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Enabling Road Side Units with Optical Access Networks: Planning and Techno-Economic Analysis

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***Abstract*—The upcoming Connected and cooperative and automated mobility paradigm (CCAM) requires the deployment of road-side units (RSUs) beside the roads to provide wireless communication to connected-vehicle on board units. The deployment of RSUs along the highways provide low-latency communication, suitable for applications where high-speed response is needed, such as autonomous driving and crash avoidance. These RSUs must be connected to the Internet through a high-bandwidth and reliable access network being the optical fiber technologies the most convenient technology for that. In this paper, we propose a planning scheme for enabling RSUs with optical access networks. The method starts choosing the locations of the access network headers (the connection points to the local service provider facilities), and then defines the connections between the headers and the RSUs in a convenient manner considering the road infrastructure. Then, two deployment technologies based on optical fibers are compared: Point to Point (P2P) and Passive Optical Network (PON). A techno-economic analysis was performed, and results show that P2P and PON approaches are very similar in terms of cost, therefore, due to technical advantages, P2P is recommended as deployment strategy for the described scenario.**

Keywords*— Network Planning, Optical networks, Passive Optical Networks (PON), Internet of Vehicles (IoV), Connected vehicle, Roadside Unit (RSU), Connected and cooperative and automated mobility (CCAM).

I. INTRODUCTION

Connected and cooperative and automated mobility (CCAM) is a trending and growing topic. With the evolving of new enabling technologies related to Internet of Things (IoT), and fifth-generation networks (5G), the concept of Internet of Vehicles (IoV) have arisen [1], and vehicular-networks planning has become more complex and challenging. To be connected, the vehicles need nearby infrastructure to establish wireless communications. These infrastructures receive the name of road-side units, or RSUs and are usually placed at the side of the roads. RSUs communicate with vehicles wirelessly, however they need a broadband connection to other RSUs and other networks, and optical fiber is the most suitable transmission media for these connections. The planning of any optical network is an important issue to face. Some works dealing with optical networks planning issues were found. Zukowski et. al. in [2], examined different Fiber To The Home (FTTH) deployment strategies for rural areas that should be used depending on the expected customer take-up rate to reduce the investment risk. Pedersen and Riaz discussed the necessity of providing fast broadband access, preferably FTTH to rural areas, they show how and why FTTH is actually being deployed in Denmark, even in the countryside [3]. A heuristic aiming to reduce PON network deployment costs compared to an intuitive random-cut sectoring approach is proposed by Li et. al. in [4], in this proposal they use Minimum Spanning Tree (MST) to exploit the benefits of cable conduit sharing, reducing the costs of PON network deployment. In [5], Agate et.al. use a combination of Steiner tree and clustering technique, to generate a suboptimal network in terms of the total cable deployment construction length based on the forecasted demand and a real road map. The objective of this paper is to propose a deployment strategy to enable RSUs along different highways and roads with optical access networks. Moreover, a techno-economic study will be carried out to determine which option results more convenient among two network architectures: Passive Optical Networks (PON), and Point-to-Point (P2P). Few articles were found dealing with optical networks for connected vehicles, and none was found proposing a solution similar to the one described in this paper, neither performing the comparison presented here. For example, in [6], Kraus *et al.*, analyze existing bus systems and propose a potential solution based on optical technologies to cope with the upcoming bandwidth requirements of autonomous vehicles. In [7], Lazaro *et. al.*, revise current state of the art of wireless and optical fiber access technologies for different communications requirements in diverse scenarios related to connected vehicles and present a review of different technologies for 5G connected vehicles as well as use cases and expected requirements. In their architecture, the multi-access edge computer (MEC) servers are placed near RRU using PON technologies to deploy backhaul networks. However, they did not solve the planning

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problem of all the elements. In [8], Mehreen et al. solve the wavelength assignation problem in a time and wavelength division multiplexed passive optical network (TWDN-PON) for vehicle to infrastructure (V2I) communication networks. They used a similar architecture than us placing ONU in each RSU. However, they do not solve the planning problem which is one of the objectives of this paper.

The remaining of this paper is structured as follows: Section II introduces the two options considered regarding the architecture of the access optical network (PON and P2P). Section III describes an algorithm proposed for the selection of network header locations and the further association between the headers and the RSUs. In Section IV we introduce the case-study that we used to validate and compare the models, and the obtained results are shown and analyzed. Finally, Section 0 presents the conclusions of the work.

II. Optical network approaches

For the deployment of the optical connections between the RSUs and their respective access network header, we consider two optical access networks technologies: point to point connections (P2P) and passive optical networks (PON). These two approaches are explained below:

A. *Passive Optical Network (PON)*

The PON architecture reduce the number of fiber runs needed to reach multiple end-user locations without the need of providing power to the transmission devices between the network header and the end users. PON is widely used in residential distribution networks, where this approach results convenient since the distance between the residences and the OLTs is usually higher than the distances between residences.

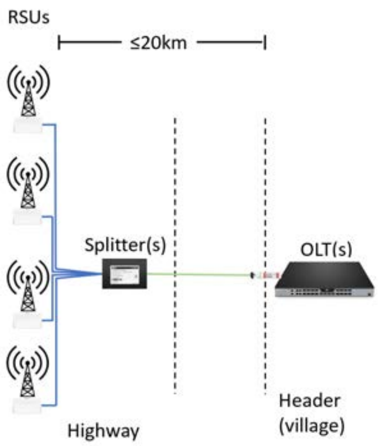

Fig. 1: PON network architectures

In the connected- vehicle scenario, a PON architecture is composed by Optical Line Terminals (OLTs) at the network header, from which a single fiber is laid to the nearest highway, where, by means of an optical splitter, the signals of each RSU are directed in a separated fiber. Besides the OLT at the network header, Optical Network Units (ONUs) are installed in each RSU, and each fiber needs an optical transceiver in each both ends. One important factor that makes PON useful in residential scenarios is the closeness among residences, and the long distance from residences to OLT. But this is not necessarily the case when there are RSUs instead of residences. Fig. 1 illustrates a basic scheme of a PON access network for RSUs

B. *Point to point connections (P2P)*

This scheme considers direct optical connections from the access network header located at each selected village to all its assigned RSUs. At the network header switches connect all the RSUs by means of a direct fiber connection to each RSU. In this case, SFP transceivers are usually also needed for any optical connection. The number of cables needed to connect villages (head ends) and RSUs is proportional to the number of RSUs to connect.

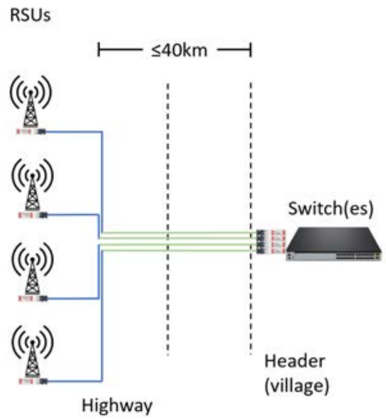

Fig. 2: Point to Point network architecture

An illustration of a simplified scheme of a P2P network architecture is shown in Fig. 2 Notice that in the PON case, the connection between the OLT and the splitter requires only one single fiber, saving resources at this segment, but in our connected-vehicle scenario, the distance between the RSUs is usually higher than the distance between OLTs and splitters. In this study we assess and compare the costs related to the deployment of the access network with both options (PON and P2P).

III. Method for connections setting

In this section, we propose a method to select the locations of access network headers and establish the connections between each RSU located along the highways, and their corresponding header. This method takes as inputs the locations of the RSUs to be connected, and the potential locations for the network headers (in our case study these potential locations are villages or cities, as described in Section IV). A matrix of the distances between each pair of points in the scenario (both RSUs and villages) is also given as input, together with the maximum permitted distance D_{max} between RSUs and their network header. Note that GPON technology only allows 20 km from the header (OLT) to the final user (ONT). Given that we are in a scenario planned for connected-vehicle services, all the distances that we consider are not Euclidean distances; instead, they are the shortest distances following the available highways and road to interconnect each pair of points. Note that highways and main roads are usually equipped with ducting for different purposes and therefore, no civil work (the most important component of CAPEX) will be needed in this scenario.

Algorithm 1: Connection between RSUs to access network header

1: **Procedure** *connections*(*RSU_list, Village_list, distances,* D_{max})
2: $h_j \leftarrow 0$ **for all** j
3: $c_{i,j} \leftarrow 0$ **for all** i, j
4: *chosen _villages = {}*
5: *pending_RSUs = RSU_list*
6: *pending_villages = Village_list*
7: **while** *pending _RSUs* $\neq \varnothing$ **do**
8: **for** *p* **in** *pending _villages* **do**
9: *reachable_RSUs*$_p$ $\leftarrow$ Subset of *pending _RSUs* at a distance less than D_{max} from Village$_p$
10: **end for**
11: *candidate_villages* $\leftarrow$ Subset of *pending _villages* with maximum number of *reachable_RSUs*
12: $v \leftarrow$ Select village from *candidate_villages* with minimum sum of distances to all its *reachable_RSUs*
13: *pending _RSUs* $\leftarrow$ *pending _RSUs-(reachable_RSUs*$_v$*)*
14: *pending _villages* $\leftarrow$ *pending _villages* – *{v}*
15: *chosen_villages* $\leftarrow$ *chosen _villages* $\cup$ {v}
16: $h_v \leftarrow 1$
17: **end while**
18: **for** *i* **in** *RSU_list* **do**
19: $j \leftarrow$ Select village from *chosen _villages* at minimum distance to RSU$_i$
20: $c_{i,j} \leftarrow 1$
21: **end procedure**

The outputs of the algorithm are two sets of binary variables; h_j will be set as one if the village j is selected to host a network header, and $c_{i,j}$, takes value one if a connection between the RSU i and the village j is performed, and is zero otherwise.

Algorithm 1 describes the mentioned procedure. The process starts by initializing variables (lines 2-6), at the beginning there are no connections, no village has been chosen to host a header, and all RSUs and villages are pending to be processed. The instructions of lines 8-16 will be executed until there are no pending RSUs. In (lines 8-10), a list of all pending RSUs within a distance not larger than D_{max} (reachable RSUs) is obtained for each pending village. Then, all the villages with the highest number of reachable RSUs are saved as candidates (line 11), and among these candidates, we select the village which obtains the lowest result by summing all the distances to its reachable RSUs (line 12). The lists of pending RSUs and villages, and the selected villages are updated (lines 13-15), h_v turns one, and the process from line 8 is repeated if there are still pending RSUs. Once all RSUs have been processed, we have a set of villages that ensure coverage to all the RSUs in the scenario. Then, to reduce the length of the connections, each RSU will be connected to its nearest header located among the list of selected villages (lines 18-20).

IV. CASE STUDY: VALLADOLID PROVINCE

For the implementation of Algorithm 1 and the comparison of the strategies described in Section 2 we use as case study the province of Valladolid, Spain.

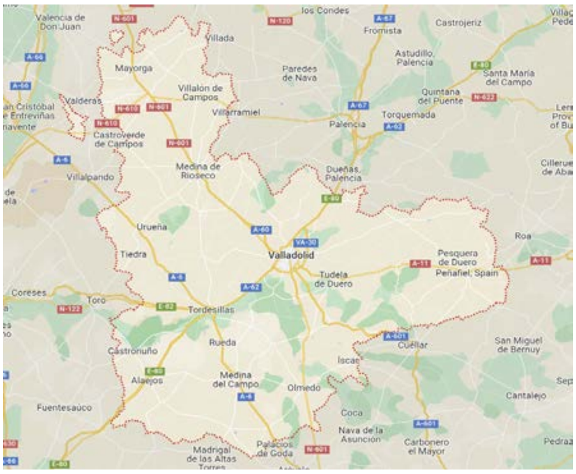

Fig. 3: Map of Valladolid province and its main highways. Source: Google maps.

We used a public dataset provided by the Spanish government [9], which includes the coordinates (latitude and longitude) of the kilometric points of all the roads of Castilla y León, where the province Valladolid is located. Also, the coordinates of all the villages in the province were used. Fig. 4 depicts the information of the used databases; The red X's are the villages, the blue dots are the kilometric points of main highways, and the yellow dots are the points of secondary roads.

With these datasets the following steps were performed to set the environment for our tests:

1) Filter the data, only mantaining the points belonging to main highways and assume that there are RSUs along these highways. We prefer to avoid local roads as the implementation of infrastructure for CCAM will start in highways.

2) Use the Python library Networkx to define a graph interconnecting the points following the paths of the highways, obtaining all the paths and distances between any pair of points, including RSUs and villages.

After having the locations of both RSUs and villages, and the graph model with all the paths and distances, we are ready to test the Algorithm 1. Initially we assume that the RSUs are installed with a separation of two kilometers and that D_{max} =20km (which is the limit in GPON standard). For the tests described in this paper we assume that all optical connections are performed using cables of 24 optical fibers, using one of these fibers to deploy each connection, we consider it a suitable solution because it allows to use a single cable for several connections, and the difference in cost against cables with less fibers is not so important. Moreover, if some fibers in a cable remain idle after the deployment, there is the possibility of using them in the future if new connections are needed.

TABLE 1. COMPONENTS AND COSTS (D_{RSUS}=2km, Dmax=20km)

	Component	Specific model	Unit price (€)	Quantity	Cost (€)
Point to Point	Fiber cable (km)	SM 1*24 (9/125)	1100	520.77	572 846
	Ducting	-	14000	517.58	7 246 182
	Switch	S5850-24S2Q	1750	20	35 000
	Transceivers	SFP-10G-ER40	47.19	540	25 483
				Total	7 879 510
PON	Fiber cable (km)	SM 1*24 (9/125)	1100	519.73	571 708
	Ducting	-	14000	517.58	7 246 182
	OLTs	OLT3610-08GP4S	2078.78	17	35 339
	Splitters	PLC 1x 32	56.87	19	1 083
	Transceivers	GSFP-43-20C	66.55	19	1 264
	ONUs	TA1710-1G	35.09	270	19 275
				Total	7 874 852
				Cost difference (P2P vs PON)	0.059%

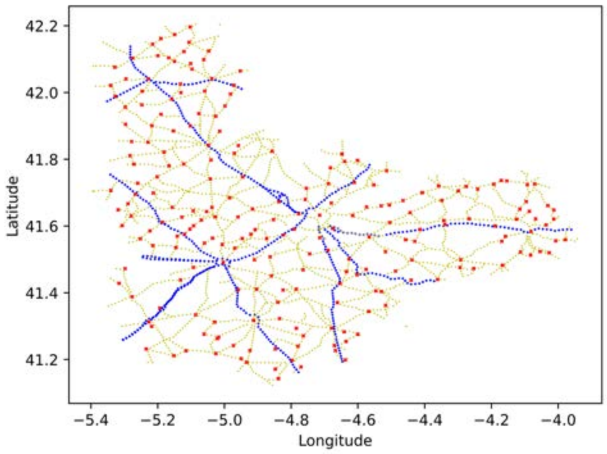

Fig. 4: Representation of datasets.

The components considered for the implementation of PON approach are summarized below:

- In each network header (in villages), we consider the necessary OLTs to cover all the RSUs connected to the header. We assume OLTs with capacity for 256 RSUs (8 PONs * 32 ONTs).
- At the nearest highway point from each header, the necessary splitters will be installed, considering a capacity of 32 RSUs per splitter.
- At each RSU, there will be an ONU.
- Every connection between OLTs and optical splitters require a transceiver, therefore, the number of transceivers is equal to the number of splitters.
- There will be one optical fiber for each connection between RSUs and splitters, and one fiber also between each splitter and its corresponding OLT. Multiple fibers can be inside the same cable, as long as they cross the same path.

Similarly, as detailed for the PON architecture, below the components of the P2P option are enumerated:

- In each network header (in villages), we consider the necessary switches to cover all the RSUs connected to the header. We assume switches with capacity for 24 RSUs.
- Every optical connection will have an optical transceiver in both ends,
- There will be one optical fiber for each connection between RSUs and switches in the network header.

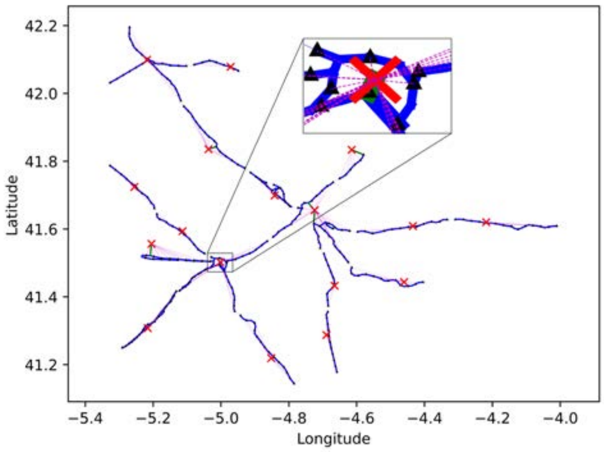

Fig. 5: Representation of 24-fiber cables (D_{RSUS}=2km, D_{max}=20km, Point-to-Point)

A complete comparison of the components and costs of the two approaches (PON and Point-to-Point) under the same conditions of Fig. 5 is presented in TABLE 1, where it is specified the model, price and needed quantity of each component for each approach. Subsequently the cost of all parts is computed and finally an estimation of the total cost is offered. The price of the cable was taken from [10], the cost of ducting, which is the civil work required to lay the cables was taken from [11], and all the other models and prices were obtained from [12].

Fig. 5 illustrates the result after following the described steps with the mentioned conditions and implementing a P2P architecture using 24-fiber cables. The blue lines represent the optical connections among RSUs, the thin red lines represent associations between the head ends (red crosses) and RSUs, note that the paths followed by the actual connections follow the highways, not the red lines and therefore red lines are virtual links. The green lines represent the connections between head ends at the villages and the nearest point in the highways. Notice also that Fig. 5 has a zoom-frame, in which it can be appreciated that a green link is wider than its blue adjacent links, and it is due to the presence of more than 24 fibers in this green link (two cables were needed). If Fig. 5 were a PON scheme, all the green links would have only one cable. This fact is certainly a saving of PON approach; however, all these green links are relatively short and most of them are covered with a single cable also in the P2P scheme.

The PON approach implies a slight reduction in the needed cable. According to TABLE 1, after computing all the costs related to other components, the overall costs of PON and P2P are very similar with only 0.097% of difference for the presented case. The costliest component of the deployment is clearly the ducting, but since it is exactly the same for both PON and P2P, it does not apport information to our comparison analysis.

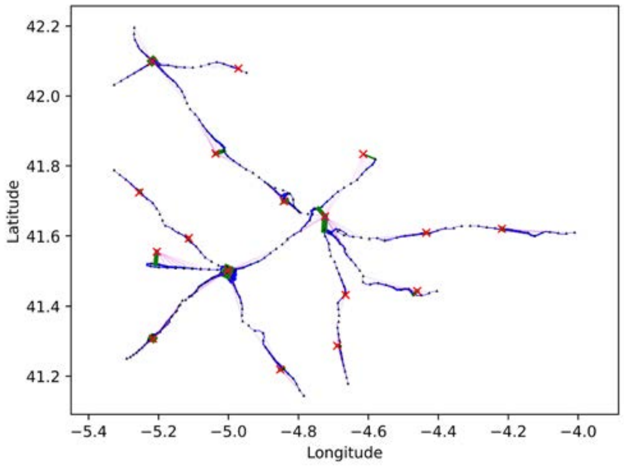

Fig. 6: Representation of individual fibers (D_{RSUS}=2km, D_{max}=20km, P2P)

Fig. 6 is a representation of the optical connections in such a way that the width of blue lines is proportional to the number of single fibers present in each section of the highways. The vicinities of red X's (network headers) have wider links, because all connections are directed to the villages where the headers are installed. Fig. 6 can be interpreted as a representation of the used fibers inside the cables illustrated in Fig. 5.

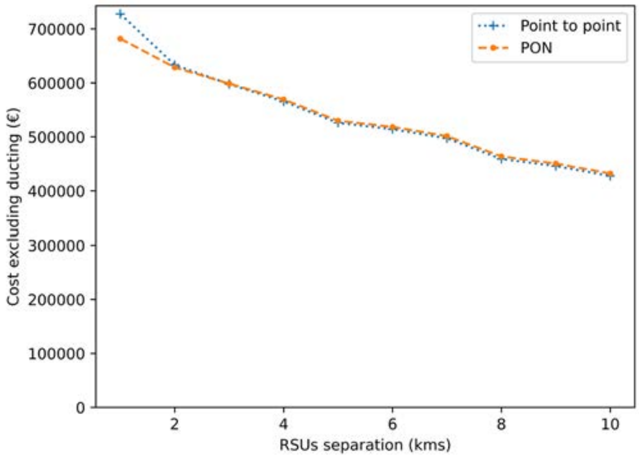

Fig. 7: Cost comparison for different separations D_{RSUS} between RSUs (D_{max} = 20km)

The changes in cost by increasing the separation between the RSUs is depicted in Fig. 7, where the overall cost of both approaches is again very similar. The cost decreases when the separation between RSUs increase because there are less nodes to connect and also less infrastructure to deploy. Fig. 7 excludes the cost related to ducting, because, as mentioned above, its value is the same in both cases, and being also the biggest component of the cost, it would shadow the difference between the approaches without giving any information. Fig. 7 also shows that for small separation between RSUs, PON is less expensive than P2P, however, when this separation increases, this tendence is reversed, although still with similar values among both approaches. P2P is more expensive for smaller separations because of transceivers: the more the separation, the less RSUs, and each RSU needs two transceivers in P2P, but not in PON.

The next three figures (8, 9 and 10) depict the behavior of the outcomes when maximum allowed distance D_{max} between RSUs and network headers changes. Regarding the individual fibers, as depicted in Fig. 8, the values grow consistently as D_{max} increases. The cause of this tendence is that Algorithm 1 tries to deploy as few network headers as possible, and if more distance is permitted, there will be less headers and therefore the required connections will be usually longer than if D_{max} were more restricted. PON has a limitation regarding maximum distance of 20 kms. Therefore, higher values of D_{max} in PON have no realistic meaning and are not included. In P2P, D_{max} can be up to 40 km if needed, which is a point in favor of P2P.

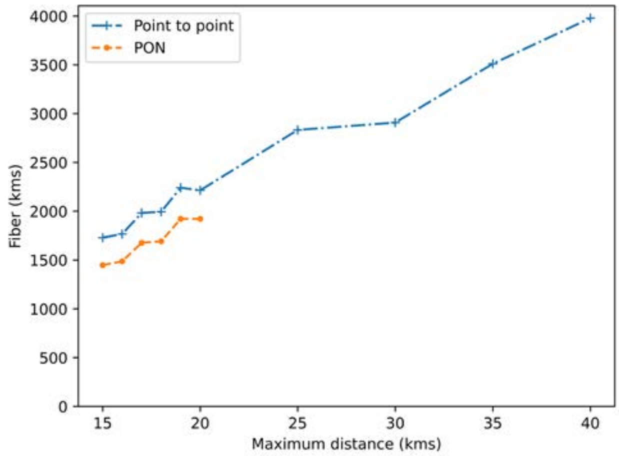

Fig. 8: Individual fibers for different Dmax (D_{RSUS}=2km)

Moreover, in Fig. 8, the fiber required by P2P is always more than of PON. The reason of that is the already mentioned fact that PON saves fiber in the connections between OLTs and splitters. Even though the fiber required by P2P is more, this difference does not significantly affect the cost because, since we use cables of 24 fibers, most sections are covered with a single cable.

The cable needed for the two approaches is almost always the same, as can be evidenced in Fig. 9. This fact supports the statement that the difference in fiber observed in Fig. 8, does not affect in a considerable manner the total cost of the deployment given that, in most cases, a single 24-fiber cable is enough to carry all the needed connections.

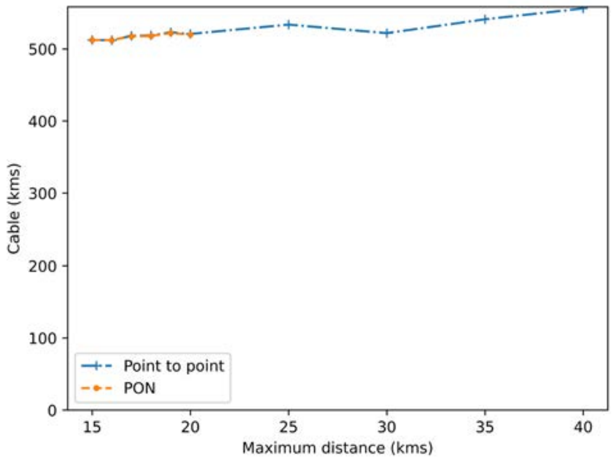

Fig. 9: Cable comparison for different D_{max} (D_{RSUs}=2)

An analysis of the changes in cost when modifying D_{max} was performed and is shown in Fig. 10. Again, P2P and PON have similar associated costs, and this time we have a new behavior: for short distances P2P is a bit cheaper than PON, and around D_{max}=17 the roles are reversed, making PON the cheapest approach. Again, the differences between them are small.

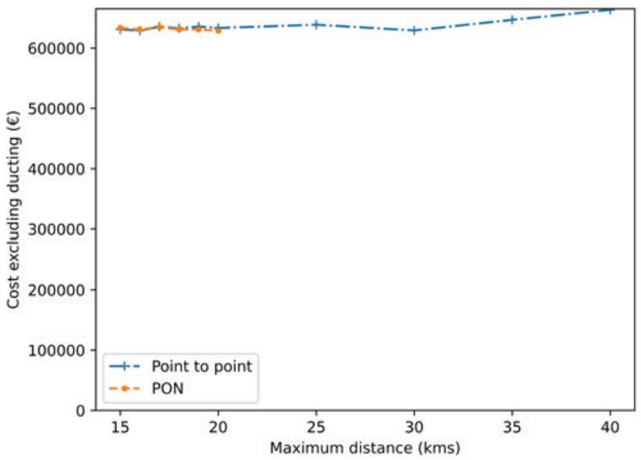

Fig. 10: Costs for different maximum distances D_{max} between RSUs and headers (D_{RSUs}=2km)

Results have shown that the differences regarding overall cost between the two approaches are relatively small (different than residential optical deployments, where PON is usually the cheaper option with notable difference). Regarding technical performance, P2P architecture has an important advantage, and it is that, since each connection is dedicated, the available bandwidth for each RSU is greater than in PON, moreover P2P provides symmetrical bandwidth for upload and download.

V. Conclusion

In this work we proposed an algorithm for the placement of the connections and devices of access networks for connected-vehicle scenarios. A techno-economic analysis over the proposed placement strategy was performed to compare two optical network architectures (PON and P2P). A case-study using real data of highways and villages of the province of Valladolid (Spain) was analyzed. Results suggest that for this kind of scenarios, the overall deployment costs of P2P and PON architectures have only small differences. On the other hand, Point-to-Point offers higher and symmetrical bandwidth for each RSU, which is an advantage. Moreover, PON has a 20 km limitation in terms of maximum distance between headers and RSUs, whereas in Point-to-Point the allowed distance increases to 40 kms, which represents an additional advantage for Point-to-Point.

VI. Future Work

The main objective of this paper is to compare two network architectures (PON vs Point-to-Point). We proposed a heuristic (Algorithm 1) to obtain the placement of network headers and optical connections; it is intended to reduce the overall cost and number of headers. The comparison between PON and Point-to-Point was performed over the placement heuristic applied to Valladolid province. However, the heuristic has not been compared against any other approach or placement optimization model. The definition of a formal optimization model and its comparison with the Algorithm 1 is proposed as future work. We also plan to extend the study to consider all the roads in the area, not only main highways.

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