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Emergency Braking in Platooning with Communication Loss

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EMERGENCY BRAKING IN PLATOONING WITH COMMUNICATION LOSS

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ABSTRACT

Platooning is an application of autonomous driving in which the vehicles travel linearly following each other. The benefits of such driving are many-fold, primarily it increases the traffic throughput and also reduces fuel consumption as the result of minimized drag experienced by the vehicles. The state-of-the-art technologies to achieve platooning involve vehicle-to-vehicle communication for receiving all the events instantaneously. However, wireless channels being prone to communication losses pose risks to the platoon operation. Therefore, it is important to study how platoons operate under communication losses. Platoons being vehicular ad-hoc networks, the information dissemination is governed by Time Division Multiple Access policies known as Information Flow Topology (IFT). Platooning being sensitive to communication losses, during an emergency braking, the requirements are even more stringent as it could lead to rear-end collisions within the vehicles.

All the performance evaluation are done on a newly designed testbed which is both cost-effective and customizable. Several kinds of IFTs have been developed in recent years. We consider four of the predominant ones and evaluate their performance during emergency braking with temporary communication loss. Since the decrease in inter-vehicle distances is the main reason for vehicle collisions during platoon, we use it as a key performance indicator when evaluating the performance. To improve the reliability of communication in the platoon, we propose to adopt an existing methodology in wireless networking and combine it with the IFTs in platooning. We additionally show the improvement in the collision probability with this method. We conclude our work with limitations and further improvements.

Keywords: platooning, robotic testbed, emergency braking, V2V

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TDMA	Time Division Multiple Access	xi
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WSU	Wireless Safety Unit	6
CAN	Controlled Area Network	6
GPS	Global Positioning System	6
CCA	Clear Channel Assessment	19
RSSI	Received Signal Strength Indicator	13
DSRC	Dedicated Short Range Communication	xiii
PWM	Pulse Width Modulation	21
UART	Universal Asynchronous Receiver-Transmitter	21
JTAG	Joint Test Action Group	21
SWD	Serial Wire Debug	21
SoC	System-on-Chip	22
HAL	Hardware Abstraction Layer	23
UDP	User Datagram Protocol	23
GFSK	Gaussian Frequency Shift Keying	25
PCB	Printed Circuit Board	xi
LBT	Listen-Before-Talking	20
PID	Proportional-Integral-Derivative	17
OBU	On-Board Unit	18
IVD	Inter-Vehicle Distance	xi
PLR	Packet Loss Rate	xii
IR	Infrared	15
VLC	Visible Light Communication	16
COTS	Commercial-Off-The-Shelf	16
OOK	On-Off Keying	16
BER	Bit-Error-Rate	16
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PQoS	Predictive Quality of Service	14
MAC	Media Access Control	18
GUI	Graphical User Interface	23
ISM	Industrial Scientific Medical	25
CPU	Central Processing Unit	19
WiFi	Wireless Fidelity	17
RF	Radio Frequency	4
ETSI	European Telecommunications Standards Institute	18
LoS	Line-of-Sight	5
RADAR	RAdio Detection And Ranging	3
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1 INTRODUCTION AND BACKGROUND

With the advent of intelligent, automated vehicles, road transportation has become safe and reliable. This is mainly enabled by the advances in the field of vehicular technologies like camera, Light Detection And Ranging (LiDAR) and RAdio Detection And Ranging (RADAR) along with Vehicle-to-Vehicle (V2V) communication between the vehicles. This gave rise to Intelligent Transportation Systems, which focuses on automating the common vehicular operations like lane following, braking, collision warning and many other applications.

1.1 PLATOONING

Platooning is an application of semi-autonomous driving in which multiple vehicles travel one behind the other intelligently while the leader vehicle is driven manually. A common platooning scenario is shown in Figure 1.1 in which a group of trucks platooning on a highway coexist with other vehicles.

Figure 1.1: Truck and car platoons on a highway [1]

Platooning technology allows for increased highway capacity, while at the same time reducing the fuel consumption due to the reduced aerodynamic drag experienced by the follower vehicles. When vehicles travel on highways, they experience resistance caused by air moving in the opposite direction of the motion of the vehicle. This causes additional fuel consumption. However, when a group of vehicles are moving in the form of a platoon, with a lower Inter-Vehicle Distance (IVD), the air resistance experienced by the follower vehicles can be reduced. This phenomenon is shown in Figure 1.2. Initial studies done showed that there can be a fuel-saving of $9-15\%$ in the follower trucks due to the reduced air drag [2]. It was found that

65% of the highways in the US have a favourable condition to support platooning.

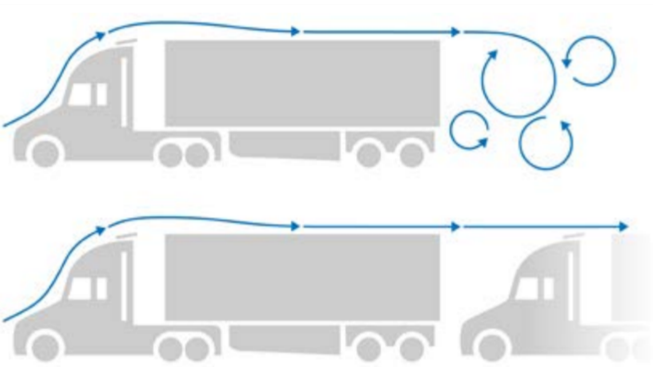


Figure 1.2: Reduced aerodynamic drag with lower IVD [2]

Additionally, platooning can reduce the reaction time taken by humans in a dynamic environment (like braking by the preceding vehicle). One such scenario is shown in Figure 1.3 [3], in which the preceding truck applies brakes and the reaction time of the following truck (represented by "Driver reaction time") is in the range of 1 to 4 seconds depending on the state of the driver [4]. For example, when a vehicle is moving at a speed of 50 km/h, in the time the driver reacts to the braking by the preceding vehicle, the vehicle would have already travelled 14 to 56 meters (assuming the driver's reaction time is in between 1 to 4 seconds). If there is a vehicle before this vehicle that is braking, it could lead to a rear-end collision. When V2V communication is equipped, this reaction time can be reduced significantly as the only reaction time would be the Radio Frequency (RF) signal propagation latency.

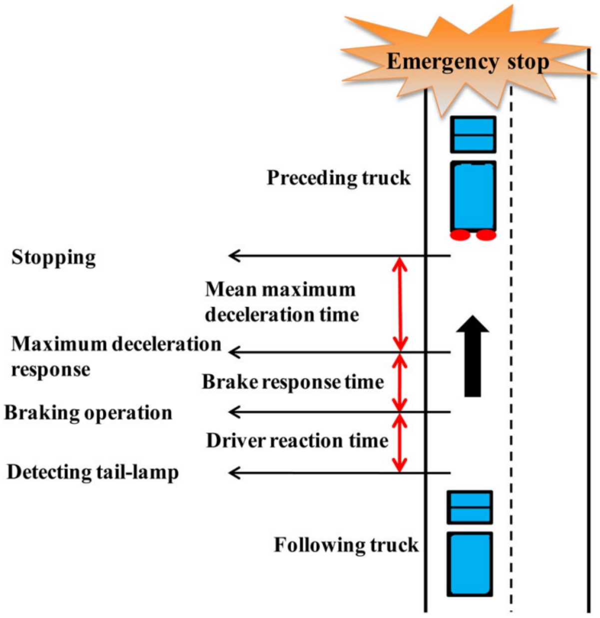


Figure 1.3: Emergency braking action sequence in manual driving [3]

Given the benefits of platooning, achieving it is challenging because the IVD between the two consecutive vehicles in the platoon is a critical factor for safety and efficiency. This is mainly because maintaining a large IVD ensures safety, however, it largely reduces the throughput on highways. On the other hand, reducing the IVD increases traffic throughput, but it also increases the risk of rear-end collisions.

Platooning was first achieved using Adaptive Cruise Control (ACC) [5], in which every vehicle is equipped with vision sensors such as LiDAR and cameras and follow their predecessor. A certain distance to be maintained in between the vehicles is set and the vehicles try to maintain this distance while they are cruising.

1.2 ADAPTIVE CRUISE CONTROL (ACC)

Introduction of ACC was the first step towards platooning. The sensory data is provided by sensor systems like RADAR, LiDAR, cameras or any combination of them. This set of sensors gives the IVD with its preceding vehicle as an input to the mobility system, which controls the acceleration and braking as required to obtain the desired IVD that is selected by the driver. This system attempts to maintain a safe distance, as specified by the manufacturer and simultaneously maintain a maximum speed set by the driver.

Benefits
While the ACC system does not provide a complete autonomy, the main benefit of using ACC systems is the increased safety, by performing automated braking and increased comfort for the driver, by maintaining a constant speed and distance. Additionally, it also increases the throughput of the traffic as compared to manually driven vehicles.

Drawbacks
As a safety precaution to avoid collision during sudden braking, the IVDs are significantly high. Due to this, there is no reduction in the drag experienced by the follower vehicles. Therefore, it does not provide any benefits to fuel consumption. Another drawback of the ACC system is that the sensing systems need the predecessor vehicle to be in the Line-of-Sight (LoS) of the vehicle. This may not always be possible in scenarios like curved roads and hilly roads where the uneven road surface makes one of the vehicles go out of sight for the follower vehicle's sensing system. Even in the presence of LoS, the inaccuracies in sensing systems result in increased reaction time.

To overcome the drawbacks of ACC, the support of V2V communication was added to ACC systems, giving rise to CACC, with which the IVD can be reduced [6].

1.3 COOPERATIVE ADAPTIVE CRUISE CONTROL (CACC)

CACC systems are built on ACC systems by integrating the capability of V2V communication between different vehicles in the platoon. CACC systems, in addition to their incorporated sensors (like LiDAR, camera), use inter-vehicle communication (V2V) to exchange vehicle specific information with the rest of the platoon to maintain a constant spacing with its preceding vehicle and reduce the reaction time. The main goal of the CACC system is to reduce the IVD while still being safe for platoon operation. This is achieved by CACC since communicating is faster than sensing. Any event detected can be disseminated through V2V communication.

Since CACC systems use V2V communication, there is no requirement for the vehicles to stay in the LoS with each other. However, when this is not possible (in an event of communication outage), they fallback to ACC systems and increase the IVD to enable a safe platoon operation.

Benefits
CACC equipped with V2V communication capabilities, reduces the IVD while not sacrificing safety. In Figure 1.3, the first stage, "Driver reaction time" takes about one-third of the time taken to stop the vehicle from the instant there is a braking requirement, known as braking time (which is the time taken from braking requirement to the moment the vehicle stops). By incorporating a CACC system, the reaction time taken is reduced to a significantly shorter time using V2V communication [3], even lower than what was experienced in ACC.

Drawbacks
With V2V communication in place, the system is based on frequent information exchange between other vehicles for proper operation. This heavy reliance on a wireless channel can make it unreliable in the presence of channel congestion. In extreme conditions, it could cause rear-end collisions. This problem is exacerbated when these platoons have to coexist with other traffic where Vehicle-to-Infrastructure (V2I) and Vehicle-to-Everything (V2X) communications use the same communication channel.

1.3.1 System Architecture

This section describes the system architecture that is needed to enable a CACC platoon [7]. Milanés et al. stated that the systems used for ACC can be retrofitted with the CACC equipment [8]. Therefore, CACC systems can have high adoption.

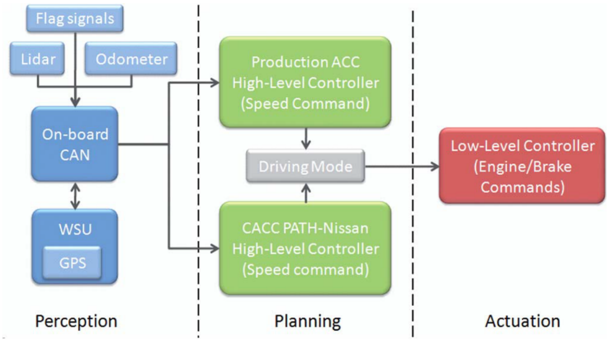


Figure 1.4: System architecture of a typical CACC implementation [7]

The overall system can be classified into the three stages as shown in Figure 1.4:

- *Perception*: The vehicle gets the information about its surroundings and performs an update to the system via their internal Controlled Area Network (CAN) bus. In addition to the sensors, the perception system also includes a Wireless Safety Unit (WSU), which acquires the data from wireless units, which include: Global Positioning System (GPS) coordinates and information (like speed, acceleration, distance, etc.) conveyed with V2V communication by other vehicles.
- *Planning*: This phase includes control-related algorithms to enable predictions for the upcoming trajectory of the vehicle. In this phase, the actual control can be switched between CACC and ACC. Whenever such a switching happens, the IVD is adjusted accordingly.
- *Actuation*: This stage is responsible for executing the commands provided by the planning phase. This is done with low-level controllers which convert the commands provided to the throttle and braking actions. It is also responsible

for sending any predictions about the braking delay to the other stages to tune the control algorithms.

The system architecture remains the same in most of the current implementations except for the variations in the IFT [8], for example, the leader-follower and predecessor-follower model, which are described later in this chapter.

1.3.2 Information Flow Topology (IFT)

The IFT in platooning defines a protocol for performing V2V communication within the platoon. Its functionalities include specifying the structure of the payload, flow and scheduling [9]. Platoons being vehicular ad-hoc networks, IFT functions as a distributed scheduling policy so that every node does not contend for the channel. Without any IFT, V2V communication would involve each node transmitting its beacon at a certain rate using Carrier Sense Multiple Access/Collision Avoidance (CSMA/CA) [10]. This approach is inefficient as it leads to frequent collisions and gives rise to an irregular beacon sequence. IFT imposes a certain TDMA schedule for transmission of vehicle's information.

Literature provides four types of IFTs: Leader Follower (LF), Predecessor Follower (PF), Leader-Predecessor Follower (LPF) and Multiple Predecessor Follower (MPF) which are described in detail below. For the purpose of illustration, a platoon with $N+1$ vehicles are shown in their respective sections, where the leader is labelled as V_0 and followers are labelled as V_1 to V_N.

1.3.2.1 *Leader Follower (LF)*

In this mechanism, the leader's information is transmitted via broadcast beacons to the whole platoon via V2V communication at a fixed beacon period. Each of the follower vehicles in the platoon receives the beacon sent by the leader and sets its corresponding state. In this topology, the communication is restricted to the leader and its followers, which implies that there is no communication between the followers.

Given the limited range of V2V communication, the coverage requirement increases with the size (number of followers) of the platoon, making the communication system inefficient. When the communication range increases, the transmissions made by the leader induces congestion in the communication range of the leader which impairs the functioning of other platoons and V2X communication as these transmissions collide with others. Therefore, in any of the vehicular ad-hoc network, the range should be confined to a small value.

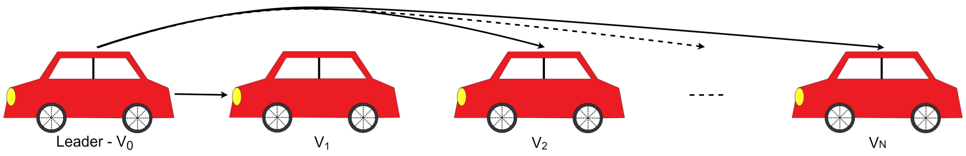


Figure 1.5: Leader Follower IFT

Benefits

- **Low-latency communication:** The latency of communication is almost the same at any vehicle in the platoon. Hence, the reaction time of all followers will be almost instantaneous (when there is no interference).

Drawbacks

- **Cannot respond to intermediate vehicle braking:** This IFT does not consider braking by a follower vehicle, even though it is a realistic scenario. In the event of unexpected braking in the middle of the platoon, there is no V2V communication about the event. In which case, the follower vehicles should rely on their sensing system to sense their predecessor's distance and apply braking to avoid collisions.

- **Unscalable**: As the number of vehicles in the platoon increase, the communication range of the leader also proportionally increases. Longer communication range causes additional interference to the other communication infrastructure and platoons in the range. This problem is exacerbated at shorter beacon periods. Therefore, this type of IFT is not scalable [11].

1.3.2.2 *Predecessor Follower (PF)*

In PF, each of the vehicles has only a direct communication link with its preceding vehicle in addition to the distance sensors. With this mechanism, the event sensed by the leading vehicle has to be propagated along the platoon chain as shown in Figure 1.6.

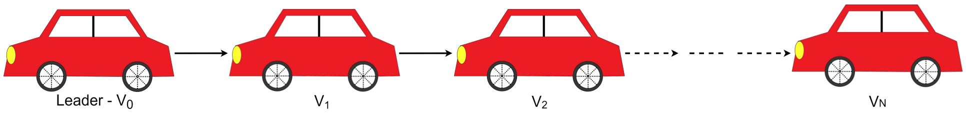


Figure 1.6: Predecessor Follower IFT

Benefits

- **Support for intermediate vehicle braking:** In an event where one of the followers experiences an emergency brake event, it can communicate to the subsequent cars through the chain propagation. Although the event update comes after a delay compared to the time event took place, with a sufficiently large IVD, a vehicle collision can be avoided.

- **Less interference:** Since each vehicle only updates its immediate follower, this communication can be supported with low power, just enough to reach its immediate followers. Therefore, it causes less interference in the channel due to their short communication ranges.

Drawbacks

- **Large IVD**: To avoid vehicle collisions in a platoon because of any intermediate vehicle braking in the platoon, each of the vehicles should maintain large IVD considering the additional brake time which is induced by the command propagation delay. However, increasing the gap reduces the benefit of reduced fuel consumption.

- **Less immune to packet loss:** This topology inherently is less immune to communication loss. A missed transmission can only be recovered by the next transmission of the leader's beacon and if the packet is lost at the leader, none of the followers is updated as the communication chain is broken right at the beginning. This implies that any missed packet between any of the vehicles in the platoon will break the message propagation in the rest of the platoon, leading to an increased period of uncertain operation of vehicles.

1.3.2.3 *Leader-Predecessor Follower (LPF)*

Unlike the previous IFT, in LPF, along with the leader's state information, every predecessor's state is communicated with its immediate follower throughout the platoon as shown in Figure 1.7.

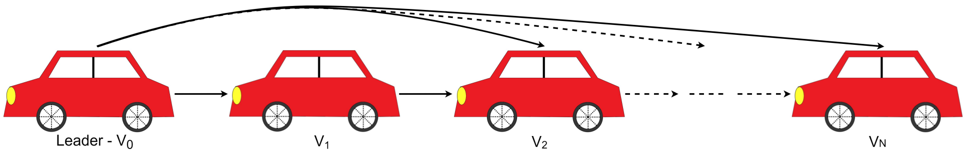


Figure 1.7: Leader-Predecessor Follower IFT

Benefits

- **Support for intermediate vehicle braking:** Any emergency braking happening in the middle of the platoon is taken care of through the message propagation by the followers.
- **Low-latency communication:** Any events taking place in the leader vehicle is also propagated to the rest of the followers instantaneously.

Drawbacks

- **Unscalable:** This topology still has the problem of having to transmit leader state to the whole of the platoon. As it would still interfere with other operations in the region. Therefore, like LF, LPF is also not scalable.
- **High propagation delay:** The propagation of any event (like emergency braking) happening in the middle of the platoon takes chain propagation to reach the end of the platoon, as the intermediate vehicles do not broadcast or multicast the packets. Therefore, any event happening in the middle of the platoon takes multiple relays to reach the end of the platoon.

1.3.2.4 *Multiple-Predecessor Follower (MPF)*

In this mechanism, every vehicle multicasts its state to only a predefined number of followers as shown in Figure 1.8, where a beacon is processed by two immediate followers. The transmission starts with the leader sending out its beacon which is received by its immediate followers and only the very immediate follower relays it further. The penultimate vehicle transmits only to the last vehicle, which ends the propagation chain.

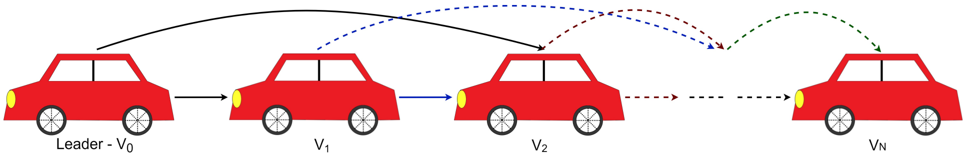


Figure 1.8: Multiple-Predecessor Follower IFT

Benefits

- **Low-latency communication:** Any incoherence within the platoon can be propagated faster as compared to the other topologies. Assume the number of followers who receive the data directly to be $\mathcal{F}$. As each vehicle multicasts its beacon to $\mathcal{F}$ number of followers, information is received faster due to the multicast nature (as compared to the other topologies like PF and LPF where the information needs to be propagated in a chain through unicast to reach the end of the platoon).

- **Scalable:** Since there is no direct transmission from the leader of the platoon, the communication range is restricted within $\mathcal{F}$ number of vehicles, as compared to the whole platoon as in the case of LF and LPF topologies, making it scalable.
- **Support for intermediate vehicle braking:** As this topology also includes the event propagation mechanism, any events happening in the middle of the platoon are also detected and made aware to the rest of the platoon with lower latency.

Drawbacks

- **Potential interference:** This IFT performs worse than any other IFT if the number of direct receivers ($\mathcal{F}$) is chosen to be closer to the length of the platoon. This is because of multiple multicasts (with the communication range closely equal to the length of the platoon) that needs to happen before reaching the end of the platoon, that causes interference to other operations in the vicinity. Therefore, $\mathcal{F}$ should be selected with care.

1.3.3 Communication Loss

Since V2V is the backbone for the safe operation of platooning, reliable communication plays an important role in achieving it. This is even more important during an emergency braking as the constraints are extremely stringent. There is no literature for how the IFTs perform during communication loss for emergency braking scenarios.

1.4 CONTRIBUTIONS

Although CACC platooning is relatively a new field, for the benefits it provides, a lot of research efforts have been put into the domain in the recent past. A vast majority of the literature targeted improving platoon operation in communication loss. While several approaches were taken from a control system standpoint which involved some degree of prediction when there is a communication loss, very few of them used communication enhancements. For scenarios like emergency braking, control system approaches tend to saturate and do not perform well. This is exacerbated during communication loss. Among all the literature, there is no work done to evaluate the IFTs for emergency braking with packet loss.

For the evaluation of performance, most of the works relied on simulations as they are economical and easily scalable. However, simulations do not take into account the characteristics of sensors and motors present in the real hardware, which are not specific to any vehicle [12]. Another end involved real cars and hardware-in-the-loop simulation for performing tests which are extremely expensive and unsafe. There are some testbeds which are moderately expensive yet do not offer full control, due to which a completely reliable implementation is missing.

In our work, we design a testbed and explore how to solve the problem of emergency braking during packet loss from a communication standpoint and trying to ensure we target both leader and intermediate vehicles braking. This combination of problems is not deeply researched. The contributions of this work are the following:

1. Propose a low-cost, easy to use and modular testbed to implement and evaluate all the experiments. In contrast to the existing testbeds, our design is

mainly focused to provide low-latency communication with a cost-effective solution.

2. Implement four of the IFTs discussed and evaluate each of them for emergency braking in the presence of a temporary communication loss and draw a comparison between them on specific metrics.
3. Propose to adopt an existing MAC layer present in wireless networking to improve the reliability of intra-platoon communication in a noisy environment and compare them to existing platooning protocols on our proposed testbed.

1.5 REPORT ORGANIZATION

This work is structured as follows: Chapter 2 describes the related work done in the field of platooning and various other problems tackled. Chapter 3 details out the testbed that we used throughout the experiments discussed in the rest of the report. Chapter 4 describes the evaluation of the IFTs for emergency braking under lossy network conditions. Chapter 5 describes our enhancement done to the communication protocol to increase the reliability of the communication. This report concludes with Chapter 6, showing the potential improvements and extensions.

2 RELATED WORK

The research that is done in the field of platooning mainly focused on making the platoon operation safe. In the majority of the literature, platooning is seen as a networked control system and proposed various control theory enhancements. In this chapter, various problems and their solutions present in the literature are discussed.

2.1 COMMUNICATION ENHANCEMENT

Since communication plays an integral role in CACC platooning, at the same time, because of the unpredictable nature of the wireless medium, platooning is far from its ideal design methodology. Inconsistent communication that is caused by various factors can lead to rear-end collisions.

When a vehicle is manoeuvring on a hilly or curve roads, simply following the preceding vehicle is not sufficient. Zhang et al. proposed that temporal communication can be replaced with a space domain approach in which followers do not follow the leading vehicle directly [13]. But each of the vehicles uses a history-based implementation where the states are stored in the database based on their time. So that the vehicles can perform the same manoeuvring that was performed by its predecessor than blindly following it. Each vehicle based on its database follows the same profile. This way, when the vehicle is at the point where it is difficult to manoeuvre, the follower vehicles match their current speeds with the profile of the leader vehicle. When there are communication delays, the profiles are predicted instead of the current state of the leader. This method, however, does not take into account any emergency events, which would require immediate response by every follower vehicle.

In LF and LPF topologies, the leader's transmission has to reach the whole platoon. Given the realistic scenario, the leader range is always limited by its transmission power. However, increasing the transmission power will cause interference to other operations in the vicinity. To remedy this problem, Marcus et al. proposed a low-overhead forwarding algorithm in which a node in the platoon is chosen as a relay node to forward the leader's transmission to the rest of the platoon which is out of communication range [14]. Every receiver vehicle close to the leader listens calculates a timeout period corresponding to the Received Signal Strength Indicator (RSSI) from the leader's transmission. The duration of timeout is directly proportional to the RSSI of the signal received from the leader. The earliest node whose timeout expires (which is the node farthest from the transmitter) relays the packet to the rest of the platoon, as the node farthest from the transmitting node observe a smaller RSSI, thus gets expired the fastest. Other close-by nodes whose timeout was set before, reset their timeout period after hearing the relay transmission. Although this method increases the communication range, it reduces the bandwidth by half as the relay takes another transmission for similar data as the leader.

2.2 COMMUNICATION LOSS

One important problem that has been studied extensively is how packet losses are handled in platoons. The communication outage when left untreated, can cause collisions [15]. The conventional method for handling communication outage is to fallback to ACC when a loss of communication is detected.

Chaoxian et al. proposed the use of adaptive Kalman filtering to predict the missed packet and act accordingly instead of transitioning to ACC immediately [16]. This method increases the margin of packet loss. It showed that this method can tolerate 10 times more packet loss compared to the conventional method. Although this is a major improvement, the prediction strategy fails when there is an emergency event (like braking).

Pfadler et al. investigated the relationship between safety-critical control and communication quality and proposed the use of packet inter-reception time (referring it the Predictive Quality of Service (PQoS)) to obtain the desired minimum IVD within the platoon [17]. The usage of packet inter-reception time as a metric for PQoS was first noted by Jornod et. al [18]. They propose a method to predict the packet inter-reception time which is then used to estimate the congestion in the network.

Sroka et al. proposed a method to enable platoon message propagation in congested DSRC channels with the use of dynamic spectrum [19]. With this method of information broadcast, the packet reception ratio of the following vehicles was improved by 5%, thereby increasing reliability.

2.3 EVENT-BASED BEACONING

For a robust platooning to be possible, frequent dispersing of the vehicles' states throughout the platoon should be made. Considering that fact, studies done in [20] suggest that 10 Hz is the lower limit for the rate of beacon transmission. This is considered sub-optimal as it uses the channel unnecessarily even in absence of no new information. As a solution to this, the usage of dynamic updates was proposed, in which they tend to change the beacon interval based on certain criteria.

Tamba et al. induced communication imperfection in the channel to emulate a denial-of-service attack in an event-triggered platoon design [21]. In their work, they proposed a control design which compares the predicted value against the value that was received from other vehicles. In case of communication loss, the inputs to the control are given from the predictor. But when there is an adversary attack, the prediction is used to evaluate if the value can be considered or discarded.

Hoang et al. propose a method of disseminating the information in two different types of slots which coexist with each other [22]. One in which periodic information is sent out and the other in which event-triggered information is sent out. While the vehicles send out the periodic information, specific time slots are reserved for time-triggered events.

Arne et al. proposed a store-and-forward mechanism to support the intervehicle communication [23]. When there is transmission by a vehicle in the platoon to its following vehicles, instead of increasing the transmission power of the leader, the message is transmitted with lower power and is picked up by the vehicles coming in other direction which later relays to the other followers as it travels to the end of the platoon. Their method is based on the fact that all the incoming traffic also uses

V2V communication.

Seagata et al. proposed to use the acceleration as the criteria for changing the update interval [24]. This was based on their observation that when the vehicle's state remains unchanged, periodic updates are considered less useful. Instead, they proposed to transmit the beacons only when a change in the acceleration is beyond a certain threshold. Figure 2.1 shows different profiles for update interval based on the acceleration in the leader vehicle. For low changes in the acceleration, the beacon interval are high. But when the acceleration change increases, the beacon interval decrease, implying frequent updates. At accelerations closer to zero, the update interval is around 1 second. They use an empty network channel coefficient (p) that increases as the beaconing interval increases but reduces safety.

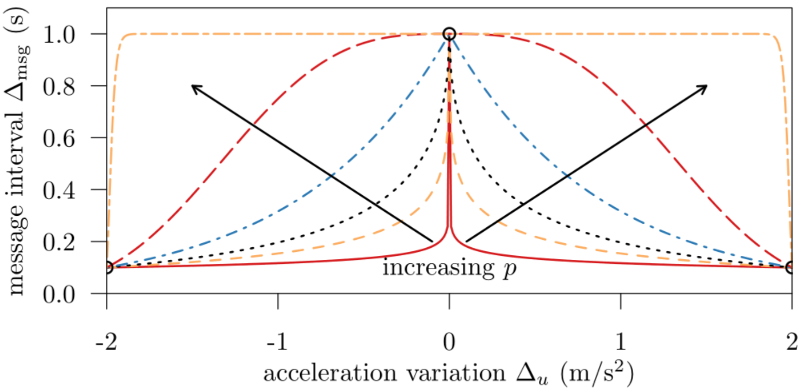


Figure 2.1: Change of beacon interval with respect to the rate of acceleration [24]

Similar approaches of event-triggered beaconing were chosen in [25] and [26] for LF to reduce the load on the channel while keeping the platoon operation safe. While all the event-triggered solutions reduce the burden on the network, they give rise to two other problems. Firstly, due to the dynamic nature of the update interval, the receiver cannot predict when it can expect a packet to transition to ACC. Secondly, any erratic behaviour in the middle of the platoon can be considered a risk to its followers if the platoon's leader chooses to have a higher beacon interval, because of the constant velocity of the leader.

2.4 HYBRID COMMUNICATION

One potential solution to reduce the congestion in the channel is to incorporate multiple communication technologies consisting of various characteristics. For example, complementing LoS communication with non-LoS communication. Doing this can alleviate the problems arising from a single point of failure. DSRC being prone to channel congestion it can best be combined with technologies which have complementary characteristics.

Pedro et al. proposed the use of Infrared (IR) communication as a complementary technology for communication in platoon [27]. While the aperiodic information (like emergency braking commands, change in acceleration) is communicated using DSRC, the other periodic information (like vehicle's health and other non-critical status) are communicated with IR in between consecutive vehicles.

In another experimental study done by Bastien et al., they used Commercial-Off-The-Shelf (COTS) components to evaluate the performance of the system [28]. Their study done in a controlled indoor environment with a On-Off Keying (OOK) with Manchester coding showed values for Bit-Error-Rate (BER) of less than 10^{-6} for an IVD of 30 m, datarate of 100kbps and the propagation delay of 4.2 ms. Segata et al. proposed a preliminary communication protocol in which the leader uses the RF channel IEEE 802.11p for communicating with all the vehicles in the platoon [29]. Each of the followers uses low intensity Light-Emitting Diode (LED) communication with only its neighbours.

Max et al. used a LED matrix to communicate with the follower vehicles [30]. By doing so, they are effectively able to transmit the data that is needed by the neighbours without blinding the other vehicles. Additionally, in case of loss of LoS, as in curved roads, where immediate LoS communication is not possible, they extend their solution to direct the light beam into the direction of its predecessor.

Although Visible Light Communication (VLC) can benefit the V2V communication when used in conjunction with DSRC, VLC is sensitive to ambient light and requires a direct LoS to have a reliable channel. For example, conditions like fog or rain cause the light to refract and corrupt the information being transmitted.

2.5 EMERGENCY BRAKING

As vehicle platooning must coexist with other traffic, it is essential to design the coordination scheme taking into account any spontaneous events. When the platoon moves at closer inter-vehicle gaps, the safety (mainly during emergency braking) cannot be guaranteed. While it is important to improve the stability, which was solved by [31], [32] and [33] using control theory, the same solutions cannot guarantee any safety during emergency braking as the control systems tend to saturate, making the prediction impossible within a reasonable amount of time. Therefore, a stable platoon itself cannot ensure a collision-free operation in case of an emergency braking.

Dharshan et al. proposed the use of buffer-spaces present in between the vehicles of the platoon to adjust the braking force of the vehicles [34]. They observed that the vehicle immediately behind the vehicle which is braking needs to apply brakes with its highest force. The braking force is made lower as we proceed to the end of the platoon. By reducing the braking force of vehicles that are present towards the end of the platoon, it can ensure that no collisions take place. This approach makes use of the fact that each of the vehicles has some braking distance (the distance that it travels before coming to a stand-still position). As the braking force decreases, the effective braking distance of the vehicle increases, which in turn can give an opportunity for increased reaction time for the follower vehicle. This increased buffer for reaction time prevents rear-end collisions. However, when there is a delay in packet reception or when there is failed packet delivery, the free buffer time requiring immediate braking keeps decreasing. This aspect is not considered in their proposal. They conclude that the vehicles closer to the vehicle stopping needs to have greater braking capabilities as they have less reaction time.

To improve the emergency braking, Shahriar et al. proposed a delayed braking scheme [35]. This method also makes use of the increased time buffer, giving each vehicle sufficient time to brake. In their proposed method, when the leader detects and sends a brake command, it does not apply brakes immediately, it delays its braking by a certain amount of period. This period is used by the followers to brake. Their analysis showed that braking in a platoon at 100 km/hr, having a wait time of 100 ms ensure that the message is processed by all the other vehicle in the platoon. This additional wait time lets the vehicle traverse 3 meters.

Another aspect of emergency braking investigated is pedestrian detection closer to platoons. Flores et al. presented a modular system for safe platooning with a PF model in which they leverage Vehicle-to-Pedestrian (V2P) communication along with odometry and V2V communication [36]. Two modules for detecting pedestrians involve V2P and LiDAR for detecting pedestrians along with V2V communication module which is used to transmit the information throughout the platoon. This modular system architecture is shown in Figure 2.2. The V2P system is used to predict the pedestrian and falls back to a slower profile when it detects a pedestrian in the surroundings. Once the V2P system does not detect any pedestrian, the speed profile gets to normal. The V2P system complements the CACC by informing about the obstructions which are otherwise out of the field of vision. This approach is restrictive to the idea of the pedestrians equipped with communication equipment.

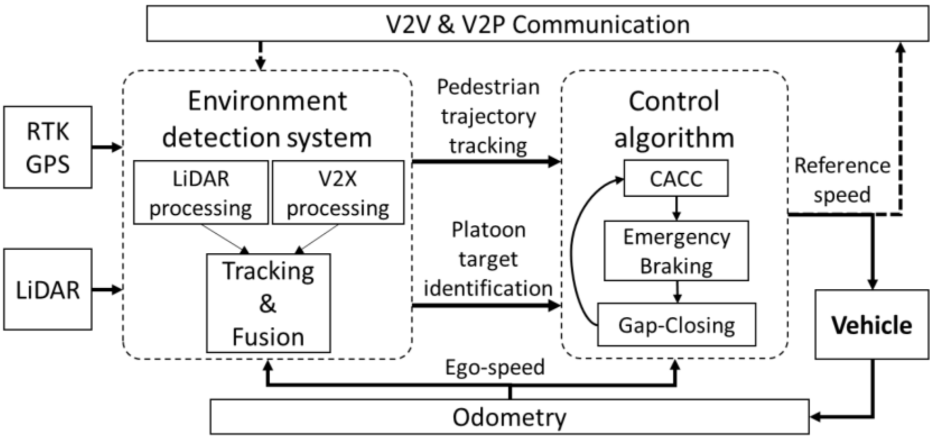


Figure 2.2: System Modules from [36]

In all of the aforementioned methods, neither packet loss nor braking in the intermediate vehicles was considered. Moreover delayed braking in the leader vehicle increases the risk of the front vehicle's collision.

2.6 EXPERIMENTAL TESTBED

Most of the proposals made in the literature have proved their feasibility using analytical models and simulations. Only a few of the proposed methods were shown in real-world down-sized experiments [7].

Among the very few experimental setups made to evaluate the performance of platooning protocols, Yuan et al. in [37] created a hardware setup to prove that the CACC can outperform ACC models and showed the benefits of CACC for small robot vehicles. Their setup equips a Linux single-board computer with a Wireless Fidelity (WiFi) card, which communicates in an ad-hoc mode with other vehicles in the platoon. In a similar kind of work, Duc et al. in [38] came up with an inexpensive testbed to implement a Proportional-Integral-Derivative (PID) controller for leader-following topology in which they also showed the working of various kinds controllers for the CACC systems.

Enio et al. developed a platform named RoboCoPlat with robotic cars which integrates the commercial European Telecommunications Standards Institute (ETSI) G5 On-Board Unit (OBU) communication equipment [12]. One evident disadvantage with this approach is that the equipment although readily available, it has closed source hardware and software, meaning that it does not support fine control and customization.

In all of the experimental testbeds in the literature used an available WiFi network stack for communication between the vehicles. This network stack involves a significant overhead for communication. This setup does not fulfil the requirements of DSRC, which requires low-latency communication along with fine control on the physical layer and Media Access Control (MAC) layer.

2.7 SUMMARY

From the literature available, emergency braking under temporary communication loss is little explored for all the IFTs, although it is required to ensure a safe platoon operation. Various control related solutions have been proposed to ensure safety during communication loss. However, they tend to saturate for emergency events. Additionally, the testbeds available in the literature do not allow customization in the MAC and physical layers. This restricts the opportunities for improvement. In the next chapter, a customizable testbed is designed.

3 TESTBED SETUP

To evaluate our work against existing methodologies used in platoon communications, a testbed has been developed. This chapter is dedicated to describing the requirements for the testbed in order to qualify as a realistic testbed and explain the setup. A realistic platooning testbed is required in order to evaluate the performance as simulations do not account inaccuracies in sensors and motors which should not be neglected. Testbeds found in the literature lack the ability to customize. In addition to the ability of customization, the testbed can be constructed for under 30 euros, which is just a fraction of the cost of the testbed proposed in the literature.

3.1 REQUIREMENTS

In this section, we state the main requirements that the testbed should satisfy for the functionality of the CACC platoon application.

1. **Controllability**: The controller computer must be able to communicate and control every car in the platoon. This way we can emulate the drivers' behaviour in the vehicle without giving up the autonomous nature.
2. **Low-latency communication**: Low-latency communication is very crucial for the platoon to function without any problem. This aspect is even more important for emergency events.
3. **Fine communication control**: While commercial WiFi chips have good interfacing options, they do not provide control over the Clear Channel Assessment (CCA) values which can alter the thresholds for energy detection and clear channel duration to enable the current transmission. With fine control over these parameters, the latency can be reduced as much as possible.
4. **High-fidelity sensors**: Since CACC systems fallback to ACC when a communication outage is encountered, it is necessary to have a reliable ACC system. For example, in presence of channel congestion, when there are consecutive packet drops, the vehicle should switch to ACC to use the sensors to navigate.
5. **High-availability**: To execute the commands in real-time in the platoon system, the main Central Processing Unit (CPU) should not be overloaded and even better, it should host a real-time operating system that respects the operations' deadlines. For example, the leader vehicle should broadcast the beacons according to its beacon interval and should not be delayed when waiting for any sensor readouts.

3.2 SETUP

The testbed is implemented on a custom-designed PCB which is mounted onto a robot car. This section elaborates on the design decisions made for each of the aforementioned requirement. Figure 3.1 shows a fully-assembled PCB.

1. **Controllability**: To ensure that every vehicle is controllable individually, a WiFi module is integrated into the board design. This WiFi module is an $ESP32$ core [39] running at 240MHz. This module is connected to a computer through WiFi and made to have a unique static IP address in the network.

2. **Low-latency and fine control communication**: To cope with the low latency requirement of V2V communication, the RF operation is fully offloaded into a separate chip, Texas Instruments TI $CC1352$ microcontroller [40] which is a dual-core microcontroller with ARM $Cortex - M4$ handling the MAC layer functionality and ARM $Cortex - M0$ handling all the physical layer functionalities.

   The $CC1352$ chip can provide fine control over the physical and MAC layer parameter that can be beneficial to tune the latency of communication. Precisely, it gives control over the threshold for CCA, which is a feature of $CC1352$ chip, enabling us to select a silence period for Listen-Before-Talking (LBT) and giving control over the RSSI threshold along with the number of retries during the busy times.

3. **High-fidelity sensors**: The testbed is equipped with low-cost and reliable ultrasonic sensor $(HC - SR04)$ [41] which has a range of 2 cm to 4 m and a resolution of 0.3 cm, sufficient for small-sized testbeds.

4. **High-availability**: To make the main CPU work only for the most important tasks of controlling the motors, sensing and processing the data from the other vehicles, an ARM $Cortex - M7$ - $STM32F767$ [42] microcontroller is used with FreeRTOS application [43] with a clock of 216 MHz. While this microcontroller primarily deals with the motion and sense, the other two microcontrollers ($ESP32$ and $CC1352$) described above are responsible for handling communication, which is going to be described in more detailed in the later section.

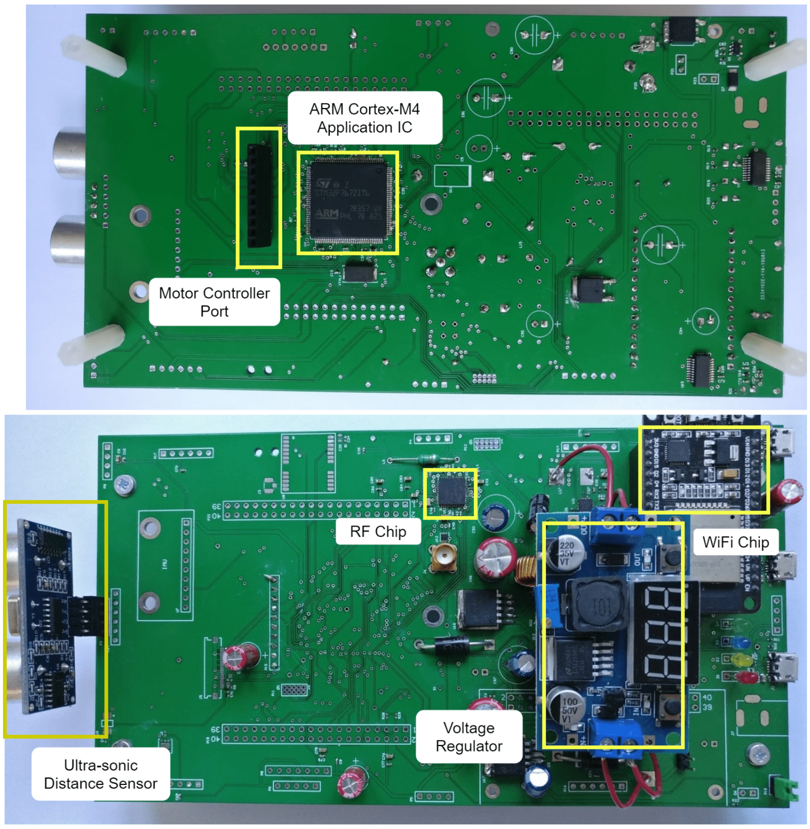


Figure 3.1: PCB housed on the robot

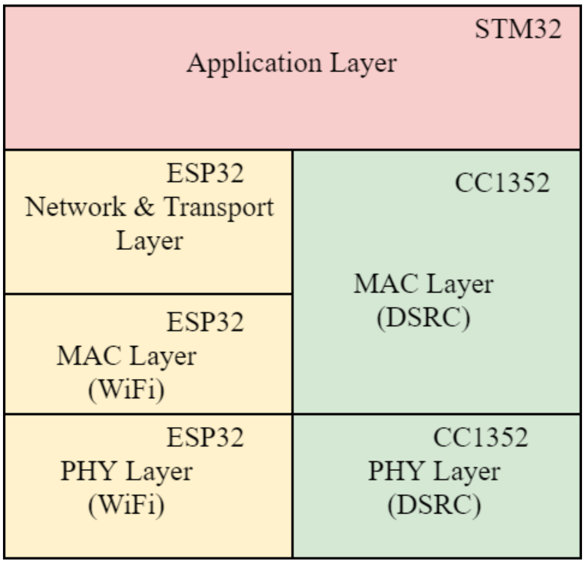


Figure 3.2: Communication protocol stack

Since we have multiple microcontrollers on the testbed, Figure 3.2 help us draw an analogy with the standard TCP/IP stack. To enable the communication with the vehicles from a computer, the *ESP*32 module's WiFi stack is used (which includes Network, Transport, MAC and physical layers provided by Espressif). It is responsible for unpacking the packets sent by the computer through WiFi and provide it to the application layer (which is run on another microcontroller). On the other end, all the V2V communication (DSRC) is handled with the CC1352 microcontroller which has MAC and physical layers. It also interfaces with the application layer. The application layer is implemented on STM32, another separate microcontroller, which controls all the motors and gets the inputs from the sensors.

The detailed hardware and software architectures showing how each of the modules is divided and interfaced with each other are discussed in Section 3.3 and Section 3.4.

3.3 HARDWARE ARCHITECTURE

The hardware architecture of the robot car is presented in Figure 3.4. The functionality of each of the modules is described below:

- DSRC MAC layer (CC1352 chipset): The interface to other robot cars on the DSRC channel happens using this interface. This chipset is a dual-core processing unit, in which one core is allotted to MAC operations and the other core performs the operations related to the physical layer. The chipset operates at 48 MHz and is programmed via the Joint Test Action Group (JTAG) interface.
- Core application (STM32F767 chipset): This chipset is responsible for running the core tasks of controlling the motors and sensing the inputs from the ultrasonic sensors. This core interfaces with the *ESP*32 and *CC*1352 Chipset using Universal Asynchronous Receiver-Transmitter (UART) protocol. The wheels of the robot are controlled with the motor controller chip, to which the chipset interacts with Pulse Width Modulation (PWM) signals. This chipset operates at 216 MHz and is programmed via the Serial Wire Debug (SWD) interface.
- External WiFi control interface (ESP32 chipset): This chipset is responsible for controlling the robot car from any other device that is connected to a common

access point as the chipset. *ESP*32 is a popular WiFi System-on-Chip (SoC) and is a dual-core chip, in which one core is responsible for IEEE 802.11*ac* related operations and the other core performs the higher-level functionality. Each of the robot car in the platoon is assigned with a unique static IP address for that network. This IP address is used for communicating with each of the robot cars individually.

- External control: It can be a computer which is capable of connecting to the same WiFi access point as the platoon.

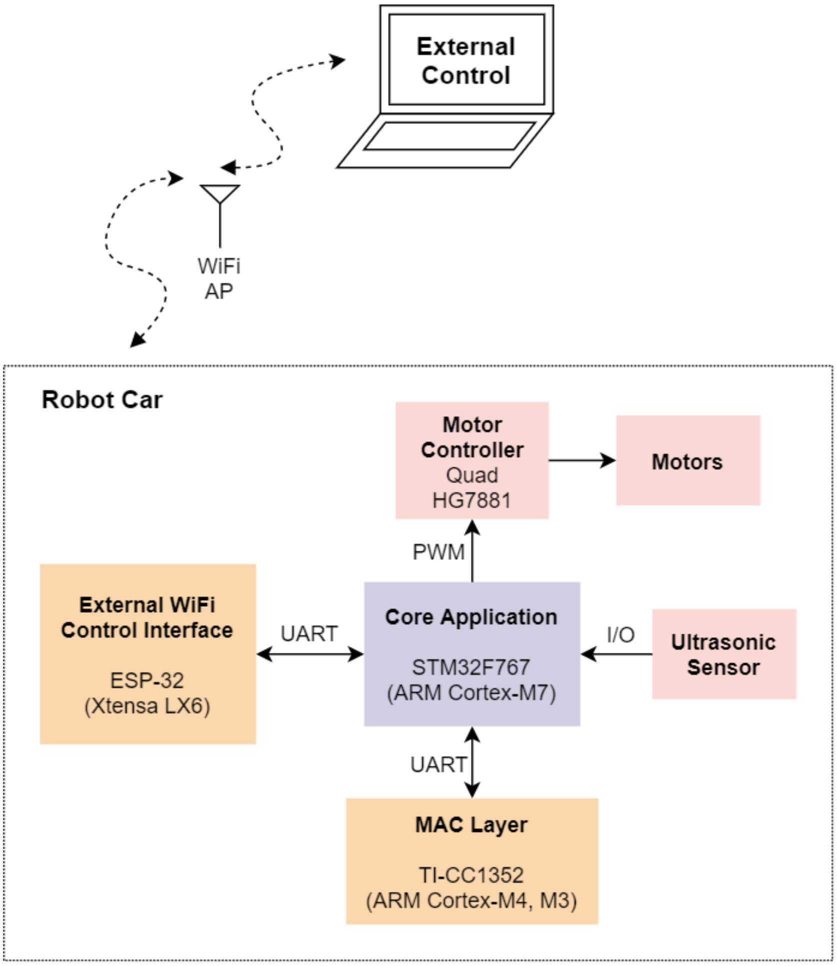


Figure 3.3: Hardware architecture of the testbed

3.4 SOFTWARE ARCHITECTURE

The software for the robot car can be split into multiple modules as shown in the Figure 3.4:

- CC1352 chipset: The Event Handlers submodule controls the incoming updates from both the DSRC channel and the Core Application layer. The MAC control software is responsible for any timing related activities like processing the packet, retransmitting and sending received packets to other layers.
- STM32 chipset: This chipset implements the module Core Application control software that is responsible for running the main control loop that processes the packets received, obtains the sensor readout and gives the command to

the motor interface that controls the speed. The motor interface deals with the low-level control of the motor like compensating for any offsets caused by different motors. The sensor interface takes a moving average of consecutive measurements and provides it to the core application. The Hardware Abstraction Layer (HAL) Driver is the module provided by the vendor of the chipset ST Microelectronics for low-level implementation of the peripheral interfaces.

- ESP32 chipset: Packet processing is the module responsible for receiving and transmitting the packets from the WiFi channel and interact with the *STM*32 Chipset application. Logger module is responsible for sending debug messages to the computer where all of them are logged. All the packet transactions used for debugging and control happen over User Datagram Protocol (UDP) protocol.
- PC (External control device): The emulation of a driver of a vehicle is done from this module. This control is automated by the Python Scripting submodule which sends the desired control packets to the desired IP address over UDP protocol. The submodule Logger Graphical User Interface (GUI) is another independent software application that is built with C++ on Qt framework [44]. All the debug information logger at any level on the vehicle is received by this module and displayed on the panel.

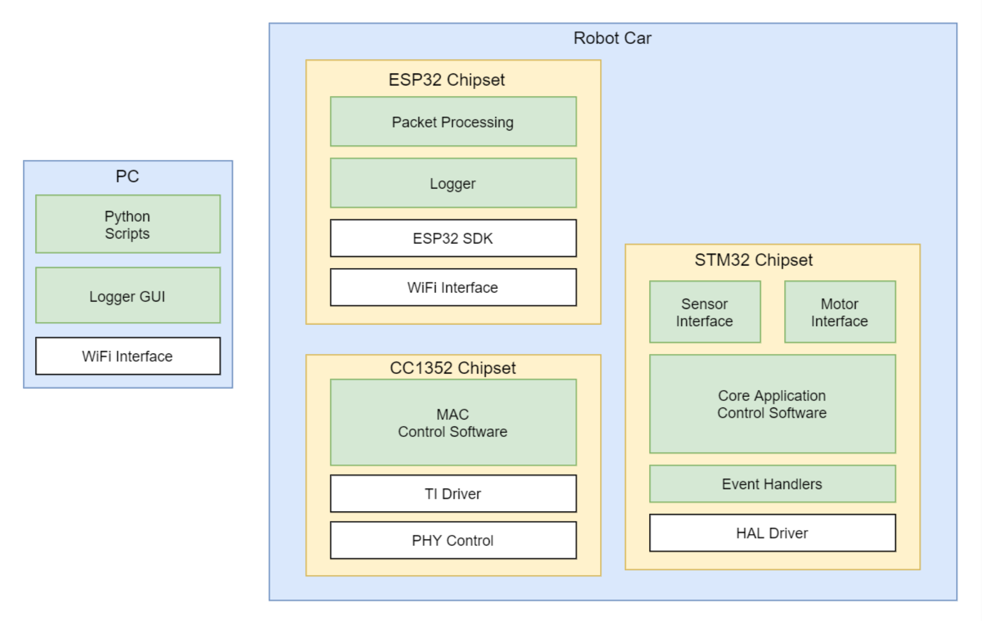


Figure 3.4: Software architecture of the testbed

The testbed with four robot cars using both communication channels (WiFi and DSRC) is shown in the Figure 3.5 and the actual testbed is shown in Figure 3.6.

3.5 IMPLEMENTATION

3.5.1 Braking time measurement

Since we are dealing with emergency braking, it is crucial to reduce the braking time (the time between applying brakes and attain a complete stop) as much as possible. The speed of the vehicle is measured using an IR sensor and a disc wheel. To reduce the braking time, a reverse acceleration is induced for a momentary period. Reverse acceleration is achieved by driving the motors in the opposite direction of

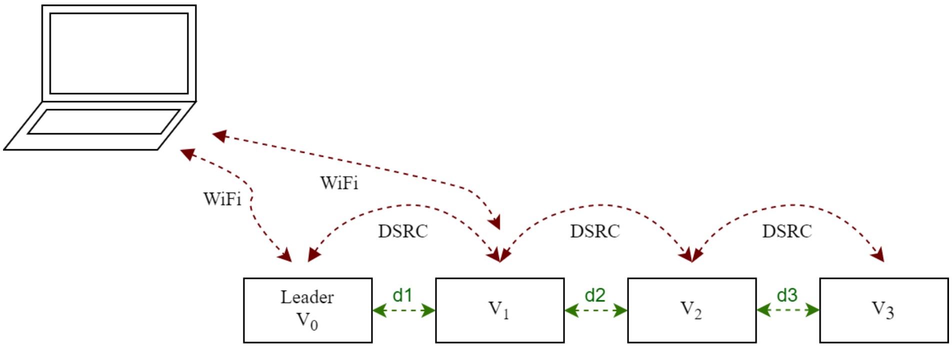


Figure 3.5: Testbed setup

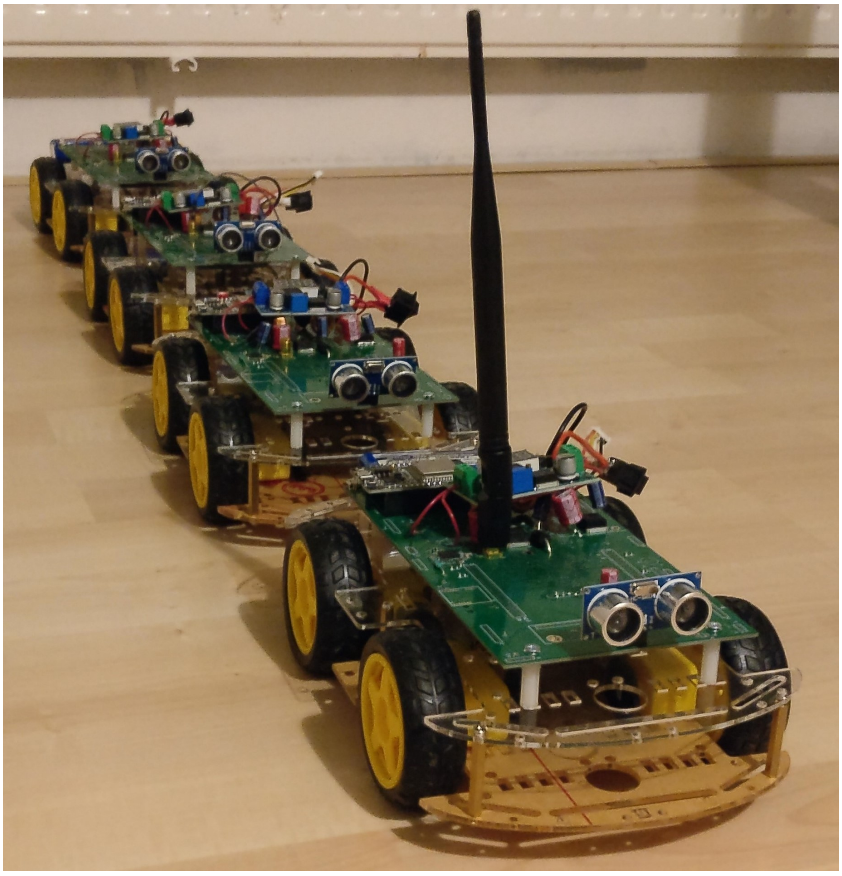


Figure 3.6: Platoon with robot cars

the actual travel direction for a very short duration (50 ms). Needless to say, with reverse braking, the vehicle was able to stop faster compared to the case where only the power is made null.

3.5.2 Communication

Each of the robot cars is equipped with two communication channels. One which is used for communication between the cars, known as DSRC used for intra-platoon communication. The payload of the beacon transmitted by each of the vehicles on the DSRC channel contains its speed and other maintenance data. The content of this beacon payloads is explained in Section 3.5.2.1. Another channel to enable each of the vehicles to be controlled manually. The manual control is done through an independent hardware device on a WiFi channel. The RF settings for the DSRC communication are as follows:

Index	Field	Details
0	Src-ID	Vehicle ID of the source
1	Sequence Number (SN)	Increments for every new transmission from the leader
2	Speed	Encoded PWM value for the speed
3	CANARY VALUE #0 (0xDE)	Corruption detection values
4	CANARY VALUE #1 (0xAD)	Corruption detection values

Table 3.1: Packet structure of data sent via DSRC

Index	Field	Details
0	Dest-ID	Destination Vehicle ID
1	Speed	Encoded PWM value for the speed
2	CANARY VALUE #0 (0xDE)	Corruption detection values
3	CANARY VALUE #1 (0xAD)	Corruption detection values

Table 3.2: Packet structure of data sent from computer to the robot

- Frequency: 868.2 MHz
- Data Rate: 50 kbps
- Gaussian Frequency Shift Keying (GFSK)

Although the frequency chosen for all the experiments is 868.2 MHz, the system can be easily adapted to higher Industrial Scientific Medical (ISM) frequencies (up to 2.4GHz).

3.5.2.1 *Packet Details*

Each of the DSRC packet transmitted by every vehicle has the fields shown in the Table 3.1:
The packet transmitted by the computer on WiFi channel consists of the fields shown in Table 3.2.

3.5.3 Modes of Operation

Each of the follower robot cars can operate in one of two modes at any given time:

1. **Autonomous mode** in which each of the vehicles processes the intra-platoon commands to operate. Communication in this mode has to follow one of the IFT as shown in Section 1.3.2.
2. **Manual mode** in which the cars don't process the intra-platoon commands but only listen to the WiFi controls from the computer. This mode is responsible for enabling intermediate vehicle braking which is an important aspect of emergency braking. This method enables us to obtain fine control over the experiment when each of the cars needs to be controlled individually.

By default, the mode of operation is set to autonomous mode for all the follower and manual mode for the leader. The mode of operation can be changed during runtime from the computer.

3.5.4 Robustness Check

While at the physical layer, CC1352 implements a robust packet corruption detection mechanism, there is no such mechanism to prevent data corruption when the communication happens within the PCB. Since the clock frequency of the main chip

(ARM $Cortex - M7$) is about five times higher than that of the RF chip, there is a chance of intermittent buffer overrun or buffer slides. When this happens while in platoon operation, the robot behaves erratically. The solution to this problem is to introduce canary values in the packet. Canary values are known values at known indices. When these values are not present at their known indices, processing the packet is omitted. When this happens consecutively for ten times, a fault is raised and indicated via lights on the PCB.

3.6 SUMMARY

In this chapter, a low-cost, easy-to-use and customizable testbed was introduced that can be used for evaluating platooning applications. This chapter also discussed the in-depth architecture of hardware and software. The overall components cost of each robot car which is part of the testbed is under 30 euros. Each car is equipped with two completely independent communication protocols, which can work independently through WiFi, so that it can be controlled by an external operator and another through a point-to-point link with DSRC, in which each vehicle communicates with each other directly. The PCB introduced here can be used with various other chassis to obtain different speed profiles.

4 INFORMATION FLOW TOPOLOGIES

For the need of CACC platooning which requires transmission of vehicle's information (like speed) to the followers, it is possible to just periodically send beacons from every vehicle in the platoon. While this is practical, it is not feasible since it sacrifices the coherent operation in the platoon, often leading to fluctuations in the IVD. Since the vehicular network is an ad-hoc network, there is no central scheduler, requiring a TDMA approach for each of the vehicle to transmit. This cannot be achieved with periodic beaconing techniques [10].

Since the beacons are transmitted periodically, there is no order of beacon arrival. For this reason, any beacons being transmitted from the rear end of the platoon are not useful when they happen to be transmitted before the preceding vehicle's transmission. To elaborate on this problem, consider a platoon with four vehicles each with periodic beaconing. When the vehicle V_2 transmits its beacon to V_3 followed by a beacon transmission from V_1 consisting of emergency braking information, V_2 after receiving it performs braking but cannot transmit it immediately as its beacon has already been transmitted in the current interval. Due to this, the braking in V_3 is delayed, which might cause a rear-end collision. Therefore, IFTs solve this problem by scheduling the beacons in a TDMA scheme to order the beacon transmissions.

IFT defines the schedule for each of the vehicles transmitting its beacon. As explained in Section 1.3.2, four IFTs have gained popularity. This chapter explains the working and observation of each of the IFTs for emergency braking in presence of packet loss.

4.1 EFFECT OF COMMUNICATION DELAY

When a vehicle brakes, the latency between the moment this event happened and the point its followers receive the information and apply braking is crucial to determine the change in IVD. For every lost communication packet for the braking event, the followers would be travelling in that duration, thereby reducing the IVD between the vehicle that braked and its immediate follower.

In order to simulate various kinds of packet loss in communication, a range of packet delays in the beacon broadcast are induced at the leader with a beacon period T, of 20 ms. To create a delay greater than the beacon period, the beacon period is temporarily changed to a different value. For example, to induce a packet delay of 40 ms, the beacon period is temporarily changed to 40 ms. This increase will simulate the loss of communication when compared with the original beacon period.

4.2 EXPERIMENTAL SETUP

Generally, platoon experiments involve the vehicles travelling linearly with a predetermined IVD between each other. However, in our experiment, each of the vehicles is displaced sideways into four lanes by a small distance as shown in the Figure 4.1. The experimental setup for evaluating IFTs has been modified to be able to measure the change in IVD as if there is no predecessor present directly ahead. This was necessary to not saturate the change in IVD upon a collision with a predecessor. This can enable a measure of the actual travel distance during communication loss.

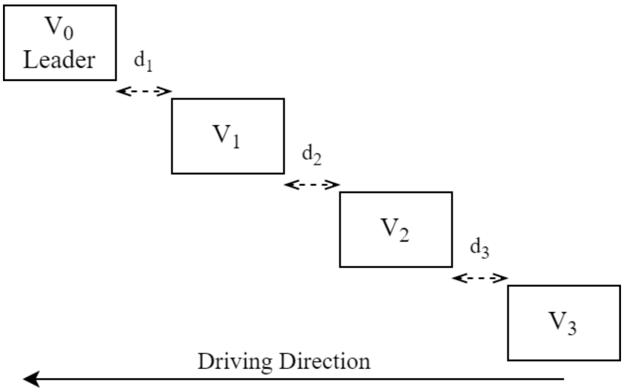


Figure 4.1: Four car platoon setup for the experiments

With the testbed introduced in the Chapter 3, the experiment consists of a platoon of four vehicles travelling at 3 m/s speed with an IVD of 6 cm. Although the IVD chosen is just an arbitrary value, it will have little effect on the result. In this experiment, the performance metric used for evaluation is the change in IVD for various packet delays. The IVD is a measure of the distance between a vehicle's rear-end and front-end of its follower. A decrease in the IVD shows the vehicle getting closer to its predecessor. When this value reaches the initial set distance of 6 cm, a collision with the vehicle's predecessor is assumed (they are assumed and not observed because the vehicles are not directly linear, but are displaced sideways), which is shown by a solid red line, like the one shown in Figure 4.4. The packet is delayed before transmission in order to simulate the packet loss. By delaying the packet transmission with a known duration, the precise control over the latency for packet reception before braking.

4.3 LEADER FOLLOWER (LF)

For all the experiments performed for evaluation, the four-lane setup introduced in Section 4.2 is used. In the LF IFT, the leader broadcasts its speed information to its followers. This broadcasts happen with a predetermined interval of 20 ms and is a simplex-communication where only the leader broadcasts and the followers receive the information from the leader and update their speed accordingly.

The packet scheduling is explained with the help of a TDMA sequence diagram shown in Figure 4.3. The leader transmits the beacon with a period of T. For every beacon transmission done by the leader, the intended receivers of the beacon are shown in the vertical bar below the transmission. In this case, when V_0 transmits its beacon, it being the leader, its beacons are processed by all the vehicles in the platoon V_1 - V_3. A failed packet reception can only have a chance for recovery after the duration T since the leader broadcasts its beacon according to its beacon period and does not have feedback about the successful reception at the receivers.

4.3.1 Algorithm

The implementation of the algorithm for LF is shown in Figure 4.2. The beaconing period of the platoon leader is *T*. The algorithm shown does not account for any packet loss. Although not shown, in LF, when the followers miss a certain threshold number of packets, they fallback to rely on the sensors and increase the IVD between the vehicles.

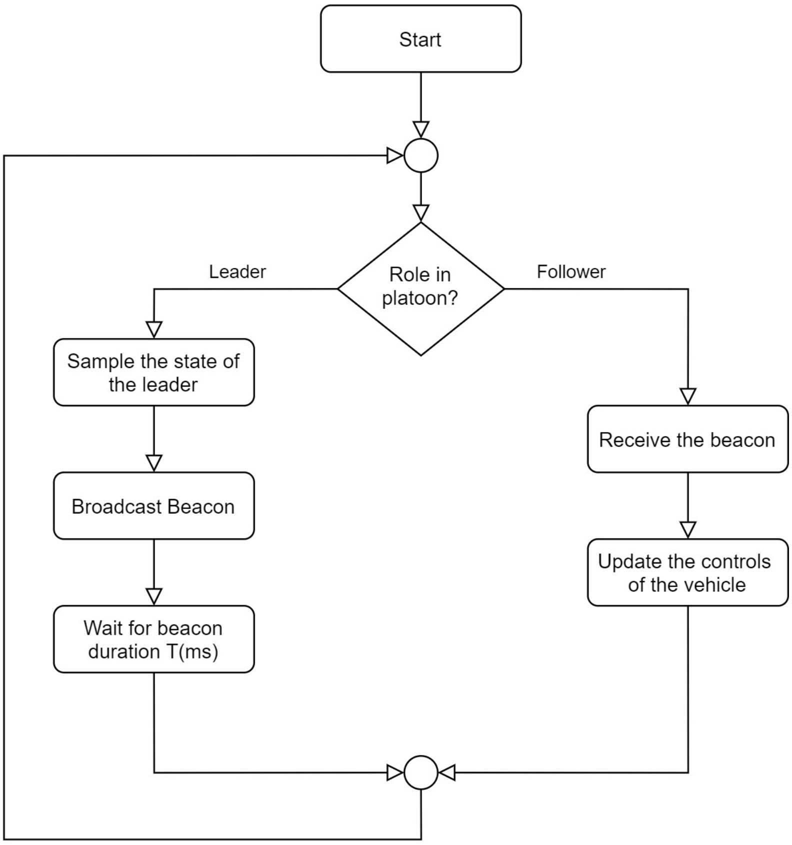


Figure 4.2: Algorithm for LF

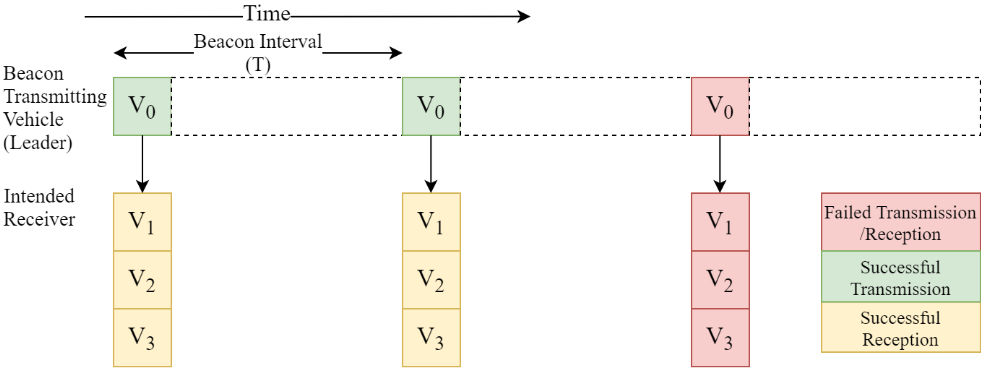


Figure 4.3: TDMA Scheduling in LF

4.3.2 Experimental Result

At the time of emergency braking in the leader, when there are packet delays, the change in IVD is seen mainly for the immediate follower of the braking vehicle (the latter being the leader in this case). This change is linear with the packet delay. While the immediate follower experiences a drastic change in IVD with the packet delay, other followers do not have any change in the IVD with its predecessors. This is because all the followers travel at the same distance during the latency and only the first follower (which is the immediate follower of the leader) will have a change in the IVD as the leader has already braked.

The change in IVD by each vehicle in the platoon with different packet delay in the event of emergency braking at the leader is plotted in the Figure 4.4. The distances plotted are obtained after averaging 10 samples of the IVD for every vehicle. When there is braking at the leader, with no packet loss (at 20 ms beacon period), the change in IVD between the vehicles is negligible. When a missed update consists of the speed made 0 (signifying an emergency braking), the leader would have already applied the braking, while its follower vehicles, after missing the update, continue to travel until they get an update in the later TDMA slots as shown in Figure 4.3. Therefore, with the increase in the packet delay, the immediate follower of the leader tends to get closer, thereby decreasing its IVD which is shown in Figure 4.4 indicated by d_1 (which is the change in IVD between V_0 and V_1). Fluctuations observed for the change in IVD for both V_2 and V_3 are the result of inaccurate motors whose speed cannot be controller precisely.

A rear-end collision between V_0 (leader) and V_1 was observed at a packet delay of 100 ms. Although this is not a physical vehicle collision (due to separate lanes), a collision is assumed when the change in IVD goes below the initial IVD (ie. 6 cm), as there would be a physical collision if they were driven linearly.

In practice, a threshold is maintained for the maximum duration in which no packet update is heard (silence period). When this duration is expired, the platoon falls back to rely on the sensors to detect the IVD with its predecessor. This threshold is set to a very large value in the experiments conducted due to which the system never falls back to the sensors.

Since only the immediate follower of the leader vehicle experiences the change in IVD severely by the packet delay, the number of collisions in this IFT can be restricted to one vehicle as long as the packet is successfully received within 100 ms of time of the braking. However, when the packet delay increases above 100 ms, a sudden change is observed in the immediate follower of V_1 (V_2), while V_3 continues to have only a little deviation. For this case, it should be noted here that the change in IVD for V_2 is measured with respect to the position where V_1 would have stopped (because of a collision with V_0) if the vehicles are put linearly. Without this method of measurement, the IVD would never decrease which is not a realistic scenario. When the packet delay continues to exceed 200 ms, a collision at V_3 is observed. Thereafter, a similar trend as V_0 is observed.

As an inherent problem of LF IFT, braking in the intermediate vehicle cannot be accounted with V2V communication alone. In this case, the followers should also use the distance sensors in parallel to detect any braking in the predecessor.

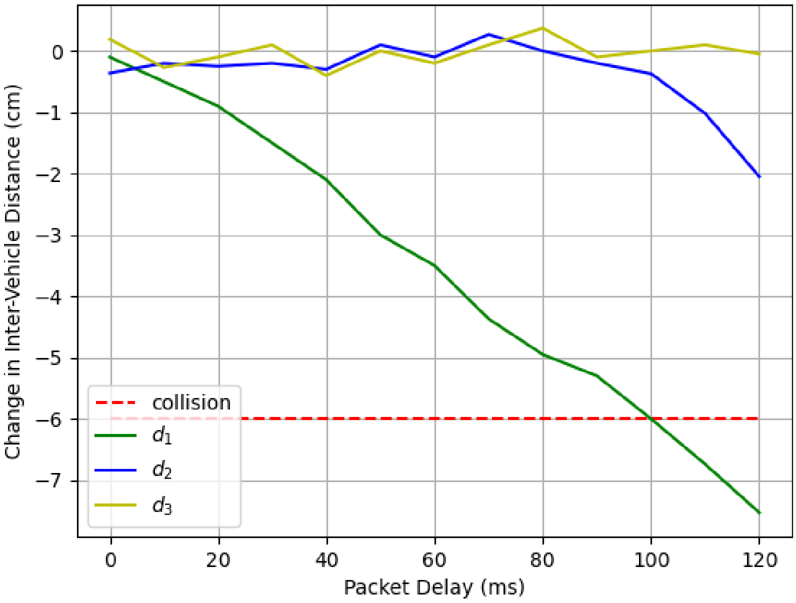


Figure 4.4: Change in IVD after emergency braking at the leader for LF with varying packet delays, where d_1 is the distance between V_0 and V_1, d_2 is the distance between V_1 and V_2, d_3 is the distance between V_2 and V_3

4.4 PREDECESSOR FOLLOWER (PF)

In this implementation of the IFT which is also based on the setup used for LF, each of the vehicles unicasts its current speed with a very small transmission power, sufficient for the immediate follower to receive. A beacon period of 20 ms is chosen, which is started at the leader of the platoon and triggers the immediate follower of the leader to transmit its information as a beacon to its immediate follower. This propagation chain continues until the beacon reaches the last vehicle.

The scheduling of the beacons is explained using a TDMA diagram shown in Figure 4.6. The vehicle unicasting the beacon is shown in the scheduling diagram. For every unicast performed by the vehicles, the intended receiver is shown for every transmission. Similar to LF, when a packet is not received, the next chance to transmit a packet is only possible in the next TDMA round (in the next instance of the beacon period). These missed packets are indicated in red in both the second and third TDMA rounds.

This topology can be seen as having no broadcaster vehicle since each vehicle is only responsible for transmitting its state to its immediate follower, while the leader only initiates the communication chain. When a vehicle fails to receive a predetermined number of frames K, depending on the system's implementation, the system falls back to rely on the sensors. However, we test the communication system in isolation by not integrating it with sensors to brake.

4.4.1 Algorithm

The implementation of the algorithm for PF IFT is shown in Figure 4.5. The beaconing period of the platoon leader is T (20 ms). Similar to the previous IFTs, PF also does not account for any packet loss. However, when the number of packet misses reaches the threshold number of packet misses K, the system falls back to ACC mode.

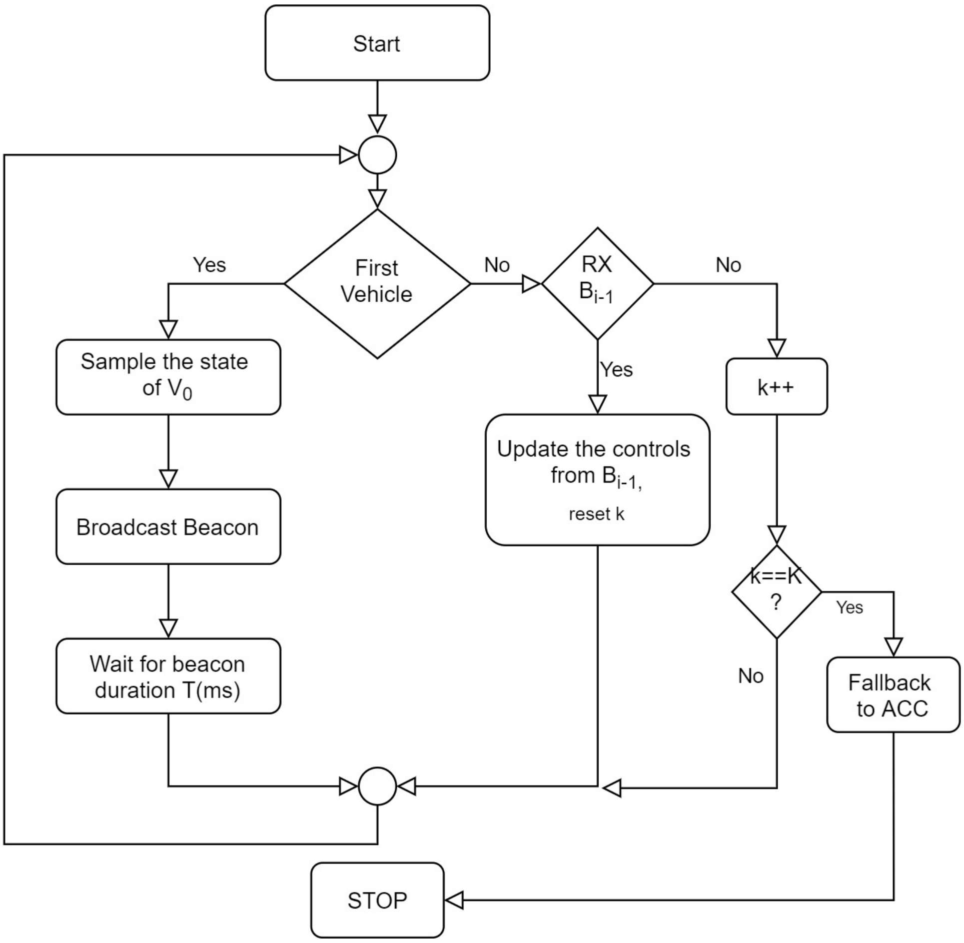


Figure 4.5: Algorithm for PF

4.4.2 Experimental Result

The beacon transmission by the leader is used to initiate the TDMA round, which is picked by the leader's immediate follower and is further transmitted to its immediate followers as an updated packet. This chain propagation is done until the message reaches the end of the platoon.

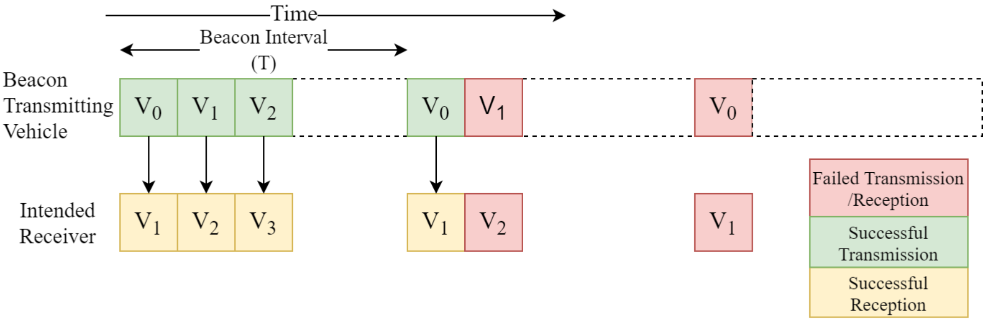


Figure 4.6: TDMA scheduling in PF

The experiment chosen for the previous IFT is also used for this IFT, in which the leader performs braking in a lossy communication network to measure the change in IVD between different vehicles in the platoon. Packet loss in the communication is induced by temporarily changing the beacon period as explained in Section 4.3.2.

It was observed that the because of the packet hop delay from V_1 to V_2 and later, the vehicles have travelled an extra distance as compared to the immediate follower of the leader (when there is no packet loss). In contrast to the LF IFT which receives the information almost instantaneously, PF experiences a slight delay which is the reason for a slight decrease in IVD for vehicles V_2 and V_3 in Figure 4.7. A collision is observed when the packet is delayed for 100 ms.

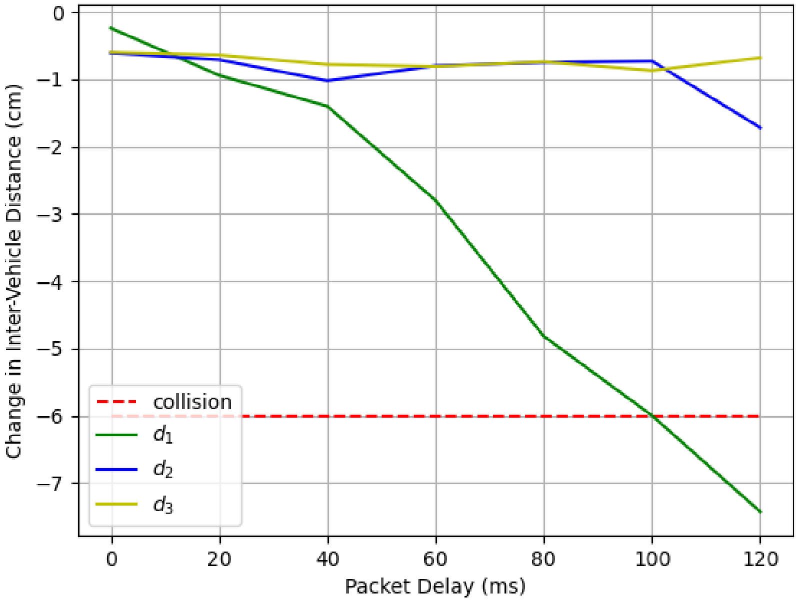


Figure 4.7: Change in IVD after emergency braking at the leader in MPF with varying packet delays, where d_1 is the distance between V_0 and V_1, d_2 is the distance between V_1 and V_2, d_3 is the distance between V_2 and V_3

The problems that are seen with the braking of the intermediate vehicles, in the LF IFT has been solved by PF. Figure 4.8 shows the change in IVDs of the followers for varying packet delay during a braking event at V_1 (the immediate follower of the leader). While the immediate follower of the vehicle performing the emergency braking is affected, the later followers are less affected. This is because the packet once received is immediately relayed successfully to the follower and the measurement is only to its predecessor.

4.5 LEADER-PREDECESSOR FOLLOWER (LPF)

LPF combines both LF and PF in which the communication in the platoon starts with the leader's state being transmitted and received by all the vehicles in the platoon as shown in Figure 4.10. The immediate follower of the leader uses this as a trigger to further transmit its state to its immediate follower. This chain propagation happens until the message reaches the last vehicle in the platoon. Similar to the previous methods, a consecutive *K* misses cause the individual vehicles in the platoon to fall-back to ACC.

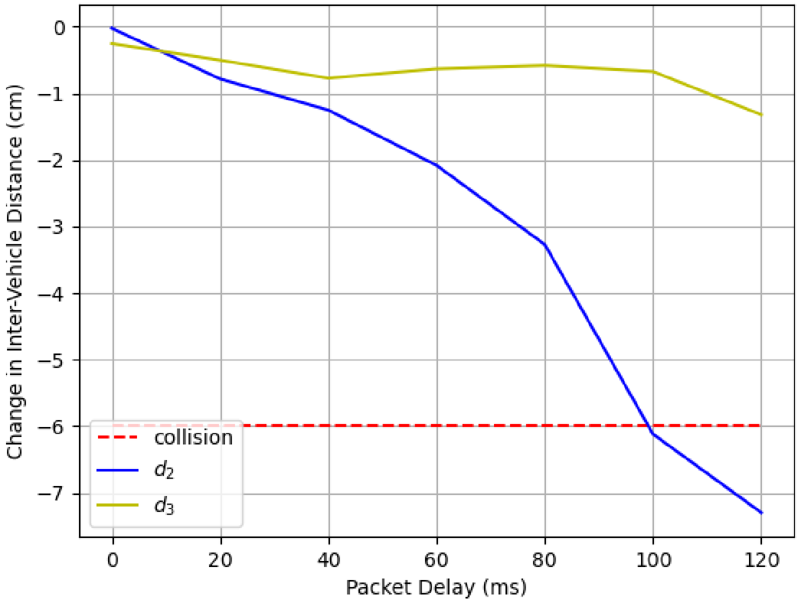


Figure 4.8: Change in IVD after emergency braking at V_1 in PF with varying packet delays, where d_1 is the distance between V_0 and V_1, d_2 is the distance between V_1 and V_2, d_3 is the distance between V_2 and V_3

In this IFT, since each of the vehicle (except for the immediate follower of the leader) receives both the speed information, one from the immediate predecessor and another from the leader, there needs to be a consensus about the speed. In this implementation, every vehicle uses the speed information from the leader when the speed is zero (indicating an emergency braking). However, when the speed is greater than zero, the speed information of its immediate predecessor is used. This ensures the vehicle reacts to the most imminent event.

4.5.1 Algorithm

The implementation of the algorithm for LPF IFT is shown in Figure 4.9. The beaconing interval of the platoon leader is T (20) ms. The algorithm shown does not account for any packet loss. However, when the number of packet misses exceeds the threshold number of packet misses K, the system falls back to ACC mode, similar to the other IFTs.

4.5.2 Experimental Results

The TDMA round is triggered by the leader's beacon transmission, which is processed by the whole platoon. But only the immediate predecessor uses this as a trigger to relay its speed information to its immediate follower until it reaches the end of the platoon as shown in Figure 4.10. In this case, if the leader misses sending its beacon successfully, it has to wait until its next time slot, which also causes its followers to not transmit their beacons for that missed packet.

Since LPF combines both LF and LPF, the change in IVD for the followers when the leader brakes is identical to the pattern observed in LF shown in Figure 4.4. However, the inherent problem with intermediate vehicle braking of causing a collision to the later vehicles is solved by implementing the PF's model. This results in a

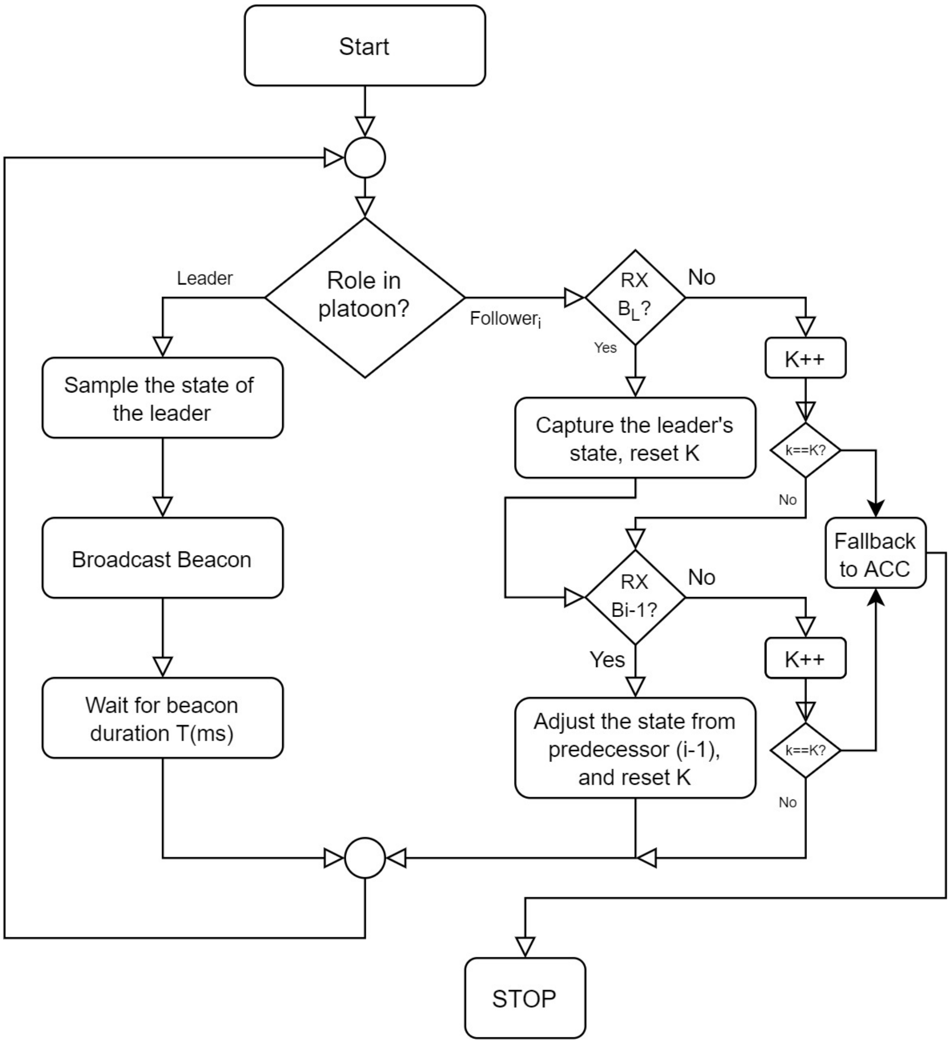


Figure 4.9: Algorithm for LPF

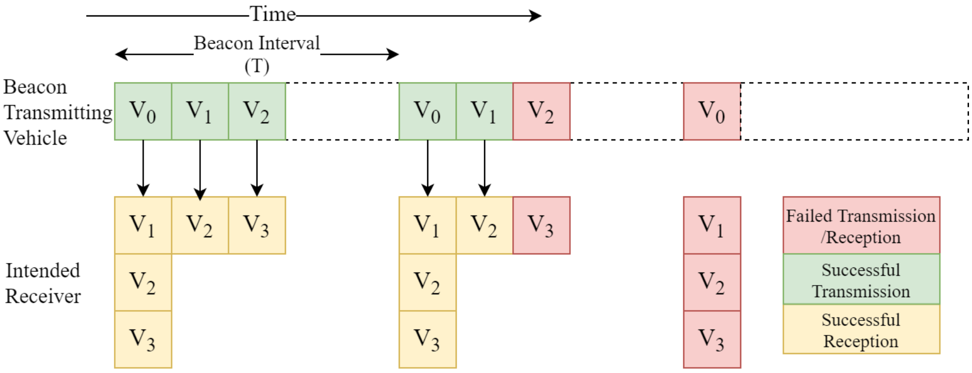


Figure 4.10: TDMA scheduling in LPF

similar change in IVD for the intermediate braking as observed for PF shown in Figure 4.8.

4.6 MULTIPLE-PREDECESSOR FOLLOWER (MPF)

The experiment uses a similar setup seen in Section 4.3.2. In MPF, a TDMA round is started with the communication from the leader to a certain number ($\mathcal{F}$) of its immediate followers (multicasting). Every vehicle which is part of the platoon, after receiving the beacon from its immediate predecessor, transmits its beacon to another $\mathcal{F}$ number of followers. However, the last $\mathcal{F}$ number of vehicles will not be able to multicast to another $\mathcal{F}$ number of its followers. The scheduling done in this IFT is shown in the Figure 4.12, where the multicast beacons are transmitted by the vehicles denoted with "*BeaconTransmittingVehicle*" in a chained manner. For every multicast done by the vehicles, the intended receivers of that beacon are shown with an arrow under them. For example, when $\mathcal{F}$ is 2, the multicast beacon transmitted by V_0 is received by V_1 and V_2. When a multicast packet is lost, the next transmission can only happen in the next TDMA round.

4.6.1 Algorithm

The implementation of the algorithm for MPF IFT is shown in Figure 4.11. The beacon period of the platoon leader is $\mathcal{T}$ (20 ms). Like all the other IFTs seen so far, this IFT also does not account for any packet loss. However, when the number of packet misses exceed the threshold $\mathcal{K}$, the system falls back to ACC mode.

Similar to LPF, each of the vehicle (except the leader and its immediate follower) receives $\mathcal{F}$ number of packets with speed information from its predecessors. An identical implementation as the one seen in LPF is used, where only the information from the immediate predecessor is used apply speed. However, packets from all the predecessors are used if there is an emergency braking required from the beacon.

4.6.2 Experimental Results

Like the previous IFTs, the TDMA round is triggered by the leader's beacon. However, unlike all the other IFTs a beacon transmission is processed by $\mathcal{F}$ number of immediate followers.

The experiment for MPF has been performed with $\mathcal{F}$ as 2. This means a beacon transmission is heard by two of its immediate followers directly. Similar to the previous experiments, the packet loss is simulated by changing the beacon period temporarily. This is equivalent to missing the packets transmitted with lower beacon period. The change in IVD with packet delay when the leader V_0 applies braking is shown in Figure 4.13. For emergency braking, when packet loss is encountered by the immediate follower of the leader, the beacon transmission can only be tried in the next round. This only affects the immediate follower severely. This is the reason for the packet loss having a drastic change in IVD for V_1. However, its later followers are not severely affected. It was found that the collision happens at a packet delay of 100 ms. Since V_2 receives the command from V_0 in the first multicast, it reacts faster than its follower V_3. Whereas, V_3 receives the information only after the first transmission from the vehicle V_0, which is later propagated by V_1.
For this reason, V_2 experiences less change in its IVD, whereas V_3 experiences a greater change in its IVD compared to V_2.

The change in IVD for varying packet delay is given in the Figure 4.14. For braking events happening in the intermediate vehicles, the immediate follower experience a similar change in IVD as V_1 when the leader performs braking. Hence, during intermediate braking the change in IVD of V_2 is similar to that of V_1 when the emer-

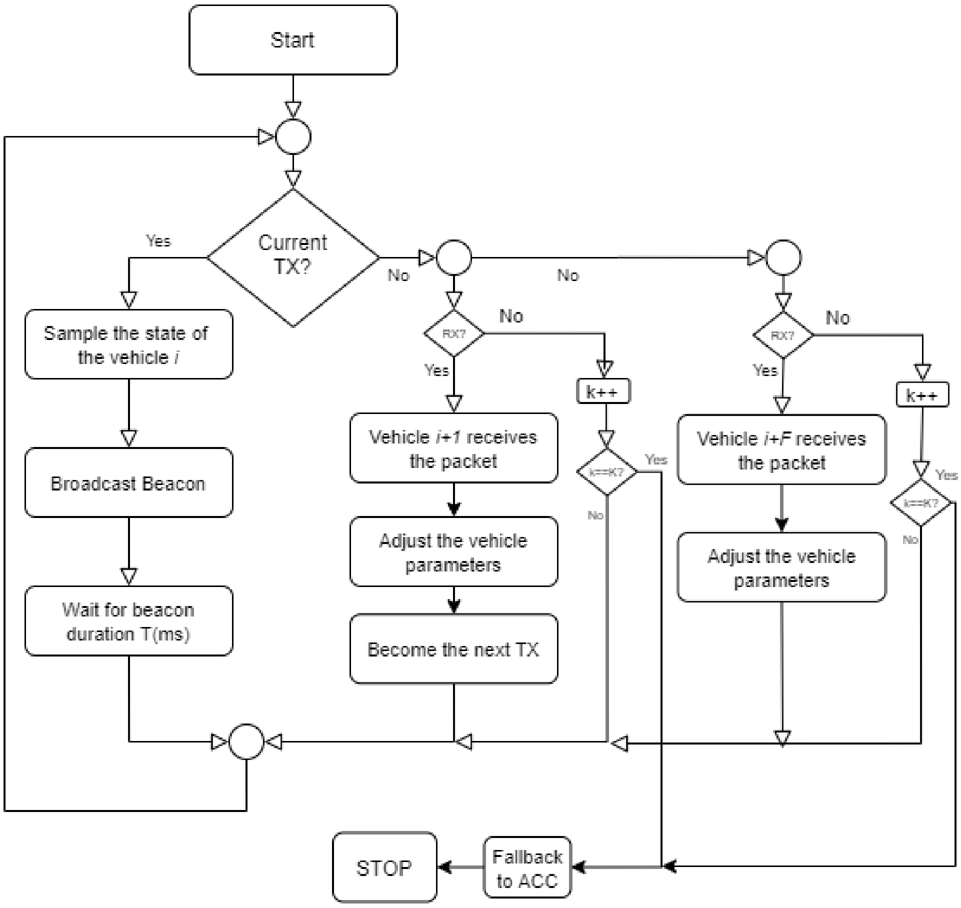


Figure 4.11: Algorithm for MPF

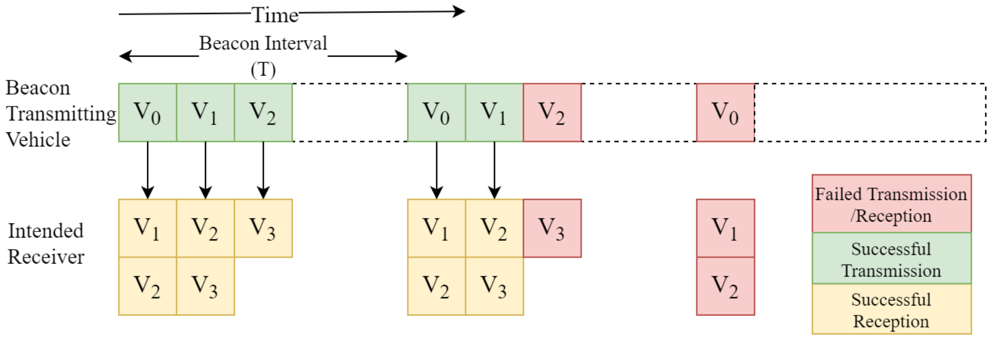


Figure 4.12: TDMA scheduling in MPF

gency braking happened at the leader.

4.7 COMPARISON OF IFTS

The most desired features of any IFT are the following:

1. To keep the transmission range to a minimum (this ensures the interference with other platoons is minimum).

2. Support for intermediate vehicle braking.

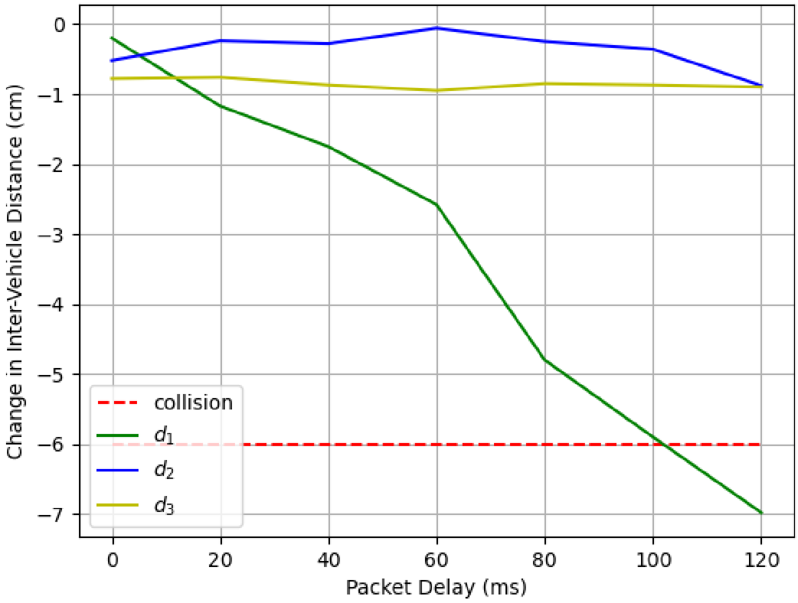


Figure 4.13: Change in IVD after emergency braking at the leader in MPF with varying packet delays, where d_1 is the distance between V_0 and V_1, d_2 is the distance between V_1 and V_2, d_3 is the distance between V_2 and V_3

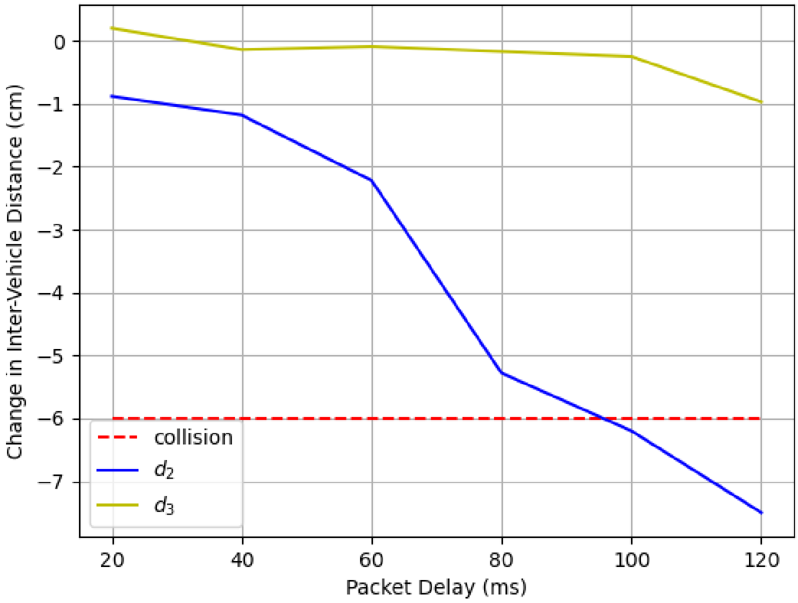


Figure 4.14: Change in IVD after emergency braking at V_1 in MPF with varying packet delays, where d_1 is the distance between V_0 and V_1, d_2 is the distance between V_1 and V_2, d_3 is the distance between V_2 and V_3

3. To keep the IVD as large as possible (have the least deviation from its original distance) after emergency braking.

A brief comparison of the characteristics of the IFTs are given in Table 4.1. Although both PF and MPF satisfies the above conditions, MPF performs marginally

	LF	**PF**	**LPF**	**MPF**
Intermediate Braking	Not supported	Supported	Supported	Supported
Desired Transmission Range	Very High	Low	Very High	Low
Response time to the leader events	Fastest	Slowest	Fastest	Fast

Table 4.1: Comparison of IFTs

better by maintaining the IVD considerably higher with the later follower as shown in Figure 4.7 and Figure 4.13.

It can be concluded that the MPF will be the ideal IFT, considering the emergency braking scenario, given its scalable nature and the response time for both events at the leader and intermediate vehicles.

4.8 SUMMARY

In this chapter, we have discussed the implementation aspects of IFTs and evaluated the performance of each of IFT with packet loss in emergency braking. The key performance indicator used during evaluation and comparison is the change in IVD during the packet loss at the time of emergency braking. Out of the four IFTs discussed, MPF was found to be better in terms of scalability, the number of vehicles experiencing a change in IVD and response time to intermediate vehicle braking. Although LF provides the quickest response time for events happening at the leader, it cannot scale without impairing the channel operation and cannot directly support intermediate vehicle braking.

5 IMPLICIT ACKNOWLEDGEMENT

In the work so far, the performance of four of the IFTs was evaluated for emergency braking in presence of packet loss. The change in IVD was used as a key performance indicator to draw a comparison between them. This chapter explores the applicability of ”implicit acknowledgement” scheme in improving the reliability of emergency braking in presence of packet loss. Similar to the evaluation done in the previous chapter, the experiments performed in this chapter also uses the change in IVD as the key performance indicators. Additionally, the probability of collision is used to show improvement.

5.1 COMMUNICATION LOSS DUE TO HIDDEN TERMINALS

When there is a hidden terminal in the vicinity of the platoon, its transmission interferes with the beacon information sent by the members of the platoon at the receiver end. Figure 5.1 shows an instance of this problem where the beacon transmission by V_0 is interfered by a transmission done at the same time by a hidden terminal. Since each of the vehicles sense the channel before transmission (also known as LBT), they will only be able to detect for channel occupancy at the source. However, when there is a hidden terminal present, which may not be within the range of the source, but will cause a collision at the receivers when both the transmissions overlap. There is a certain delay before the vehicle can transmit new data, which is going to be in its next TDMA schedule. These TDMA schedules for various IFTs have been explained earlier in Chapter 4 (specifically through Figure 4.3, 4.6, 4.10 and 4.12).

Making the communication bidirectional could be a solution where each of the receivers sends an acknowledgement after the reception is successful, as in infrastructure-based WiFi networks. However, this mechanism adds significant overhead to the platoon's communication as the followers should themselves contend for the channel access to send out the acknowledgements which increase the interference. Hence, sending out acknowledgements to every packet is not considered an optimal solution [45].

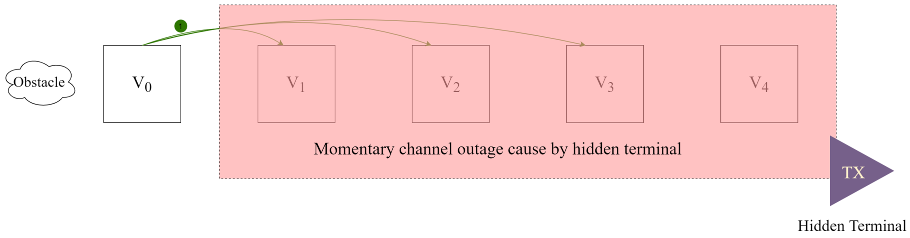


Figure 5.1: Effect of hidden terminal on platoon communication (shown for MPF)

5.2 IMPLICIT ACKNOWLEDGEMENT

To overcome the aforementioned problem of increased delay to transmit the next update, there needs to be a mechanism in place to ensure a successful transmission with a minimal interference and overhead. This problem with the hidden terminal was tackled in the field of wireless networking by Ergen et. al [46]. In their work, a wireless token ring protocol was design at the MAC layer to reduce the contention among the transmitters. This is achieved by terminals taking turn to transmit and suspend the access until another node nearby triggers its transmission. We adopt this solution to platooning in which the use of transmission relay as an acknowledgement for the previous transaction. For example, in an event of a packet loss from V_0 to the intended receiver which is the immediate follower (V_1), would not relay its packet further. Since V_0 can also listen to the transmission from V_1, it notes the absence of this relay and can be considered as a packet loss and consequently, V_0 can immediately transmit instead of waiting for the next TDMA schedule round. On the other hand, when the packet is successfully delivered to V_1, it further relays its information to V_2. This relay can be overheard by the predecessor (V_0) and skip retransmitting. Using this relay transmission as an acknowledgement is know IA [46].

The important criteria for the IA to work is the chained relay of information, which can be applied to LPF, PF and MPF as discussed in Chapter 4. Since, LF IFT lacks this chain propagation, IA cannot be applied to it. In absence of this IA, the transmitter of the beacon can only transmit its next beacon in the next TDMA slot. However, with IA, the duration for retransmission for the unsuccessful packets is significantly reduced. Due to this reduced retransmission time, the update in the form of beacon is received a little early. When this update is about emergency braking, the vehicles can stop at a larger IVD, preventing a collision.

5.3 HANDLING BURST PACKET LOSSES

When there are consecutive packet losses when trying to transmit, it could mean that the wireless channel is dominated by severe interference or unfavourable environment conditions are prevailing. Trying to transmit continuously with IA in this scenario would be a wasteful use of channel as it could interfere with other transmissions in the vicinity. Therefore, a solution to this is crucial.

One solution is to use a counter in the beacon header which is incremented by the followers when there is a transmission happening in a TDMA round. This counter is incremented for both relaying and retransmitting. When this counter reaches a certain threshold, the vehicle can simply drop the packet than relaying it further with the assumption that an updated packet would be received. By completely dropping the packet and not relaying it further, it can cause less interference. However, when this repeats in consecutive TDMA rounds, the delay could grow without a bound. For the followers that do not receive the beacons will remain in silence period during which their knowledge about its predecessor is uncertain. Once this silence period exceeds a certain threshold, the follower vehicles switch back to ACC to rely on their sensors.

Another solution to overcome the problem of unbounded silence time is to keep retransmit even when there are packet drops. This solution can potentially reduce the silence time by trying to transmit the information continuously for a certain threshold number of times N, with a waiting period of K. After N transmissions without succeeding, the previous wait period K is doubled for every N tries. This process is repeated for a *ThresWait* period, after which the followers fallback to ACC. Although, this method adds interference, due to the exponential backoff time, it is relatively a less burden. If a follower when trying to relay the previous packet, receives a new packet from its predecessor, it uses the sequence counter which is embedded in the beacon header to compare and send only the latest packet. This method not only increases the opportunity to keep retransmitting until it succeeds but also reduces the interference as the retry interval keeps increasing exponentially. However, this accumulated growth should be less than or equal to the *ThresWait*.

5.4 VEHICLE COLLISION PROBABILITY

One of the key performance indicators to show the improvement of IA against IFT without IA (vanilla IFT) is the collision probability. For a platooning system with a given packet loss probability, beacon period and desired IVD, the probability of collision gives the tolerance of the system to the packet loss before it encounters a vehicle collision. From the observations made in Chapter 4, the change in IVD is directly related to the beacon period. Therefore, increasing the beacon period leads to a greater change in IVD and makes the platoon more prone to collision. The collision probability calculation shown in this section is IFT-agnostic.

A collision is observed when an update about braking event is missed in consecutive tries. The number of consecutive packets to be lost for a collision to happen (N) is calculated with the following equation:

$$N = \frac{D}{S * T_r}$$

where,
D is the initial IVD
S is the speed of the vehicle
T_r is the time between two consecutive retransmissions by a certain vehicle

With a packet loss probability p_l, for a vehicle collision to happen, a consecutive number of packet misses should take place. Therefore the vehicle collision probability is given by:

$$p_c = {p_l}^N$$

$$p_c = {p_l}^{\frac{D}{S*T_r}}$$

For the setup introduced in Section 4.2, the chosen value for D is 6 cm with S of 30 cm/s and T of 0.02 s. For vanilla IFTs, the duration between consecutive tries T_r is equal to its beacon period. This is because the next chance to transmit a lost beacon is only in the next TDMA slot. For a packet of loss probability p_l of 0.3, for vanilla IFT is given by:

$$N = \frac{6}{30 * 0.02} = 10,$$

$$p_c = (0.3)^{10}$$

For a similar environment, ie. with a packet of loss probability p_l of 0.3, for an IFT with IA and retransmission period T_r as 0.005 s is given by:

$$N = \frac{6}{30 * 0.005} = 40,$$

$$p_c = (0.3)^{40}$$

The above calculation shows that p_c with IA is significantly lower than that of vanilla IFT. Figure 5.2 shows the p_c for different p_l. While the p_c of IFTs with an IA and vanilla IFTs converge to 1 when p_l is high, at a lower p_l, p_c is significantly lower for IFTs with IA compared to the vanilla IFTs.

The performance of both vanilla and IA IFT are comparable when the beacon period for the vanilla IFT is equal to retry period T_r. However, this value for T_r should be as small as possible approximately equal to the roundtrip latency of a packet. Therefore, smaller values for the beacon period are not feasible as they increase the congestion. Literature suggests the beacon interval to be in the range of 50 ms to 100 ms [10]. For such values, IA provides a significant performance improvement.

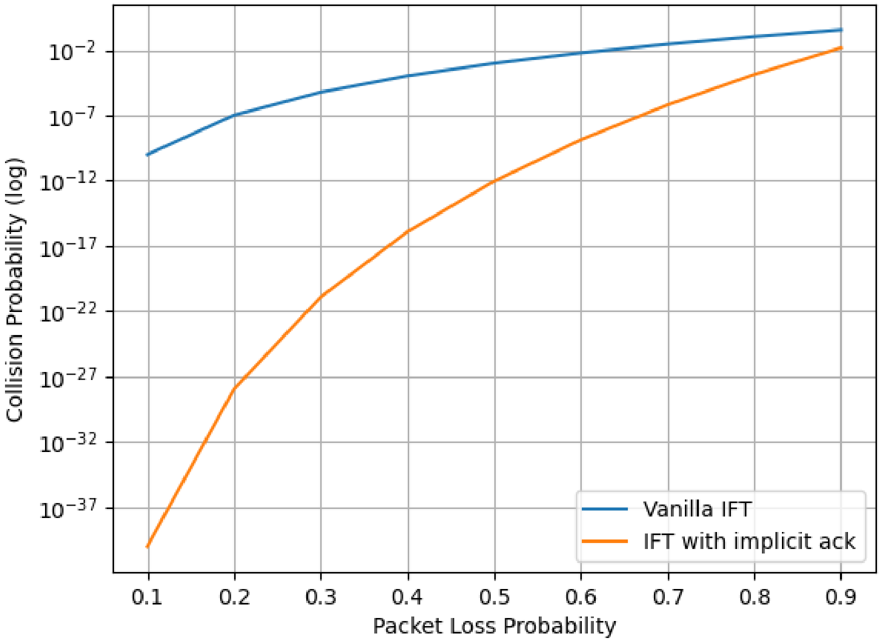


Figure 5.2: Vehicle collision probability with varying packet loss probability for vanilla IFT and implicit ack IFT

5.5 ALGORITHM

5.5.1 Implementation of Predecessor Follower and Multiple-Predecessor Follower

To explain the algorithm of IA for both PF and MPF, a common flow chart is used in Figure 5.3. The steps corresponding to IA is marked in green. The TDMA round is started with the leader broadcasting its beacon to F number (for PF, $F = 1$) of its followers. When there is no interference in the channel, the immediate follower processes the packet (sets its speed), builds a new packet and transmits its new speed to its follower(s). This process is repeated until the information reaches the end of the platoon. When a packet is transmitted, a timer is started for a duration of K. When the immediate follower responds with a relay, the predecessor which transmitted previously, stops and resets the timer and stays idle until the next TDMA round. However, when there is an interference, the relay will fail, making the timer expire. When the timer expires, the vehicle retransmits the beacon. It keeps retrying until the total number of retransmissions reaches the threshold.

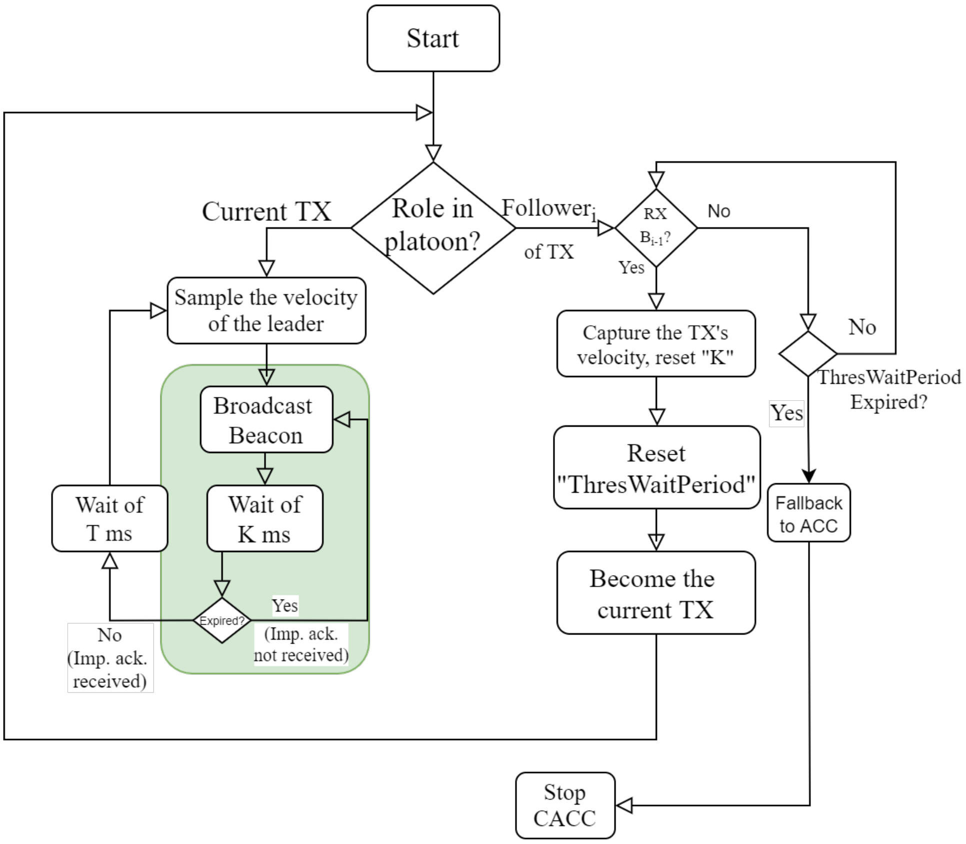


Figure 5.3: Implicit ack used for PF and MPF

The packet scheduling for both PF and MPF with IA is explained with the help of a TDMA sequence diagram shown in Figure 5.4 and Figure 5.5, respectively. A TDMA round starts with the leader transmitting its beacon, to which the intended receivers of the beacon are shown in the vertical bars below the transmission. That is, when the beacon transmitting vehicle is V_0, for PF the intended receiver is only its immediate follower V_1 and for MPF with $F = 2$, the intended receivers are two of its immediate followers V_1 and V_2. When a packet transmission is unsuccessful, the next transmission is tried after waiting for a duration T_r. When implementing implicit ack, for both PF and MPF the last vehicle (V_3), should make a dummy transmission to give the feedback to its immediate predecessor from whom the relay was received. This serves as an acknowledgement to V_2.

5.5.2 Implementation of Leader-Predecessor Follower

Each of the vehicles uses its predecessor's speed from its beacon, while the beacon from the leader is used only if it is a braking event (with an exception for V_1 which will use V_0's speed as well). Although in practice weighted average is used to set the speed of the current vehicle, to verify the emergency braking, the weighted average is omitted and the braking is done immediately.

The packet scheduling for LPF with IA is explained with the help of a TDMA sequence diagram shown in Figure 5.7. Similar to PF and MPF, the TDMA round starts

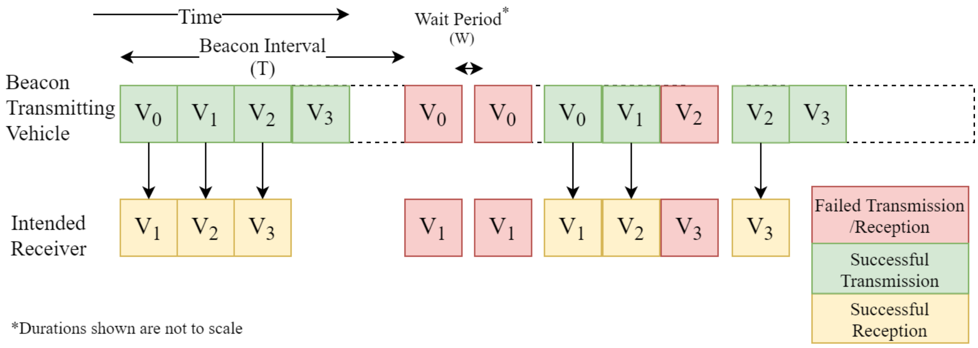


Figure 5.4: TDMA schedule for PF with implicit ack

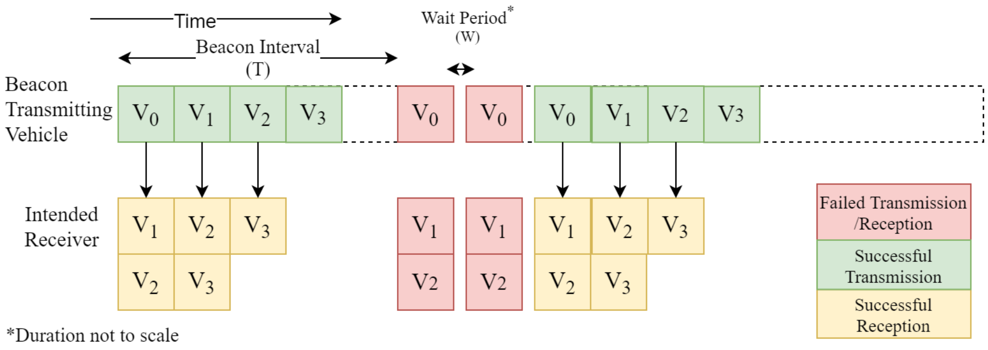


Figure 5.5: TDMA schedule for MPF (having $F = 2$) with implicit ack

with the leader transmitting its beacon, to which the intended receivers of the beacon are shown in the vertical boxes below the transmission. When the beacon transmitting vehicle is the leader (V_0), the intended receivers are all the followers (V_1-V_3) in the platoon. However, for a beacon transmitted by one of the followers, the intended receiver is only its immediate follower. For example, for a beacon transmitted by V_1 will only be processed by V_2. When a packet transmission is unsuccessful, the next transmission is tried after a duration of T_r. Similar to PF and MPF, the last vehicle (V_3), should make a dummy transmission in order to give the feedback to its immediate predecessor to serve as an acknowledgement to V_2.

5.6 EXPERIMENTAL RESULTS

The experimental setup is similar to the one used in Chapter 4. In order to control the packet loss precisely, a transmission failure probability is assigned to each packet during its transmission. Based on this probability, the packet is either dropped or transmitted. Lower PLR signifies less channel congestion. Since each of the vehicles in the platoon has a probability of packet loss assigned, the change in IVD for intermediate vehicle braking is similar to that of the leader braking. Hence, the results for intermediate vehicle braking are not presented. In the rest of this section, we describe the observations of the experiments.

5.6.1 Predecessor Follower (PF)

With IA for PF IFT, its performance against its vanilla PF IFT is compared which is shown in Figure 5.8. Each of the change in the IVD are obtained by averaging over

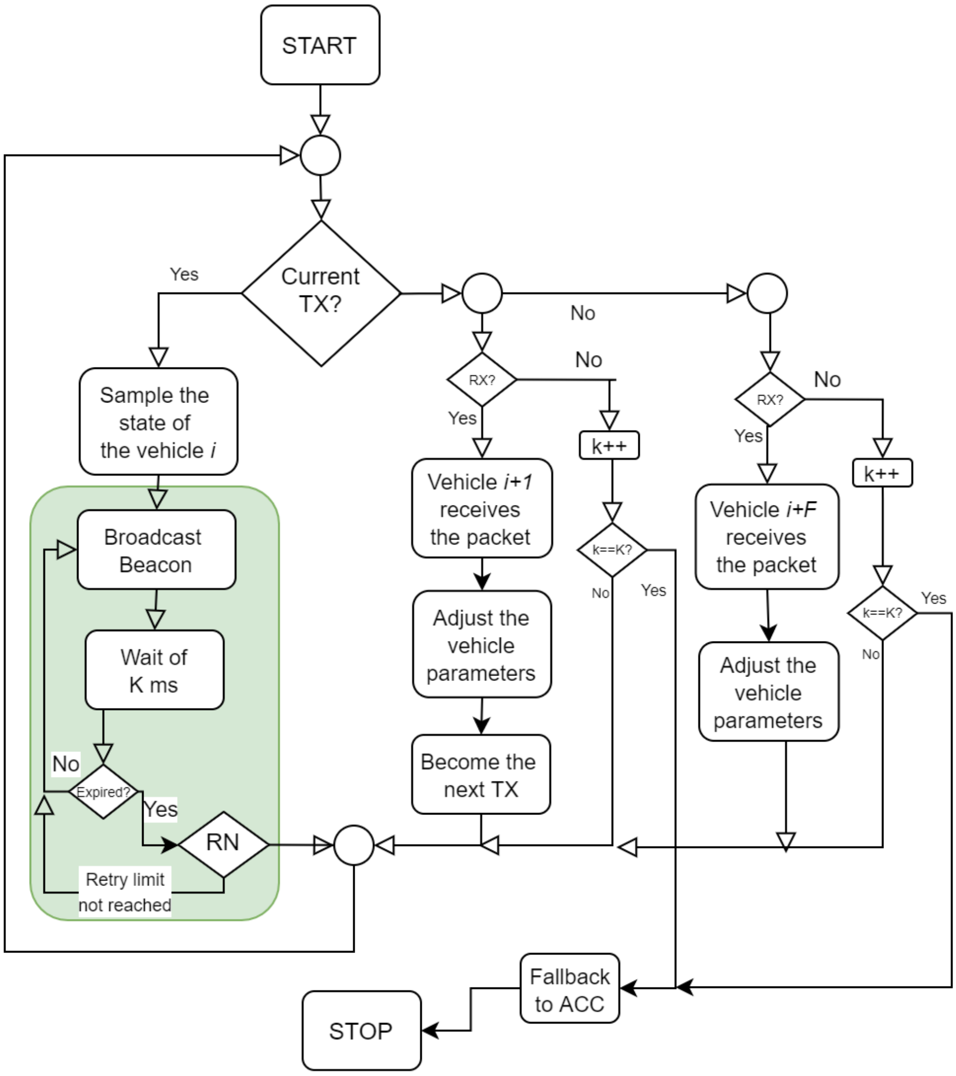
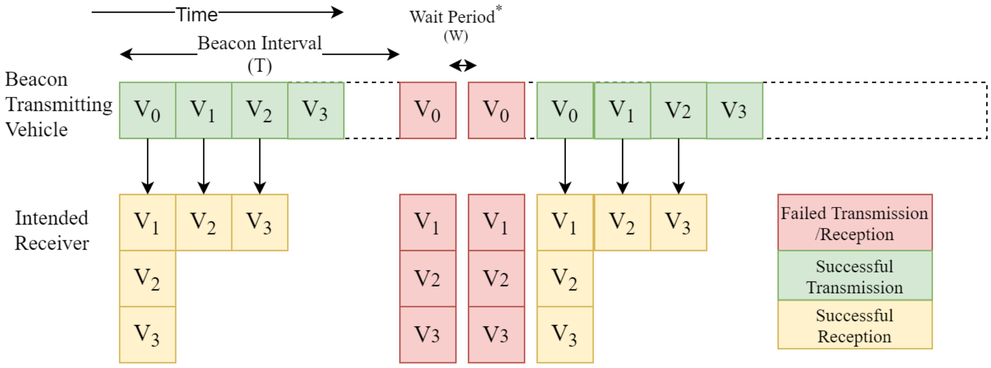


Figure 5.6: Implicit ack used for LPF



*Duration not to scale

Figure 5.7: TDMA schedule for LPF with implicit ack

20 beacon packets. In vanilla PF IFT, which only has a periodic beaconing, the IVD starts to decrease at 70% PLR, while with IA, the IVD starts to fall when the PLR decreases below 30%. When no IA is used, a collision can be observed when the PLR is 30% and below. However, for PF with an IA, a collision is observed for PLR below 10%. The less change in IVD experienced by IA compared to the vanilla PF is because of the reduced time for the next retransmission. Since the PF IFT consists of

chained propagation with only one predecessor hearing the unicast beacon, all the vehicles experience a similar change in their IVD, as the probability of packet loss also applied to every vehicle in the platoon.

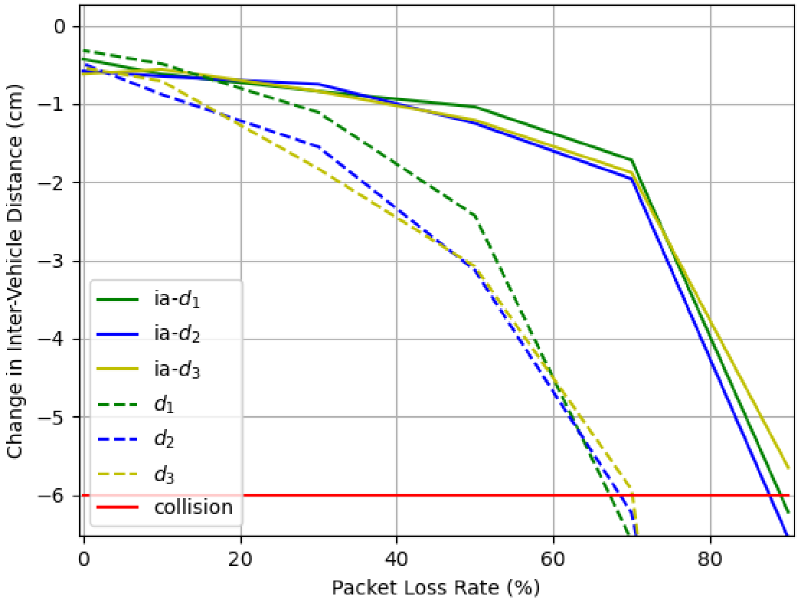


Figure 5.8: Change in IVD after braking by the leader in PF with IA and vanilla IFT; ia-d_1, ia-d_2, ia-d_3 are the change in IVD between V_0 and V_1, V_1 and V_2, V_2 and V_3, respectively with IA; d_1, d_2, d_3 are the change in IVD between V_0 and V_1, V_1 and V_2, V_2 and V_3, respectively with vanilla PF

The change of IVD values obtained previously are the result of averaging out 20 samples. Because averaging out the samples would take away the identification of outliers, a histogram for the change in IVD for V_1, V_2 and V_3 are shown in Figure 5.9, Figure 5.10 and Figure 5.11, respectively.

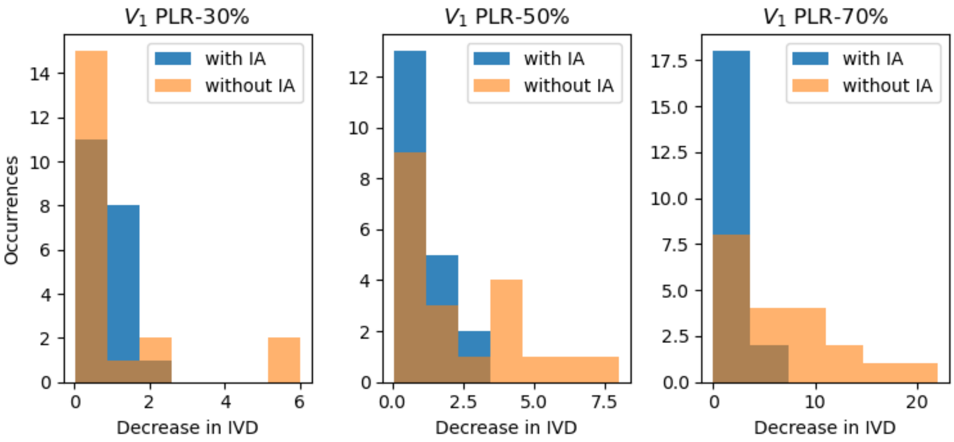


Figure 5.9: Histogram for decrease in IVD for V_1 in PF for different PLR

When the PLR is 30%, 50% and 70%, the vehicle V_1 has a change in IVD for less than 6 cm with IA. However, vanilla PF has exceeded the change in IVD of 6 cm indicating a collision. Since each vehicle in PF can only receive updates from their direct

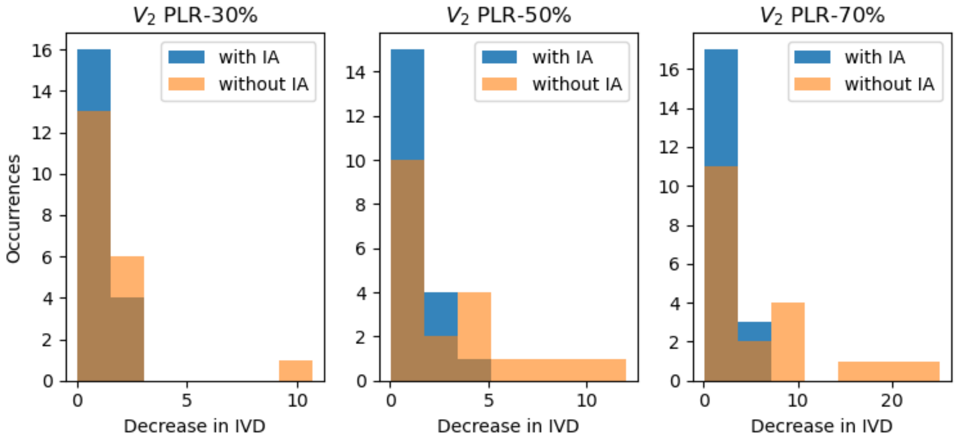


Figure 5.10: Histogram for decrease in IVD for V_2 in PF for different PLR

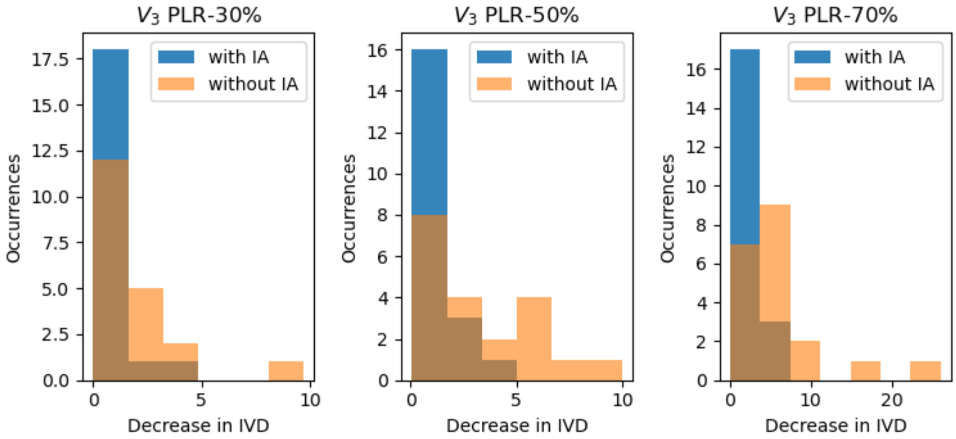


Figure 5.11: Histogram for decrease in IVD for V_3 in PF for different PLR

predecessor, other vehicles (V_2, V_3) also have a similar histogram. This indicates that the number of collisions observed for IFTs with IA is far less than the number of collisions observed for a vanilla IFT.

5.6.2 Leader-Predecessor Follower (LPF)

This experiment consisted of braking at the leader with a varied packet loss probability. Similar to the results shown in Figure 4.3.2 for braking at the leader, the immediate follower of the leader is only vehicles affected by the communication loss, which starts to fall from 50% PLR shown in the Figure 5.12. However, with for the same IFT with IA, the system can withstand until a PLR of 30%. The improvement observed for the IA can be accounted for the reduced retransmission time at the leader.

Unlike PF, the other followers (V_2, V_3) show very little deviation even when the channel is dominated by packet loss. However, the immediate follower of the leader V_1 tends to get close as the packets are lost from the leader. This is because the leader's transmission being broadcast, all the other followers travel the same distance as the immediate follower of the leader and they all stop at the same time, thereby maintaining the same IVD, except for the immediate follower whose predecessor is already stopped. Since only the change in IVD is observed for V_1, the histogram for the change in IVD for only V_1 is shown, in Figure 5.13.

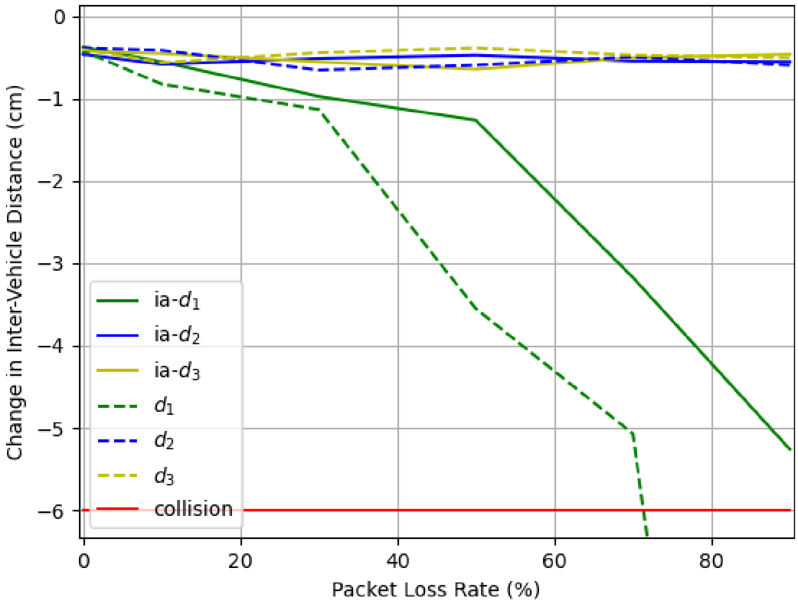


Figure 5.12: Change in IVD after braking by the leader in LPF: with IA and vanilla IFT; ia-d_1, ia-d_2, ia-d_3 are the change in IVD between V_0 and V_1, V_1 and V_2, V_2 and V_3, respectively with IA; d_1, d_2, d_3 are the change in IVD between V_0 and V_1, V_1 and V_2, V_2 and V_3, respectively, with vanilla LPF

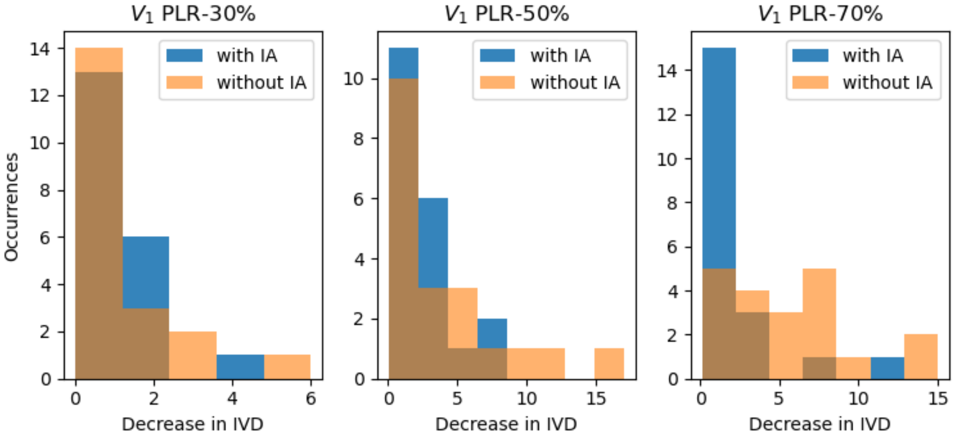


Figure 5.13: Histogram for decrease in IVD for V_1 in LPF for different PLR

5.6.3 Multiple-Predecessor Follower (MPF)

The implementation of MPF is done with the number of followers that can hear a beacon as two, ie. when a beacon is transmitted by any vehicle in the platoon, it will be received and processed by two of its immediate followers. PF can be considered as a specific case of MPF in which only the immediate follower can receive and process the information.

Due the nature of information dissemination, which is multicast, the follower that is not the immediate follower that still receives the beacon successfully will have the least deviation in its IVD, which is shown in Figure 5.14. V_2 will receive the information at the same time as V_1, however V_1 being the immediate follower, will experience a change in IVD compared to V_2. V_3 being part of the next relay hop, it will also experience similar change in IVD as V_1.

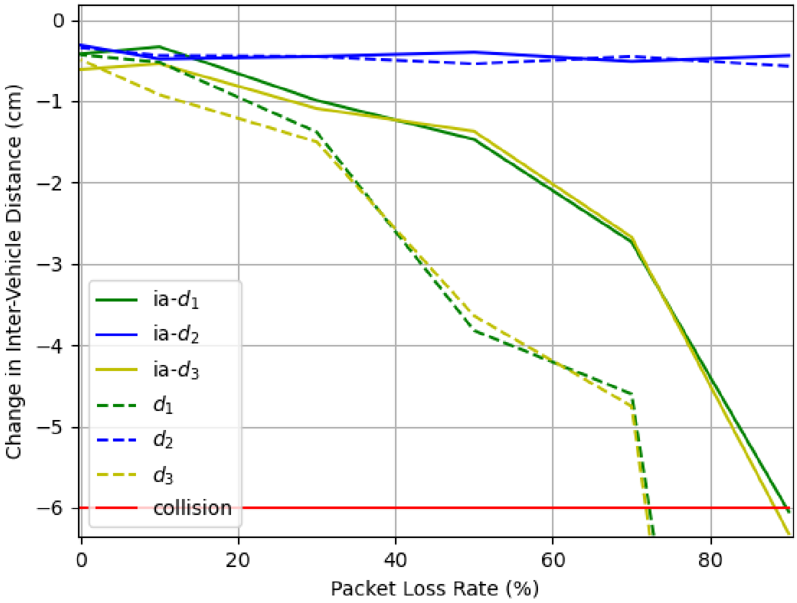


Figure 5.14: Change in IVD after braking by the leader in MPF: with IA and vanilla IFT; ia-d_1, ia-d_2, ia-d_3 are the change in IVD between V_0 and V_1, V_1 and V_2, V_2 and V_3, respectively with IA; d_1, d_2, d_3 are the change in IVD between V_0 and V_1, V_1 and V_2, V_2 and V_3, respectively, with vanilla MPF

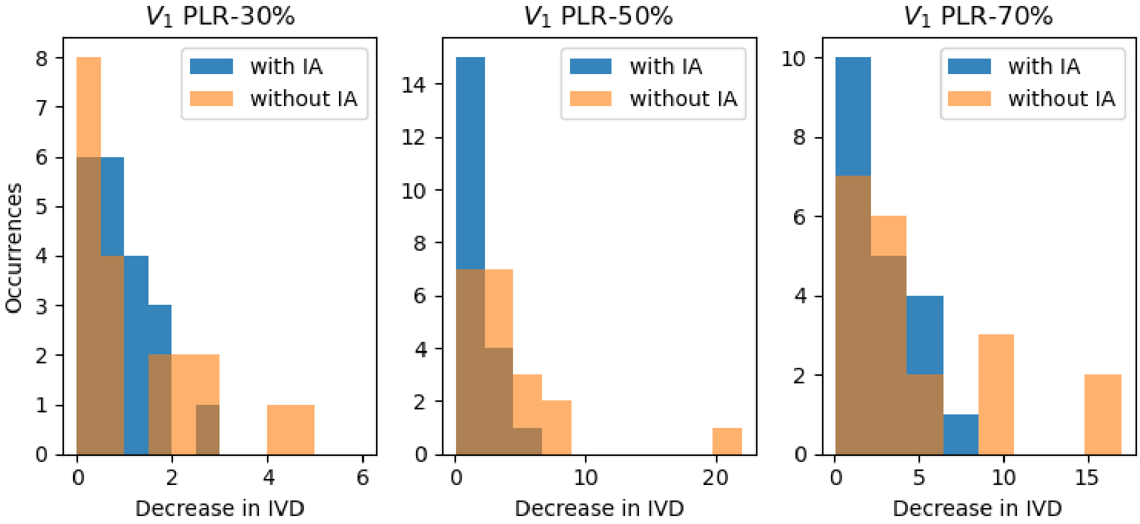


Figure 5.15: Histogram for the change in IVD for V_1 in MPF for different PLR

5.7 SUMMARY

This chapter discussed how IA was adopted for platooning with various IFTs. Through extensive experiments, it was noticed that the IA introduces a significant improvement in the performance of the platoon in terms of change in the IVD. We also validated over several trials of the experiment. The improvement is seen in all the IFTs in which chain propagation takes place. This suggests that IA has the potential to be incorporated into future platooning systems for guaranteeing safety even in presence of high packet losses.

6 CONCLUSION AND FUTURE WORK

With V2V communication involved in platooning for information dissemination between the vehicles, the communication channel is the weakest link in the whole system. Any communication loss within the system can cause rear-end collisions within the vehicles. Requirements are more stringent when emergency braking is involved in the platoon. Therefore, it is crucial to study how platoons perform in presence of communication losses for emergency braking.

In this work, we designed a low-cost and customizable testbed that can incorporate low-latency communication protocols by giving fine control over MAC and physical layer. This is one of the important requirement in platooning applications as communication is the backbone of platooning. The main components of the testbed are robot cars, which are mounted with custom-designed PCBs. Each of the robot car in testbed consists of two communication devices that can operate in parallel. One, which is used for direct communication with other robot cars in the platoon. Another, which allows a user to control the robot through a computer, to emulate the actions of a driver, such as braking in the intermediate vehicles.

In the subsequent part, on the proposed testbed, we analyzed the performance of emergency braking for different IFTs in presence of packet loss. In addition to the braking at the leader, the performance when braking is applied in the intermediate vehicles is also analyzed. The key performance indicator used is the change in IVD between the vehicles after emergency braking at the leader. Out of the four IFTs discussed, MPF was observed to be better in terms of both scalability and response time to an emergency braking event. Although the LF IFT showed the quickest response time, it cannot scale without causing interference in the channel.

To improve the communication reliability in platooning, an existing method in wireless networking is adopted to work with IFTs. Using this method, the vehicle collision probability has been reduced compared to the vanilla IFTs. This addition was tested for all IFTs to draw a direct comparison with their vanilla counterparts. The change in the IVD for the vehicles showed that even during packet loss, this system showed only a little change in IVD for all the three IFTs (LPF, PF and MPF).

6.1 DISCUSSION

The testbed designed consisted of low-speed motors that do not reflect the real-world speeds. However, the study done is work is still applicable for high-speed vehicles, as the only parameter that would change is the desired IVD accounting for the braking time. Due to the limited resources available, we had to choose small low-speed motors in the testbed. The PCB proposed in this work can be used on any other chassis that can be operated with PWM, without any modifications.

Another limitation of our work is the confinement of testing with only one platoon. Although the proposed method reduces the probability of vehicle collision, the impact of repeated transmission on other vehicular networks on the highway has not been studied. As a remedy to the foreseen problem of interference, a short communication range could solve the problem to a certain extent, if not completely.

6.2 FUTURE WORK

In this work, we had chosen the DSRC to happen at a RF transmission frequency of 868 MHz with a data rate of 50 kbps. But the hardware can also support 2.4 GHz, at which the data rates can be quadrupled. This can reduce the latency of point-to-point communication in the DSRC by a factor greater than 5. However, in our work, we had to resort to the sub-gigahertz transmission frequency due to the unavailability of debugging resources for 2.4 GHz.

Although this work had independently evaluated the working of implicit ack. for all the IFTs, extending the testbed with multiple platoons and implicit ack in every platoon would emulate a real platooning application. This extension would evaluate the performance of implicit ack in mixed traffic (where other vehicles are equipped with V2V as well as multiple platoons). This is a realistic use case since platoons can coexist with other independent traffic as well as other platoons, like multiple platoons coming in the other direction where the overlapping area would experience severe communication congestion.

While implicit ack. was well tested for emergency braking scenarios, testing it for packet loss for dynamic vehicle speeds would give an exhaustive evaluation of the method. To that extent, adding complementary control theory for the safe operation would lead to another enhancement that is worth pursuing.

While many of the works including ours were done on custom hardware, very few works used the COTS platooning equipment (like $ETSI-ITS-G5$) which is the actual equipment that is used in vehicles. It would be an engineering challenge to modify the network stack to implement implicit ack on such hardware. The current network stack used in these equipment [47] uses the MAC layer similar to the WiFi stack.

To enable a flexible and scalable platooning application, a leaving strategy has to be explored with an implicit ack. As a vehicle simply leaving the platoon will affect the chain propagation in the platoon, leaving the follower vehicles in a silent zone. Additionally, a vehicle joining strategy at both the end and the middle of the platoon has to be studied.

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