OLT}	Cost of one OLT.
C_{OLT}	Total cost of OLTs (PON).
D_{max}	Maximum distance between headers and their RSUs (40 km for PtP and 20 km for PON).

Table 3
Notation of the ILP models (main variables).

Symbol	Meaning
x_{ij}	Binary variable $=1$ if RSU i is connected to a header in PHL j.
y_j	Integer variable. It represents the number of devices (non-aggregation switches for PtP and OLTs for PON) present in PHL j.
w	Integer variable. It represents the number of aggregation switches in the WAN gateway in the PON architecture.
Y_j	Binary variable $=1$ if PHL j is a header.
AS_j	Binary variable $=1$ if PHL j needs an aggregation switch.
q_{ke}	Integer variable. It represents the number of k-type cables to be placed in edge e.
F_e	Integer variable. It represents the minimum number of fibers needed in edge e.
s_j	Integer variable. It represents the number of splitters to be connected to PHL j.
b_e	Binary variable $=1$ if ducting is performed along edge e.
z_{eij}	Binary variable $=1$ if edge e is in the path from RSU i to PHL j and they are connected ($x_{ij}=1$).
v_{ej}	Binary variable $=1$ if PHL j is a header and edge e is in its path to the WAN gateway.

5. ILP formulations for network planning

The optimal solution for network planning, which minimizes the total deployment cost, can be found by solving an ILP formulation. In fact, two formulations are proposed in this paper: one for PtP, and another for PON.

Tables 2 and 3 summarize the symbols used in the formulations and their meanings, which are explained below.

There is a known set of R RSUs and V PHLs, all located at pre-defined locations. Additionally, the highway and road network is provided as input. Using these data, a graph $\mathcal{G}$ is generated, as described in Section 4, in such a way that the locations of RSUs and PHLs are nodes, and PCSs are the edges. Thus, a set of E edges with different lengths l_e is determined, and a matrix with the distances, d_{ij}, between each RSU and each PHL is computed and used as an input for the formulation. The distances are not straight euclidean distances, instead, they follow the shortest distance path along the highway network graph.

Both architectures, PtP or PON, need ducting, cabling, and transceivers; however, the quantity of these components may vary depending on the network architecture. Additionally, each architecture requires different devices: switches, or OLTs, splitters and ONUs. Each component has a unit cost, denoted by a lowercase c in the model, while total costs in the network are represented by a capital C. For instance, c_{ONU} represents the cost of a single ONU, but C_{ONU} is the total cost of all ONUs in the network. Switches, OLTs and splitters have a certain number of ports (output ports in the case of splitters), which are denoted as p_{sw}, p_{OLT} and p_{sp}, respectively.

Let $\mathcal{K}$ represent the set of K available cable types, where each cable type k is characterized by the number of fibers it carries, f_k, and its associated cost per kilometer, c_k. The formulation determines, as part of the solution, the optimal (i.e., less expensive) combination of cables based on the required number of fibers for each edge. Formally, the set $\mathcal{K}$ is defined as

$$\mathcal{K} = \{(f_k, c_k) \mid k \in [1, K]\}. \tag{4}$$

The maximum allowed distance between RSUs and their header is given by D_{max} (40 km for PtP and 20 km for PON).

The variables to be determined by solving the model are listed in Table 3. The binary variable x_{ij} determines the connection between RSU i and PHL j. It takes the value 1 if RSU i is connected to a header in PHL j, and 0 otherwise. The number of devices (switches for PtP, and OLTs for PON) required in PHL j is defined by y_j. If PHL j is a network header, the binary variable Y_j will be 1. The binary variable AS_j indicates whether PHL j requires an aggregation switch. It is assumed that the available physical space in each PHLs is limited. Specifically, we assume that the number of devices that can be placed in a PHL is not higher than the number of ports on the aggregation switch. Therefore, at most one aggregation switch is required for each PHL.

Since ducts can accommodate multiple cables, each edge (PCS) will contain a certain number of cables (and thus fibers) along its length. To account for this, we introduce the variable F_e, which represents the total number of fibers to be placed along edge e, the variable b_e, which indicates whether ducting is performed along edge e, and the variable q_{ke}, which indicates the number of k-type cables to be placed along edge e. Additionally, two auxiliary binary variables, z_{eij} and v_{ej} are introduced into the model. If edge e is in the path between RSU i and PHL j, and they are connected, then $z_{eij}=1$. Similarly, if PHL j is a header, and edge e is in its path to the WAN gateway, then $v_{ej}=1$. These two auxiliary variables are introduced to determine the total number of fibers F_e in each edge, as shown later in equations (20) and (32).

5.1. Point-to-point

The first part of the formulation is the objective function, which represents the deployment cost (CAPEX). Our goal is to minimize this cost, which is given by the sum of the total costs of the network components. For the PtP case, the objective function is given by Equation (5):

$$\text{Minimize} \quad C_{tptp} + C_{sw} + C_c + C_d, \tag{5}$$

where the total cost associated with each component is given by equations (6) to (9). As described in Equation (6), PtP connections require two transceivers for each link: one at each end. This applies to both links between RSUs and headers, as well as connections between non-aggregation switches and the aggregation switch at each header (or directly to the WAN gateway), and also between the aggregation switches at headers and the WAN gateway. The PHL with index $j=1$ corresponds to the WAN gateway; therefore, the summation in the last term in Equation (6) starts from $j=2$.

$$C_{tptp} = 2c_{tptp}(R + \sum_{j=1}^{V} y_j + \sum_{j=2}^{V} AS_j) \tag{6}$$

$$C_{\text{sw}} = c_{\text{sw}}(\sum_{j=1}^{V} y_j + \sum_{j=2}^{V} AS_j) \tag{7}$$

$$C_{\text{c}} = \sum_{e=1}^{E} \sum_{k=1}^{K} q_{ke} c_k l_e \tag{8}$$

$$C_{\text{d}} = c_{\text{d}} \sum_{e=1}^{E} b_e l_e \tag{9}$$

The problem is subject to constraints (10) to (19), which apply to both architectural models (PtP and PON).

- Each RSU is connected to exactly one header.

$$\sum_{j=1}^{V} x_{ij} = 1 \quad \forall i \in [1, R] \tag{10}$$

- Every header has devices (non-aggregation switches in PtP or OLTs in PONs).

$$y_j \geq Y_j \quad \forall j \in [1, V] \tag{11}$$

- Every PHL with devices is a header.

$$Y_j \geq \frac{y_j}{V+R} \quad \forall j \in [1, V] \tag{12}$$

- The number of devices per header is limited by the number of ports on the aggregation switch. However, this limitation does not apply to the WAN gateway location. Therefore, j is in $[2, V]$.

$$y_j \leq p_{\text{sw}} \quad \forall j \in [2, V] \tag{13}$$

- The distance between headers and their associated RSUs is bounded.

$$x_{ij} d_{ij} \leq D_{\max} \quad \forall i \in [1, R], j \in [1, V] \tag{14}$$

- If edge e is in the path from RSU i to header j, z_{eij} is 1.

$$z_{eij} = \begin{cases} x_{ij} & \text{if } e \in p^*_{ij} \\ 0 & \text{if } e \notin p^*_{ij} \end{cases} \quad \forall e, i, j \tag{15}$$

- If edge e is in the path from header j to the WAN gateway (W), v_{ej} is 1.

$$v_{ej} = \begin{cases} Y_j & \text{if } e \in p^*_{j,W} \\ 0 & \text{if } e \notin p^*_{j,W} \end{cases} \quad \forall e, j \tag{16}$$

- The total number of fibers in edge e is at least the number of fibers needed.

$$\sum_{k=1}^{K} f_k q_{ke} \geq F_e \quad \forall e \in [1, E] \tag{17}$$

- If a header needs more than one device, an aggregation switch is needed.

$$AS_j \geq \frac{y_j - Y_j}{R} \quad \forall j \in [2, V] \tag{18}$$

- If an edge requires the installation of fibers, ducting is performed along the edge.

$$b_e \geq \frac{F_e}{V+R} \quad \forall e \in [1, E] \tag{19}$$

The following constraints, (20) to (22), are exclusive of the PtP formulation.

- The needed number of fibers of edge e is equal to the sum of all connections along the edge.

$$F_e = \sum_{j=1}^{V} (v_{ej} + \sum_{i=1}^{R} z_{eij}) \qquad \forall e \in [1, E] \tag{20}$$

- Every header has the necessary devices (switches) for its RSUs.

$$p_{\text{sw}} y_j \geq \sum_{i=1}^{R} x_{ij} \quad \forall j \in [1, V] \tag{21}$$

- The WAN gateway has enough switches for its RSUs and for all headers.

$$p_{\text{sw}} y_1 \geq \sum_{i=1}^{R} x_{i1} + \sum_{j=2}^{V} Y_j \tag{22}$$

5.2. Passive optical network (PON)

Similar to the PtP case, the PON cost is determined by the sum of all component costs. As described in Section 3.3.2, the elements contributing to the cost of the PON network are ONUs, OLTs, splitters, aggregation switches, transceivers, cables and ducting. Therefore, the objective function is given by Equation (23):

$$\text{Minimize} \quad C_{\text{ONU}} + C_{\text{OLT}} + C_{\text{sp}} + C_{\text{sw}} + C_{\text{tpon}} + C_{\text{tptp}} + C_{\text{c}} + C_{\text{d}}, \tag{23}$$

where the equations for the costs of cable (C_{c}) and ducting (C_{d}) are the same as in the PtP formulation (Equation (8) for cable and (9) for ducting). The costs of ONUs, OLTs and splitters are given by equations (24) to (26), respectively, where s_j is the number of splitters that will be connected to PHL j.

$$C_{\text{ONU}} = c_{\text{ONU}} R \tag{24}$$

$$C_{\text{OLT}} = c_{\text{OLT}} \sum_{j=1}^{V} y_j \tag{25}$$

$$C_{\text{sp}} = c_{\text{sp}} \sum_{j=1}^{V} s_j \tag{26}$$

As shown in Fig. 5, an aggregation switch may be required at each header to combine the traffic from several OLTs towards the WAN gateway. Additionally, the WAN gateway may include more than one aggregation switch to handle traffic from its own OLTs as well as from other headers. In this case, we assume there are no space limitations at the gateway location, allowing for multiple aggregation switches instead of just one. Thus,

$$C_{\text{sw}} = c_{\text{sw}}(\sum_{j=2}^{V} AS_j + w) \tag{27}$$

where w is an integer variable which represents the number of aggregation switches in the WAN gateway location, so that

$$w \geq \frac{\sum_{j=2}^{V} Y_j + y_1}{p_{\text{sw}}} \tag{28}$$

Unlike PtP, PON does not require transceivers at RSUs, as the ONUs located there already include a built-in transceiver. However, OLTs require a transceiver to communicate with all the ONUs connected to each splitter, resulting in the cost described by Equation (29).

$$C_{\text{tpon}} = c_{\text{tpon}} \sum_{j=1}^{V} s_j \tag{29}$$

Additionally, the PON scenario requires connections between non-aggregation switches and the aggregation switch at each header (or directly to the high-capacity router at the WAN gateway), as well as between the aggregation switches at headers and the high-capacity router at the WAN gateway. Each of these connections require two transceivers.

$$C_{\text{tptp}} = 2c_{\text{tptp}}(\sum_{j=1}^{V} y_j + \sum_{j=2}^{V} AS_j + w) \tag{30}$$

Table 4
Decision variables in each model and their asymptotic counts.

Variable	Count	Model
x_{ij}	$R \cdot V$	Both
y_j	V	Both
w	1	PON
Y_j	V	Both
AS_j	V	PtP
q_{ke}	$K \cdot E$	Both
F_e	E	Both
s_j	V	PON
b_e	E	Both
z_{eij}	$E \cdot R \cdot V$	Both
v_{ej}	$E \cdot V$	Both

Table 5
Constraints in each model and their asymptotic counts.

Constraint	Count	Model
(10)	R	Both
(11)	V	Both
(12)	V	Both
(13)	$V-1$	Both
(14)	$R \cdot V$	Both
(15)	$E \cdot R \cdot V$	Both
(16)	$E \cdot V$	Both
(17)	E	Both
(18)	$V-1$	Both
(19)	E	Both
(20)	E	PtP
(21)	V	PtP
(22)	1	PtP
(28)	1	PON
(31)	V	PON
(32)	$R \cdot V$	PON
(33)	V	PON

As mentioned, constraints (10) to (19) apply to both PtP and PON architectures. The following constraints, (31) to (33), are exclusive of the PON formulation.

- In each header, at least one OLT port is required for each splitter.

$$p_{\mathrm{OLT}} y_j \geq s_j \quad \forall j \in [1, V] \tag{31}$$

- In the PON architecture, splitters are positioned along the highway at the nearest point to their corresponding header, following the graph's path. The link between each header and its splitters requires one fiber per splitter. Additionally, a fiber is required to connect the header to the WAN gateway (as it will also go through the same edge). Therefore, the number of fibers for each segment is given by Equation (32). If a segment is an access edge, A_j (it connects the PHL j to a highway), the required number of fibers is at least the number of splitters of the header. If the segment is not an access edge, the number of fibers is computed as in the PtP architecture.

$$F_e \geq \begin{cases} s_j + v_{ej} & \text{if } e = A_j \\ \sum_{j=1}^{V} (v_{ej} + \sum_{i=1}^{R} z_{eij}) & \text{if } e \neq A_j \end{cases} \quad \forall e, j \tag{32}$$

- There are as many splitters as required for each header.

$$s_j \geq \frac{\sum_{i=1}^{R} x_{ij}}{p_{\mathrm{sp}}} \quad \forall j \in [1, V] \tag{33}$$

5.3. Complexity analysis

Most variables and constraints are common to both the PtP and PON formulations, including those that dominate the size of the model, such as z_{eij} and the constraint (15). The PON formulation introduces a few additional decision variables (s_j and w) and their associated constraints (28), (31), (32), and (33), but these do not alter the asymptotic growth order.

5.3.1. Variable counts

Table 4 lists all decision variables for both formulations with their asymptotic counts. Summing over all decision variables, the total asymptotic variable count is the same for both PtP and PON formulations:

$$\begin{aligned} |\mathcal{X}| &= \Theta(ERV + EV + RV + KE + E + V + 1) \\ &= \Theta(ERV + EV + RV + KE), \end{aligned} \tag{34}$$

where the linear terms E and V as well as the constant, are omitted in the second expression because they are asymptotically dominated by the remaining terms.

5.3.2. Constraint counts

Table 5 lists all constraints with their asymptotic counts. The set of constraints common to both models is augmented by a small number of formulation-specific constraints in PtP and PON. In the formulation, K does not multiply the number of constraints because cable-type decisions appear only in (17) as a sum over k, yielding one constraint per e rather than per (k, e).

Summing over all constraints, the total asymptotic constraint count is the same for both PtP and PON formulations:

$$\begin{aligned} |\mathcal{C}| &= \Theta(ERV + EV + RV + E + R + V) \\ &= \Theta(ERV + EV + RV), \end{aligned} \tag{35}$$

where the linear terms E, R, and V are omitted from the second equality because they are asymptotically dominated by the others. This holds under the assumption that E, R, and V all grow asymptotically.

5.3.3. Asymptotic complexity

From (34) and (35), the overall model size (including variables and constraints) is:

$$\Theta\left(ERV + EV + RV + KE\right). \tag{36}$$

In practical scenarios, the dominant term is ERV. Thus the formulation complexity is driven primarily by the connectivity variables z_{eij} and their associated path-based constraints. Although the PON formulation introduces a small number of additional variables and constraints (e.g., s_j, w), their growth is at most linear in V or constant. Consequently, these terms are asymptotically dominated by the others. Thus, both formulations have the same asymptotic growth order.

6. Alternative heuristics

The ILP formulations we have just presented describe the problem mathematically and, when solved, provide its optimal solution. However, since the problem is NP-hard, solving the ILP for large-scale scenarios can result in significant increases in solving time, making it computationally unfeasible. Therefore, alternative methods are necessary. In this paper, we compare the simulation results of the ILP models described in Section 5 with two other approaches: Best Coverage First (BCF) and a new genetic algorithm. A brief description of these approaches is provided below.

6.1. Best coverage first (BCF)

This heuristic was originally introduced in our previous work [8]. A summary of the steps performed in this approach is presented below:

- Identify the PHL with the most RSUs at its reach (closer than $D_{\max}$) and designate it as a network header. Then, assume that these reachable RSUs are covered.

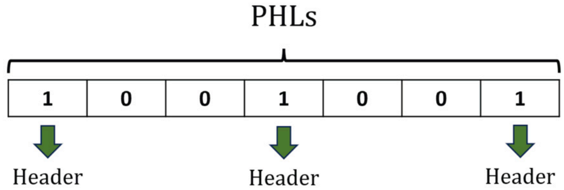


Fig. 7. An individual of the genetic algorithm.

- Exclude the already covered RSUs and the selected PHL (which became a header), and select the next available PHL with the most uncovered RSUs within its reach. Repeat this step until all RSUs are covered.
- Once the list of selected PHLs to be headers is complete (i.e., all RSUs are covered), rearrange the allocation of RSUs so that each RSU is assigned (and connected) to its nearest header.
- After obtaining the list of headers and their RSU allocations, compute the necessary devices and infrastructure for deploying the optical access network. Finally, calculate the total cost.

A complete description and analysis of the BCF approach can be found in [8].

6.2. Genetic algorithm

In this section, we propose a novel genetic algorithm to solve the network planning problem. Genetic algorithms [34] represent potential solutions to a problem by means of individuals or chromosomes, which are evolved by means of genetic operators like crossover or mutation with the aim of maximizing a fitness function (or minimizing a cost function.

In our approach each individual is represented as a binary vector. The length of the vector corresponds to the number of PHLs, including the WAN gateway, which may or may not function as a header. Each position in the vector indicates whether a PHL is selected as a header. Specifically, '1' means that the PHL is selected as a header, while '0' means it is not. As an example, Fig. 7 represents an individual of a scenario with 7 PHLs, where 3 of them are selected as network headers.

Each individual translates into a network planning solution, with an associated cost determined by the cabling, ducting and number of devices required. Starting from an individual or binary vector (such as the one depicted in Fig. 7), the procedure for determining the associated network planning (and thus its cost) is as follows:

- Identification of headers and assignment of RSUs: The binary vector directly indicates which PHLs serve as headers, making their identification straightforward. Each RSU is then assigned to its nearest header.
- Determination of fibers and cable types: The number of fibers to be deployed in each edge (F_e) can be easily determined by following the descriptions provided in sections 3 to 5 once the location of headers is known. Fiber connections between RSUs and their respective headers must be established according to the chosen architecture (PtP or PON), as well as connections between headers and the WAN gateway, all following the shortest path in the graph. Then, the number and type of cables to deploy along an edge depend only on the required number of fibers on that edge (not on the edge itself) and the characteristics of the available cable types (cost per kilometer, c_k, and number of fibers per cable, f_k). Therefore, to determine the most cost-efficient selection of cable types to lay F fibers in any given edge, the following ILP formulation is solved:

$$\text{Minimize} \quad \sum_{k=1}^{K} c_k q_k$$

$$\text{subject to} \quad \sum_{k=1}^{K} f_k q_k \geq F,$$

$$q_k \geq 0, \quad \forall k \in [1, K],$$

where q_k is the number of cables of type k to deploy. This problem can be solved using either an ILP solver or a dynamic programming approach. Since the set of cable types is limited (K), the formulation only has K variables and $K+1$ constraints, so it can be solved very quickly. The solution is precomputed for different values of F before executing the genetic algorithm, generating a table that specifies, for each value of F, the optimal number of cables of type k (for all $k \in [1, K]$) to be deployed and the associated total cost per kilometer. The genetic algorithm will then consult this table to determine the specific setup and cost for each edge e, based on the required number of fibers on that edge (F_e) and the length of the edge (l_e).
- Ducting: If an edge has at least one cable, ducting is needed along it.
- Devices: The minimum number of devices required for each header is determined based on the network architecture (PtP or PON), the number of device ports, and the number of connected RSUs.

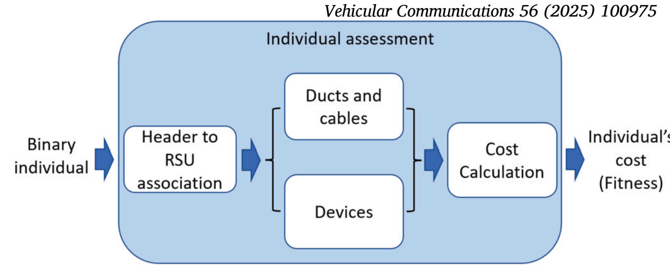


Fig. 8. Cost (fitness) calculation of an individual.

A block diagram summarizing the calculation of the cost of an individual is shown in Fig. 8. The steps described above are executed according to the sequence shown: starting with the binary vector, headers and RSUs are linked, the required components (ducting, cable and devices) are determined, and the total cost is computed. The lower the cost of an individual, the fitter it is. If the number of required devices exceeds the available ports on the aggregation switch, the individual is discarded by assigning it a large cost value. This consideration aligns with Constraint (13).

A scheme of the complete genetic algorithm procedure is illustrated in Fig. 9. In the first generation ($g = 1$), the population consists of N individuals, including one generated using the BCF heuristic, and the rest initialized pseudo-randomly, in such a way that villages with a higher number of RSUs within their reach have a greater probability of being selected as headers. Each individual is evaluated as described in Fig. 8. Subsequently, selection, crossover and mutation operations are applied to form a new generation, and the process is repeated until the total number of generations is reached ($g = G$).

The operators used in our implementation are briefly described below:

- Select: Tournament selection is applied, where a subset of $size_{\text{tour}}$ individuals is randomly chosen for each tournament. Several tournaments are conducted, and for each one, the fittest individual is selected to be included in the new generation.
- Crossover (or mating): The crossover operator combines genetic material (chromosomes) from two parent individuals to create a new individual for the next offspring. We used two-point crossover, where two crossover points are selected randomly along the parent chromosomes. The genetic material between these two points is swapped between the parents, creating two children. Out of every

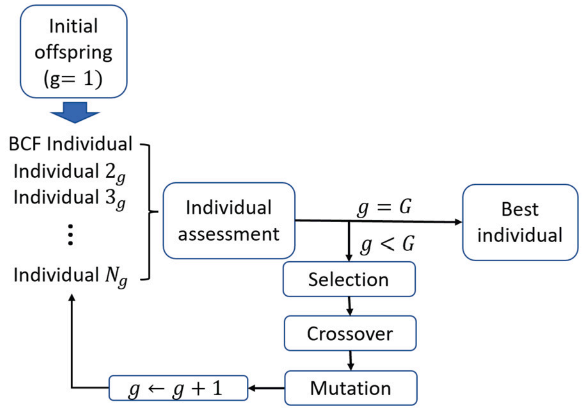


Fig. 9. Genetic algorithm general scheme.

possible parent couple, the algorithm mates them with probability p_{cross}.
- Mutate: Specific bits of an individual are mutated (i.e., changed from 1 to 0 or viceversa) with a predefined probability p_{mut}.

This new generation is then evaluated, and the process is iteratively repeated for the required number of generations, after which the best individual is saved. Additionally, we ensure that the best individual found so far is included in every new generation. This guarantees that the best solution remains part of the offspring until a superior individual is identified.

7. Performance evaluation

To simulate and evaluate the proposals, we have used multiple libraries and tools.

For the definition and analysis of graphs, we have used the Python NetworkX library [35], which allows us to create a graph based on a set of points (RSU and PHL locations), and connections between them (edges along highways). Among other functionalities, NetworkX enables to easily obtain the minimum distance path between each pair of nodes, and the distance between them, following the trajectory defined by the highways in the graph using Djikstra algorithm (as described in Section 4). This library is useful for retrieving the distances that we use as input data in the techniques described in Sections 5 and 6.

For solving the ILP models, we have used Pyomo [36], a Python-based, open-source optimization library that allows users to define and solve complex mathematical models. Pyomo integrates with solvers like CPLEX, Gurobi, and GLPK, making it a versatile tool for both academic research and industrial applications. In our study, we have used IBM CPLEX optimizer [37].

For the implementation of the genetic algorithm, we have used DEAP (Distributed Evolutionary Algorithms in Python) [38], a flexible framework for implementing evolutionary algorithms and other metaheuristics. It provides tools for creating, evaluating, and evolving populations of individuals using genetic programming, genetic algorithms, and more. The parameters of the genetic algorithm (GA), listed in Table 6, were empirically tuned through multiple preliminary experiments aimed at balancing solution quality and computational time. This empirical tuning process ensured the selected configuration yielded consistent and satisfactory results across different scenarios.

A diagram summarizing the simulation and evaluation process is shown in Fig. 10. The input consists of a dataset containing the coordinates (latitude and longitude) of RSUs and PHLs. Using these coordinates, a graph is constructed with NetworkX, where edges are defined between contiguous RSUs based on the highway configuration. Once the graph is built, the selected solving model (ILP, Genetic Algorithm or BCF) is executed. This process determines the placement of headers and connections, while also computing the associated cost.

Table 6
Genetic algorithm parameters.

Symbol	Meaning	Value
N	Generation size	100
G	Number of generations	1000
p_{mut}	Mutation probability	0.4
p_{cross}	Crossover probability	0.2

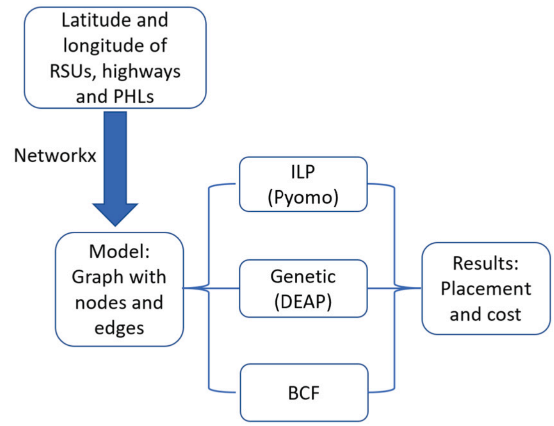


Fig. 10. General simulation process.

For each component of the deployment, we consider features from specific sources. The ducting cost (c_{d}), is set at 14000 € per kilometer, based on [39]. Device prices, including OLTs, switches, transceivers, and splitters, were obtained from [40]. Since the complexity of the models (particularly ILP) increases with the number of cable types considered, all experiments in this study use cables with 12 and 24 fibers, as specified in Table 7. Cable prices were taken from [41]. Table 7 summarizes the components used in these experiments, specifying the source of the data, specific models, and the symbols used in the formulations. For switches, OLTs and ONUs, the number of ports ($p_{\text{sw}}, p_{\text{OLT}}, p_{\text{sp}}$) is also specified, with values 24, 8 and 32, respectively.

7.1. Generated scenarios

To study different environments under customizable conditions, we have generated multiple artificial scenarios consisting of PHLs and RSUs connected by highways. This approach allows us to adjust key features such as the coverage area, the distance between RSUs, and the highway network topology. Fig. 11 illustrates the process of generating custom scenarios based on input parameters.

Generated scenarios can be customized using five input parameters. Below, we enumerate and explain these parameters, following an ordered sequence that also describes the step-by-step process of scenario generation.

1. Area: The total area of the scenario, measured in km^2.
2. Number of PHLs: PHLs are randomly positioned within the defined area. The WAN gateway is randomly placed in one of these PHLs.
3. Number of corners: A corner is defined as any change in direction along a highway, regardless of the angle. Highway endpoints are also considered corners. Corners are randomly positioned, and each hosts an RSU. If two corners are specified, only one straight highway will be generated. With three corners (assuming no loops), the highway will have two segments. The first four corners, are always placed at the vertices of a square whose area matches that of the defined scenario. If four or fewer corners are defined, they are positioned at these square vertices. Once the corners are set, a spanning tree is generated using Kruskal's algorithm [42] to connect all corners, forming the highway network.

Table 7
Component list.

Component	Model	Source	Architecture	Symbol	Value
12-fiber cable (km)	Cable 1X12 FO SM 9/125 OS2	[41]	Both	c_1	850 €/km
24-fiber cable (km)	Cable 24 FO (2T12F) SM 9/125 OS2	[41]	Both	c_2	1500 €/km
Ducting (km)	-	[39]	Both	c_d	14000 €/km
Transceiver PtP	SFP-10G-ER40	[40]	PtP	c_{tptp}	47.19 €
Switch	S5850-24S2Q	[40]	PtP	c_{sw} p_{sw}	1750 € 24
Transceiver PON	GSFP-43-20C	[40]	PON	c_{tpon}	66.55 €
OLT	OLT3610-08GP4S	[40]	PON	c_{OLT} p_{OLT}	2078.78 € 8
Splitter	PLC 1x 32	[40]	PON	c_{sp} p_{sp}	56.87 € 32
ONU	TA1710-1G	[40]	PON	c_{ONU}	35.09 €

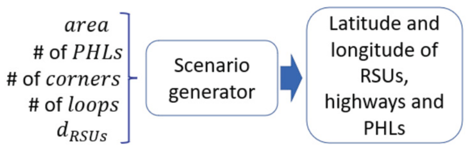


Fig. 11. Custom scenario generation.

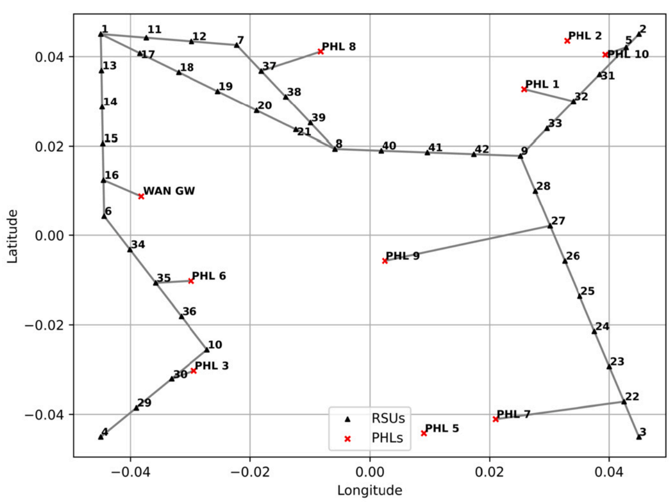


Fig. 12. Example graph for urban scenario.

4. Number of closed loops: Closed loops are created by connecting points in different branches of the spanning tree.
5. RSU separation d_{RSUs}: RSUs are placed at intervals of approximately d_{RSUs} along each straight segment of a highway. For instance, if a segment is 3.4 km long and $d_{RSUs} = 1$ km, considering RSUs are already positioned at its ends, two additional RSUs will be placed equidistantly along the segment.

An example of a generated scenario is depicted in Fig. 12. This scenario was generated with parameters setting an area of 100 km^2, 10 PHLs, 10 corners, $d_{RSUs} = 1$ km and one closed loop. PHLs are depicted as red crosses, RSUs are black triangles

7.1.1. Results for computationally solvable ILP scenarios

In [8], we observed small differences in cost between PtP and PON solutions (when using the BCF heuristic to plan the network) and concluded that PtP was the most convenient choice for the conditions of that study, as it provides dedicated (rather than shared) bandwidth to RSUs compared to PON.

In this section, we extend the comparison between PtP and PON under a wider range of conditions. Moreover, we incorporate the two novel approaches presented in this paper: the ILP formulation (Section 5) and the genetic algorithm (Section 6.6.2), alongside the BCF heuristic that we introduced in [8].

Since the ILP formulations cannot be solved for large scenarios, this section presents the outcomes for two limiting cases that were solvable. A scenario may be too large to be solved by the ILP for two reasons: either the RSUs are positioned very close to each other, or the overall area of the scenario is significantly large. These cases correspond to urban and rural scenarios, respectively, as described below.

- Urban scenario (close RSUs): As we studied in [2], the required RSU density is proportional to the number of users and the complexity of the services they require. Consequently, urban environments typically require more RSU density than rural areas. In urban scenarios, PHLs can be any point within the area, such as buildings or convenient locations for header installation.
- Rural scenario (large area): In these scenarios the area to be covered is larger, and traffic is lower compared to urban settings. Hence, a lower RSU density is required. In rural environments, we assume that PHLs are located in villages.

According to [2], d_{RSUs} should be between 0.25 km and 5 km to ensure complete coverage in a realistic scenario. However, in some of the cases presented in this section, particularly in the rural scenario, larger spacings had to be used to make the ILP models solvable. As a result, full coverage is not guaranteed and certain zones may lack sufficient RSUs to provide coverage for all vehicles in the area. While this is not ideal, it reflects a realistic challenge, as achieving complete RSU deployment across all roads is difficult. These cases represent real-world scenarios where RSUs are placed only at strategic locations, such as intersections, high-risk areas or densely populated areas.

A graphical example of the solution obtained by the genetic algorithm for a generated urban scenario is shown in Fig. 13. In fact, this figure illustrates the solution for the scenario presented in Fig. 12. In the diagram, blue lines indicate optical connections along highways, while green lines represent connections between highways and headers. The thickness of these lines is proportional to the number of optical fibers. Magenta dashed lines depict the association between RSUs and headers; however, the actual connection paths follow the green and blue lines, not the magenta ones. In this example, the selected headers were PHL 10 and the WAN gateway. By comparing 12 and 13, it can be observed that the solution does not deploy fiber (or ducting) along one segment of the closed loop, despite the presence of a highway crossing that segment.

More comprehensive results for the urban scenario are shown in Fig. 14. For this figure, 100 scenarios were randomly generated, with different locations of PHLs and RSUs, but with common parameters as follows: an area of 200 km^2, 5 PHLs, 10 corners, no closed loops, and

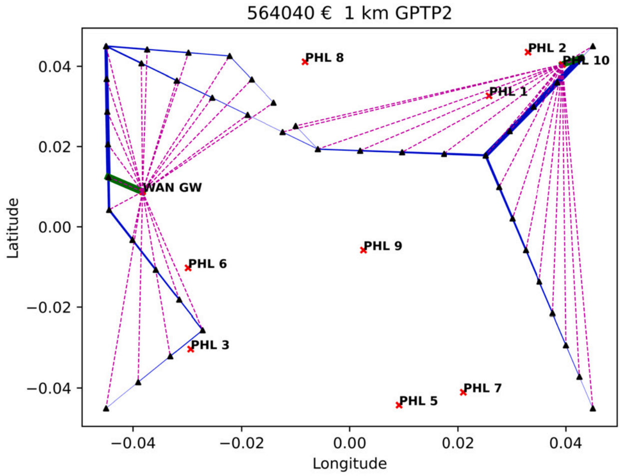


Fig. 13. Example solution (from Fig. 12).

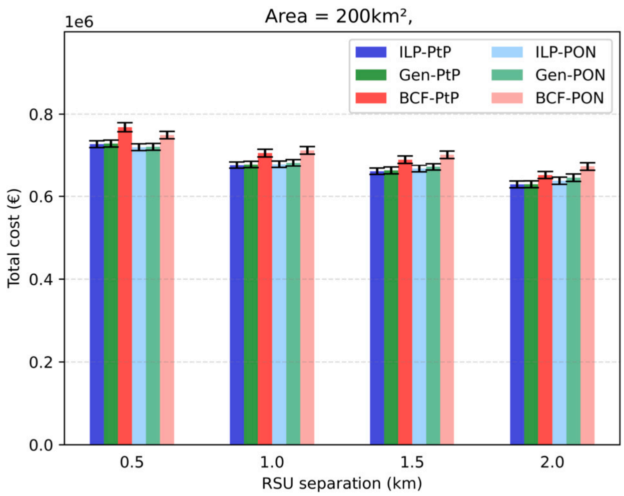


Fig. 14. Results for 100 urban-dense scenarios solvable by ILP.

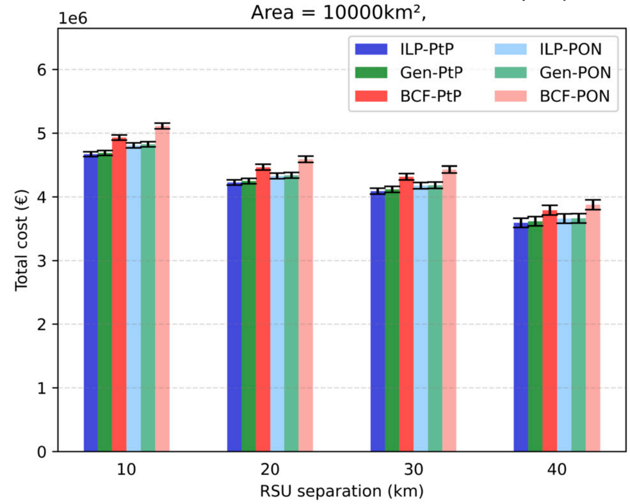


Fig. 15. Results for 100 rural-sparse scenarios solvable by ILP.

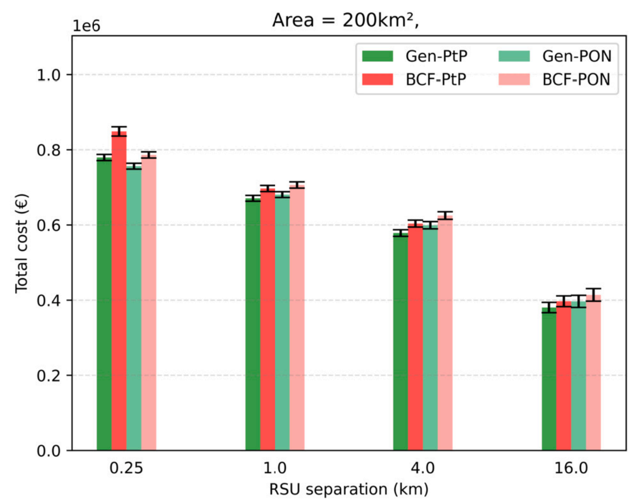


Fig. 16. Results for 100 urban scenarios (not solved by ILP).

d_{RSUs} between 0.5 and 2 km. This experiment was run considering the maximum reach, $D_{\max}$, of each architecture (40 km for PtP and 20 km for PON). In the figure, the height of the bars represents the average cost of the 100 tests, and the black vertical lines represent the 95% confidence interval. The horizontal axis is the RSU separation distance, d_{RSUs}.

The results in Fig. 14 show that the costs of the PON and PtP solutions are very similar due to the small area considered. In both approaches, ducting represents the dominant cost, but remains consistent across all methods and overshadows the differences between them. However, for small d_{RSUs}, the PON approach is slightly cheaper than PtP. Additionally, the results demonstrate that both the ILP formulation and the genetic algorithm outperform the BCF heuristic. The ILP formulation provides the optimal solution, but the novel genetic algorithm achieves results very close to ILP while consistently leading to lower-cost network plannings compared to BCF.

For the rural scenario we also performed 100 tests, considering an area of 10,000 km^2, 700 PHLs and d_{RSUs} between 10 and 40 km. In this context the trend differs from the urban scenario, as shown in Fig. 15: PtP is cheaper than PON. This behavior is attributed to the stricter distance limitation of PON ($D_{\max} = 20$ km) compared to PtP ($D_{\max} = 40$ km). As seen in Fig. 14, the difference in $D_{\max}$ between PtP and PON has little impact in urban scenarios because the total area is small. However, in larger areas, this difference makes PtP more cost-effective, as it requires fewer headers than PON.

For both presented scenarios, it is important to highlight that genetic algorithm produces results that are very close to, and sometimes even match, those of the ILP. On the other hand, the total cost of PtP and PON solutions is very similar in all cases.

7.1.2. Results for computationally unsolvable ILP scenarios

Given the challenges ILP faces in solving large scenarios, this subsection focuses on comparing BCF and the genetic algorithm while analyzing scenarios with higher RSU density.

Fig. 16 shows the results for d_{RSUs} ranging from 0.25 to 16 km in 100 urban scenarios (200 km^2). Again, the genetic algorithm notably outperforms BCF, particularly for small d_{RSUs}. This effect is more pronounced in this case because the first step of the BCF heuristic is to select the PHL with the highest number of reachable RSUs. In small, dense scenarios, the first chosen PHL is generally assigned to many (if not all) RSUs, leading to excessive cable requirements as RSUs connect to the same header rather than a closer one. Under these conditions, the difference between PtP and PON becomes more evident than in Fig. 14. PtP is more expensive than PON for small d_{RSUs}, but this trend is reversed as d_{RSUs} increases. PON is advantageous in dense scenarios due to its fiber-sharing capability, whereas PtP may be more suitable for large, sparse scenarios given its greater flexibility in $D_{\max}$.

Fig. 17 shows the results for 10,000 km^2, with d_{RSUs} ranging from 1 to 32 km. With the inclusion of smaller values of d_{RSUs}, a change in the results compared to Fig. 15 emerges. In denser scenarios, PtP is more

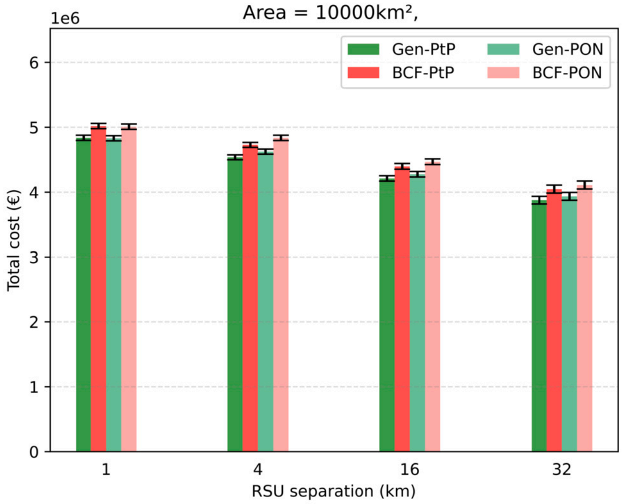


Fig. 17. Results for 100 rural scenarios (not solved by ILP).

expensive than PON. However, as d_{RSUs} increases, the trend reverses, and PON becomes the more expensive option. As mentioned earlier, the main cost-saving advantage of PON lies in the ability to share fibers among RSUs in the segment between splitters and headers, which PtP cannot do. This leads to lower costs in that segment. The fiber-sharing advantage of PON is more effective when there are a large number of RSUs to share this segment. In contrast, when there are fewer RSUs (larger d_{RSUs}), a single cable in that segment is often sufficient, reducing the advantage of PON over PtP. Additionally, in large areas, PtP benefits from the less restrictive $D_{\max}$, further enhancing its cost-effectiveness.

Anyway, as also shown in the previous subsection, the total costs of the PtP and PON alternatives are very similar in all cases.

7.2. Results and analysis on OpenStreetMap-based data

After evaluating the performance of the different approaches under various conditions in artificially generated scenarios, we have further validated them in real-world cases using road network data from different locations. For this purpose, we have employed OSMnx [43], a Python package designed for downloading, modeling, analyzing, and visualizing urban networks and other geospatial features extracted from OpenStreetMap (OSM) [44]. To make these datasets suitable for our optimization approaches, a preprocessing stage was required, as described below:

1. **Graph extraction.** We first download the complete OSM graph for a chosen region. From this graph, we filter road segments according to their category (e.g., highway, trunk, primary, secondary).
2. **Map simplification.** Although filtering by road type reduces the graph size, the resulting networks still contain an excessive number of nodes and edges, particularly around intersections and roundabouts. This density is especially problematic for solving the ILP models. To overcome this issue, we implemented a simplification algorithm governed by a user-defined distance parameter *rsu_dist* (distance between RSUs):
   - Nodes at necessary intersections are always preserved to maintain connectivity.
   - Along the remaining road segments, nodes are removed so that the spacing between surrounding RSUs is approximately *rsu_dist*.
   - For edges longer than *rsu_dist*, additional equidistant nodes are inserted to ensure full coverage.

   Then, each resulting node is assumed to represent an RSU.
3. **Placement of PHLs.** Potential Header Locations (PHLs) are randomly selected from the original OSM map, with the constraint that each RSU must have at least one PHL within 20 km, which corresponds to the maximum reach requirement of PON architecture.
4. **Final graph.** The final topology therefore consists of:
   - RSUs obtained from the simplified graph,
   - randomly placed PHLs satisfying the PON reach requirement, and
   - connectivity information (edges) between all nodes.

   This graph is then used as input to evaluate the proposed optimization techniques.

As test scenarios, we selected three representative cases: the metropolitan area of Valladolid (Fig. 18), the province of Valladolid (Fig. 19), and the region of Castilla y León in Spain, where Valladolid is located (Fig. 22). These three scenarios, ranging from the smallest (metropolitan area) to the intermediate (province) and the largest (region), illustrate how deployment trends vary depending on the geographical scale and network density. Moreover, they highlight the ability of the proposed Genetic Algorithm to handle large-scale instances that become computationally intractable for the ILP formulations.

We have first solved the PtP and PON ILP models for the Valladolid metropolitan area and for the Valladolid province considering a fixed value of the *rsu_dist* parameter of 1 and 10 km, respectively. The cost comparison between the two architectural solutions (PtP and PON) is shown in Table 8. Additionally, Figs. 18 and 19 illustrate the deployment layout, with RSUs, fibers, headers and the gateway (which is located at Valladolid city).

In the metropolitan scenario, PON achieves a marginal advantage, primarily due to its ability to share fiber in the access segment through the header–splitter duct, which slightly reduces cable requirements. However, when the deployment area becomes larger and sparser, as in the province case, the stricter distance limitation of PON (20 km) compared to PtP (40 km) leads to the installation of a larger number of headers. This, in turn, results in higher equipment costs and, more critically, increased ducting expenses to connect the additional headers to the backbone network. Consequently, PtP becomes more cost-effective at the province scale, with savings exceeding 11% over PON. Additionally, although not quantified in this work, it is evident that a larger number of headers would also lead to higher operational expenditures (OPEX), including energy consumption as well as infrastructure and equipment maintenance.

In order to complement this study, we have also analyzed the metropolitan area and the province scenarios for different values of *rsu_dist*. In this case, the Genetic Algorithm (GA) and the BCF heuristic have also been employed, and the results are presented in Fig. 20, together with those obtained with the ILP formulations. The province case (Fig. 20.b) clearly highlights the increasing cost disparity between PtP and PON as the deployment area expands, reinforcing the scalability limitations of PON under sparse deployments. Moreover, the GA results are shown to closely approximate those of the ILP models, validating GA as a practical alternative for larger instances where exact optimization becomes computationally infeasible.

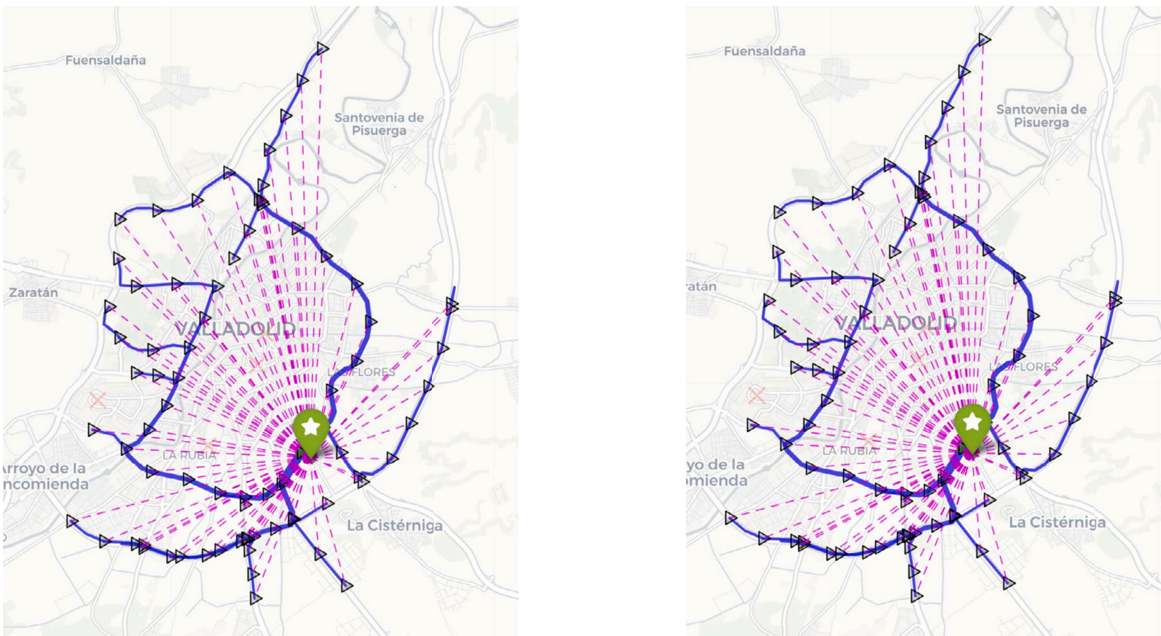
Finally, we include in Fig. 21 the results for the Spanish region of Castilla y León, in order to demonstrate that the Genetic Algorithm can solve large-scale instances that become intractable for the ILP formulation. The outcomes preserve the same trend observed in the Valladolid province scenario, with PtP being the most cost-effective option. This is explained by the fact that Castilla y León constitutes a wide and sparse region, where the stricter 20 km distance limitation of PON requires additional headers and ducting, thereby increasing deployment costs compared to PtP. Fig. 22 illustrates the deployment map of the Castilla y León region for the PtP architecture, considering an *rsu_dist* of 10 km.

8. Conclusion

Access optical networks for RSUs in vehicular networks provide a long-term solution for delivering reliable and high-quality connectivity to Intelligent Transportation Systems. In this work, we have analyzed

Table 8
Cost comparison and savings between PtP and PON for Valladolid metropolitan area and Valladolid province using ILP models.

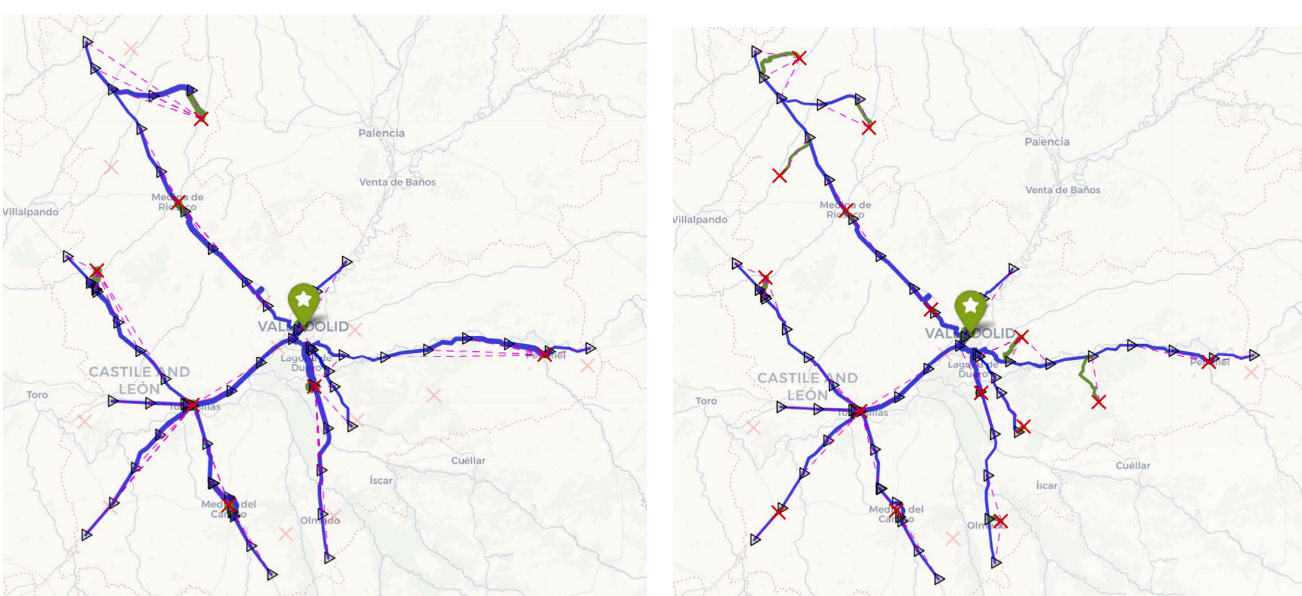
Scenario	# RSUs	rsu_dist (km)	Headers	Cost ducting (€)	Total cost (€)	Lower-cost	Saving (%)
Metropolitan PtP	61	1	1	778,746	854,111	PON	0.74
Metropolitan PON			1	778,746	847,805		
Province PtP	77	10	8	6,217,841	6,615,865	PtP	11.03
Province PON			16	6,970,123	7,436,255		



(a) Metropolitan PtP

(b) Metropolitan PON

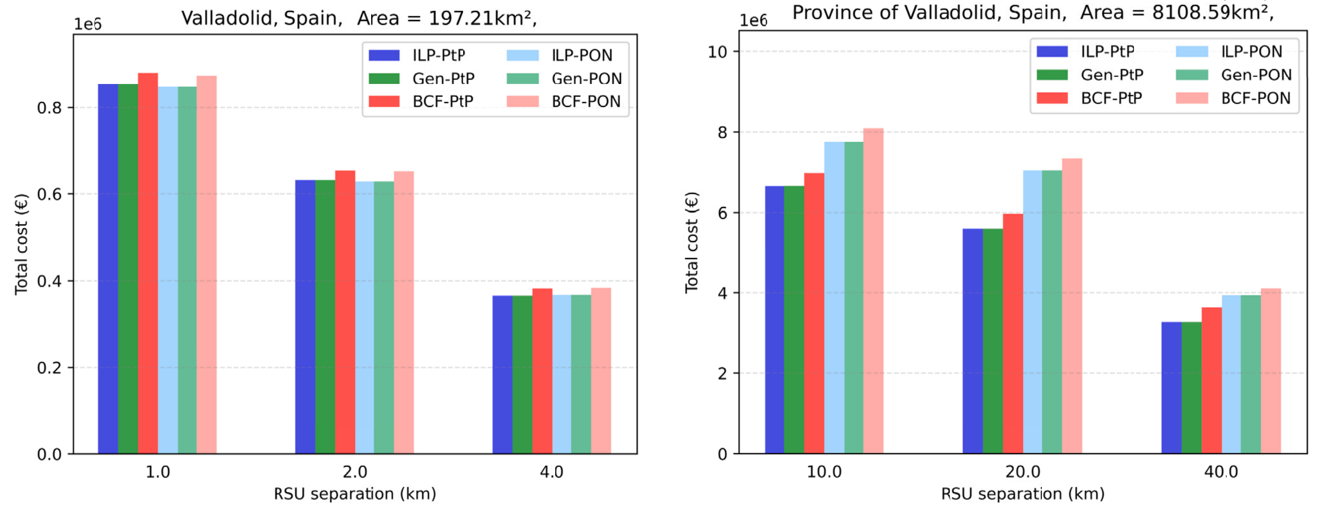
Fig. 18. Deployment layouts for the Metropolitan-level scenario (PtP vs. PON).



(a) Province PtP

(b) Province PON

Fig. 19. Deployment layouts for the province-level scenario (PtP vs. PON).



(a) Metropolitan-level costs

(b) Province-level costs

Fig. 20. Cost breakdowns for the metropolitan and province scenarios.

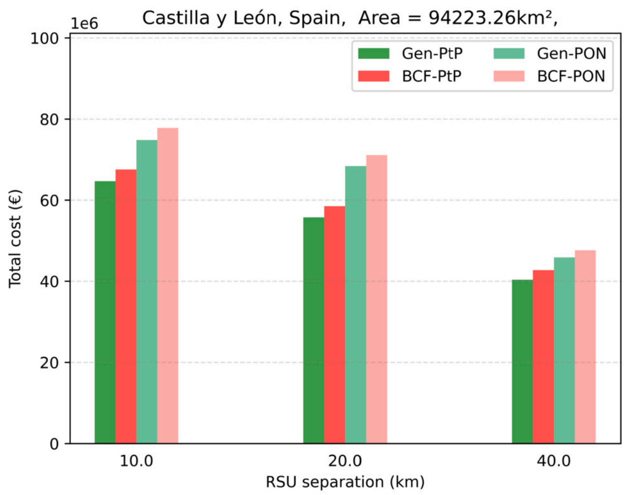


Fig. 21. Cost results for the Castilla y León region using the Genetic Algorithm.

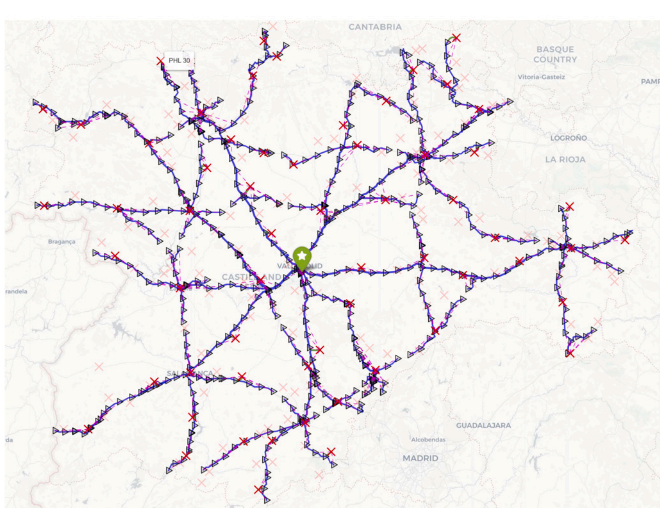


Fig. 22. Deployment map of the Castilla y León region for PtP with $rsu\_dist = 10$ km.

two different architectures (PtP and PON) for deploying optical access networks for RSUs. We have also proposed and compared three network planning solutions (an ILP formulation, the BCF heuristic and a genetic algorithm), all aimed at reducing the implementation cost of the fiber network. After conducting multiple tests under different scenarios, some trends were observed:

- The proposed ILP formulation provides a formal definition of the problem and yields optimal solutions, but, like other ILP approaches, it is impractical for large-scale scenarios. To overcome this, the proposed genetic algorithm offers a faster alternative, consistently outperforming the BCF heuristic and achieving near-optimal—or even identical—results compared to the ILP formulation in medium-scale scenarios, while maintaining significantly lower computation times. This makes it suitable for networks of any size.
- The improvement of GA (and ILP) over BCF is greater in dense scenarios. Since BCF prioritizes PHLs with more reachable RSUs, it often selects only a few PHLs as headers. This results in higher expenses for cables needed to interconnect RSUs with headers that are farther away.
- PtP is more cost-effective in large-area scenarios due to its longer maximum distance between headers and RSUs (40 km vs. 20 km for PON), which reduces the number of required headers. In contrast, PON is more cost-effective in dense deployments, as RSUs can share fiber between splitters and OLTs, with cost savings increasing with the number of RSUs per OLT. However, since PON splits bandwidth among RSUs, it is essential to ensure that shared capacity meets the demand. When total costs are similar, PtP—offering dedicated bandwidth—is generally the preferred option.

For future work, we plan to explore proposals related to resource allocation and computation offloading strategies, aiming to identify the most effective techniques for operating the networks planned in this paper. Additional directions include optimizing and comparing the energy consumption of PtP and PON architectures, extending the ILP formulations to support multi-gateway topologies or hierarchical aggregation layers that better reflect real-world 5G/6G ITS deployments, and investigating hybrid architectures combining PtP and PON. A more detailed evaluation of operational expenditures (OPEX) will also be pursued, as a complement to the CAPEX analysis developed here. The GA parameters used in this work were empirically selected after preliminary testing of several alternatives. A full sensitivity analysis could provide further insights. Therefore, we identify systematic parameter tuning as an interesting direction for future research. Additionally, we plan to conduct a sensitivity analysis on key cost parameters, such as ducting and transceiver prices, to identify cost trends and assess the impact of price variations on deployment decisions. Finally, it should also be noted that our study does not address security implications, such as vulnerability to physical-layer attacks (e.g., fiber tapping), nor the integration of optical access with emerging 6G vehicular frameworks. While both aspects are highly relevant for the long-term evolution of vehicular networks, their proper assessment requires dedicated models and is therefore also left as future work.

CRediT authorship contribution statement

Camilo Anzola-Rojas: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Formal analysis, Conceptualization. **Ignacio de Miguel:** Writing – review & editing, Validation, Supervision, Resources, Project administration, Methodology, Funding acquisition, Conceptualization. **Noemí Merayo:** Writing – review & editing, Validation, Resources, Project administration, Funding acquisition. **Juan Carlos Aguado:** Writing – review & editing, Validation. **Rubén M. Lorenzo:** Writing – review & editing, Validation. **Ramón J. Durán Barroso:** Writing – review & editing, Validation, Supervision, Resources, Project administration, Methodology, Funding acquisition, Conceptualization.

Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work the authors used DeepL and ChatGPT in order to improve the grammar and readability of some sentences. After using these tools/services, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Prof. Durán Barroso assumes the role of a guest editor for seven special issues in JCR-indexed journals, organizes workshops at four conferences, and is a member of the TPC for various conferences.