Impact of Network Delays on Edge-Assisted Platooning Systems in 5G Networks: Addressing Latency Challenges

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Abstract. The low latency offered by 5G mobile network and edge computing paved the way for a new approach to platoon control. Moving the controller to the edge overcomes the scalability issues and the limited radio coverage of the vehicles, typical of traditional distributed platoon controllers based on dedicated short-range communication (DSRC) solutions. However, mobile operators must provide a suitable level of quality of service (QoS), offering good radio coverage, but also preventing congestion at the base station level, to guarantee a low latency control loop for sending motion data to the controller and getting the desired acceleration instruction back from the controller, within a short time. In this paper, we investigate the influence of uplink and downlink network delays on an edge-assisted platooning system. We simulate specific scenarios of network congestion by saturating the physical radio resource of the base station, which leads to an increase in communication latency. Through a simulation campaign, we analyze the performance of the platooning system in terms of target distance preservation and string stability.

Keywords: Platooning · Mobile network · Simulation

1 Introduction

The advent of 5G mobile network, combined with the edge computing paradigm, has opened new opportunities for autonomous driving supporting services. In particular, vehicle platooning is getting new attention with the possibility of controlling the vehicle remotely, exploiting the combination of low latency offered by the new radio standard [1] and the availability of computation capabilities close to the radio access network [7].

Traditionally, platooning control is realized through a distributed system supported by dedicated short-range communication (DSRC), using 802.11p, C-V2X, and VLC [2,4,16,17]. Recently, edge-assisted platooning has been proposed [3,6,9,11], to overcome the poor scalability of DSRC platooning, due to limited radio coverage of the vehicles, and to facilitate the integration with other ITS

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systems running at the edge, thanks to the centralized control of the platoon. This approach to platooning requires full mobile network coverage to operate and mobile operators have to guarantee suitable quality of service (QoS) levels to preserve the correct behavior of the platoon system, i.e., distance policy and string stability. Some previous works have investigated the impact of network delays on platooning performance. In [11] has shown that the system can tolerate round trip time delays up to 70 ms. However, the results were obtained by modeling network latencies as probability distributions, neglecting congestion phenomena and realistic radio channel conditions. In another work, Nardini *et al.* [9] analyzed the case of platoons involving vehicles from different network operators, considering realistic radio channel using the popular Simu5G [10] framework. Nevertheless, the analyses do not consider uplink and downlink delay separately. In [6], Hidayatullah *et al.* presented a complete analysis of delay impact on platoon considering both distributed and centralized platoon management and investigating the platoon system performance under realistic power-train and network models. Also in this case, the evaluation does not split uplink and downlink channel delays.

In this paper, we investigate the influence of uplink and downlink network delays on an edge-assisted platooning system. Differently from the previous works, we consider uplink and downlink delays separately, by investigating the centralized platooning system reactions in the presence of delays in data and instructions. We simulate specific scenarios of network congestion at the mobile base station level, leading to an increase in communication latency due to the saturation of the physical radio resource of the base station. We run a preliminary simulation campaign considering different levels of congestion severity to evaluate the performance limit of the platoon system. From the results it has emerged that the edge-assisted platooning system is more sensitive to downlink delay as increases misalignments in vehicle motion, while can tolerate moderated delays in uplink without compromising the platoon maneuvers.

2 Edge-Assisted Platooning

A simplified architecture of edge-assisted platooning proposed in [11] is depicted in Fig. 1. Each vehicle is directly connected to a radio base station, which provides the vehicle with uplink and downlink connectivity towards the edge computing platform. Differently from the traditional platooning supported by the dedicated short-range communication (DSRC) paradigm, the access to radio medium is completely under the control of the base station scheduler, eliminating the contention overhead and minimizing signal interference. The platoon vehicles communicate with an edge server where an instance of the platoon controller is deployed. Each vehicle periodically sends motion data (e.g., position, speed, acceleration) to the remote controller, which computes the control law and sends back the acceleration instruction to the vehicle.

In traditional DSRC-based platooning, the platoon control is realized in a distributed fashion, in which each vehicle is responsible for the computation of its

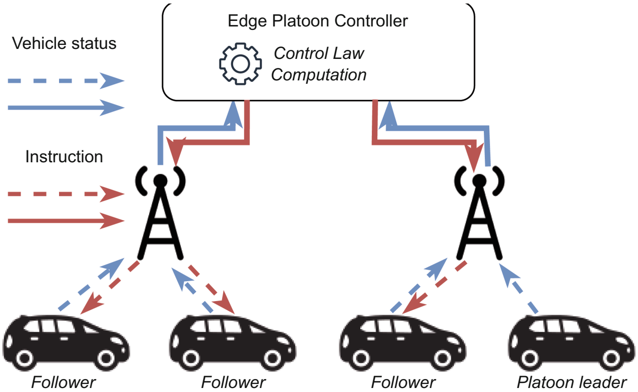


Fig. 1. Edge-assisted platooning architecture.

instructions. Conversely, edge-assisted platooning offers a centralized approach to controlling the entire platoon. As discussed in [11], the centralized control allows the controller to have a unified view of the platoon by recreating a virtual representation of the physical platoon on the edge. Moreover, long platoons can be easily managed without the limits of vehicle radio coverage and additional delays due to multi-hop transmissions. However, moving the platoon control remotely introduces new delay components. In addition to the delays caused by uploading the motion data to the edge server through the base station and the backhaul network, edge-assisted platooning introduces the instruction delay, caused by the delivery of the instruction messages from the edge server to the platoon vehicles. In the following sections, we present in detail the different components of the centralized platoon control system.

2.1 Network Delay Schema

In Fig. 2, we report the schema of the delay components of edge-assisted platooning.

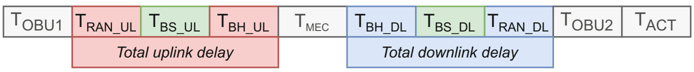


Fig. 2. Schema of the delay components.

The components in grey are delays caused by onboard computation (T_{OBU1} to read motion sensors data and T_{OBU2} to instruct the onboard actuators), and edge server computation of the control law (T_{MEC}), while T_{ACT} refers to the actuation lag due to physical inertia of the vehicle. The other delay components are directly induced by the mobile and edge networks. More specifically, the uplink is made of three parts:

1. T_{RAN_UL} represents the transmission time of a message between the vehicle and the base station that is serving it. This component considers the whole uplink communication process, that is the actual message transmission and the acknowledgment from the base station.
2. T_{BS_UL} is the time spent by the base station to receive, decode and process the message and send it to the edge server through the backhaul network. This component includes the control plane overhead for granting the transmission, performed by the uplink scheduler of the base station.
3. T_{BH_UL} is the transmission time of the message between the base station and the edge server. Being the backhaul network equipped with optical fiber offering high data rate, the delay is mainly caused by the geographical distance between the base station and the edge server where the platoon controller is deployed. According to previous studies [9,11], the remote controller can be easily deployed on an edge facility at the access ring of the telco operator network. This solution allows the edge facility to serve directly a large group of base stations, maintaining backhaul delay to a negligible level.

Analogously, the downlink delay is composed by:

1. T_{BH_DL} is the transmission time of the message between the edge server and the base station across the backhaul network.
2. T_{BS_DL} is the time spent by the base station to receive, decode and process the message and schedule it for sending to the vehicle. This component includes the control plane overhead for informing the vehicle that a message is going to be transmitted.
3. T_{RAN_DL} represents the downlink transmission time, i.e., the actual transmission and the final acknowledgment.

The most critical delay components are the ones that involve the base station processing and radio transmissions, i.e., T_{RAN_UL}, T_{RAN_DL}, T_{BS_UL}, T_{BS_DL}. This is because the radio channel quality is highly variable, directly affecting the transmission time and amount of consumed physical layer resources[1]. Moreover, the base station represents a bottleneck when is overloaded, because the transmission requests are queued by the base station scheduler due to the lack of available physical resources, causing extra delays [13]. In this work, we focus on T_{BS_UL} and T_{BS_DL} delay components, investigating the impact of the congestion of the base station on the performance of the platoon.

[1] The base station adopts the so-called Adaptive Modulation and Coding scheme approach, by dynamically changing the coding and modulation parameters according to the quality of the radio channel. The higher the quality, the more efficient the modulation and coding scheme, resulting in fewer physical resources consumed for transmitting the same quantity of data.

2.2 Cooperative Adaptive Cruise Control Control Law

The standard definition of Cooperative Adaptive Cruise Control (CACC) [12] is

$$\ddot{x}_{i\_des} = \alpha_1 \ddot{x}_{i-1} + \alpha_2 \ddot{x}_0 + \alpha_3 \dot{\varepsilon}_i + \alpha_4 (\dot{x}_i - \dot{x}_0) + \alpha_5 \varepsilon_i \quad (1)$$

$$\dot{\varepsilon}_i = \dot{x}_i - \dot{x}_{i-1} \quad (2)$$

$$\varepsilon_i = x_i - x_{i-1} + l_{i-1} + d_{des} \quad (3)$$

$$\alpha_1 = 1 - C_1 \quad (4)$$

$$\alpha_2 = C_1 \quad (5)$$

$$\alpha_3 = -\left(2\xi - C_1\left(\xi + \sqrt{\xi^2 - 1}\right)\right)\omega_n \quad (6)$$

$$\alpha_4 = -C_1\left(\xi + \sqrt{\xi^2 - 1}\right)\omega_n \quad (7)$$

$$\alpha_5 = -\omega_n^2 \quad (8)$$

on of the i-th vehicle. $\ddot{x}_0$ and $\dot{x}_0$ are the acceleration and the speed of the platoon leader, respectively. x_{i-1}, $\dot{x}_{i-1}$, $\ddot{x}_{i-1}$ and l_{i-1} represent the position, the speed, the acceleration and the length of the preceding vehicle, respectively. $\dot{\varepsilon}_i$ is the delta speed between the i-th vehicle and the preceding one. ε_i is the distance error with respect to the target distance d_{des}. CACC has three parameters: the weighting factor between the accelerations of the leader and the preceding vehicle C_1, the damping ratio ξ and the controller bandwidth ω_n. The output of the control law is the desired acceleration the vehicle i-th ($\ddot{x}_{i\_des}$) should implement to maintain the target inter-vehicle distance, (d_{des}) and the string stability property.

2.3 Control Loop and Age of Information Schema

In traditional DSRC-based platooning, each vehicle periodically computes the control law onboard using the data read from its sensors and the ones obtained by other vehicles through V2V communication. The constant availability of fresh data from onboard sensors and other platoon members usually sent every 100 ms [2], allows the vehicle to finely adjust the acceleration at any time. Under low radio medium contention and low interference, the communication delay is below 1 ms [5,15], bounding the age of information of the data of other vehicles around 100 ms. Under these settings, the OBU can compute the control law synchronously at fixed time intervals and pass the computed acceleration instruction to the actuators immediately.

On the contrary, in edge-assisted platooning, the computation is performed asynchronously, every time the remote controller receives updated motion data from a platoon vehicle. As proposed in [11], the edge controller builds a dependency graph telling which vehicles depend on the update sent by a specific vehicle. The graph topology is strictly based on the control topology *Leader-and predecessor-following* that is often proposed for the Cooperative Adaptive Cruise Control control law. For example, suppose that the edge controller receives data

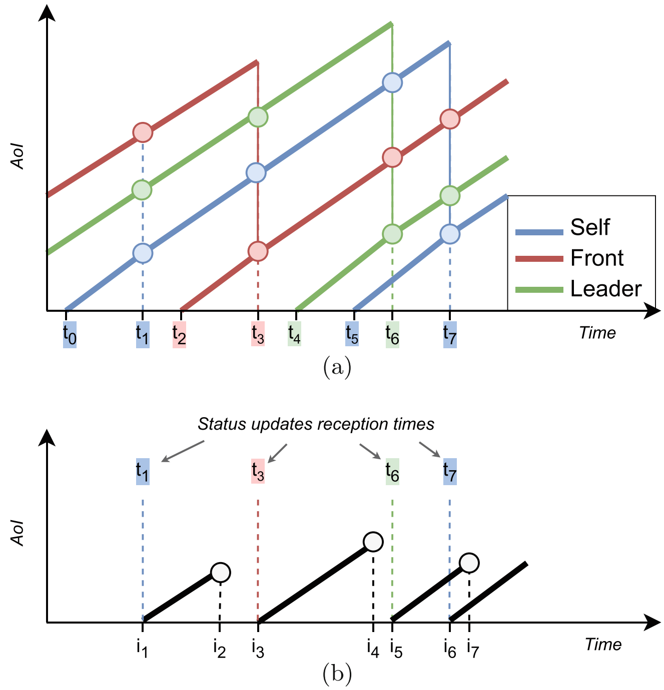


Fig. 3. Age of the information schema.

from the vehicle i. According to the Cooperative Adaptive Cruise Control control law (see Sect. 2.2), the data of the vehicle i are used to compute the instruction of the follower vehicle, $i + 1$, and the vehicle itself. Therefore, the reception of the data of vehicle i triggers the computation of two instructions that will be sent unicast to the vehicles. In case leader data are updated, the instructions are computed for all the followers, since all the followers depend on the platoon leader.

The paradigm shift of the control loop from onboard-synchronous to remote-asynchronous introduces new delay components that affect the age of the information (AoI) model of the platoon system. The Fig. 3 shows the evolution of the AoI of the vehicle data (Fig. 3a) and the instruction (Fig. 3b) for a generic i-th follower ($i > 1$). At t_0, the vehicle i reads the data from the onboard sensors and sends them to the edge controller. The uplink message is received at t_1 and triggers the computation of the desired acceleration instruction ($t_1 = i_1$ in Fig. 3b[2]), using the new data of vehicle i and the previously received data of the other platoon members, i.e., leader and front vehicle. The colored dots in the figure indicate the AoI of the vehicles' data. For example, at t_1, the oldest information is the one of the front vehicle, while the freshest is of i-th vehicle.

[2] In this work, we assume that the computing time of the control law, T_{MEC} in Fig. 2, is negligible.

Similarly, at t_2 and t_4 the front and the leader vehicles send their updates that will be received at t_3 and t_6, respectively, leading to instruction computation at i_3 and i_5.

Differently from DSRC-based platooning, the remote platoon controller always deals with delayed data, whose delay is determined by the uplink delay components (see Fig. 2). Therefore, the platoon controller builds its virtual delayed representation of the platoon, of course, the lower the uplink delay, the more precise the computed instruction. Moreover, the data update time interval could significantly vary due to radio link quality, serving base station scheduling policy, and its congestion. Another key difference compared to DSRC approach is the extra control loop delay introduced by the delivery of the instruction message to the vehicles. In Fig. 3b, timestamps i_2, i_4 and i_7 represent the time when the instruction message is delivered to the vehicle. This is particularly critical because instructions are directly responsible for the synchronization and safety of the vehicles. Indeed, a delay in instructions leads to misalignments in vehicle motion by increasing the risk of collision and the platoon efficiency. Instead, data can tolerate small delays without compromising the platoon maneuvers.

For the aforementioned reasons, the mobile network has to be able to guarantee a suitable level of QoS in both uplink and downlink, to minimize the error with respect to the target distance and to preserve the string stability. In the following, we will show the impact of the delays caused by the congestion of base stations on the platoon performance.

3 Simulation Setup

To evaluate the impact of the network delay components, we simulate a highway scenario with a fleet of 8 light-duty commercial vehicles. We develop a simulator framework using OMNeT++ on top of the SUMO simulator [8]. In particular, we rely on the Veins [14] and Simu5G [10] frameworks to model vehicles and 5G mobile network, respectively. In Table 1, we report the main simulation parameters and mobile network configuration. The mobile network consists of 8 base stations, each deployed 1000 m apart from one another along the highway. This guarantees suitable radio coverage for the whole platoon journey. Each base station offers 3 physical resource blocks (RBs) every 1 ms, leading to an offered gross data rate between 1.5 and 3.5 Mbps, depending on the radio channel quality (see 5G standard [1]). The offered data rate by a single base station is sufficient to handle all the data traffic of the platoon, which is around 500 kbps for an 8-vehicle platoon.

3.1 Background Traffic Generation Scenarios

To generate congestion at the base station level (see T_{BS_UL} and T_{BS_DL} in Fig. 2), we simulate background traffic, generated by mobile devices that do not belong to the platoon. We consider three scenarios of traffic generation: *(i) uplink background*, where most traffic is generated in uplink (uplink packet size

Table 1. Simulation parameters.

General parameters	
Simulated road	Straight 3-lane highway
Simulation duration	300 s (100 s of warm-up time)
Simulation scenario repetitions	20 random seeds
Platoon parameters	
Number of platoon members	8
Leader speed pattern	Sinusoidal 90 km/h (± 5 km/h), 0.1 Hz
CACC parameters (see [12]*)*	
Weighting factor (C_1)	0.5
Damping factor (ξ)	1
Controller bandwidth (ω_n)	0.2 Hz
Target distance (d_{des})	15 m
Mobile network configuration	
Number of base stations	8 (along the highway)
Inter-Base station distance	1000 m
Base station physical resource	3 RBs per TTI (1 ms)
UE Tx power (gain)	26 dBm (+0dBi)
Base station Tx power (gain)	46 dBm (+18dBi)
Carrier frequency	800 MHz
Base station model	ITU-Urban macrocell
Pathloss model	Free Space with $\alpha = 3.5$
Base station scheduler	Max Channel Indicator
Background network traffic	
Number background device (N_{bg})	0, 30, 60, 90 UEs
Application type	UDP Constant Bit Rate
Packet size (UL/DL)	10, 500 byte
Packet frequency (UL/DL)	20 pkt/s
Generation starting time	120 s–140 s
Generation ending time	220 s–240 s

of 500 bytes, downlink 10 bytes); *(ii) downlink background*, where the traffic is concentrated in the downlink (uplink packet size of 10 bytes, downlink 500 bytes); and *(iii) symmetric background*, which is the combination of the two previous scenarios (uplink and downlink packet size of 500 bytes). For each scenario, we consider 4 levels of background traffic, simulating 0, 30, 60 and 90 background devices that generate traffic for 100 s. These four levels of background traffic allow us to generate different congestion levels at the base station, in which the base station resources are reserved for platoon vehicles, i.e. no-background, and situations in which resources are shared among other vehicles or devices that do not belong to the platoon.

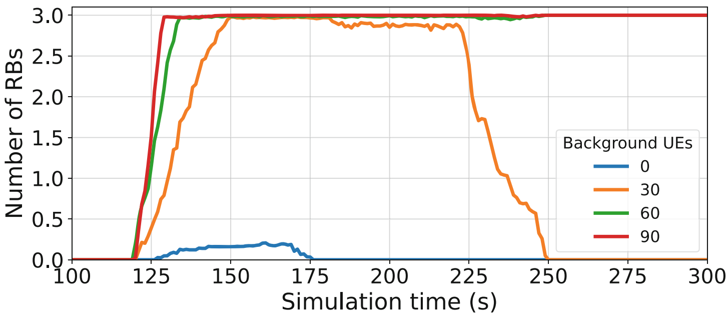


Fig. 4. Example of base station physical resources utilization considering different numbers of background devices. (Color figure online)

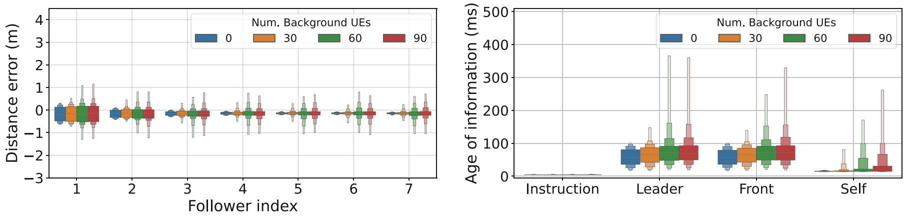
In Fig. 4, we show the utilization of the uplink physical resources of the base station that serves the platoon vehicles. The blue line represents the case of no background traffic, from which we can observe that the platoon traverses the base station coverage area between 125 s and 175 s, using a limited amount of resources. With 30 background devices (orange line), we observe a mild level of saturation, but still, the base station is able to manage all the generated traffic. However, as the number of background devices increases to 60 and 90, network congestion becomes severe. The base station, overwhelmed by the high volume of traffic, cannot process transmissions efficiently, resulting in increased latency, causing an increase in the transmission time. In particular, in the case of 90 background devices, the level of resource saturation rises very fast and it is maintained constant until the end of the simulation. In the next section, we show the performance of the edge-assisted platooning system under the different background scenarios.

4 Results

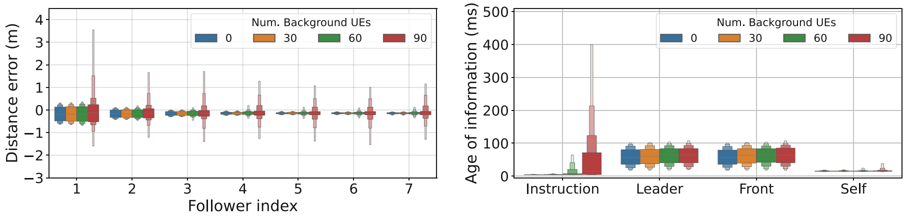
In this section, we present the results of the simulation campaign. For each background scenario, we repeat the experiment 20 times, by varying the initial random seed. To ensure our analysis focuses on the platoon's steady-state behavior, we excluded the first 100 s of simulation data, eliminating initial transient effects.

In Fig. 5, we report the overall results, considering the distance error as a quantitative metric for the evaluation of the platoon performance. On the left of the figure, we show the box plot[3] of the distribution of the distance error for

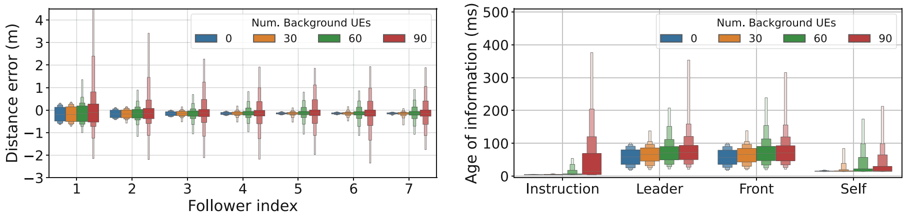
[3] The whole box plot shows up to 90th percentile, largest boxes represent the 2nd and 3rd quartile, as a classical box plot.



(a) Uplink background



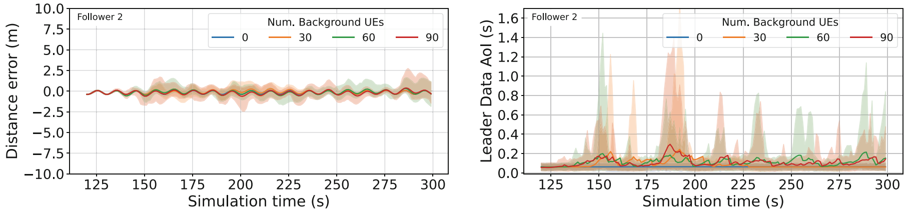
(b) Downlink background



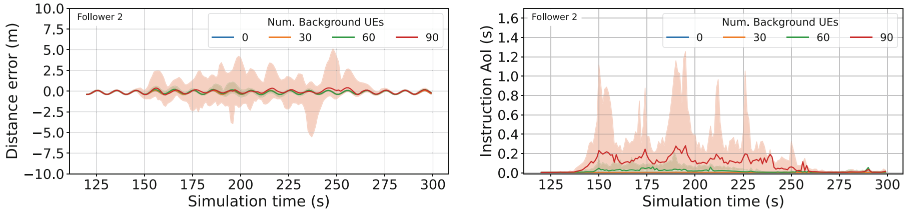
(c) Symmetric background

Fig. 5. Box plot of the distribution of distance error for all the followers (left) and box plot of the distribution of the age of the information of data and instruction (right), under different levels of base station congestion.

all the followers, while, on the right, we report the box plot of the distribution of the age of the information of motion data and instruction. As we can observe, the platoon system is able to guarantee low distance error and string stability for up to 30 background devices, this is because the mobile network can guarantee a suitable level of QoS, maintaining the age of the information of motion data up 100 ms and less than 15 ms for the instruction. The performance level significantly drops considering the scenarios with 60 and 90 background devices. As shown in Fig. 4, in these cases the base station is unable to handle the whole traffic in time, causing extra delays, which significantly affect the age of the information. However, the system behaves differently in the case of *uplink background* (Fig. 5a) and *downlink background* (Fig. 5b) scenarios. Although string stability is lost in both these cases, the downlink case exhibits larger distance errors, demonstrating that the edge-assisted platooning system is more sensitive to instruction message delays. This increased sensitivity results in vehicle motion misalignment, confirming our analysis in Sect. 2.3.



(a) Uplink background



(b) Downlink background

Fig. 6. Evolution of distance error (left) and age of the information of leader data and instruction (right) over time in uplink and downlink background scenarios.

This aspect is more evident when focusing on a single vehicle. In Fig. 6, we report the evolution of the distance error (on the left) and the age of information of leader data and instruction (on the right) over time for the second follower. The solid lines represent the median values, while the areas cover the 90th percentile. As we can observe, although the peaks of the age of information (on the right) reach similar high values, the impact on the platoon system is significantly different. In particular, the distance error in the case of the uplink scenario is bounded between −2.5 and 2.5 m, for all the background traffic levels. On the contrary, in the downlink scenario, the error peaks are below/above −5/+5 m. As for the *symmetric background* scenario (Fig. 5c), the performance is worse than the other two cases, as it combines the effects of both scenarios.

The results have shown the high sensitivity of the edge-assisted platooning system to the delay of the instruction computed by the remote controller. While the system can tolerate moderately long delays in transmitting the motion data to the remote controller, even for a prolonged time, the downlink delay must be kept low, and delay peaks should be only temporary and sporadic, avoiding congestion at the base station level. These preliminary results provide indications for mobile operators to tune the base station scheduler to reserve resources for critical services and prevent congestion by limiting the number of critical services that can be safely managed. Moreover, these findings can be the starting point for designing and tuning specific control laws tailored to remote and centralized platoon controllers, accounting for the intrinsic and unavoidable network delays.

5 Conclusion

In this paper, we have presented an evaluation of the impact of mobile network delays on edge-assisted platooning system. In particular, we analyze the sensitivity of the system to uplink and downlink delay separately. What has emerged from the preliminary simulation results is that downlink delay components are more critical than the uplink ones.

The follow-up of this study is twofold. First, to provide the network operator with specific QoS requirements for uplink and downlink channels; second, to formulate and test control law specifically designed to tolerate non-negligible delay components.

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