Techno-economic Analysis of MEC Clustering Models for Seamless CCAM Service Provision

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***Abstract*—The latency requirements of delay-sensitive applications such as Cooperative, Connected and Automated Mobility (CCAM) services challenge the capabilities of traditional vehicular radio access technologies, i.e., IEEE 802.11p and cellular networks. To this end, the fifth-generation (5G) cellular network is adopting the Multi-access Edge Computing (MEC) paradigm. Yet, the use of this technology comes with several challenges. In this paper, MEC placement challenges and their impact on network deployment costs are studied. We propose three MEC clustering models and compare them from a cost perspective. Results show that all the MEC clustering models outperform the non-clustering approach. In addition, the conditions in which specific clustering models yield the most optimal results are analyzed. Results aim at providing insights into cost-effective MEC deployment models.**

***Index Terms*—5G mobile networks, CCAM services, clustering models, TCO cost model, MEC, MEC placement, techno-economics.**

I. INTRODUCTION

Multi-access Edge Computing (MEC), Software-Defined Networking (SDN), and Network Functions Virtualization (NFV) are seen as the key enabler technologies for meeting the fifth-generation (5G) promised Key Performance Indicators (KPIs) [1]. High capacity, low latency, and high reliability are among the requirements needed to provide the three famous 5G use cases: ultra-Reliable Low Latency Communications (uRLLC), enhanced Mobile Broadband (eMBB), and massive Machine Type Communication (mMTC). One sector that has strict requirements concerning the abovementioned KPIs is the automotive sector, and even more so specifically when it comes to Cooperative, Connected and Automated Mobility (CCAM) use cases. In particular, CCAM safety-related services are delay-sensitive applications [2]. MEC technology, with its capacity to reduce latency by hosting services close to users and data generators, is considered essential for providing CCAM services [2].

The European Telecommunications Standards Institute (ETSI) stated that "MEC offers application developers and content providers cloud-computing capabilities and an IT service environment at the edge of the network. This environment is characterized by ultra-low latency and high bandwidth as well as real-time access to radio network information that can be leveraged by applications" [3].

Furthermore, according to the 5G Automotive Association (5GAA), "MEC technology is substantial for the realization of the V2X use cases that require low latency on the one hand and are expected to increasingly generate data that can be collected and processed closer to the user on the other hand" [4].

Within the scope of the 5G-CARMEN project, several CCAM use cases require low latency and high reliability, such as cooperative and automated lane-change maneuvers and cooperative and automated in-lane maneuvers. The latter have been investigated in a more specific cross-border context, where roaming will introduce a significant additional latency [5]. Therefore, the developed architecture relies on the use of MEC technology to meet these KPIs [6].

Although the MEC paradigm puts computation and storage capabilities close to the edge or a Radio Access Network (RAN), suitable MEC placement within the network topology raises significant challenges for Mobile Network Operators (MNOs). From a cost perspective, a transition from centralized hosting models to distributed/decentralized models results in significant deployment costs. From a technical perspective, a highly distributed MEC deployment (i.e., next to each cell tower) introduces security and technical challenges, such as the need for dynamic service placement optimization and control of the impact on the latency KPI due to the required inter-MEC switches. Therefore, a trade-off between latency and cost needs to be reached to benefit from the potential of this new technology while keeping the cost of network investment as low as possible.

Numerous papers in the literature have studied the MEC paradigm adoption to support delay-sensitive services from different perspectives, such as challenges and opportunities in [1] and [2], and dynamic service placement and migration between MEC servers for all types of services in [7] and CCAM services in [8]. However, there is a need to shed more light on the MEC placement issue from a cost perspective while fulfilling required CCAM service KPIs.

In this paper, we develop a Total Cost of Ownership (TCO) model to assess the impact of MEC placement at different yet fixed levels within the network topology on the network investment cost to support 5G-CARMEN use cases.

Furthermore, to find a trade-off between CCAM-required latency and the cost of MEC deployment, given certain parameters like the existence of certain network infrastructure or the possibility of active/passive network sharing, we propose three MEC clustering models. Concretely, we propose two variants of the star topology model and the collapsed star topology model. We use the developed TCO model to compare these three proposed MEC clustering methods. In addition, since the star topology model requires links between the MEC node and the next-generation Node-B (gNB) under the same cluster, an optimization algorithm is developed to find the optimal MEC node position that minimizes the total required fiber length.

II. Total Cost of Ownership model

A. Structure of the generic Total Cost of Ownership model

The generic TCO model structure for MEC deployment is presented in Fig. 1. The proposed model considers both the Capital Expenditures (CAPEX) and Operational Expenditures (OPEX) as well as overhead costs such as marketing and helpdesk costs. The main inputs of the model are related to the costs of the hardware equipment. More specifically, these costs concern the MEC servers, the cabinets to host the MEC hardware, the cooling system, the fiber backhaul, and the cost of renting sites to host MEC nodes. These inputs feed into the CAPEX calculation where costs of hardware as well as installation costs are considered. The OPEX, which represent the costs to keep the network operational, consist of site rental, power consumption, and hardware maintenance. The cost of software licensing is excluded from the calculation due to a lack of inputs. Next, overhead costs, which cover marketing, helpdesk services, human resources, finance, etc., are approximated, based on the work of Casier [9], by adding 20 percent to the sum of the CAPEX and OPEX. Finally, summing up CAPEX, OPEX, and overhead costs results in the TCO of the MEC deployment. It is worth mentioning that the application of this model is case-specific. In some cases, we do not need to deploy new fiber to connect the MEC node to the rest of the network since a fiber backhaul is already in place. In other cases, there is enough space next to the tower (gNB) to host the cabinet, so there is no need to rent new sites to deploy the MEC nodes. In addition, based on the placement of the MEC nodes in the network, the need for a cabinet and a new cooling system is to be decided.

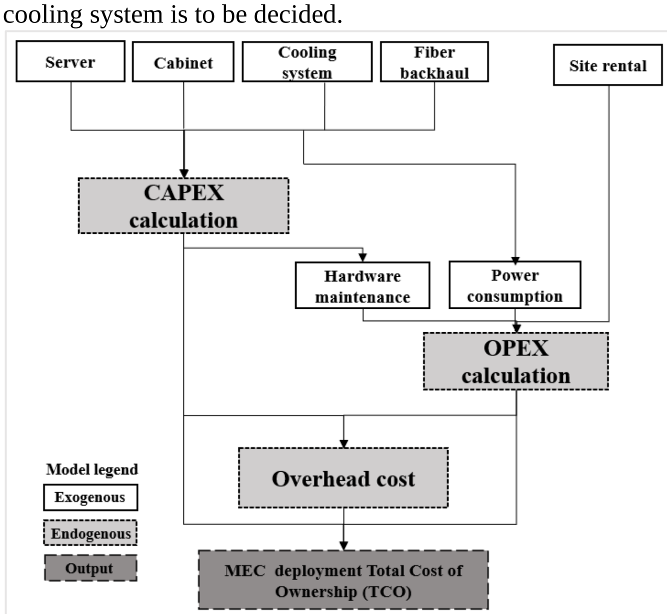

Fig. 1. MEC cost model structure

B. Application of the TCO model to different MEC placements within the network architecture

Given a generic network architecture, as presented in Fig. 2, we studied the cost of placing MEC nodes at the different levels of the network: at the MNO data centers (DCs), at the core transmission sites, at the radio aggregation sites, or at the RANs. We applied the cost model to the entire Bologna-Munich corridor case, a corridor under study in the 5G-CARMEN project that covers 600 kilometers (km) and spans three countries. Assuming an average inter-gNB distance of 3 km, we have around 200 gNBs in total installed next to the corridor. Since three countries are involved, three DC sites operated by three different MNOs are considered. In the reference mobile network architecture shown in Fig. 2, which has been put forward in collaboration with two MNOs active in the 5G-CARMEN project, there are 100 aggregation sites, which corresponds to almost one for every second radio site. For every ten aggregation sites, there is one core transmission site, which yields ten for the network in total. We considered the use of one server per MEC node when the node is installed at a radio or aggregation site. In case the MEC node is installed at the core transmission site or the DC, we consider the use of two servers per MEC node, assuming that spare DC processing resources can be used to support the processing of peaks in traffic.

We used the following costs to run the proposed TCO model: the cost of a MEC edge server of type "gigabyte-h242-z10" is €10,000 [10]; cooling system and cabinet costs for the MEC deployment are around €2,200 and €2,500, respectively [11]; maintenance of mobile network equipment is assumed to be 10 percent of the original CAPEX [8], and the price of electricity is €0.1085 per kWh [12].

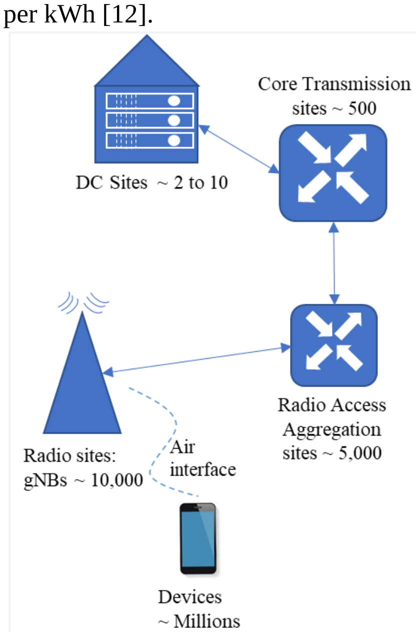

Fig. 2. Reference mobile network architecture

Table I shows a breakdown of the cost per cost type related to a MEC deployment over a period of 10 years for each MEC location option. Note that the cost results presented in Table I do not include the cost of fiber cables that link the RANs to the aggregation sites. Even though this cost has been excluded, which represents a significant cost due to the cable installation cost, deploying MEC at the RANs is the costliest option. We refer to the latter deployment option in the rest of the paper as the non-clustering MEC deployment. Yet, moving the MEC placements up in the hierarchy of the network topology, i.e., closer to the DC, significantly decreases the cost of the MEC deployment due to the lower number of required MEC nodes. The latter impacts the end-to-end (E2E) latency for the CCAM services, however. By placing the MEC nodes higher up in the network topology, multiple hops are introduced between the connected vehicle and the CCAM application instance, which is hosted at the MEC server. Therefore, the round-trip time is affected, hence the need to find a relevant balance between targeted latency and network deployment costs.

Nonetheless, rather than choosing one location type, one solution could consist of performing MEC clustering, where one MEC node serves multiple gNBs at the same time within the so-called cluster. Different clustering models are identified and detailed in the next section.

TABLE I

DIFFERENT MEC PLACEMENT COSTS

Item	Unit	Radio sites	Radio access aggregation sites	Core transmission sites	Core data center sites
Number of sites	#	200	100	10	3
MEC CAPEX	€k	2,940	1,220	244	74
Cumulative MEC OPEX over 10 years	€k	3,070	1,285	295	89
Cumulative overhead costs over 10 years	€k	1,202	501	108	33
MEC TCO (10 years)	€k	7,212	3,006	647	195

III. Proposed MEC Clustering Models

In addition to representing a costly solution, installing MEC nodes at each tower has other disadvantages. First, it introduces security challenges, among which are the need for physically securing each MEC node on the corridor and securing it against intrusions at the software level. The exact required security measures in a distributed deployment model are still unknown since MEC is currently being deployed at MNO DCs. Accordingly, the related additional costs are still unknown. Second, installing MEC nodes at each tower has an impact on the E2E latency because, if we increase the number of MEC nodes with a short inter-distance, latency increases since switching from one MEC to another requires the transfer of service-related data and sessions, which induces new latency of roughly 1–2 milliseconds (ms) per MEC switch. Therefore, MEC clustering could be viewed as a solution that considers cost, security, and latency requirements. But the question of how to define a MEC cluster still holds.

A. Star topology model

In this model, the MEC node is situated at the same distance from all the gNBs within the MEC cluster and connected directly point to point with the gNBs with two possible options:

- Option 1: The number of gNBs within the same MEC cluster is different from the number of gNBs that are served by the radio access aggregation site, so hosting MEC at the aggregation site will not make sense. In this case, we need to lease a new site between the aggregation site and the radio access sites to host the MEC node, as illustrated in the top left-hand side of Fig. 3. In addition, installing fiber cable is needed to connect each tower to the MEC node.
- Option 2: The number of gNBs within the same MEC cluster is the same as the number of gNBs that are served by the radio access aggregation site, so it can be placed at the radio access aggregation site. This option is depicted in the top right-hand side of Fig. 3.

In both cases, we have to consider the cost of linking the MEC nodes to each other with fiber cable to ensure inter-MEC communication.

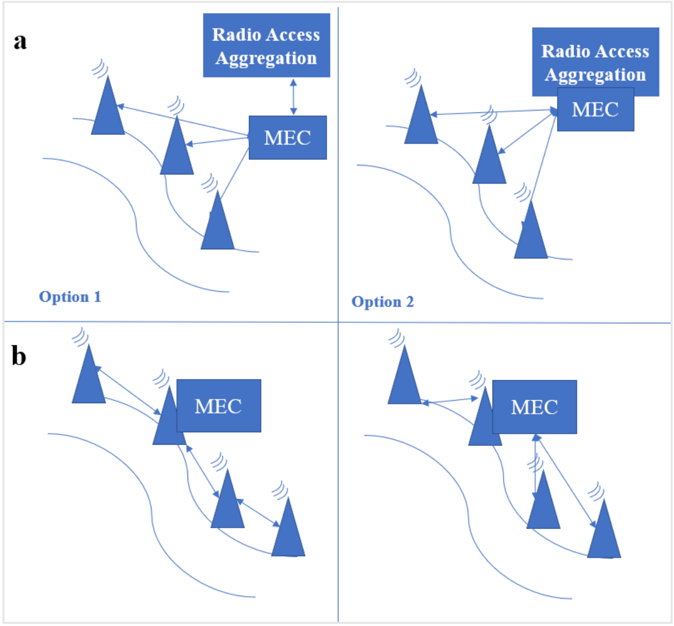

Fig. 3. a) star topology with option 1 on the left-hand side and option 2 on the right-hand side; b) bus topology on the left-hand side and collapsed star topology on the right-hand side.

B. Collapsed star topology model

An alternative option to deploy MEC clustering is to co-allocate the MEC node with one of the gNBs in its cluster instead of leasing a new site. The right-hand side of Fig. 3 presents this model. Connecting the MEC node to the different gNBs can be done in two different ways:

- Option 1: As the bus topology, represented in the bottom left-hand side of Fig. 3, introduces more hops in the link between gNBs and the MEC, we have decided to exclude this option for the sake of preserving latency.

- Option 2: Point-to-point connections between each gNB within the cluster and the MEC node could be installed, as illustrated in the bottom right-hand of Fig. 3. Hence, fiber cables are needed for the different links. An optimization algorithm is developed to determine the best position to host the MEC node while aiming at minimizing the total fiber cable needed given the certain number of gNBs per MEC cluster.

Another option could consist of leasing fiber cables from road operators if they have already been installed along the corridor. These two different options will be compared from a cost perspective to give more insights to MNOs for the MEC deployment options in section V.

IV. End to End latency for different MEC deployment options

MNOs and MEC service providers have been looking for deployment models that help reach trade-offs between the required service KPIs and deployment costs. In order to illustrate the impact of MEC placement on E2E latency, system-level simulations were carried out by Poli et al. [13] within a centralized Cooperative Lane Change (CLC) use case involving three vehicles. The targeted round-trip latency is typically in the order of tens of ms, while the exchange delay requirement should be kept lower than 100 ms from the generation time to the reception time [15]. In these simulation-based evaluations, different road traffic conditions were considered as well as a varying proportion of connected road users generating their own CCAM data traffic (i.e., with up to 25 percent of the simulated vehicles active in transmission, besides the three CLC vehicles under test). This comparison encompassed decentralized, clustered, and centralized MEC deployment options (respectively with one MEC per gNB, one MEC per radio aggregation site, or one MEC per MNO DC). RAN latency was simulated through ns-3 up to the application layer, including jitter at the radio level depending on link quality, resource scheduling, and network load effects. Conversely, higher-level latency components beyond radio access were set a priori as abstract bounds, for example, by integrating typical extra delays related to backhaul, core network, and possibly fast inter-MEC connections in the overall latency budget. For instance, for backhaul latency and core network latency terms, a distance-driven penalty of 2 ms was assumed for each component. These assumptions are typically based on a coarse estimate of 1 ms per 100 km for fiber transport. In addition, ultra-fast inter-MEC connections of typically 1–2 ms per MEC switch for transferring service-related data/sessions were also considered, whenever needed.

As expected, the overall E2E latency was hence shown to increase as a function of network load (e.g., 6–12 ms for uplink messages, depending on the tested configurations and radio settings). Moreover, the latency magnitude specifically imputable to radio access seemed to dominate by far all other higher-level latency components present in the overall budget (1–6 ms, depending on the MEC placement assumption). This simplified illustration suggests that a fully decentralized MEC option would be only marginally advantageous while requiring more costly orchestration efforts and associated latency (not accounted for in the previous study though), and hence, even larger latency. Therefore, a clustered MEC deployment is likely to offer a relevant balance between performance and cost.

V. Cost comparison between the proposed MEC clustering models

In order to find the best MEC clustering model in specific circumstances, we run the MEC TCO model, as described in the second section, for each of the three models described in the previous section, namely:

- **M11**: star topology model option 1, MEC node hosted in between the radio sites and the aggregation sites;
- **M12**: star topology option 2, MEC hosted in the aggregation site;
- **M2**: collapsed star topology, MEC hosted next to one of the towers within the MEC cluster.

Multiple initial condition scenarios per MEC clustering model can be identified and are parametrized in the models. They range from having no infrastructure in place at all to already having part of the required infrastructure installed. For models M11 and M2, two parameters have been used to describe four scenarios per model. Specifically, one parameter captures the existence of fiber cables that link the gNBs to the MEC node, and the other captures the need to lease a site to host the MEC node. For model M12, however, the MEC node will be hosted in the aggregation site, so there is no need to lease an additional site to host it. The M12 clustering model instead requires fiber linking the different aggregation sites to ensure a direct inter-MEC connection. The prior existence of this link is captured by an additional parameter, yielding four scenarios for M12 as well. In this paper, we only compare the worst and the best scenarios of the three models. The worst scenarios represent the greenfield deployments, which means no prior availability of the infrastructure. Yet, the best scenarios consider the availability of some of the required infrastructure. The worst scenarios of the three models combining the abovementioned parameters are as follows:

- **M11**: no prior availability of fiber from the gNBs to the MEC node and no prior availability of hosting site;
- **M2**: no prior availability of fiber from the gNBs to the MEC node and no prior availability of hosting site;
- **M12**: no prior availability of fiber from the gNBs to the MEC node (hosted in the aggregation site) and no prior availability of fiber between aggregation sites.

The best scenarios of the three MEC clustering models combining the aforementioned parameters are:

- **M11**: prior existence of fiber from the gNBs to the MEC node and prior availability of hosting site;
- **M2**: prior existence of fiber from the gNBs to the MEC node and prior availability of hosting site;

- **M12:** prior existence of fiber from the gNBs to the MEC node (hosted in the aggregation site) and prior existence of fiber between aggregation sites.

The corridor under consideration has 200 gNBs spanning 600 km of highway from Munich to Bologna. Since the required number of gNBs that can be clustered per MEC node is not known, the total required number of MEC nodes is unclear. Thus, a range of values is analyzed between four gNBs per MEC node and 24 gNBs per MEC node. Twenty-four gNBs are chosen as a higher bound because of the hardware performance of the assumed MEC server, which can support traffic of up to 24 gNBs [10].

The results of the cost models are visualized in Fig. 4 and Fig. 5. Fig. 4 shows the cost results of the greenfield deployment, which means no prior availability of the infrastructure. As shown in Fig. 4, M12 is the costliest clustering model. It is 32–44 percent and 19–89 percent more expensive than M11 and M2, respectively, depending on the number of gNBs per cluster. This is due to the total fiber length needed to connect the 200 gNBs to the aggregation sites and the aggregation sites to each other. Contrast this to clustering model M11, in which the fiber links to the MEC node are aggregated, and only one cable is required to link the MEC node to the aggregation site, reducing the total length of expensive fiber connections required. Another important observation is that the collapsed star topology (M2) is the most cost-effective model as long as fewer than 17 gNBs are grouped per MEC cluster. If more gNBs are clustered per MEC node, the total length of required fiber increases significantly, which makes the model more costly than M11. This can be explained by the fact that if we increase the number of gNBs per MEC cluster, the average distance between gNBs and the MEC node in a collapsed star topology becomes bigger than in the one using the star topology model.

When a significant number of gNBs per MEC cluster is considered, an inconsistent relationship between the number of MEC clusters and the total cost is noticed in M2. In fact, increasing the number of MEC clusters by one can be cheaper than having more gNBs per MEC cluster and their related fiber connections. This phenomenon can be observed starting from point (17, 11) on the M2 curve in Fig. 4.

Especially for the star topology model (M11), it seems rather unrealistic that fiber cables would already be in place. In contrast, in the collapsed star model (M2), where the MEC node is hosted next to one of the gNBs within the MEC cluster, it is more likely that fiber cables are already present. These connections would generally run along the roadside and might already be deployed by road operators or MNOs. Therefore, we simulated a variant of the M2 model with different prior infrastructure availability assumptions. Concretely, it is assumed that the MNO will save on fiber cables by sharing the infrastructure in a passive or active way with a different operator, which could be a road operator or an MNO. Using network-sharing models results in different cost savings. According to a report by BEREC [14], passive infrastructure sharing could save 16–35 percent of CAPEX and 16–35 percent of OPEX, while active infrastructure sharing could result in savings of 33–35 percent of CAPEX and 25–33 percent of OPEX. Taking these assumptions into account, we compared the collapsed star clustering model (M2) without prior infrastructure with active and passive fiber-sharing options to the worst scenarios in Fig. 4.

The results show that by sharing the fiber installation, the TCO can be reduced by up to 31 percent (Fig. 4). Active sharing yields more savings than passive sharing: 32 vs. 25 percent. Importantly, even with a high number of gNBs per MEC cluster, the collapsed star topology model (M2) with active sharing is the least costly of all clustering models.

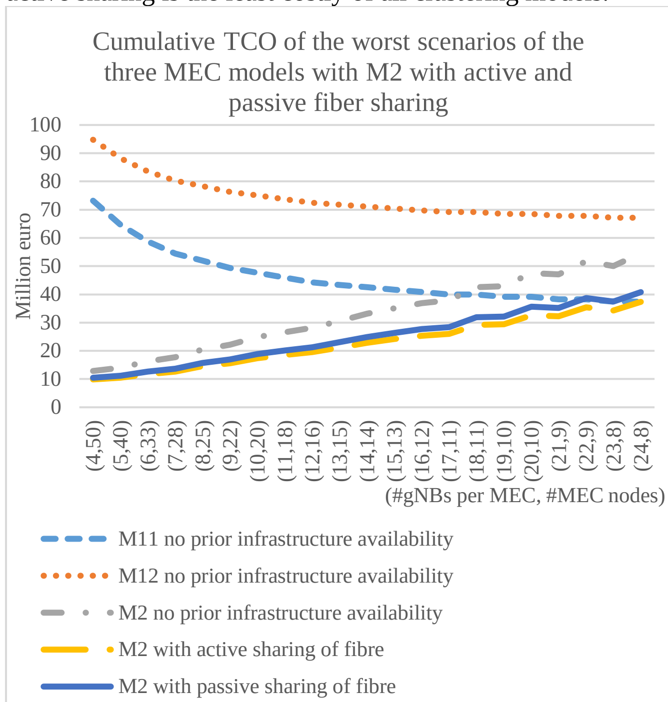

Fig. 4. The Cumulative TCO plotted against the number of MEC nodes for the three MEC models, given no prior infrastructure availability, as well as for two variations on M2 with active and passive sharing of fiber cable.

What if some of the required infrastructures for the MEC deployment are already in place? Fig. 5 depicts the best scenarios with the prior infrastructure available for all models. It is found that the clustering model M12, in which MEC nodes are hosted at the aggregation sites, is the most cost-effective clustering option given prior infrastructure availability by 17 percent as a cost reduction compared to the two other models. The source of the cost advantage of M12 over M11 and M2 is the cost of the cabinet required to host the MEC hardware, since it is assumed that there is enough space to host the required hardware at the aggregation site. Additionally, models M11 and M2 are identical from a cost perspective when prior infrastructure is maximally available. This makes sense because exactly the same hardware needs to be deployed, since fiber connections are already present and MEC hosting sites are available. Importantly, even the most expensive clustering models M11 and M2 are less costly compared to the non-clustering option described earlier. They have a TCO of €2 million, given the highest number of MEC nodes required, compared to €7 million for the non-clustering model presented in Table I, which resulted in 71 percent cost saving on the TCO.

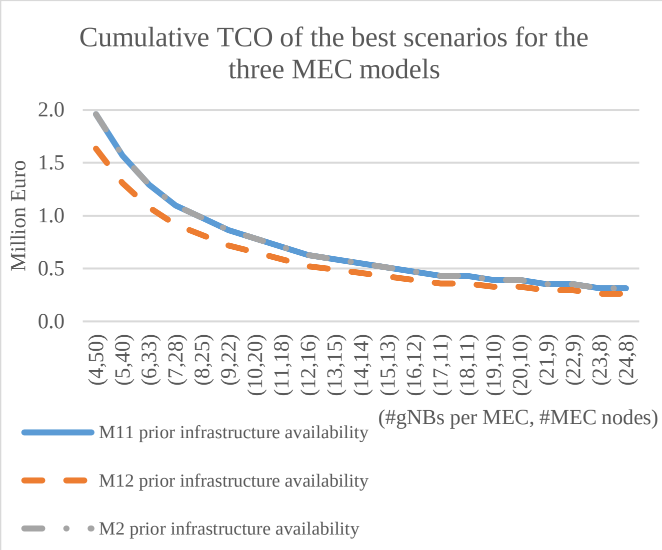

Fig. 5. The cumulative TCO as a function of the number of MEC nodes for best scenarios of the three MEC models.

The main takeaways from this analysis are as follows. First, it is found that all the MEC clustering models are less costly than the non-clustering approach, where MEC nodes are hosted next to each gNB. Second, when no prior infrastructure is available, the star topology model with MEC nodes hosted at the aggregation site (M12) is the costliest model, while the collapsed star topology model (M2) is the most cost-effective model as long as 17 or fewer gNBs are grouped per MEC cluster. When more than 17 gNBs are grouped per MEC cluster, the star topology model with MEC nodes hosted in between aggregation sites (M11) is the least costly. Finally, when prior infrastructure is maximally available, the star topology model with MEC hosted at the aggregation site (M12) is consistently the most cost-effective clustering model.

In practice, no MEC clustering model fits all networks. The derived cost results can help network operators decide which option to adopt given the status of their network in the considered deployment region. In areas where a good fiber infrastructure is already present, the star topology clustering model is likely to be the optimal one. Yet, for remote areas where no fiber is installed, the collapsed star topology model is likely the optimal clustering method, especially if passive or active network-sharing strategies can be adopted.

VI. Conclusion

In this paper, three different MEC clustering models addressing the MEC placement challenge are analyzed from a cost perspective, given latency requirements. The analysis showed that all MEC clustering models outperform the non-clustering deployment in both cost-effectiveness and efficiency: MEC clustering models allow a saving of up to 71 percent on the TCO and a reduction of E2E traffic latency of 1–6 ms. Given the prior availability of network infrastructure along the considered highway, certain models are cheaper than others. For instance, the collapsed star topology (M2) is 19–89 percent less expensive than the other models when no prior infrastructure is available. Yet, the star topology with hosting MEC at the aggregation site (M12) is 17 percent cheaper when some of the infrastructure is available. Network sharing in both its active and passive flavors significantly decreases the cost of the MEC deployments by 31 and 25 percent, respectively. Since a comparison of latency was only performed between centralized, clustered, and decentralized models, future work could consist of performing system-level simulations to compare the E2E latency between the three clustering models. In addition, future work could address the impact of the variation of bandwidth requirements and the network traffic loads over time on the dimensioning of the number of servers needed per MEC node.

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