End-to-End Latency of V2N2V Communications under Different 5G and Computing Deployments in Multi-MNO Scenarios

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***Abstract*—Cellular networks usually support non-safety-critical V2X services using Vehicle-to-Network (V2N) connections. However, the flexibility and capabilities of 5G have triggered interest in analyzing whether 5G could also support advanced V2X services using Vehicle-to-Network-to-Vehicle (V2N2V) connections instead of direct Vehicle-to-Vehicle (V2V) connections. V2N2V requires the integration of the 5G network with computing platforms for processing the V2X packets. The flexibility introduced by 5G facilitates the integration with multiple computing platforms such as Multi-access Edge Computing (MEC), edge cloud, shared data center or central cloud. This results in alternative 5G network deployments with the computing platform installed at different locations between the base station and the Internet. These deployments can have important technical implications for supporting V2X services. In this study, we analyze the impact of different 5G and computing platform deployments on the end-to-end (E2E) latency of V2N2V communications under multi-MNO (Mobile Network Operator) scenarios since vehicles may be served by different operators. We also identify which deployment strategies are more suitable to meet the latency requirements of V2X services for connected and automated driving.**

Keywords*—5G, CAV, central cloud, computing platform, connected and automated vehicles, E2E latency, edge cloud, MEC, shared data center, V2N2V, V2X.

I. Introduction

Cellular networks usually support V2X services (e.g., traffic management, infotainment or location-based services) using Vehicle-to-Network (V2N) connections. However, 5G has been designed with unique capabilities and flexibility with the objective to support advanced and demanding services such as automotive applications. This has generated interest on whether 5G could support advanced V2X services between vehicles using Vehicle-to-Network-to-Vehicle (V2N2V) communications (Fig. 1) instead of direct V2V connections. To this aim, it is necessary that the 5G network interacts with computing platforms hosting the V2X application server (AS) that receives V2X packets over the V2N uplink from vehicles, processes them and then forwards back to vehicles over the V2N downlink.

The flexibility introduced in 5G supports the integration with different computing architectures or platforms that can be installed at different locations between the base station and the Internet. This includes Multi-access Edge Computing (MEC), edge cloud, central cloud, and shared data centers. All possible 5G and computing deployment alternatives are considered by 5GAA (5G Automotive Association) and ETSI (European Telecommunications Standards Institute) in [1] and [2], respectively. The selected 5G and computing platform deployment can have important performance and technical implications for supporting V2X services, and [1] highlights the need for studies that analyze the performance that can be reached with the different 5G and computing platform deployments. These studies must consider multi-Mobile Network Operator (MNO) scenarios since vehicles may be supported by different MNOs. However, we should note that multi-MNO scenarios generate multiple challenges since MNOs might implement different 5G and computing platform deployment strategies.

A key aspect to support advanced and critical V2X services is the end-to-end (E2E) latency. In this study, we analyze and quantify for the first time the impact of different 5G and computing platform deployments on the E2E latency experienced when supporting V2X services using V2N2V communications in multi-MNO scenarios. Our evaluation helps identify which deployment strategies are more suitable to support advanced and latency-critical V2X services using V2N2V communications in realistic multi-MNO scenarios. We also analyze the potential of the different 5G and computing platform deployments to support the requirements of connected and automated driving services, using the cooperative lane merge service as a case study.

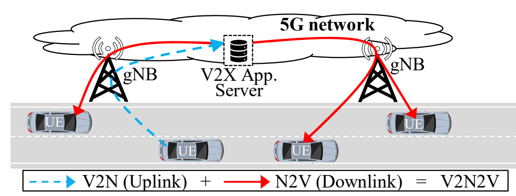

Fig. 1. Vehicle-to-Network-to-Vehicle (V2N2V) communication scenario.

II. Integration of 5G and Computing Platforms

Fig. 2 illustrates the different 5G and computing platform deployment alternatives that are currently considered under 3GPP, ETSI and 5GAA to support V2N2V communications. For illustration purposes only, Fig. 2 considers that the integration of 5G and the computing platforms deployed at the edge (edge cloud, MEC, shared data center) occur at the multiplexing node M1 of the transport network. The integration could also happen at the gNB, or any multiplexing node of the transport network (M1, M2 or M3). For the sake of clarity, we describe in this section all 5G and computing platform deployment strategies for a single-MNO scenario.

A. Central Cloud

The central cloud is located outside of the MNO domain, and it is accessed through the public Internet. The integration with the 5G system is realized through the N6 interface of the user plane function (UPF) node of the Core Network (CN) [3GPP-23.501]. For the support of V2N2V, the V2X AS can benefit from powerful computing and storage resources available on the central cloud. The integration of 5G with the central cloud could also facilitate the deployment of V2X services that can reside, for example, at an automotive OEM's (original equipment manufacturer) cloud. However, the support of V2X services at the central cloud is challenging due

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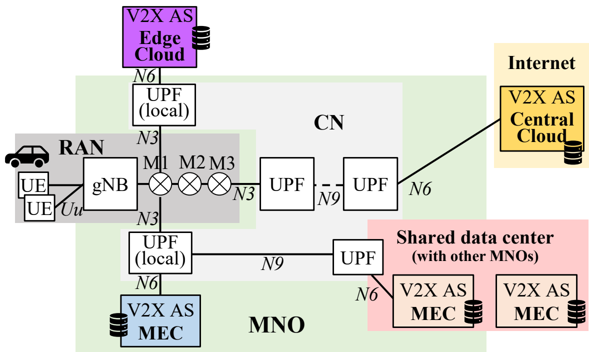

Fig. 2.Integration of central cloud, edge cloud, MEC or shared data center computing platforms with the 5G system architecture.

to the latency that V2X packets would experience as they need to traverse the entire 5G network. A further challenge is that the Internet access required to reach the V2X AS does not provide QoS guarantees.

B. Edge Cloud

The edge cloud represents a cloud point-of-presence on the same "operator's premises" as the MNO, but it is outside the MNO's control and trust space [2]. The closer location of the edge cloud to the edge of the 5G network compared to the central cloud helps reducing the latency that V2X packets experience to reach the V2X AS. Another benefit of moving the computing resources to the edge arises from the possibility of processing regional data that can be dispatched locally instead of being uploaded over the Internet to the central cloud [1]. It is also important to note that even though the edge and central clouds are both integrated with the 5G network through the N6 interface of the UPF, a local UPF collocated with the gNB or a multiplexing node of the transport network (M1, M2 or M3) is used to steer the traffic towards the V2X AS hosted at the edge cloud. Another important difference between the central and edge cloud is related to the way they connect to the MNO. While the central cloud relies on the Internet to connect to the MNO, the edge cloud is connected to the MNO's network via high-performance links over which the MNO can enforce strict QoS requirements [2].

C. Multi-Access Edge Computing (MEC)

The integration of MEC with the 5G network exhibits some similarities with the case of the edge cloud described above. As depicted in Fig. 2, the MEC also interfaces with a local UPF of the CN, and it also uses high-performance links over which the MNO can enforce strict QoS requirements [2]. Deployments integrating 5G and MEC can then also reduce the latency that V2X packets experience to reach the V2X AS, and benefit from local processing of regional data. There are however important differences between the MEC and edge cloud deployment strategies. Edge clouds are out of the MNO's control. On the other hand, MECs are installed as part of the MNO's network, and MNOs can fully control them and provide services at the edge.

D. Shared Data Center

MNOs can also integrate MEC computing platforms in their 5G network using a shared data center. In this case, MNOs do not host the MECs within their domains, but instead they host them at a shared facility. The integration of the shared data center with the 5G system architecture benefits from the flexibility introduced in 5G to deploy the UPF nodes that route the data traffic through the CN. As shown in Fig. 2, the UPF node that provides access to V2X AS hosted at the MEC is physically collocated at the shared date center. 5GAA considers in [1] that the interconnection from the local UPF and the UPF collocated at the shared data center is performed with a "controlled connection" or peering point link in order to control the QoS from the MNO to the shared data center. Peering point links could be remote (public) or local (private) when they are established through the public Internet at Internet exchange points, or by means of direct private links. A local peering point link is considered in this paper for the interconnection between the UPFs of the MNO' network.

III. 5G and Computing Deployment Strategies in Multi- MNO Scenarios

MNOs might follow different strategies to integrate computing platforms in their 5G networks. Then, we analyze in this section the V2X scenarios that result from the combination of possible 5G and computing platforms deployments in multi-MNO scenarios. The multi-MNO scenarios that can be realized depend on the definition and specification of the necessary interfaces between the computing platforms utilized by each MNO. These interfaces are utilized by the (V2X) applications running on the computing platforms to exchange control information for a seamless (V2X) service provisioning in multi-MNO scenarios. In our multi-MNO analysis, we consider that the V2X packets generated by the transmitting vehicle are processed in the computing platform to which the MNO is connected. The V2X packets are then forwarded to the other MNO network and routed towards the receiving vehicle without being processed again at the computing platform of the receiving vehicle's MNO. This is enabled thanks to the interfaces and control information exchanged between the computing platforms in the background [2].

A. Central Cloud – Central Cloud

A possible deployment for supporting V2N2V in multi-MNO scenarios is when the two MNOs integrate their 5G networks with the central cloud that hosts the V2X AS (Fig. 3). This scenario benefits from the native support to interconnect multiple MNOs' connection at the central cloud, especially when a third party provides the V2X service installed at the V2X AS. However, this scenario is constrained by the QoS challenges highlighted in Section II.A.

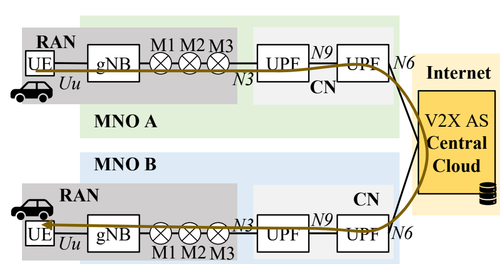

Fig. 3. Multi-MNO 5G deployment with central cloud.

B. MEC - MEC

This scenario is illustrated in Fig. 4, and represents the case where each MNO deploys its own MEC, and each one hosts a V2X AS. 5GAA indicates in [1] that in this scenario the MNOs can be interconnected through their Point of Presence (PoP) using the public Internet (Fig. 4-left). Alternatively, 5GAA also considers the interconnection between MNOs' PoPs using "controlled connections" or

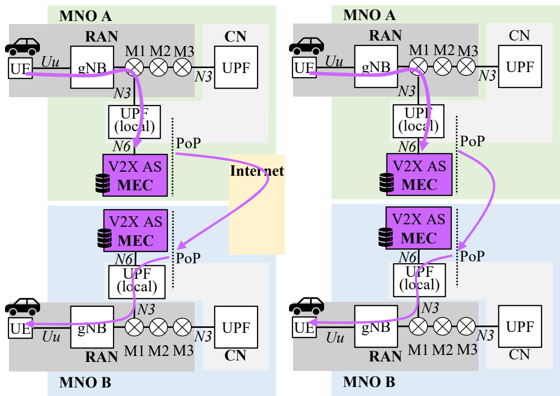

Fig. 4. Multi-MNO 5G deployment with MECs interconnected via public Internet (left) or local/remote peering point links (right).

local/remote peering point links (Fig. 4-right). This alternative requires a Service Level Agreement (SLA) with a Wide Area Network (WAN) provider (could be one of the MNOs) for the peering point link between PoPs [1]. The feasibility of this scenario is guaranteed thanks to the specification by ETSI [2] of the necessary interfaces to communicate with MEC computing platforms.

Fig. 4 considers the case where both MNOs integrate MECs. Alternatively, both MNOs could integrate edge clouds instead, or one MNO could integrate an edge cloud and the other a MEC. Following Section II, similar capabilities would be achieved with all the options. However, we should note that the necessary interfaces to connect two edge clouds or one edge cloud and a MEC like in Fig. 4 have been identified by 5GAA in [1], but they have not been specified yet. If such interfaces are not available, vehicles could only communicate with other vehicles served by the same MNO and connected to the same MEC or edge cloud platform.

C. Shared Data Center

Fig. 5 shows the scenario where the MECs of the different MNOs are located at a shared data center. The shared data center provides a native support and ability for communicating with different MNOs and their MECs. The use of a shared data center also brings additional capabilities [1] and facilitates the scalability of supporting V2X services with 5G. For example, it could help address limitations experienced when an MNO does not support a particular V2X service in the region covered by the shared data center. The subscribers of this MNO could be served by the MEC of another MNO sharing the data center. 5G deployments with a shared data center would also provide MNOs with the possibility to coordinate their MEC deployments. This would avoid each MNO implementing the same V2X services in every location.

D. Central Cloud - MEC

Fig. 6 considers a heterogeneous 5G deployment in which a MNO locates the V2X AS at the central cloud and another MNO at a MEC. An equivalent scenario would result if the MEC is substituted by an edge cloud. The necessary interfaces between the central cloud and the MEC (or edge cloud) are identified in [1], but they have not been specified yet. ETSI analyzes this heterogeneous scenario in [2]. However, it focuses only on the case where a vehicle roams from one MNO to another MNO, and the V2X application running on the cloud of the first MNO needs to be transferred to the MEC

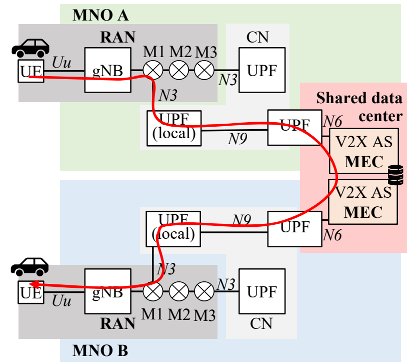

Fig. 5. Multi-MNO 5G deployment with shared data center

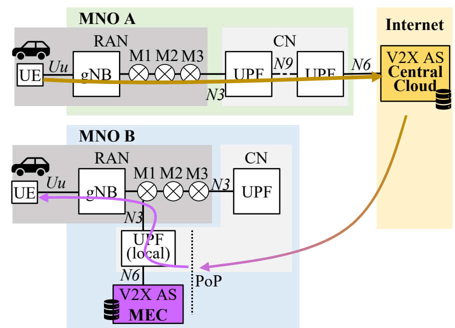

Fig. 6. Multi-MNO 5G deployment with central cloud and MEC

of the second MNO. In this study, we consider that the central cloud-MEC interfaces necessary for V2N2V communications in multi-MNO scenarios are available. Under this assumption, the V2X traffic generated by the vehicle supported by MNO A reaches the central cloud through the Internet. Then, the central cloud forwards the V2X traffic towards the MNO B's PoP through the Internet to reach its MEC. Finally, the MNO B delivers the V2X traffic to the receiving vehicle.

E. Other Multi-MNO Scenarios

Additional multi-MNO scenarios (with different combinations of the computing platforms) are also possible. For example, one MNO utilizes a V2X AS hosted at a shared data center and the other MNO uses a MEC, edge cloud or central cloud. These additional scenarios are not considered in this study since, to the best of our knowledge, they could not support V2N2V communications as the interfaces they would require in multi-MNO scenarios have not yet been identified nor specified.

IV. V2N2V Latency Analysis of 5G and Computing Deployments in Multi-MNO Scenarios

A. 5G End-To-End Latency Model

This study analyzes the impact of different computing platform deployments on the E2E latency of 5G V2N2V communications in multi-MNO scenarios. To this aim, we utilize and adapt the E2E latency model introduced by the authors in [3]. Fig. 7 depicts the latency components of the model for a centralized 5G network deployment that deploy the AS at the central cloud (i.e., central cloud – central cloud deployment in Section III.A). The E2E latency (l_{E2E}) model accounts for the latency experienced at the radio network l_{radio}, the transport (l_{TN}) and core (l_{CN}) networks, as well as the latency generated by Internet connections, the communication link between the Core Network's (CN's) UPF node and the

V2X AS ($l_{UPF\text{-}AS}$), and the processing latency at the V2X AS (l_{AS}). The E2E latency model also accounts for the latency introduced in the peering point links between the MNOs (l_{pp}). Fig. 7 depicts the case of a central cloud – central cloud deployment. However, l_{E2E} models have been also derived in [3] for 5G deployments with MECs (i.e., MEC – MEC, Section III.B) located at the CN, transport network (TN) or gNB. For all deployments, we consider that the radio access network (RAN) and the CN are interconnected using the hierarchical TN proposed by ITU-T in [4] that integrates 3 multiplexing nodes M1, M2 and M3. We extend in Section IV.B the utility of this model to compute the E2E latency of the 5G and computing platform deployments in multi-MNO scenarios introduced in Section III.

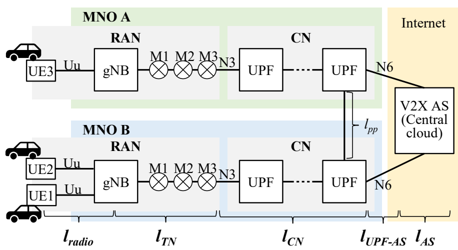

Fig. 7. Latency components of the 5G E2E latency model [3]. A centralized network deployment is utilized for illustrative purposes only.

The term l_{radio} accounts for the latency experienced between the vehicle (UE) and the gNB at the Uu radio interface. l_{radio} is derived by the authors in [5] considering different 5G New Radio (NR) configurations (e.g., numerology, retransmission and scheduling schemes), system parameters (e.g., bandwidth), characteristics of the data traffic (e.g., periodic or aperiodic), and density and distribution of vehicles in the scenario. The term l_{radio} includes the latency introduced by the scheduling process and the time needed to transmit and receive the initial packet.

The latencies l_{TN} and l_{CN} are computed as the sum of the propagation and transit delays over the TN and CN. The propagation delay represents the time that packets need to travel through the links that interconnect the nodes of the TN or CN. It depends on the total distance that the packets travel through the TN or CN, and varies with the specific 5G network deployment. In central cloud-central cloud deployment, the packets travel through the entire TN and CN. The distance that packets travel in MEC-MEC deployments depends on whether the MEC is located at the gNB, TN or CN. In the MEC-MEC deployments, the CN's UPF node is collocated with the MEC hosting the V2X AS. Therefore, the CN distance is negligible, and so is the propagation delay. The transit delay accounts for the time that packets spend at TN and CN nodes, namely, the time needed to receive, process (including dequeuing) and transmit the packets. The transit delay is computed using queueing theory and depends on the number of nodes that packets pass through, the V2X network traffic load, and the link capacities allocated to support the V2X traffic. The transit latency depends on the specific 5G network deployment, in particular the configuration of TN and CN nodes used.

The Internet latency $l_{UPF\text{-}AS}$ is computed based on empirical measurements reported in [6] of the round-trip time observed between source-target Internet nodes located in the same country; other scenarios are also considered in [6], but this is the most likely scenario for V2N2V communications between neighboring vehicles.

The latency l_{AS} introduced by processing the V2X packets at the AS is computed considering that the V2X AS only forwards the received packets as in [7]. The sufficient processing power of the AS should be provisioned to avoid backlogging of packets at the AS queue regardless of the considered computing platform.

The term l_{pp} represents the latency introduced in the peering point link between MNOs' PoPs. It is modeled based on the empirical study reported in [8]. We distinguish between local (or private) and remote (or public) peering points established between MNOs. Note that local peering point links are also present in the 5G deployment with a shared data center to interconnect the UPF nodes (see Section II.D).

B. Latency Analysis

We now analyze the E2E latency experienced in 5G-based V2N2V communications using the latency components previously described. The analysis is conducted for the deployments in multi-MNO scenarios described in Section III. Unless otherwise specified, round-trip latencies for the latency components are considered to account for the uplink and downlink paths. This will apply for symmetric multi-MNO deployments even though the uplink and downlink paths pass through the network and interfaces of different MNOs.

1) Central Cloud – Central Cloud

The E2E latency experienced when the two MNOs access the V2X AS that is hosted at the central cloud (Fig. 3) can be expressed as:

$$l_{E2E}=l_{radio}+l_{TN\_cent}+l_{CN\_cent}+l_{UPF\text{-}AS}+l_{AS} \quad (1)$$

where l_{TN_cent} and l_{CN_cent} refer to the TN and CN latency of the 5G centralized network deployment.

2) MEC – MEC

This scenario considers different solutions to interconnect the MNOs and enable the communication between vehicles supported by MECs hosted at different MNOs. If the Internet is used to interconnect the MNOs (Fig. 4-left), the E2E latency can be estimated as:

$$l_{E2E}=l_{radio}+l_{TN\_MEC}+l_{CN\_MEC}+l_{AS}+0.5\cdot l_{UPF\text{-}AS} \quad (2)$$

where, l_{TN_MEC} and l_{CN_MEC} represent the TN and CN latency for any of the possible 5G network deployments with MECs. If the MNOs are interconnected using local/remote peering points (Fig. 4-right), the E2E latency is then computed as:

$$l_{E2E}=l_{radio}+l_{TN\_MEC}+l_{CN\_MEC}+l_{AS}+l_{pp} \quad (3)$$

3) Shared Data Center

In this scenario, vehicles supported by different MNOs access the V2X AS at a shared data center (Fig. 5). The V2X packets are then routed in the uplink path from the MNO's PoP to the UPF collocated at the shared data center through a peering point link. In the downlink path, the V2X packets are routed back again through a peering point link to the PoP of the other MNO. Without loss of generality, we consider that the PoPs of the two MNOs are at the same location of the TN. Then, the E2E latency for V2N2V communications between two vehicles can be computed as:

$$l_{E2E}=l_{radio}+l_{TN\_MEC}+l_{CN\_MEC}+l_{AS}+2\cdot l_{pp} \quad (4)$$

4) Central Cloud – MEC

Finally, this scenario considers the case in which an MNO utilizes a central cloud to host the V2X AS and the other MNO relies on a MEC (Fig. 6). The E2E latency in this asymmetric multi-MNO scenario can be expressed as:

$$l_{E2E}=l_{radio}+ l^{UL}_{TN\_cent} +l^{UL}_{CN\_cent} + l^{DL}_{TN\_MEC} +l^{DL}_{CN\_MEC}+ l_{UPF\text{-}AS} + l_{AS} \quad (5)$$

where $l^{UL}_{TN\_cent}$, $l^{UL}_{CN\_cent}$, $l^{DL}_{TN\_MEC}$, and $l^{DL}_{CN\_MEC}$, refer to the TN and CN latency of the centralized and MEC-based 5G network deployments in the uplink (UL) and downlink (DL) paths, respectively. The same E2E latency as in (5) would be obtained if the V2X traffic is considered to go in the uplink through the MEC deployment and in the downlink through the centralized deployment.

V. Evaluation

This section evaluates the E2E V2N2V latency for the different 5G network and computing platform deployments under multi-MNO scenarios.

A. Scenario

We consider the network topology recommended by ITU in [4], i.e., a hierarchical transport network architecture that is made of 3 levels of multiplexing nodes (M1, M2 and M3). Each M1 node multiplexes traffic from 6 gNBs, each M2 node from 24 M1 nodes, and each M3 node from 12 M2 nodes. M3 nodes serve as gateways to the 5G core network. The network is configured with distances of 3, 12, 60 and 200 km for the links gNB-M1, M1-M2, M2-M3 and M3-UPF (that connects to the Internet), respectively. The network is configured with link capacities of 10, 300, 6000 and 6000 Gb/s for the links gNB-M1, M1-M2, M2-M3 and M3-UPF, respectively.

This study does not focus on a specific V2X service. Instead, we consider that V2X packets generated by vehicles arrive at each gNB at different rates λ^{UL}_{gNB} ranging from 1,040 pkts/s to 41,600 pkts/s. These rates correspond to different traffic densities and packet transmission periods [3], and allow us to analyze the impact of variable network loads. We dimension the network and determine the fraction (α) of the link capacities that should be allocated to support the V2X traffic so as to avoid backlog at the TN and CN nodes following the methodology in [3] and network planning practices described in [9] for the highest considered network load (i.e., λ^{UL}_{gNB} = 41,600 pkts/s). The dimensioning results in an α equal to 2.12% for the MEC - MEC and shared data center deployments (see Section III) where the local UPF nodes that provide access to the MECs or shared data center, respectively, are located at the gNB or M1. α is equal to 6.09% when the local UPF is located at the CN, as well as for central cloud - central cloud deployment. We consider the same values of α for all values of λ^{UL}_{gNB} under evaluation.

B. Latency Components

Table I reports the round-trip latency for each one of the links utilized in the four multi-MNO scenarios described in Section III. The radio network latency l_{radio} is calculated following the results in [5] that considers a common FDD reference configuration with SCS (Sub-Carrier Spacing) of 30 kHz and a cell bandwidth of 20 MHz. Results are depicted for the central cloud-central cloud ("Centralized" in Table I) and MEC–MEC deployments with MECs located at gNB (MEC@gNB), M1 (MEC@M1) or CN (MEC@CN). The links utilized in the 5G deployment with a shared data center depend on the location of the local UPF utilized to interconnect with the UPF collocated at the shared data center (Section II.D). Note that the local UPF can be located at the gNB, M1 and CN. Then, the 5G deployment with the shared data center shares common links with the MEC@gNB, MEC@M1 and MEC@CN reported in Table I. Average and 99.9th percentile latency values are reported in Table I. The 99.9th percentile is chosen since it is the most common latency requirement for advanced V2X use cases analyzed by 5GAA in [10]. A range of latency values are reported when applicable for the lowest and highest network traffic loads (i.e., λ^{UL}_{gNB} equal to 1,040 pkts/s and 41,600 pkts/s).

TABLE I. Latency (in ms) for the different link components

a) Average

Link	MEC@gNB	MEC@M1	MEC@CN	Centralized
l_{radio}	1.5 – 14.23			
l_{TN}	0.41 – 0.42	0.85 – 0.88	2.36 – 2.36	2.36 – 2.36
l_{CN}	< 0.001	< 0.001	< 0.01	2.005
$l_{UPF\text{-}AS}$	0	0	0	10.3
l_{pp}	0.306 (local) or 13.001 (remote)			
l_{AS}	0.5			

b) 99.9th percentile

Link	MEC@gNB	MEC@M1	MEC@CN	Centralized
l_{radio}	2.008 – 28.557			
l_{TN}	0.48 – 0.56	0.99 – 1.15	2.41 – 2.42	2.41 – 2.42
l_{CN}	< 0.001	< 0.001	< 0.01	2.005
$l_{UPF\text{-}AS}$	0	0	0	42.8
l_{pp}	1.43 (local) or 99.21 (remote)			
l_{AS}	0.7			

C. E2E latency of 5G and computing platform deployments

1) MEC - MEC

This scenario considers that each MNO deploys its own MEC and the MNOs are interconnected through the Internet (Fig. 4-left) or a local/remote peering point link (Fig. 4-right). The E2E latency in this scenario depends on the location where the MECs are deployed at the MNOs' network and on the network load. As it is reported in Table II, the E2E latency increases as the MEC is deployed closer to the CN due to the larger distances that packets need to travel through the TN and CN and the higher network load that is processed by the TN and CN's nodes. In particular, the average E2E latency increases between 1.6% and 13.9% (0.4% and 9.95% for the 99.9th percentile of E2E latency) when MEC@M1, and between 6.4% and 41.7% (1.4% and 29.5%) when MEC@CN with respect to MEC@gNB. MEC@gNB achieves higher E2E latency reductions under the lowest network load (i.e., λ^{UL}_{gNB}=1,040 pkts/s). Although the MEC location and traffic load impact the E2E latency in this scenario, the type of MNO interconnection has a higher impact on E2E latency. In particular, the average E2E latency increases between 21.8% and 64.1% (37.6% and 81.2%), or between 42.2% and 82.4% (74.7% and 95.5%) when the Internet or a remote peering point, respectively, is used to interconnect the MNOs with respect to using a local peering point.

TABLE II. E2E latency in ms for 5G deployments with MEC-MEC

	MEC@gNB	MEC@M1	MEC@CN
a) MNOs interconnected with local peering point			
$\overline{l_{E2E}}$	2.712– 15.45	3.16 – 15.92	4.67 – 17.40
99.9th pctl (l_{E2E})	4.62 - 31.25	5.13 - 31.84	6.55 – 33.108
b) MNOs interconnected with remote peering point			
$\overline{l_{E2E}}$	15.41 – 28.15	15.85 – 28.61	17.36 – 30.09
99.9th pctl (l_{E2E})	102.40 – 129.03	102.91 – 129.62	104.33 – 130.88
c) MNOs interconnected via Internet			
$\overline{l_{E2E}}$	7.56 – 20.30	8.00 – 20.76	9.51 – 22.24
99.9th pctl (l_{E2E})	24.59 – 51.22	25.10 – 51.80	26.52 – 53.08

2) Shared Data Center

Table III shows the E2E latency experienced when vehicles supported by different MNOs communicate through a MEC located at a shared data center as in Fig. 5. This deployment results in lower E2E latency values compared to the MEC-MEC deployment when the MNOs are interconnected via Internet or a remote peering point. For example, locating the MEC at the shared data center reduces the average E2E latency by up to 60.1% (75.4% for the 99.9th percentile of E2E latency) with respect to the MEC-MEC deployment and MNOs interconnected via Internet. Lower E2E latencies (up to 11.3% and 30.9% for the average and 99.9th percentile of E2E latency) than the ones reported in Table III are obtained when the MNOs are interconnected via local peering point links in the MEC-MEC deployment.

TABLE III. E2E LATENCY (IN MS) FOR 5G DEPLOYMENTS WITH SHARED DATE CENTER

	MEC@gNB	MEC@M1	MEC@CN
$\overline{l_{E2E}}$	3.02 – 15.76	3.46 – 16.22	4.97 – 17.70
99.9th pctl (l_{E2E})	6.05 – 32.68	6.56 – 33.27	7.98 – 34.54

3) *Central Cloud – Central Cloud*

The E2E latency experienced by vehicles communicating through the central cloud (Fig. 3) is shown in Table IV. This deployment increases the average E2E latency by up to 81.8% (87.9% for the 99.9th percentile of E2E latency) compared to the deployment with a shared data center. The MEC-MEC deployment further reduces the E2E latency when a local peering point is used to interconnect the MNOs. Using a remote peering point in the MEC-MEC deployment could result in higher average E2E latencies compared to the deployment with central cloud under high network loads.

TABLE IV. E2E LATENCY (IN MS) FOR 5G DEPLOYMENTS WITH CENTRAL CLOUD

	$\overline{l_{E2E}}$	99.9th pctl (l_{E2E})
Centralized	16.66 – 29.39	49.92 – 76.48

4) *Central Cloud – MEC*

Finally, Table V reports the E2E latency for heterogeneous 5G deployments where an MNO uses a central cloud and another one a MEC (Fig. 6). This deployment reduces the average E2E latency by up to 11.8% (3.9% for the 99.9th percentile of the E2E latency) with respect to the scenario in which the two MNOs connect to a central cloud. However, this heterogeneous deployment increases by up to 440.6% (938.2%) the E2E latency compared with the MEC-MEC deployment that uses a local peering point link. The results show that V2N2V communications between a vehicle served by an MNO with a MEC and a vehicle served by an MNO with a central cloud could be challenging.

TABLE V. E2E LATENCY (IN MS) FOR 5G DEPLOYMENT WITH CENTRAL CLOUD AND MEC

	MEC@gNB	MEC@M1	MEC@CN
$\overline{l_{E2E}}$	14.69 – 27.42	14.91 – 27.65	15.66 – 28.39
99.9th pctl (l_{E2E})	47.96 – 74.55	48.21 – 74.84	48.92 – 75.48

D. *Support of Advanced V2X Services*

We now analyze the capability of each 5G and computing platform deployment to support advanced V2X services. To this aim, we consider cooperative lane merge that requires a 20-ms E2E latency and a 99.9% reliability for the V2X messages exchanged between two vehicles coordinating a maneuver following [10]. If we consider vehicles supported by different MNOs, the results reported in Section V.C show that these requirements can be achieved under low to moderate traffic loads using MEC-MEC deployments and a local peering point to interconnect the MNOs. The deployments analyzed in Section V.C that utilize the Internet to interconnect the MNOs or reach the computing platform do not represent a viable solution to meet strict end-to-end V2N2V latency requirements; this is in line with [1]. In addition, we have identified that the "controlled connection" to interconnect the MNOs in the multi-MNO scenarios analyzed in Section III must be a local peering point. The results also show that the 5G deployment with MECs at a shared data center can also meet the requirements of the cooperative lane merge service under low to moderate network loads. This represents an alternative to MEC-MEC deployments and provides benefits and cost incentives for MNOs to coordinate and share their MEC deployments at different locations.

VI. CONCLUSIONS

The flexibility and capabilities of 5G have raised expectations on the possibility to support advanced V2X services using V2N2V communications. Supporting V2N2V communications requires the integration of the 5G network with computing platforms such as MEC, edge cloud, central cloud or shared data center, to process the V2X packets. We have first analyzed and discussed different 5G and computing deployment alternatives. We have then quantified for the first time the E2E latency of V2N2V communications experienced under different 5G and computing platform deployments in multi-MNO scenarios. Considering multi-MNO deployments is important for adequately evaluating the latency of V2N2V communications since neighboring vehicles may be attached to different MNOs. Our analysis shows that 5G deployments in which MNOs host the V2X AS at the edge (MECs or edge cloud) and interconnect with local peering point result in the lowest E2E latency. The only alternative deployment that can meet the stringent latency requirements of advanced V2X services is using 5G networks with a shared data center. Using shared data centers has additional scalability benefits. For example, MNOs could coordinate the locations at which they deploy a MEC, and then share them with other MNOs. This would allow avoiding each MNO to deploy their own MEC at the same location. The consequent cost reduction could compensate the cost of the local peering points needed to reach the shared data center.

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