High-Resolution Vehicle Telemetry via Heterogeneous IVC

Julian Timpner Martin Wegner Hendrik-Jörn Günther Lars Wolf
{timpner, wegner, guenther, wolf}@ibr.cs.tu-bs.de
Institute of Operating Systems and Computer Networks
Technische Universität Braunschweig
Braunschweig, Germany

ABSTRACT

Backend services enable the large-scale aggregation of vehicle data. This Floating Car Data (FCD) can be used to detect traffic disturbances. Although today's vehicles are able to determine their position on a per-lane level, FCD is typically only used on a per-street level granularity. In this paper, we show that using the fleet-data from one Original Equipment Manufacturer (OEM) alone as the database (i. e., on a backend) is not sufficient to detect lane-level traffic phenomena, independent from the accuracy of the vehicle localization. We thus present a high-resolution telemetry service based on heterogeneous Inter-Vehicle Communication (IVC). We introduce a holistic IVC simulation framework which we make publicly available and use it to experimentally verify the proposed telemetry service. Results show a significant leverage of IVC on both the resolution of FCD and the accuracy of detecting lane-level traffic phenomena.

CCS Concepts

•**Networks → Network simulations;** *Cyber-physical networks;* Location based services;

1. INTRODUCTION

Innovative driver assistance and infotainment functions increasingly rely on *backend services*. Examples such as the Volkswagen (VW) Car-Net, BMW Connected Drive, Audi Connect, and others provide convenience functions such as online services (weather, parking availability, etc.) and remote controls (e. g., battery management and air conditioning). Vehicles typically establish a connection to an Original Equipment Manufacturer (OEM) backend via a cellular network. The European initiative "eCall" [1], seeking to bring rapid assistance to motorists involved in an accident, mandates OEMs to integrate cellular radios into all new cars from 2018 on. Thus, eCall will likely enable the large-scale proliferation of backend services in the automobile.

The OEM backends also aggregate and process vehicle data, therefore providing customer functions [2] which are only rendered possible due to a large pool of available information. A typical example for this is Floating Car Data for the detection and prediction of traffic phenomena [3].

Additionally, future Advanced Driver Assistance Systems (ADASs) will also be able to interact with each other via Vehicle-to-Vehicle (V2V) communication technologies, thus enabling a whole new set of applications. To this end, most European OEMs, together with automotive suppliers and research organizations, have joined forces in the Car2Car Communication Consortium (C2C-CC)[1] to develop and to promote a European standard for V2V communication with the objective of increasing road traffic safety and efficiency. V2V communication can complement (cellular) data for aggregation purposes across OEMs.

If detailed enough, Floating Car Data (FCD) could be used to implement novel services such as the detection of *micro traffic jams* which last shorter than 1 min, e. g., because of left-turning, parking or slow driving vehicles, and only affect specific lanes as opposed to the entire road. Depending on the installed ADAS, today's vehicles are able to determine not only the road they are currently driving on via Global Navigation Satellite System (GNSS), but the exact lane via additional sensors (i. e., cameras, etc.). This renders the required degree of position accuracy possible. Micro jam detection could then be used to recommend the best lane to use, in order to reduce gas/energy consumption as well as travel times and the overall flow of traffic.

In this paper, we use micro-jam detection as an example for a more general provision of near real-time traffic information. We show that for some applications, an OEM cannot only rely on the data sent to its backend of its own fleet alone. Regardless of the realistically assumed OEM's market share, we show that the determination of the fine grained microscopic traffic situations that are required by the envisioned assistance functions—independent of the accuracy of the vehicle localization—require a theoretical market share which is unrealistic. This finding is especially interesting for smaller OEMs as, for security, competition and non-disclosure reasons, it is unreasonable to assume that a common backend employed by the majority of today's OEMs will exist in the near future. Only by additionally aggregating and transmitting the broadcasted V2V-based status information of vehicles received from the vehicles of other OEMs, a significant service quality can be provided.

[1] https://www.car-2-car.org

For the analysis, we developed *ArteryLTE*, a holistic Inter-Vehicle Communication (IVC) simulation framework capable of simulating different communication technologies, namely the European Telecommunications Standards Institute (ETSI) ITS G5 and the cellular Long Term Evolution (LTE) protocol stacks. This framework is available as open source. We use *ArteryLTE* to show that heterogeneous vehicular networks allow a much higher resolution of data aggregation than a single OEM can accomplish on its own. We evaluate a backend-based high-resolution telemetry service which detects local traffic phenomena at a higher resolution than typically possible with FCD.

The remainder of this paper is structured as follows. Section 2 discusses related work on backend communications and heterogeneous vehicular networks. Section 3 describes our simulation framework *ArteryLTE*. The used traffic scenario and simulation setup is described in Section 4. Section 5 presents our findings based on a large-scale simulation study. The paper concludes in Section 6.

2. RELATED WORK

Transmitting vehicular data to a backend via cellular or short range radio connections has been investigated thoroughly in literature. Pögel et al. [4] collect data about the vehicles' current communication conditions and transfer the data to a central server database via a cellular link. The server can make predictions about the future connectivity by taking into account various influences and the network dynamic in order to ensure an efficient and interference-free backend connection. Wireless Local Area Networks (WLANs), however, are not considered. Kolios et al. [5] offload all data to roadside Access Points (APs), facilitating V2V relaying to balance the load. Similarly, Arkian et al. [6] aggregate vehicle reports in a cluster, in which the cluster head is responsible for transmitting the aggregated data to a Roadside Unit (RSU). Both approaches, however, do not consider cellular networks at all.

The idea of using multiple network stacks, where WLAN is combined with cellular communications, has more recently been adapted to vehicular networks, too, resulting in *heterogeneous vehicular networks* [7]. Dressler et al. [7] identify two classes of heterogeneous vehicular networking. Class A abstracts away from lower layers, providing data offloading or always best connected services to applications. Class B exposes information and control of lower layers to applications, allowing them to selectively use the best fitting technology. As an example of Class B, Tung et al. [8] employ a clustering approach, in which short-range radio is used for exchange in clusters and cellular networks for inter-cluster traffic. Vehicles are clustered in groups moving into the same direction. Remy et al. [9] follow a different approach and let a central service decide about cluster affiliations. MobTorrent [10] establishes a control channel via a cellular network to coordinate data transfer via roadside APs. Finally, VeinsLTE [11] presents an integrated simulation framework for heterogeneous vehicular networks, which we discuss in detail in Section 3.

3. SIMULATION FRAMEWORK

As outlined in Section 1, we intend to depict a scenario in which vehicles will communicate with each other by means of V2V communication as well as with a backend service of their respective OEM by means of cellular communication. We subsume both types of communication under the umbrella term Vehicle-to-X (V2X). The purpose of this scenario is an analysis of the requirements for providing a significant service quality for a high-resolution telemetry service. This section presents the utilized simulation framework for our analysis as well as the employed simulation scenarios.

To allow for the analysis of different communication strategies based on heterogeneous vehicular networks, a framework which allows for the dedicated simulation of various communication technologies is required. What is more, the movement of vehicles is constrained to the road network and also has to adapt to the general traffic situation. A study presenting different approaches for integrating realistic node movement for the simulation of vehicular networks is presented by Sommer et al. [12]. The most realistic approach for resembling node mobility according to traffic rules and a street network is the combination of a dedicated network simulator and a dedicated traffic simulator. A popular representative is the coupling between the network simulator *OMNeT++* [13] and the traffic simulator *Simulation of Urban Mobility* (SUMO) [14] realized by the *Vehicles in Network Simulation* (Veins) framework [15]. Vehicles in Network Simulation (Veins) implements Simulation of Urban Mobility (SUMO)'s control protocol Traffic Command Interface (TraCI) in OMNeT++ and therefore realizes the online import and manipulation of the vehicles simulated by SUMO through functionalities implemented in OMNeT++. For V2V communication, Veins implements the Wireless Access in Vehicular Environments (WAVE) protocol stack.

Within the research community, several extensions for Veins exist, rendering it as the chosen candidate for our analysis. Riebl et al. [16] present an extension for the Veins framework, called *Artery*, which focuses on the implementation of applications (so-called *Artery* services) for the vehicles within the simulation. The modular architecture of *Artery* enables heterogeneous vehicle capabilities, by dynamically configuring both, the penetration rate of a communication technology as well as the applications the vehicles are capable of. Furthermore, *Artery* introduces *Vanetza*, an implementation of the ETSI Intelligent Transport System (ITS) G5 protocol stack instead of the WAVE stack provided by Veins. As part of this extension, *Artery* already provides a service for disseminating Cooperative Awareness (CA) [17] messages.

As mentioned in Section 2, VeinsLTE [11] introduces the capability of heterogeneous communication technologies on mobile network nodes. Next to Veins' original WAVE stack, VeinsLTE also integrates *SimuLTE* [18], a complete representation of an LTE stack within OMNeT++. VeinsLTE extends the *SimuLTE* framework by the option of dynamically adding and removing a network node during the simulation, i. e., whenever a vehicle in SUMO is either added or removed from the street network. Additionally, VeinsLTE offers a high-level *decision maker* which can be used by the vehicle applications in order to choose the communication technology for message dissemination. As a communication stack between the LTE backbone elements, the *INET*[2] protocol suite is used.

VeinsLTE, however, lacks the option of simulating a different set of applications per vehicle as well as the ETSI ITS

[2]https://inet.omnetpp.org/

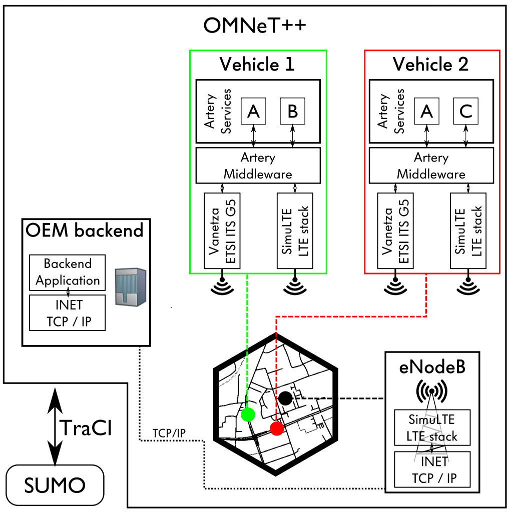


Figure 1: Architecture of the *ArteryLTE* simulation environment.

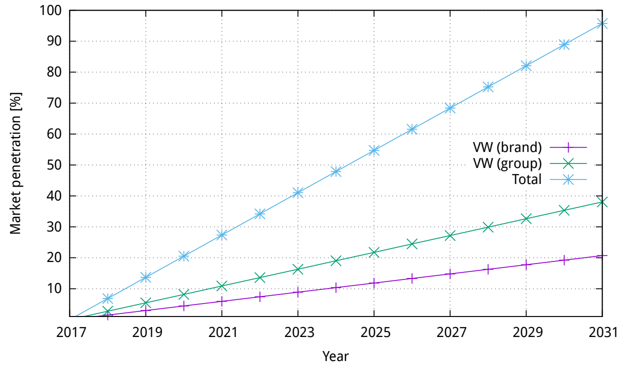


Figure 2: Projected market penetration for V2X technology in Germany by end of the given year. VW (group) includes VW (brand), Audi, Porsche, Seat and Skoda.

G5 protocol stack for direct V2V communication. As part of our research, we combined *Artery* and VeinsLTE, therefore circumventing these shortcomings. Instead of the *decision maker* provided by VeinsLTE, *Artery*'s middleware is extended by the option of choosing either the ITS G5 or the LTE stack for communication. Upon message generation, the *Artery* services provide information to the middleware for choosing the appropriate communication technology.

As we intend to introduce a backend service into our simulation, a static network node is introduced to the network which is connected to the base stations (eNodeBs) of the LTE network. The backend is used to run our high-resolution telemetry service in order to detect local traffic phenomena as indicated in Section 1. The overall architecture of our resulting simulation framework *ArteryLTE* is depicted in Figure 1. Located within the presented cell of the eNodeB are two vehicles 1 and 2 which are equipped with both, an LTE and an ITS G5 stack. The location and dynamic status of the vehicles are extracted from SUMO via the TraCI protocol. Each vehicle can be provided with different *Artery* services A, B or C. The *Artery* middleware on the vehicles is responsible for selecting the appropriate communication stack. When transmitting data via LTE to the OEM backend, a TCP/IP-based connection between the eNodeB and the backend is utilized.

4. SIMULATION

In this section, we describe the simulation setup for the high-resolution telemetry service. To this end, we first present a market analysis of the V2X penetration rate. Again, we define V2X to subsume both V2V (i. e., ETSI ITS G5) and Vehicle-to-Infrastructure (V2I) (cellular-based) communications. We then describe the scenario and its parameters.

4.1 Preliminary Market Analysis

In the following, we provide a projection of the market penetration of V2X technology. We use Volkswagen (VW) as a case study, as it is the largest European OEM.

The total vehicle population of passenger cars in Germany is about 44 400 000 [19] as of January 2015. In 2014, there was a total of 3 036 773 registrations of new cars. 656 494 of these registrations were VW (brand) vehicles. The VW group (for passenger cars this includes VW (brand), Audi, Porsche, Seat, Skoda) accounted for 1 207 030 registrations. For the following considerations, we keep the size of the market as well as the market shares constant as they have been relatively stable [19] over the last decade.

Figure 2 shows the extrapolated V2X market penetration at the end of each year for the German market as a whole, for VW as a brand as well as for VW as a group. In concordance with the “eCall” [1] initiative as well as the US National Highway Traffic Safety Administration (NHTSA) proposal [20], we assume that every new car on the German market will be equipped with both V2I and V2V technologies from 2018 on. It can be seen that, at the current replacement rate, about 100 % of all vehicles in the market will be equipped with V2X by the end of the year 2032. V2X-equipped vehicles of VW brand and group will account for about 15 % and 25 %, respectively, of the total market by the end of 2026, for instance. At the same time, the total equipment rate of V2X (and thereby V2V) enabled vehicles by the end of 2026 will be much higher at about 60 %.

4.2 Simulation Setup

We use a scenario from Kurczveil et al. [21] that represents a section of the road traffic of the city of Braunschweig, Germany, between 08:00-10:00. This area has been exported from OpenStreetMap and converted to a SUMO road network. Traffic measurements were taken from the city's traffic intensity map [22] and used for calibration as described by Kurczveil et al. [21].

The scenario is used within the simulation framework presented in Section 3. The vehicles in the simulation can be equipped to either communicate (a) with a backend via LTE, (b) with other vehicles via ETSI ITS G5, or (c) both. Per default, vehicles have no communication equipment at all. Vehicles of Type (a) send their dynamic state (i. e., their current position, speed, etc.) with a given frequency f_{lte} to the OEM backend only. Type (b) vehicles broadcast CA messages as specified in the standard [17] and therefore represent those vehicles from other OEMs. Just like the vehicles of Type (a), Type (c) vehicles, in addition to broadcasting CA messages, also send a status update to the OEM backend at a rate of f_{lte}. Besides their own dynamic state, the status

General	Traffic simulation time	7193 s (≈2 h)
	Network simulation time	6x300 s (every 15 min)
	Map area	2.0 km x 1.5 km
	TraCI log interval	1 s
	Total number of vehicles	14119
	Number of lane sections	2011
	To-backend frequency f_{lte}	$^1/_{3.6}$ Hz
	Vehicle lengths avg/stddev	4.84/1.56
ITS-G5	Tx Power	126 mW
	Carrier frequency	5.90 GHz
	Minimum signal attenuation	−89 dBm
	Path loss coefficient	2.0
LTE	eNB Tx Power	45 dBm
	UE Tx Power	26 dBm
	Carrier frequency	2100 MHz

Table 1: Summary of simulation parameters.

updates include a concatenation of the single most recently received CA messages of all V2X vehicles in their vicinity since their last communication attempt with the backend.

Type (a) and (c) vehicles report their exact positions to the backend, including the lane number. To achieve a higher than lane-level resolution of local traffic phenomena, every lane is subdivided into lane sections of 50 m [4] each. As each vehicle should at least report its status once per section, the minimum update frequency should be $f_{\text{lte}} = {}^1/_{3.6}$ Hz, due to a nominal speed limit of 50 km/h. As the driver imperfection in the simulation might lead to vehicles exceeding the speed limit, they alternatively report their status after every 50 m. The high-resolution telemetry service implemented in the backend aggregates the status reports and calculates the metrics as required by the customer functions (cf. Section 5.2).

The main simulation parameters are described in Table 1. From a networking point of view, the main focus is on the impact of aggregating additional data collected via V2V communication which is simulated in detail, by employing a two-ray interference [23] and obstacle shadowing model [24]. Channel properties of the cellular network are out of the scope of this paper.

5. EVALUATION

In this section, we evaluate the efficiency of the high-resolution telemetry service in terms of its accuracy and the induced networking overhead depending on the market penetration rate of the communication technologies.

5.1 Simulation Scenarios

In our simulations, we aim to determine the required market penetration rates of LTE and ITS G5 communication technologies to achieve a sufficient accuracy in the description of the current traffic situation estimated on an OEM's backend. For this purpose, we conducted two main simulation stages and performed the analysis from the perspective of an OEM's backend:

Stage 1: The purpose of this stage is to establish the minimum required market penetration rate of the LTE backend communication in order to enable the envisioned service. We conducted 16 simulation runs, varying the penetration rates p_{oem} for the vehicles equipped with the LTE backend communication capabilities according to the presented preliminary market analysis in Section 4.1 for the VW group (Type (a) vehicles only). Hence, the backend will only receive information transmitted by vehicles of the VW group.

Stage 2: In order to determine the additional impact of V2V communication, the second stage adds Type (b) vehicles according to the assumed total market penetration rate p_{total} (cf. Section 4.1). These vehicles transmit CA messages within their local communication range. Consequently, the VW group vehicles are now of Type (c) and therefore transmit the collected CA messages to the OEM's backend as well. This causes a virtual increase of the number of vehicle positions in the backend, therefore yielding a larger database for estimating the current traffic situation.

5.2 Data Analysis

To assess the accuracy of the telemetry service, we opted for the occupancy of lane sections as a relevant evaluation metric, in line with the envisioned use cases such as detection of micro traffic jams, etc. Moreover, the occupancy is a value that can be retrieved directly from SUMO via TraCI as a ground truth. The occupancy o of a section s is defined as

$$o = \frac{\sum_{v \in V_s} \text{length}(v)}{\text{length}(s)}$$

where V_s is the set of vehicles reported on section s. Given the typical length of a simulated passenger car of 4.5 m and a lane section with a length of 50 m, the resulting occupancy would be $o = 0.09 = 9\%$ for one vehicle, for instance.

The actual assessment is then based on a comparison between the occupancy values calculated in the backend and the ground truth values from TraCI. To this end, we determined two occupancy values, o_{backend} and o_{TraCI}, for every section of all lanes every 3 s for the entire simulation time. o_{backend} is based on the positions of vehicles reported to the backend by OEM vehicles (Type (a) or Type (c)). o_{TraCI} is based on the actual position of every vehicle as obtained via TraCI. As o_{TraCI} represents the ground truth, we determine the error Δo of the telemetry service as the difference between the two values:

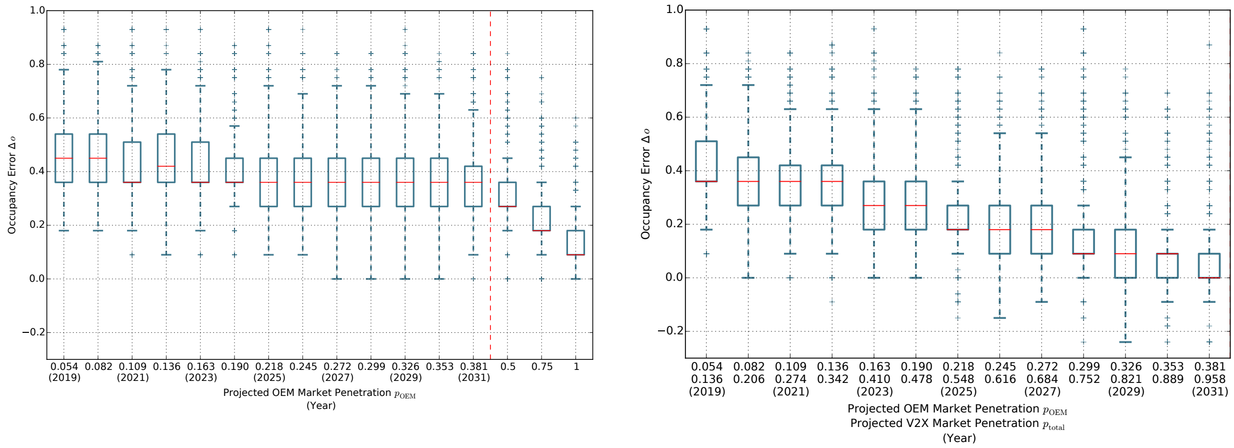
$$\Delta o = o_{\text{TraCI}} - o_{\text{backend}}$$

5.3 Findings

Figure 3 shows the distribution of the occupancy error Δo for increasing market penetration rates p_{OEM} (Figure 3a) and p_{total} (Figure 3b). We only considered lane sections with at least 3 vehicles according to TraCI data ($o_{\text{TraCI}} \gtrsim 27\,\%$) since situations with higher traffic densities are more interesting for the envisioned use cases such as micro traffic jam detection or lane-specific navigation.

Figure 3a shows that with an increasing market penetration rate p_{OEM} of Type (a) vehicles, the occupancy error Δo decreases. However, it becomes clear that with the OEM's maximum penetration rate $p_{\text{OEM}} = 38.1\,\%$ (achieved by the end of 2031), Δo is not significantly lower than at the time of market introduction in the year 2018. Even with a (very large) theoretical market share of $p_{\text{OEM}} = 75\,\%$ a median occupancy error Δo of about 20 % occurs. This shows that using the fleet-data from one OEM alone will not be sufficient for realizing the envisioned telemetry service.

Figure 3b shows the leverage of introducing V2V communication. An OEM market share of $p_{\text{OEM}} = 38.1\,\%$ now corresponds to a total V2V market penetration of $p_{\text{total}} = 95.8\,\%$. In other words, the OEM's fleet can now provide



(a) Stage 1: LTE

(b) Stage 2: LTE and V2X

Figure 3: Comparison of occupancy errors Δo per simulation stage.

data points for about 95.8 % of the vehicles within their surroundings, enabled by V2V communication. As shown in Figure 3a, increasing p_{OEM} alone has no significant impact on the occupancy error Δo. However, under the assumption of a parallel introduction of V2V technology to the market, the potential for a high-resolution FCD aggregation can be fully leveraged. This is supported by the fact that $p_{\mathrm{total}} = 95.8\,\%$ (i. e., 95.8 % of the vehicles on the market are V2V-enabled) results in a very low occupancy error: 50 % of all values Δo lie within the interval $[0.0; 0.1]$. More specifically, 25 % are off by approximately the length of one passenger car, while another 25 % show no error at all. In the case of Stage 1, however, where only Type (a) vehicles are present, 50 % of Δo indicate a deviation of at least three times of this magnitude.

The variance of the remaining values for $p_{\mathrm{total}} = 95.8\,\%$ is an effect of transmission delays: some vehicles have already moved on to the next section before their status update has been received and processed by the backend. Similarly, Δo assumes negative values when the backend overestimates the number of vehicles on that particular section. Both effects result from the delay implied by the value of f_{lte} and by the collective transfer of concatenated CA messages every 3.6 s.

The higher the number of V2X-enabled vehicles, the higher the observed network load. In combination with the aggregation of V2X messages on the vehicles, large amounts of data need to be transmitted to the OEM's backend, thus increasing delays and communication costs. Figure 4 depicts the network load for increasing market penetration rates p_{OEM} (Figure 4a) and p_{total} (Figure 4b). Figure 4a shows a linear increase of both the total number of messages and the size of transmitted data to the backend. Additionally transmitting aggregated CA messages significantly increases both metrics, as shown by Figure 4b. It becomes clear that the resulting data volume requires appropriate mechanisms, such as in-network aggregation, clustering and others in order to reduce the communication overhead. This will be an important factor of our future work.

6. CONCLUSION

In this paper, we have introduced *ArteryLTE*, a holistic IVC simulation framework capable of simulating different communication technologies, namely the ETSI ITS G5 and the cellular LTE protocol stacks. *ArteryLTE* is also publicly available as open source[3]. Using *ArteryLTE*, we have shown that fleet-data from one OEM alone is not sufficient to achieve lane-level accurate FCD. We have thus presented a backend-based high-resolution vehicle telemetry service that facilitates heterogeneous IVC to complement FCD aggregation via cellular networks across OEMs. A large-scale simulation study has shown that this telemetry service indeed detects local traffic phenomena at a higher resolution than typically possible with FCD. This holds true for smaller and larger OEMs alike: By employing our exemplary FCD-based occupancy metric, we have shown that the accuracy can be improved so that in the majority of all cases the error is negligible (less than the length of one vehicle) which is only possible using aggregated V2V data. As future work, we plan to integrate local perception sensors [25] such as radar into *ArteryLTE*. We will use this extended functionality to further improve the presented high-resolution telemetry service by environmental perception data, both local and from other vehicles. Additionally, mechanisms to cope with the increased network load will be investigated, especially local aggregation and deduplication of FCD (e. g., clustering).

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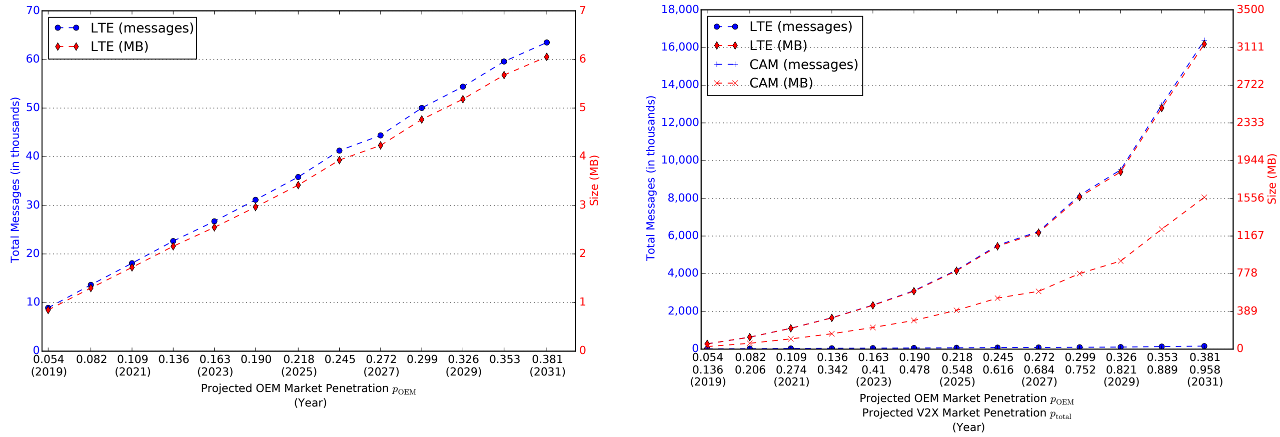

(a) Stage 1: LTE

(b) Stage 2: LTE and V2X

Figure 4: Comparison of network load per simulation stage.

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