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Improving Joint Planning of MEC and Fiber Deployment with Duct and Optical Cable Sharing

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***Abstract*— In Multi-access Edge Computing (MEC) network planning, the main goal is to find the optimal network topology, including the location and dimensioning of MEC data centers (MEC-DC), and the connections between them, with base stations (BSs), and with the wide area network (WAN) gateway for Internet and cloud services. Moreover, the assignment of traffic to the servers must also be solved. When solving that problem, it is especially important to consider the connections if the deployment has to be done in sparsely populated areas with long distances to interconnect and where it is likely to find no adequate infrastructure previously deployed. In a previous paper, we presented an Integer Linear Programming (ILP) formulation that solves that problem assuming straight and dedicated cable ducts between network nodes. However, reusing cables ducts and exploiting space division multiplexing (using different fibers of each cable to reach different nodes) can lead to more cost-effective solutions. Moreover, it is crucial to implement redundancy between MEC-DCs and WAN gateways to provide survivability against failures in this network segment. In this paper, we present a heuristic to improve the result obtained with our previous ILP formulation, assuming shared fiber ducts and cables, and creating a ring topology between MEC-DCs and WAN gateways. Results show that our proposal reduces the total deployment cost, while fulfilling latency constraints of MEC applications and providing fault tolerance.**

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

I. INTRODUCTION

Multi-access Edge Computing (MEC) is a disruptive technology based on bringing distributed computing resources in the network closer to end users. Thanks to the use of MEC, latency and congestion in networks are reduced, making possible the implementation of novel applications such as virtual reality, augmented reality and autonomous driving, to name a few. Therefore, MEC facilitates the implementation of IoT applications and services which require real-time operations [1].

Network planning is an important step for the introduction of MEC technologies. In order to make these technologies and associated services available to all people, regardless of where they live, planning must include urban areas as well as sparsely populated ones, like rural environments. Research on MEC network planning has usually focused on urban areas, where the distances to interconnect are relatively small, and where a high-performance optical communication network already exists. However, sparsely populated areas usually lack of such an infrastructure. Thus, besides enabling network nodes with edge computing capabilities becoming MEC data centers (MEC-DCs from now on), the underlying cabling infrastructure connecting base stations with MEC-DCs, and with WAN gateways, must also be developed in these environments. Moreover, as the population is sparsely distributed, the return of investment for potential stakeholders is low. Therefore, it is essential to reduce as much as possible the cost of deployment, including fiber connections.

In this paper, we address the problem of MEC network planning including sparsely populated areas. The main objective is to reduce cost, while complying with technical requirements. Applications that rely on MEC usually have stringent demands, especially regarding latency and bandwidth, therefore the required infrastructure must meet a set of requirements. We assume a network model as shown in Fig. 1. End users or devices connect wirelessly to their nearest base station, and MEC servers are collocated with some of those base stations (MEC-DC). However, those BSs that are not equipped with computing resources must be associated with a MEC-DC, which will handle their computing tasks. Those connections between BSs and MEC-DCs are deployed through an optical fiber (MEC link in Fig. 1). Similarly, at least one optical connection should be deployed from every MEC-DC to a WAN gateway (WAN link in Fig. 1).

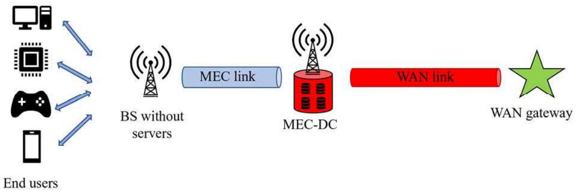

Fig. 1: MEC network model

In this MEC network structure, the MEC planning problem consists of determining:

- the location of MEC-DCs,
- the number of MEC servers in each MEC-DC.
- the association of each BS with one MEC-DC,

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- the fiber connection between each BS and its associated MEC-DC.
- the fiber connection between each MEC-DC and a WAN gateway.

In [2], we proposed an Integer Linear Programming (ILP) formulation which solves this complete problem (in contrast to previous works, focused only on the server placement subproblem). We now extend that work by introducing a re-design phase which is executed after the ILP model. It maintains the location and dimensioning of MEC-DCs provided by the ILP model, but optimizes fiber connections reusing ducts and cables. This improvement phase leads to cost reductions, and also makes the backhaul network resilient, i.e., it provides survivability to the connections between MEC-DCs and WAN gateways.

The remaining of this paper is structured as follows. First, Section II describes related work. Then, Section III details a proposal to improve the cost-efficiency of the connections between BSs and MEC-DCs by reusing ducts and cables, while complying with latency requirements. In Section IV, we present an approach to modify the connections between MEC-DCs and the WAN gateway, changing from a star topology to a ring topology, providing the network with resiliency against failures and also reducing costs. Section V evaluates the proposed methods when applied to a specific case study (the province of Valladolid in Spain). Finally, Section VI presents the main conclusions of this work.

II. RELATED WORK

Multiple existing works deal with MEC network planning, but most of them only address the placement of servers and their associations with BSs or access points. In [3], Lee *et al.* propose an heuristic method to reduce the number of servers while ensuring a certain service latency. Santoyo-González *et al.* [4] propose a method to assign computing capacity to edge nodes that are connected to the traffic generators. Lahderanta *et al.* [5] propose an algorithm for server placement, which minimizes the distances between servers and their associated access points, while taking into account capacity constraints for load balancing and enabling workload sharing between servers.

Regarding optical network deployment, multiple works have been carried out, for example, Zukowski *et al.*[6], examine real-world fiber to the home (FTTH) deployment scenarios, taking as a case study one of the most rural counties in Ireland. Pedersen and Riaz [7] show the development of broadband and FTTH in Denmark, and that FTTH is also being deployed in rural areas. Li *et al.* [8] propose a heuristic whose objective is the cost minimization for greenfield passive optical networks (PON), considering a generic approach for network deployment, which is capable of planning a large network scenario with hundreds of optical network units (ONUs).

However, to the best of our knowledge, there is no published work issuing the deployment of MEC networks considering BSs, MEC-DCs and WAN gateways together with the optical connections among them, and including sparsely populated areas, except our prior work [2], which we will now describe. Furthermore, all the reviewed research papers either assume direct connections between network elements or do not specify the connection topology.

In [2], we proposed an ILP model to solve the MEC planning problem in sparsely populated areas, including the placement of MEC servers, MEC-DCs and optical fibers between BSs, MEC-DCs, and WAN gateways. The mentioned proposal minimizes the total deployment cost, but assumes that all the links are direct, straight and dedicated.

The contribution that we introduce in this paper is twofold. First, we exploit the fact that ducts can be reused, and cables can host several fibers. Therefore, rather than deploying new straight routes for each fiber, ducts can be reused, and the different fibers within each cable can also be used to reach different nodes, thus minimizing costs. Second, we propose the introduction of a ring topology between MEC-DCs and the WAN gateways to provide resiliency in this essential network segment.

III. HEURISTIC METHOD FOR COST-EFFECTIVE CONNECTIONS FROM BSS TO MEC-DCS

In this section, we describe a heuristic to re-design the fiber connections by reusing cable ducts. The MEC planning process starts with the solution of the ILP model described in [2]. This model assumes that all BSs are connected to their respective MEC-DC through a direct, straight, and dedicated optical fiber duct. However, deploying a dedicated duct for each BS results in a non-efficient outcome. Hence, we propose an additional procedure to reduce the deployment costs. It consists in implementing shared paths for the connections between BSs and MEC-DCs, in such a way that ducts can host several cables, and different fibers of each cable are used to connect each BS with the MEC-DC. In summary, each connection has its own dedicated optical fiber, but multi-fiber cables can share the same duct or path.

An example is shown in Fig. 2. The left side of the figure shows the initial network with direct and dedicated cable ducts between BSs and their associated MEC-DC, and the right part corresponds to a solution exploiting cable duct sharing.

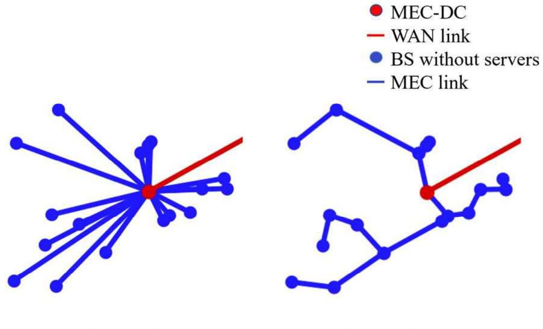

Fig. 2: Reduction by path sharing.

However, when reusing paths, it is important to consider the maximum delay allowed for MEC applications. The ILP model in [2] follows the shortest distance path between BSs and MEC-DCs (as shown in Fig. 2-left). However, when reusing ducts, the paths between BSs and MEC-DCs will not be necessarily straight anymore (Fig. 2-right). Therefore, the total length of the fibers will increase. Given that MEC has stringent latency requirements, the total length of the fibers connecting BSs with MEC-DCs must be bounded.

Algorithm 1 describes the process for replanning the connections between BSs and MEC-DCs (as shown in Fig. 2), sharing ducts and optical cables while ensuring that the latency constraint is not exceeded. The algorithm takes as inputs (line 1) the maximum allowed distance between a BS its associated MEC-DC (D_{max}), the list of BSs in the network (*BS_list*), the distances between BSs ($d_{i,j}$) and the connections to be established between each BS and its associated MEC-DC ($x_{i,j}$). Following the notation of [2] , $x_{i,j}$ is a binary variable which takes the value of 1 if BS i is associated to the MEC-DC located in BS j (and thus a connection must be established), and 0 otherwise.

The algorithm produces the following outputs:

- $duct_{a,b}$ is 1 if ducting between BS a and BS b must be deployed.
- $Z_{i,j}^{a,b}$ takes value 1 when the connection between BS i and BS j uses the duct between BS a and BS b.
- $num\_cables\_duct_{a,b}$, the number of cables to be installed in $duct_{a,b}$, which can be calculated with the following equation,

$$num\_cables\_duct_{a,b} = \left\lceil \frac{\sum_i \sum_j Z_{i,j}^{a,b}}{num\_fibers\_per\_cable} \right\rceil \quad (1)$$

The algorithm begins with the initialization of the variables (lines 2-4). Besides initializing $duct_{a,b}$ and $Z_{i,j}^{a,b}$, $path\_distance_i$, which will represent the length of the fiber connecting BS i with its associated MEC-DC, is also initialized. Then, for each BS j, the list of BSs that will use its computing resources, and thus must be connected to it through a ducting route (*unreachable_BS_list*) is obtained (lines 6-13). Note that if BS j does not have computing resources (i.e., it is not a MEC-DC), that list will be empty, thus nothing will be done, and the algorithm will continue with the next BS. In contrast, if BS j is a MEC-DC, then *unreachable_BS_list* will not be empty, and *connected_BS_list* (which contains the list of BSs which already have a ducting route towards that MEC-DC) will initially consist of only BS j. Then, we look for the nearest pair of BSs between the unreachable BSs and the already connected BSs in the corresponding lists (line 15). If the total path distance does not exceed the D_{max} bound (line 17), a duct between those BSs is established (line 19), the path from the unreachable BS to the BS with MEC-DC (BS j) is built (lines 18, 20-25), and that BS is moved from the *unreachable_BS_list* to the *connected_BS_list* (lines 26-27). If the condition in line 17 is not met, the process will be repeated with different BSs (lines 14-16) until a suitable one is found. Note that at least establishing a direct duct with BS j will meet the condition. The whole process is repeated (lines 5-30) until all connections defined by $x_{i,j}$ are established.

IV. RING TOPOLOGY FOR WAN GATEWAY CONNECTIONS

Even though MEC networks rely on the premise of placing servers near the end users, these networks must have at least one interconnection point to the Internet and cloud services. That interconnection point is the WAN gateway. The WAN gateway can be far from MEC-DCs, thus leading to expensive ducting and cabling deployment. Therefore, it is of utmost importance to take care of this aspect at the planning stage. Moreover, the connectivity of many BSs (and consequently of many users) depends on these links between MEC-DCs and the WAN gateway, so that a strategy to overcome link failures is also required.

Algorithm 1: Duct and cable sharing between BSs and MEC-DC

```
1: Procedure duct_cable_sharing_BSs_MEC($D_{max}$, BS_list, $d_{i,j}$, $x_{i,j}$)
2:     $duct_{a,b} \leftarrow 0$ for all a, b
3:     $Z_{i,j}^{a,b} \leftarrow 0$ for all i, j, a, b
4:     $path\_distance_i \leftarrow 0$ for all i
5:     for j in BS_list do
6:         unreachable_BS_list ← ∅
7:         connected_BS_list ← j
8:         BS_pairs_analyzed ← ∅
9:         for i in BS_list do
10:            if $x_{i,j} = 1$ then
11:                unreachable_BS_list ← unreachable_BS_list ∪ i
12:            end if
13:        end for
14:        while unreachable_BS_list ≠ ∅ then
15:            (c,u) ← Select the tuple of BSs (c,u) with minimum
                    distance between them, taking c from
                    connected_BS_list and u from
                    unreachable_BS_list,
                    so that the tuple (c,u) is not in BS_pairs_analyzed
16:            BS_pairs_analyzed ← BS_pairs_analyzed ∪ (c, u)
17:            if $path\_distance_c + d_{c,u} \leq D_{max}$ then
18:                $path\_distance_u \leftarrow path\_distance_c + d_{c,u}$
19:                $duct_{c,u} \leftarrow 1$
20:                for a in BSs_list do
21:                    for b in BSs_list do
22:                        $Z_{u,j}^{a,b} \leftarrow Z_{c,j}^{a,b}$
23:                    end for
24:                end for
25:                $Z_{u,j}^{c,u} \leftarrow 1$
26:                connected_BS_list ← connected_BS_list ∪ u
27:                unreachable_BS_list ← unreachable_BS_list – {u}
28:            end if
29:        end while
30:    end for
31:    Compute $num\_cables\_duct_{a,b}$ (using eq. 1) for all a, b
32: end procedure
```

As mentioned before, we assume the initial solution provided by [2], which consists in deploying a single dedicated straight duct and cable between each MEC-DC and the WAN gateway, i.e., setting a star topology. However, that topology does not provide failure protection. Therefore, as a second improvement (besides the one presented in Section III), we propose to replace the star topology by a ring topology. In that way, all MEC-DCs and the WAN gateway are interconnected by a cable duct forming a closed loop. Fig. 3 illustrates the difference between star and ring topologies. Given that the distance between neighbor MEC-DCs is usually shorter than the distance between MEC-DCs and the gateway, the ring topology generally implies savings in ducting costs, and makes the ring topology especially suitable to be applied in sparsely populated areas.

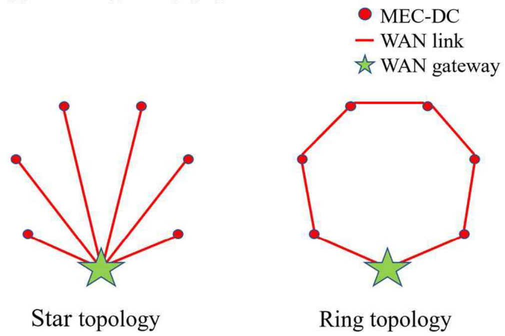

Fig. 3: Star and ring topologies

Although ducts (and cables) follow a ring topology, it is important to note that there is still a dedicated fiber directly connecting each MEC-DC with the WAN gateway. A cable is launched from the WAN gateway in clockwise direction, and a different fiber of that cable is terminated at each MEC-DC to provide connectivity between the WAN gateway and that MEC-DC. Moreover, in order to provide resiliency, another cable is also launched in counterclockwise direction. In this way, each MEC-DC will be connected to the WAN gateway with two fibers (each following a different direction of the ring), one acting as the primary link and the other as backup, thus providing protection against single cable failures.

Finding the optimal way of interconnecting a given set of points in a ring topology is not a trivial problem. Indeed, it is a well-known NP-hard problem in combinatorial optimization called the Traveling Salesman Problem (TSP). There are multiple approaches for solving TSP, and for our tests we have use the Two-opt algorithm[9], whose main idea is to reorder a given route, eliminating crossings over itself to obtain a shorter route. Although Two-opt does not guarantee finding the optimal solution, its application brings advantages over the star topology in terms of both cost and failure protection.

V. PERFORMANCE COMPARISON

As a case study, we have considered the sparsely populated province of Valladolid, in Spain (area of 8111 km^2 and 64 inhabitants per km^2). We have combined two datasets related to Valladolid province: the first one contains the location of 218 Telefónica BSs [10], and the second one contains the population data of each village/city [11]. The workload of each BS has been estimated based on the amount of population connected to it (the fraction of population simultaneously connected has been varied from 0.1% to 3%), and assuming a mixed traffic profile composed by 70% of video traffic, 15% of car traffic, 10% of smart factory and 5% of augmented/virtual reality [12]. Also following [12], we have assumed that all MEC servers are composed by 16 machines of 4 cores at 3.4 GHz, and that such a server is able to serve up to 75 simultaneous users with the mixed traffic profile. The cost of one server (C_S) is around 30,000 € (based on the current cost of 16 Dell R340 machines with the mentioned configuration [13]). The cost of civil works has been assumed to be 15,000 €/km [14] and the cost of 24-fiber cables 1,100 €/km [15]. We have assumed that each connection needs one out of the 24 fibers of the cable, so that a single 24-fiber cable can host up to 24 different connections, and a single ducting path can host several cables. The cost of additional network sub-systems has not been considered.

To obtain the initial network design, we ran the ILP model from [2], including a latency-related constraint that makes connections between BSs and MEC-DCs not to exceed 50 km. As mentioned before, the ILP solution deploys straight and dedicated ducts between each BS and its associated MEC-DC, as well as between each MEC-DC and the WAN gateway (which is located at the capital of the province). Fig. 4 shows a map of the initial network design when assuming that 1% of the population of each village/city province is simultaneously connected. After applying the procedures detailed in sections III and IV (MEC path sharing and WAN ring topology), we obtain a modified network design (shown in Fig. 5). It has exactly the same location and dimensioning of MEC-DCs, and the same associations between BSs and MEC servers. However, the connectivity between BSs, MEC-DCs and the WAN gateway is different, although it fulfills the same technical requirements (maximum latency and workload bearing capabilities).

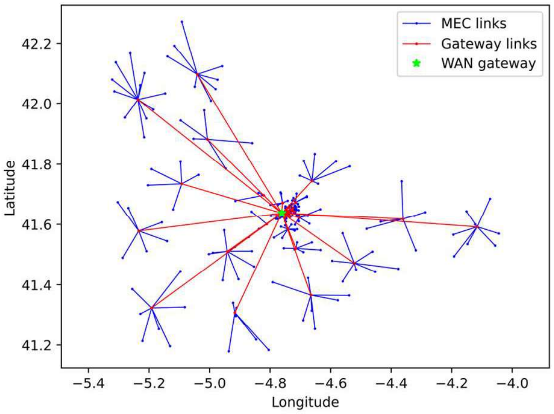

Fig. 4: Initial network design (ILP solution).

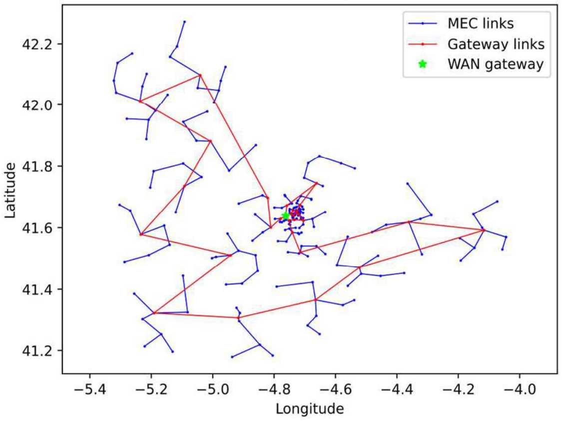

Fig. 5: Final network design (ILP solution with path sharing and ring topology improvements).

TABLE 1: COMPARISON OF COSTS FOR THE DIFFERENT DESIGN OPTIONS.

	ILP solution [2]	**ILP solution [2] and path sharing (Section III)**	**ILP solution [2] and ring topology (Section IV)**	**ILP solution [2] and both improvements (path sharing and ring topology)**
MEC-DCs	30	30	30	30
MEC Servers	76	76	76	76
Servers cost (€)	2 280 000	2 280 000	2 280 000	2 280 000
Ducting (km)	1 495.49	1 214.03	1 342.75	1 061.29
Ducting cost (€)	22 432 312	18 210 491	20 141 196	15 919 375
Cable (km)	1 495.49	1 214.03	1 747.47	1 466.02
Cable cost (€)	1 645 036	1 354 436	1 922 219	1 612 619
Total cost (€)	26 357 348	21 825 927	24 343 415	19 811 994
Cost reduction (%)	0	17.19%	7.64%	**24.83%**

Thus, Fig. 5 shows the new network design after executing both improvements (MEC path sharing and WAN ring topology), which reduce the length of ducting and cabling required (and consequently costs). The effect of path sharing between BSs and MEC-DCs can be observed in the figure focusing on the blue lines, which show the ducts used to connect those nodes. The BSs (blue dots in the figure) are not always connected through a straight duct to their MEC-BSs, but instead they have been iteratively connected by a duct to the nearest BSs that already has a duct connection to the MEC-DC, as long as the resultant path from the non-connected BS to the MEC-DC does not exceed 50 km. Otherwise, the BS is connected by a direct straight duct to the MEC-DC. Fig. 5 also shows a ring topology connecting MEC-DCs and the WAN gateway (red lines in the figure) in contrast with the star topology of the initial design (Fig. 4). As we mentioned, in the ring topology each MEC-DC has two fiber connections to the gateway (one for each direction of the ring) to provide survivability.

Numerical results are shown in TABLE 1. The total cost for each design option, as well as the costs broken down by category, are specified. Four design options are considered there: the solution provided by the ILP formulation (the design shown in Fig. 4), the solution if only the path sharing improvement (described in Section III) is applied on the ILP solution, the solution if only the ring topology improvement (described in Section IV) is applied, and the solution if both improvement mechanisms are used (i.e., the design shown in Fig. 5). All these options require the same number of MEC servers, so they have the same cost associated to this category. However, there are significant differences in terms of cabling and, above all, ducting costs, the latter being the category that contributes most to the total cost. The results show that the implementation of the MEC path sharing strategy reduces the total cost of the network by 17.19% when compared with the initial ILP design, the change of the star topology to a ring topology for the WAN links leads to a reduction of 7.64%, and the application of both improvement techniques reduces the cost by 24.83% in this scenario when compared to the initial design.

It is worth mentioning that when the ring topology is applied, more km of cable than km of ducting are needed. The reason of this difference is that, as previously mentioned, each MEC-DC is connected to the WAN gateway with two fibers, one following each direction of the ring, and more than one cable (in particular, two) must be deployed to equip the ring with the proper number of fibers. It is interesting to note that, despite the ring implementation requires more cabling than the ILP solution, it still implies a reduction in total cost, given that it requires less ducting, which is the costliest component of the deployment.

A summary of results for different percentages of simultaneously connected population (from 0.1 to 3%) is shown in Fig. 6, which plots the total cost for each design option. The results are consistent with those shown in TABLE 1.

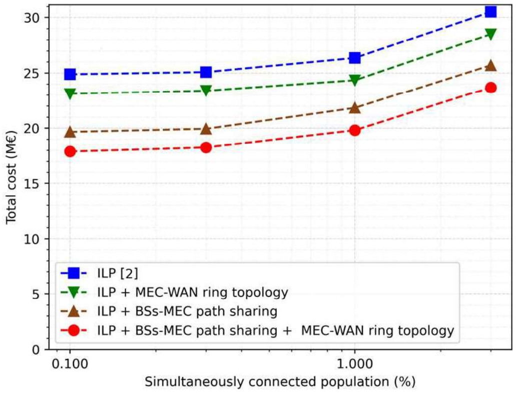

Fig. 6: Cost comparison for the different design options.

The introduction of the WAN ring reduces the cost, the introduction of MEC sharing leads to a greater reduction, but the greatest reduction is obtained when both procedures are combined. A noteworthy aspect is that the cost increases with population due to the MEC servers, since the larger the population, the higher the workload and, therefore, more servers will be required. Summarizing, we can conclude from Fig. 6 that the application of the proposed strategies reduces the deployment cost, and the increase of the connected population increases the cost associated to servers.

The results of Fig. 7 show the required kms of civil works (ducting). The effect of the improvements proposed in this paper is evident, and the combination of the two techniques reduces the amount of required civil works notably. The amount of required ducting barely changes as the connected population increases, confirming that the variations observed in Fig. 6 are an effect of the increase in the number of MEC servers.

Regarding cabling, Fig. 8 shows that, as previously discussed, the adoption of the ring topology implies an increase in the needed cable. However, it reduces the amount of ducting required, which is more expensive, and provides the network with resilience. Anyway, the final design, which consists in applying both improvement techniques also requires less cabling than the solution provided by the ILP model.

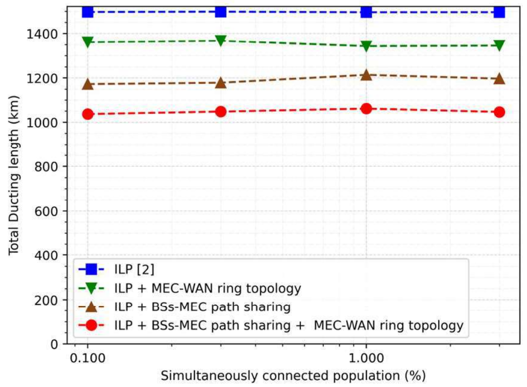

Fig. 7: Ducting length comparison for the different design option.

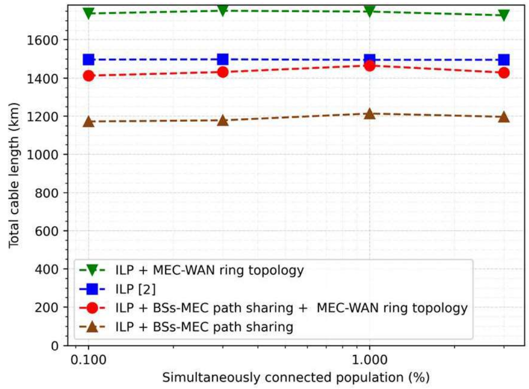

Fig. 8: Cable length comparison for the different design options.

VI. CONCLUSION

In sparsely populated areas, the availability of high-quality communication networks is not guaranteed. Additionally, since these environments are frequently far from urban areas, the length of the connections to be deployed, and therefore their cost is generally high. MEC technologies enable the implementation of novel applications and services, but require the use of high-performance communications infrastructures. Therefore, to bring these new services to sparsely populated areas, it is important to perform a careful planning of those infrastructures. In a previous work, we proposed an ILP formulation which determines where to locate MEC data centers, how to dimension them, how to assign the workload from different base stations to those data centers, and which fiber connections should be deployed to connect base stations, MEC data centers and a WAN gateway. In this paper, we have proposed and demonstrated two mechanisms to improve the solutions provided by the ILP model in terms of the optical cabling infrastructure. The first improvement reduces the cost of the links between base stations and MEC data centers by using multi-fiber cables sharing the same ducts or paths as much as possible and subject to latency constraints. The second improvement focuses on the connections between MEC data centers and the WAN gateway by replacing direct connections with a ring topology, which keeps the functionalities of the former, but reduces costs and provides resiliency to this network segment.

We have evaluated our proposals in a case study on the sparsely populated province of Valladolid (Spain), and the quantitative results show that, for this scenario, the proposed improvements lead to cost savings of around 25% when compared to the initial design provided by the ILP formulation.

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