Analysis of the Influence of Information Flow Topology in Platoon Applications

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Abstract. *In a vehicle platoon, the Information Flow Topology consists of the structure and organization of the communication network that interconnects the vehicles. When there is a high Frame Error Rate in the communication network, the vehicle platoon can become unstable and put drivers and passengers at risk. This work investigates the influence of the Information Flow Topology on a platoon in scenarios with different speeds, acceleration and deceleration amplitude, and levels of packet loss. Simulation results demonstrated that the Predecessor Follower topology can maintain safety and a more accurate inter-vehicular distance even in nonideal vehicular communication scenarios.*

1. Introduction

Data from [World Health Organization 2022] shows that more than 1.2 million people die yearly as victims of road accidents, which cost about 3% of the gross domestic product of most countries. Some risk factors associated with such accidents include speeding, distracted driving, unsafe road infrastructure, unsafe vehicles, and inadequate law enforcement of traffic laws, among others. In order to address road traffic injuries, emerging and enabling technologies of Intelligent Transportation Systems (ITS) have been increasingly coming out [Sharma and Murali 2017].

Among ITS applications, grouping connected vehicles in platoons have attracted significant interest from the scientific community, and the road transportation sector [Robinson et al. 2010]. A vehicular platoon can be defined as an emerging technology where vehicles are organized in a row and move cooperatively, accelerating or braking simultaneously to maintain safe spacing and relative speeds close to zero [Rodonyi 2018]. This provides several advantages over traditional transportation methods. Coordinating the speeds of all vehicles in a platoon can help improve congestion management and optimize road use [Ruan et al. 2022].

The spacing policies used by vehicles in a platoon aim to optimize various aspects of a platoon's performance, such as fuel economy, travel time, and stability, by carefully controlling the acceleration and deceleration of vehicles in the platoon. These policies help to ensure that vehicles can respond to unexpected events, such as sudden braking or lane changes, without colliding with each other. The Constant Time Headway policy (CTH) [Zhao et al. 2021a] maintains a fixed time interval between each vehicle in the platoon, regardless of the speed of the vehicles. Additionally, using platoons can provide a smoother and more comfortable ride for passengers, as the vehicles in the platoon move synchronously and respond to traffic conditions more quickly and efficiently.

A crucial aspect of a platoon is the Information Flow Topology (IFT), which refers to the structure and organization of the communication network within a vehicle platoon. The IFT determines the communication patterns between the vehicles in the platoon, including which cars can communicate with each other and in which direction the communication flows. Thus, different communication strategies in the Vehicle-To-Vehicle (V2V) network can create different types of IFT.

Furthermore, the synchronization of the vehicles and the overall performance of a platoon depends on how the nodes in the V2V network connect to other nodes and how data moves between them. Therefore, the quality of the V2V communication network is critical for a platoon's performance and stability. The Frame Error Rate (FER) of the V2V network refers to the percentage of data frames transmitted over the network that are received with errors. In a vehicular platoon, a high FER can cause communication errors and instability, potentially causing the platoon to disband or creating life-threatening situations for vehicle occupants. In addition, for a vehicle in the platoon that does not receive emergency braking warnings in time due to a high FER, the vehicle's reaction time could be reduced, potentially causing accidents.

In this work, we analyze, through simulations, the behavior of platoons when the leader's velocity is cyclically varied with different periods and amplitude levels, affecting the spacing and relative speed of other vehicles from ideal conditions with excellent connectivity to situations with no connectivity between the vehicles. In our approach, we create more than 100,000 scenarios comparing the performance of IFTs. The results provide a more comprehensive understanding of the performance of platoons under different IFTs. In a nutshell, the main contributions of this work are:

- Through simulations, we evaluate the performance of vehicle platoons for several IFTs under different packet loss levels;
- We investigate platoons in scenarios with different speeds and acceleration amplitude varying with different periods;
- We analyze simulation scenarios that resulted in collisions.

The remainder of this paper is described as follows. In Section 2, we survey the literature related to the topic addressed. Section 3 describes our methodology and details experiments and simulations. The results obtained are detailed in Section 4. After that, we present the conclusions of our work in Section 5.

2. Related Works

In a platoon, vehicles often move at high speeds and change their positions relative to one another, which can cause intermittent links and dynamic changes in the network architecture. Additionally, environmental obstacles, such as buildings and other vehicles, can interfere with the wireless communication, preventing vehicles from receiving important information about their predecessors' speed, acceleration, and position.

In this context, [Zhao et al. 2021a] analyzed the performance of a cooperative platoon in a constant time interval spacing policy with communication failures. The authors consider scenarios where information from the lead vehicle or predecessors might not reach the recipient vehicle. The authors used the perturbation matrix method to analyze the effects of packet loss on the inter-vehicular distances in the platoon. By obtaining the upper bound on the FER, it is possible to ensure that the vehicles in the platoon maintain a safe distance, with minimum perturbations or changes from each other, based on their speed. This approach analyzed the effects of imperfections in V2V communication on the stability of a platoon and considered a single IFT.

[Zhao et al. 2021b] analyzed the performance of a cooperative longitudinal controller for a platoon to maximize efficiency and safety in an ITF with multiple predecessor followers. The tests consider different levels of packet loss and delays and evaluate the controller's performance in scenarios where the vehicles in the platoon have to brake. However, the experiments did not consider scenarios with a variable cruising speed, a pattern that could also affect the performance of the platoon. Based on their results, the authors concluded that the performance and effectiveness of the platoon depend on the quality of the communication between the vehicles and the IFT used by the controller. The authors also defined a limit on the communication delay that the system can handle without affecting its stability, achieving a high tracking accuracy of the position within 1.2 meter for a relative velocity of 0.04 m/s.

[Ge et al. 2022b] investigated the use of scheduled event-triggered communication subject to finite resources in a cooperative longitudinal controller for a vehicle platoon. The authors present a vehicle longitudinal dynamics model incorporating external disturbances, such as road conditions or speed changes, to evaluate the controller's performance. The paper considered four different IFTs for the controller. The proposed method has shown effectiveness in heavy traffic and bandwidth congestion scenarios due to its ability to balance the trade-off between communication efficiency and performance.

The approach proposed by [Gao et al. 2019], called CACC-grained, combines Cooperative Adaptive Cruise Control (CACC) with granulation techniques to overcome communication range and information delay limitations. The authors used unidirectional information flow in the CACC-grained approach, where information is sent from vehicles with a higher hierarchy to vehicles with a lower hierarchy, to improve the scalability of vehicle platoons. The author's proposed approach allows the controller to overcome communication range limits. However, it could also prevent the leader of the platoon from being aware of events that occur in the middle of the platoon.

Given the works presented above, our approach aims to address their limitations by conducting a quantitative investigation through simulations to evaluate the performance of vehicle platoons under varying communication topologies and packet loss levels. Using multiple IFTs allows a more comprehensive evaluation of the platoon's performance and its behavior under different communication topologies. Our work analyzes the impact of the FER on the platoon performance, which is an essential consideration since an imperfect communication is prevalent in real-world scenarios. Furthermore, using varying FER levels in this paper allows for a more realistic evaluation of the platoon's performance and the robustness of different IFTs in the presence of communication errors. Additionally, our work analyzes the platoon's behavior in scenarios resulting in collisions, providing a more realistic assessment of the platoon behavior and identifying potential safety issues. This is distinct from prior studies which focus on ideal conditions or limited variations in input parameters without considering collision scenarios.

3. Methodology

3.1. Simulation Framework

Our approach uses a framework composed of a network simulator, an urban mobility simulator, and a platoon simulator. The framework components and how they interact with each other are detailed below.

The OMNeT++ (Objective Modular Network Testbed in C++) [Varga 2010] provides a wide range of protocols and standards for various types of networks, including wired networks, wireless networks, MANET (Mobile Ad Hoc Networks), and VANET (Vehicular Ad Hoc Networks). One of the main applications of the study of VANETs is SUMO (Simulation of Urban Mobility) [Lopez et al. 2018], which is open-source software that simulates traffic flow and the physical properties of vehicle movement in urban environments. The VEINS framework (Vehicles In Network Simulation) [Sommer et al. 2011] is an inter-vehicular communication sub-module of OMNeT++. VEINS provides a bidirectional coupling between OMNeT++ and SUMO through the Traffic Control Interface (TraCI), allowing them to communicate and exchange data. This way, SUMO acts as a TCP server so that a simulation can occur in parallel in both simulators [Mena-Oreja and Gozalvez 2018].

In addition to providing a connection between OMNeT++ and SUMO, VEINS is also responsible for implementing the IEEE 802.11p protocol stack. This protocol, also known as Wireless Access in Vehicular Environments [WAVE 2010], was designed to enable wireless communication between vehicles in vehicular ad hoc networks (VANETs). Furthermore, VEINS can also emulate the upper layer models of the IEEE 1609.4 DSRC/WAVE stack, which is responsible for exchanging information between vehicles in a VANET, using a type of message called a Cooperative Awareness Message (CAM) [Sommer et al. 2011].

For the simulation of vehicle platoons, the OMNeT++ submodule called Plexe (Platooning Extension for VEINS), developed by [Segata et al. 2022], was used. Plexe uses SUMO's vehicle dynamics models to control the acceleration, braking, and maneuvers of vehicles in a platoon. In addition, Plexe also uses the TraCI interface to obtain and update information about the status of the simulation, which allows it to coordinate with SUMO and OMNeT++. Figure 1 shows the communication flow between Plexe, VEINS, SUMO, and their submodules.

3.2. Experiments

The simulations were based on a homogeneous platoon composed of 6 vehicles traveling along a highway without any other traffic. The V2V communication uses the IEEE 802.11p protocol. Our approach is based on the simulation setup of [Segata et al. 2014]. During the simulations, the vehicles send periodic messages in the platoon using a V2V communication. These periodic messages, called beacons, carry essential information about the state of each vehicle, such as its speed, position, acceleration, GPS location coordinates, and other pertinent information for platoon control. The FER was systematically varied as an input parameter to investigate the effects of communication quality on the platoon's performance. In each scenario, all communication links in the platoon had the same FER to maintain consistency in the simulation [Zhu et al. 2020].

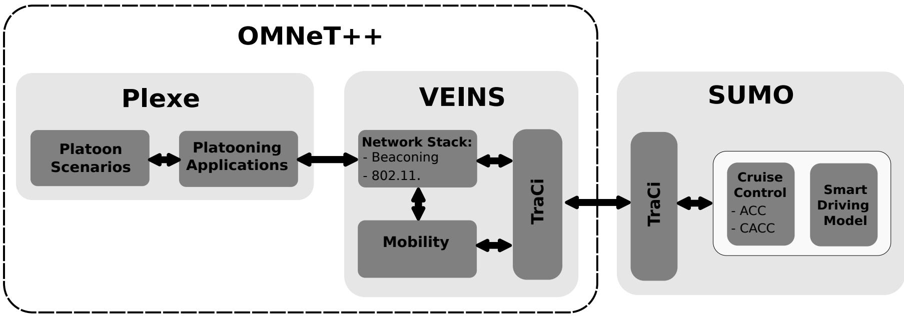

Figure 1. Framework architecture for platoon simulation.

Our simulations created different scenarios by matching the variations of speed, IFTs, FER, frequency of acceleration and deceleration, and acceleration amplitude of these stages. The variation of these parameters allowed the creation of more than 100,000 different simulation scenarios. Each of these scenarios was simulated for 40 seconds, enough time for the lead vehicle to complete at least two periods of acceleration and deceleration.

In the set of IFTs used in this experiment, the Two Followers (TF) topology involves communication between the leader vehicle and the two vehicles directly behind it in the platoon [Li et al. 2022]. The Two Predecessor Followers (TPF) topology involves communication between the leader vehicle and the two vehicles directly in front of the platoon [Liu et al. 2019]. The Leader Two Followers (LTF) topology involves communication between the leader vehicle, the two vehicles directly behind it, and the vehicle directly behind the leader [Ge et al. 2019a]. The Leader Two Predecessor Followers (LTPF) topology involves communication between the leader vehicle, the two vehicles directly in front of it, and the vehicle directly in front of the leader [Chen et al. 2020]. The Leader-Follower (LF) topology involves communication between the leader vehicle and the vehicle directly behind it [Ge et al. 2019b]. The Leader Predecessor Followers (LPF) topology involves communication between the leader vehicle and the vehicle directly in front of it [Ge et al. 2022a]. Finally, the Predecessor Follower (PF) topology involves communication between the two vehicles directly in front of the leader vehicle [Leal et al. 2021]. A summary of all the above topologies is shown in Fig.2.

In our approach, the leading vehicle's speed can be constant or follow a sinusoidal pattern with different frequencies and amplitudes. As a result, the change in cruising speed of the leading vehicle along the highway can significantly impact the spacing and relative speeds of the vehicle's followers, requiring them to adjust their speeds more frequently, potentially affecting the stability and efficiency of the platoon. In simulations, only vehicles with the same longitudinal dynamics were analyzed. Therefore, the platoon analyzed was composed of vehicles with 4 meters in length and with mass of 1460 kg. The CONSENSUS controller [Santini et al. 2015], in each vehicle, sets the time headway of the CTH spacing policy to 0.8 second. The communication protocol used in the simulations is IEEE 802.11p. All these parameters were selected to evaluate the platoon's behavior under different IFTs and a FER.

The longitudinal acceleration pattern was modeled from a sinusoidal velocity equation, which approximates the behavior of a human driver. In this scenario, the pla-

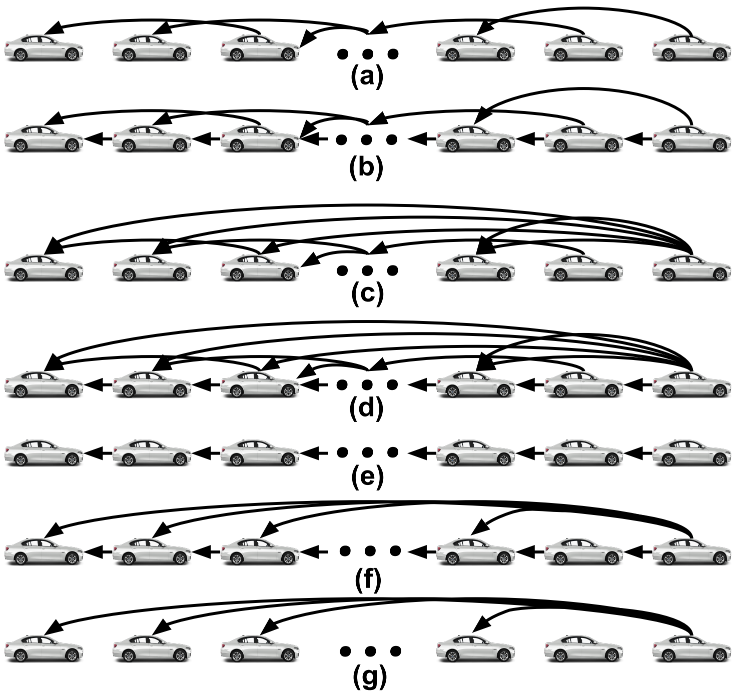

Figure 2. IFTs analyzed: (a) TF, (b) TPF, (c) LTF, (d) LTPF,(e) PF, (f) LPF, and (g) LF.

toon's leading vehicle accelerates and decelerates, changing its cruising speed several times, in the same simulation to verify the influence of external disturbances on the platoon's performance. Sinusoidal modeling is based on Oscillation Amplitude (OA) and Oscillation Frequency (OF) parameters. Table 1 details all parameters used in the simulations.

3.3. Performance Metrics

The data used in our approach consider the inter-vehicular distance and the length of the platoon. These data were extracted from the log generated by the simulation framework and used to calculate two metrics, The Average Percentage Error of Inter-Vehicular Distance for the Predecessor (APEP) and the Average Percentage Error of Inter-Vehicular Distance for the Leader (APEL). The APEP metric is calculated based on the PEP metric [Ge et al. 2020], and the APEL metric is calculated based on the PEL metric[Khalifa et al. 2021]. Both metrics are detailed below.

The Percentage Error of Inter-Vehicular Distance for the Predecessor, or PEP, measures the inter-vehicular distance between a vehicle and its predecessor in the platoon. PEP is the percentage change between the distance from a vehicle to the predecessor (DP) and the desired distance between both (EP):

$$PEP = 100 \times \frac{(EP - DP)}{DP}. \tag{1}$$

A negative PEP value indicates that the actual inter-vehicular distance is less than the optimum distance, which may be unsafe as it could increase the risk of accidents. On the other hand, a positive PEP value indicates that the actual inter-vehicular distance is greater than the optimum distance, which may affect the efficiency of the platoon.

Table 1. Set of parameters used in simulations.

Parameters	Discrete Values	
Simulation Time (s)	40	
Number of Vehicles	6	
Speed (km/h)	Low Speed Scenario: Medium Speed Scenario: High Speed Scenario: Ultra High Speed Scenario:	[1, 2, 3, 4, 5, 10] [20, 40, 60, 80] [100, 120, 140] [160, 180, 200]
Information Flow Topologies	[TF, TPF, LTF, LTPF, LF, LPF, PF]	
Frame Error Rate (%)	[0, 5, 10, 15, 20, 25, 30, 35, 40, 45, 50, 55, 60, 65, 70, 75, 80, 85, 90, 95, 100]	
Oscillation Frequency (mHz)	[0, 5, 10, 15, 20, 25, 30]	
Oscillation Amplitude (km/h)	n $\times$ (¼ of the leader's speed), where n = $\{0, 1, 2, 3, 4, 5, 6, 7, 8\}$	
Headway Time (s)	0.8	
Vehicle Size (m)	4	
Vehicle Mass (kg)	1460	

The Percentage Error of Inter-Vehicular Distance for the Leader, or PEL, measures the inter-vehicular distance between a reference car and the platoon leader. PEL is the percentage change between the distance calculated by the controller between the reference car and the leader (EL) and the actual distance between the two (DL):

$$PEL = 100 \times \frac{(EL - DL)}{DL}. \tag{2}$$

A high PEL value indicates that the actual inter-vehicular distance is greater than the optimum distance, which may affect the efficiency of the platoon as it could result in increased fuel consumption and low efficiency on road space utilization. On the other hand, a low PEL value may indicate that the actual inter-vehicular distance is less than the optimum distance, which could impact the stability of the platoon.

The APEP and the APEL metrics are averages of the PEP and PEL values, respectively:

$$APEP = \frac{\sum_{i=0}^{n} PEP_i}{n}, \tag{3}$$

and

$$APEL = \frac{\sum_{i=0}^{n} PEL_i}{n}, \tag{4}$$

where the calculation has to consider all vehicles in the platoon. In both equations, i represents the i-th car in the platoon, and n is the number of vehicles in the group. These two metrics can provide a summary measure of inter-vehicular distances and the platoon's safety. In addition, these metrics serve as a reference to compare the performance of different platoon configurations.

4. Results

In the experiments, the speed of the convoy's leader was configured according to four pre-established scenarios: Low Speed Scenario (speed range of 0-10 km/h), Medium Speed Scenario (speed range of 20-80 km/h), High Speed Scenario (speed range of 100-140 km/h), Ultra High Speed Scenario (speed range of 160-200 km/h). The APEL and APEP metrics were calculated based on the average values obtained in each simulation of the speed scenarios. In each experiment, the platoon leader's velocity followed a sinusoidal pattern with different periods and amplitude levels, affecting the other vehicles' acceleration and deceleration, impacting the spacing and relative speeds.

In a platoon, the vehicles rely on communication to coordinate their movement and maintain a safe distance from each other. When the FER is equal to 100%, all communication between vehicles in the platoon is lost, and the platoon's behavior becomes unpredictable. The vehicles may not be able to detect the presence or movements of other vehicles, which can lead to collisions or other types of accidents. In the simulated scenarios, the value of FER ranged from 0 to 100%, with increments of 5%. However, the data is shown in Figs. 3 to 6 with increments of 25% because the results for FER values below 75% did not show significant differences, even for different ITFs.

4.1. Low Speed Scenario

The first experiment considers a Low Speed scenario where the vehicles travel at slow speeds on a highway or in controlled environments such as production lines or warehouses. Low speed platooning applications may be used when vehicles need to move slowly and steadily, such as in heavy traffic or automated guided vehicle systems.

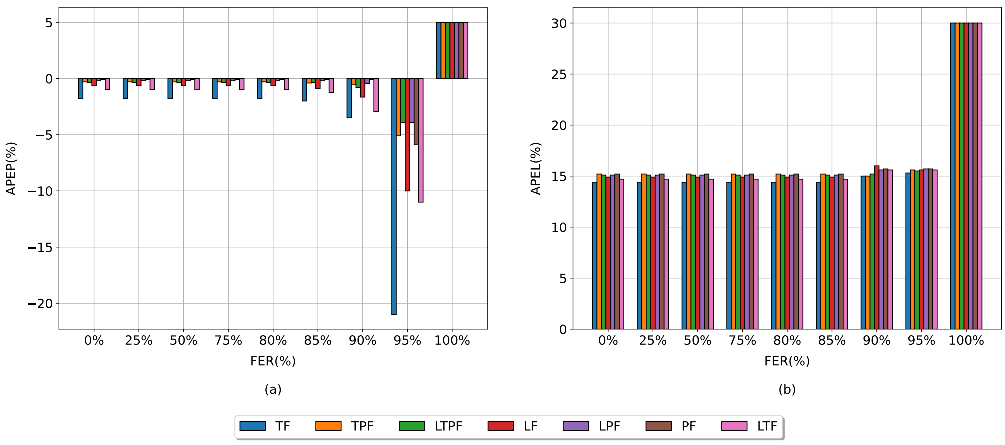

Figure 3. APEP and APEL metrics for a Low Speed scenario.

The results in Fig.3(a) show the APEP metric for different IFTs under different FER. The graph indicates that the APEP value becomes more negative as the FER increases, suggesting that the platoon becomes less safe as communication deteriorates. The graph also shows that all IFTs have worse performance for a FER above 85%. For a critical scenario with the FER equal to 95%, the TF topology has an average error of 21% in the safe spacing policy. Both LTPF and LPF topologies stay below 5% in the same conditions. Thus in Low Speed scenarios, IFTs with direct communication with the convoy leader perform more satisfactorily from a safety standpoint. The graph in Fig.3(b) presents the APEL metric analysis applied to the same scenario. The results indicate a very close performance for all IFTs. However, the TPF topology performs better in poor communication scenarios. The LTPF topology had the worst performance in this experiment, with an APEL equal to 15.9%.

4.2. Medium Speed Scenario

The second scenario simulates a medium speed for a vehicle platoon, in which the vehicles are traveling at typical average speeds on urban roads. Even though platooning systems may be designed for something other than urban scenarios, connecting them with other communication networks, such as infrastructure, may improve the management of traffic jams in these areas.

The graph in Fig. 4(a) indicates that the APEP metric is negative for all IFTs, which means that the average distance between vehicles in the platoon is less than the distance defined by the spacing policy of the controller. The results shown than TF topology presents the worst performance in this metric of all IFTs. Fig. 4(b) depicts a slight variance in the APEL metric values of all IFTs while FER is below 95%.

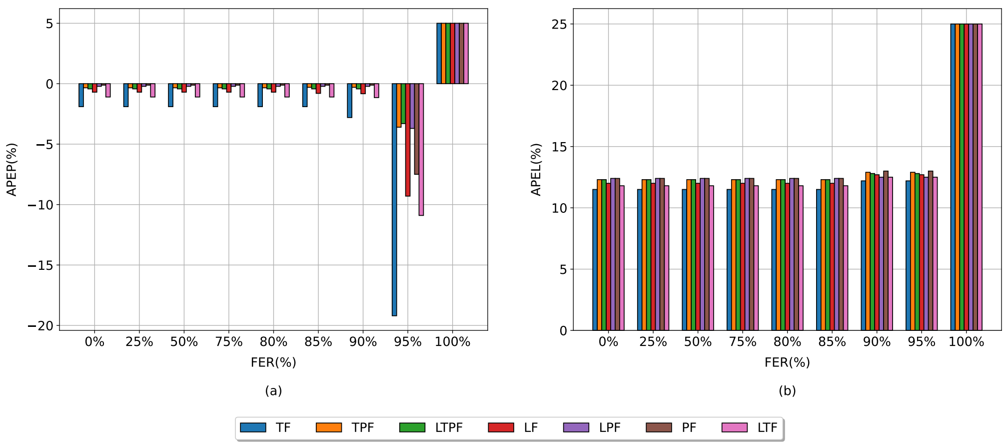

Figure 4. APEP metric for a Medium Speed scenario.

For a FER equal to 95%, the LTPF topology had the worst performance with an error of 15.99%, which indicates low efficiency in the use of the road area. The TPF, LTFP, and LPF topologies performed better than the other IFTs in terms of the APEL metric in this experiment. These results suggest that the best-performing IFTs in Medium Speed scenarios communicate directly with the leading vehicle and receive messages from at least the two predecessor vehicles.

4.3. High Speed Scenario

For a FER of 95%, as velocity increases, the performance of all IFTs concerning the APEP metric improves. In a high-velocity scenario, the TF topology had the worst performance. However, the APEP metric dropped almost eight percentage points compared to the medium-speed scenario, as shown in Fig. 5(a). In this scenario, the TPF topology had the best performance, with an average error of 2.5%. Fig. 5(b) shows that the APEL metric also presents better results than the other scenarios, suggesting that the platoon uses a road area more efficiently as the speed increases.

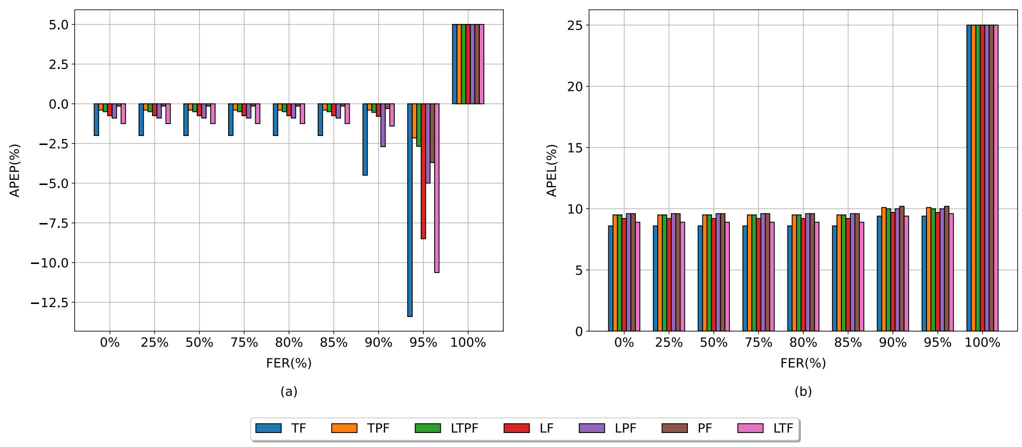

Figure 5. APEP and APEL metrics for a High Speed scenario.

The metric APEL for all ITFs has very close performance with a slight variance. The difference between the best and worst performance is around 2%. In this scenario, the TF topology had the best performance in the APEL metric among all IFTs.

4.4. Ultra High Speed Scenario

It is essential for platooning systems to consider all potential hazards and risks associated with high-speed driving and implement appropriate safety measures to mitigate them. The Ultra High Speed scenario results, shown in Fig. 6, reach the best values for APEP and APEL metrics compared with the other scenarios. Using a CTH spacing policy for high speed platoons allows for better control over the spacing between vehicles. By maintaining a constant time interval between vehicles, the spacing policy can help to ensure that there is a sufficient distance between vehicles to avoid collisions.

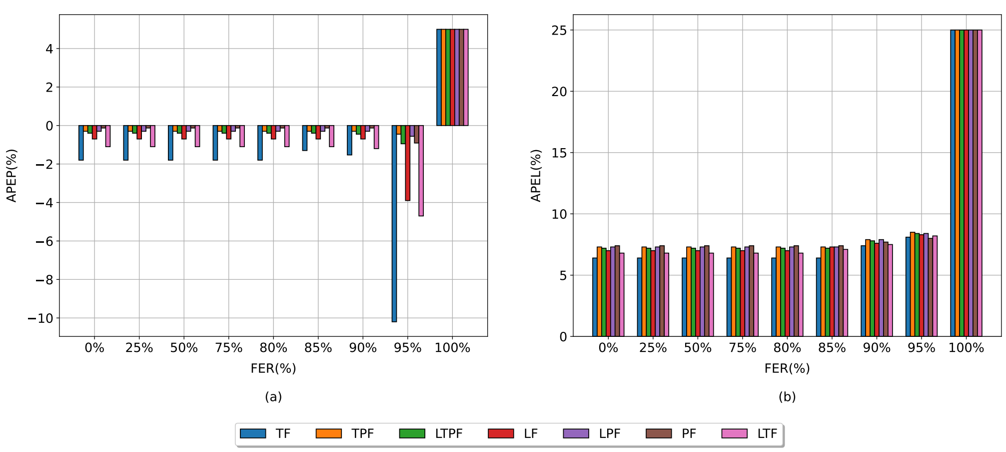

Figure 6. APEP and APEL metrics for an Ultra High Speed scenario.

Fig. 6(a) shows that the TF topology had the worst performance in terms of the APEP metric, with an average error of 10.19% for a FER of 95%. The TPF topology had the best performance in the APEP metric, with an average error of 0.45%. Fig. 6(b) shows that the TF topology performs relatively well in the APEL metric in the Ultra High-Speed Scenario compared to the other scenarios. A low value for the APEL metric indicates that the actual inter-vehicular distance is close to the desired distance, which may improve the efficiency of the platoon by reducing fuel consumption and minor highway area utilization.

4.5. IFTs and Collisions

Among more than 100,000 simulations, only 119 involved vehicle collisions. Fig. 7 shows the Collision Rate for each IFT. All simulations that resulted in a collision occurred for a FER above 95%.

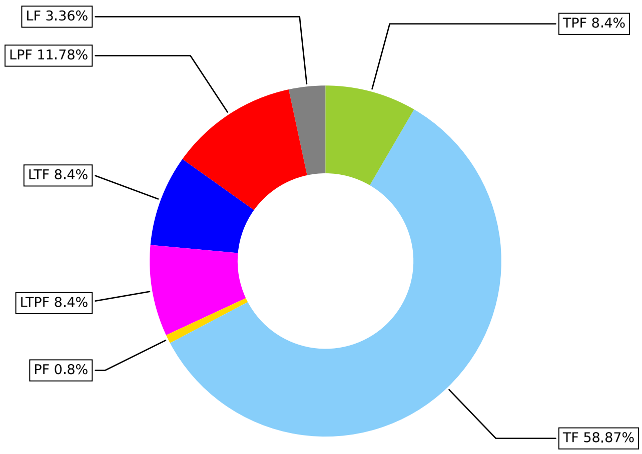

Figure 7. Collision rate for each IFT.

The overall result of the simulations showed that the IFT with the highest number of collisions was the TF topology, regardless of the speed of the platoon. However, it is also noted that there were no collisions in scenarios with speeds greater than 120 km/h due to the spacing policy that ensures a sufficient distance between vehicles to avoid collisions. This suggests that the TF topology may not be as effective at avoiding collisions as the other IFTs under high FER. However, it is still generally effective at higher speeds. Just one collision occurred in the PF topology, which reinforces the results obtained with the APEP metric. The graph in Fig. 8 shows the number of collisions that occurred in each scenario, providing further information about the performance of the different IFTs in terms of collision.

5. Conclusion

This work analyses the performance of a vehicular platoon using a specific controller (CONSEUS) and different information flow topologies (IFTs) in scenarios with different speeds and Frame Error Rates (FER). The occurrence of collisions and two metrics, APEP and APEL, were used in our investigations. The LF topology performed better in low-speed scenarios even with high FER, while PF topology performed better in medium and

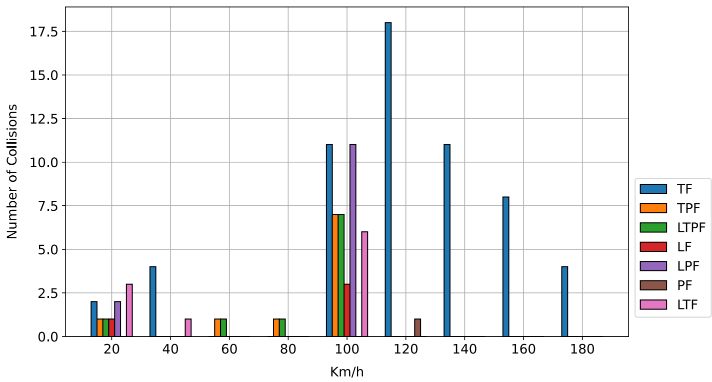

Figure 8. Number of collisions per speed.

high-speed scenarios. The PF topology can maintain the desired safe distance between vehicles even in scenarios with high FER, suggesting that it is relatively resistant to poor communication conditions. In contrast, the TF topology had the worst performance in all experiments, suggesting that it may not be a suitable choice from a safety standpoint in any scenario.

The results obtained with the APEL metric showed that the higher the platoon leader's average speed is, the more optimized the physical space the platoon occupies on the road. The results also show that the LF topology had the best performance in terms of highway area use for low-speed scenarios, while the TF topology had the best performance in medium and high-speed scenarios. These results suggest that the LF topology may be more suitable for low-speed scenarios where maximizing highway use is a priority. At the same time, the TF topology may be more suitable in medium and high-speed scenarios.

The collisions occurred in simulations with a FER above 95%, in medium-speed and high-speed scenarios, precisely at 20 and 100 km/h, respectively. These results indicate that the PF topology recorded the lowest number of collisions between vehicles in the platoon, while the TF topology recorded the highest number collisions. These data are consistent with the results obtained through the APEP metric, indicating that the PF topology maintains a safe distance between vehicles, even with high FER, reducing the risk of collisions. On the other hand, the APEL results indicate that the TF topology keeps the vehicles closer to each other, optimizing the use of the highway area. These results suggest that the PF topology may be more suitable from a safety standpoint. In contrast, the TF topology may be more suitable for maximizing the use of the road area. However, it is crucial to consider a platoon's specific requirements and goals to determine the most appropriate communication topology.

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