An integrated V2X simulator with applications in vehicle platooning*

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***Abstract*— One of the most exciting applications of V2X technologies, that is envisioned, is the platooning of a series of semi-autonomous vehicles. However, the realization of this application depends entirely on the efficacy of a platoon control algorithm and the communication channel amongst the platoon members. There are many different control algorithms that are being considered to maintain a constant distance/time Gap amongst the platoon members based on the speed and acceleration profile of the other vehicles in the platoon. However, before a particular control algorithm can be deployed, it needs to be thoroughly analysed to see if it can indeed produce the desired effect under all sorts of traffic conditions and with varying penetration rates of V2X technology. In addition, one would also need to collect data on data packet delivery rate and the amount of delay, using different platoon management protocols. This information can then be utilized as a feedback to fine tune both the protocol and the control algorithm itself. This work aims to provide a holistic platform which integrates three simulators VISSIM (Traffic Simulation), NS-3 (Network Simulation) and MATLAB (Platoon control algorithm) that allows testing control algorithm stability in the presence of realistic communication constraints. To illustrate the usability of this co-simulation framework, we have presented results on velocity tracking of leader by follower vehicles while maintaining a specified inter-vehicular gap, for a small platoon along with results on data packet delivery for larger platoons.**

I. INTRODUCTION

The concept of vehicle platooning has been receiving considerable attention in the last couple of decades due to plethora of benefits that it is expected to offer, once implemented. The main goals for platooning are to increase road capacity by spacing vehicles as tightly as possible along with improving safety, fuel efficiency and reduction of travel time. However, before any form of commercial implementation can be carried out, the necessary technologies that will allow the realization of a full-fledged platoon will have to undergo a thorough phase of testing and validation, to be deemed safe for application. The overall conception of a platoon is an interdisciplinary problem involving control theory, communication engineering, software programming etc. It is obvious that the testing process will involve field trials to ensure all the components complement each other. However, field trials are typically expensive to conduct and one can only re-create a small subset of the actual number of traffic scenarios in which the platoon is expected to operate. While considerable research has been conducted in fields tests for platooning, these studies were mostly performed in controlled environments [1], [2], [3]. Naturally, it is much harder to conduct any tests in practical environments. One alternative is to deploy a simulation framework that can realistically model the on-ground conditions. The aim of this work is, therefore, to provide a simulation environment which is capable of combining the fundamental elements for modelling a platoon which are traffic, communication and a platoon control algorithm. For this purpose we chose the microscopic traffic simulator VISSIM , NS3 for network simulation and MATLAB for application simulation. VISSIM is a commonly employed micro-simulator. It provides functionalities such as being able to replicate and control the trajectories of any vehicle in simulations, simulate both right and left hand driving, allows access to vehicular and infrastructure (e.g. signals) information at every simulation interval as little as 100 ms and provide real-time data exchange with external programs and traffic modules via the Component Object Model (COM) or through Dynamic Link Libraries (DLL) [4]. SUMO is another commonly used micro-simulator in the domain of vehicular communication research [5], [6]. However, it does not possess the capability of simulating left-hand driving, which is necessary to model traffic in many countries such as Singapore. In addition, SUMO does not possess good visualization capabilities. We chose NS3 for network simulation since it contains model libraries for simulating the the Wireless Access for Vehicular Environment (WAVE) system architecture [7] and is one of the most trusted simulators for testing V2X protocols. The resultant integrated simulator will allow one to test a wide range of V2X applications in addition to platooning, such as Green Light Optimized Speed Advisory (GLOSA), intersection collision avoidance, etc. The platform has already been applied for demonstrating the GLOSA [8]. In this work, simulations of vehicle platooning have been carried out, using the platform, and results on leader vehicle velocity tracking and inter-vehicular constant distance gap maintenance have been presented for a 5 vehicle platoon. In addition, results on packet delivery ratio for platoons of various lengths have also been presented along with some preliminary results on leader velocity tracking for a 16 and 25 vehicle platoon. The rest of the paper has been structured as follows. In

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section II, a literature review of available simulation tools for vehicle platooning has been provided. In Section III, we have given a brief description of the simulator design along with explaining how the platoon control and communication aspects were modelled and simulated. In Section IV, we have discussed the Simulation Setup and the Results that we obtained while in Section V, the conclusions from this work and the future work have been shared.

II. Literature Review

Development of technology that supports smooth movement of a platoon of vehicles has been the focus of research for a multitude of groups, both in academia [9], [10] and industry [1], [2]. In order to realize a platoon, it is an imperative that both a robust control and communication strategy be developed. One of the most ambitious endeavours towards realization of a functioning platoon is obviously the California PATH program [1]. In this project, it was established that a close spacing between vehicles is possible if each platoon member has access to the speed and acceleration vehicle of its preceding and the leader vehicle every few hundreths of a second. The experiments in this project were carried out on the field with eight automated vehicles. The study considered various aspects the of the problem including control development based on longitudinal and lateral dynamics to the communication specifications to the sensor fusion and finally the experimental verification.

However, due to the interdisciplinary nature of this field, most research groups tend to focus on one of the aspects of platooning. Kavathekar et al. [11] classified platooning research into inter-vehicular communication methodologies, collision avoidance and obstacle detection, longitudinal and lateral control design, string stability and trajectory planning. The theoretical basis for string stability were laid down by Swaroop et al. [9] while Rajamani [10] introduced a platoon control algorithm using principles of classical control theory, which uses information from preceding and leading vehicle. Naus et al. [12] worked on a Potential-Derivative (PD) control law. More sophisticated control laws have been developed by Assad et al. [13] whose law is based on the Linear Quadratic Regulator framework while Stanger et al. [14] developed a model predictive coperative adaptive cruise control approach. On the communication side, considerable work has been done in developing robust platoon management protocols. Fernandes and Nunes [15] proposed a platoon information management strategy that can help in reducing communication delays while Amoozadeh et al. [16] proposed a series of commands that enable a non-platoon vehicle to select a platoon, merge and split from the platoon.

One unifying component in every research work carried out is the utilization of simulation tools to validate ideas. Most of the above mentioned works were tested using different simulation platforms. Naus et al. [12] worked with MATLAB/Simulink to model the vehicle dynamics and control while the communication component has been modelled using a time delay function. Stanger et al. [14] also employed MATLAB to validate the MPC control idea. MATLAB has also been utilized to simulate the communication architecture such as by Shooshtary [17], however this component is not just restricted for platooning. Fernando and Nunes [18] developed a car following module which was then added to the traffic simulator SUMO to simulate the movement of platoons with constant spacing. Some research groups have put together their own integrated platforms for modelling control and communication in platooning. Lei [19] developed a simulation platform that combines SUMO for traffic simulation, OMNET++ for network simulation and Simulink for modelling the control laws that govern the follower vehicle behaviour. They converted the Simulink model into a C++ shared library using Real-Time Workshop so that it can be called by the SUMO source code. Jia et al. [20] developed an Intelligent Driver Model which essentially defines the car-following algorithm for all platoon members except the leader. This work takes advantage of the Veins framework and extends SUMO with the IDM model to simulate a platoon. Also, there is PLEXE [21], a dedicated tool that has been designed for testing platooning strategies and communication protocols. This tool has been built on top of the Veins framework and has extended the OMNET++ network simulator by modelling the IEEE 802.11p protocol communication stack. In addition, it has also has enhanced the capabilities of SUMO by adding models for Cruise Control (CC), Adaptive Cruise Control (ACC) and Cooperative Adaptive Cruise Control (CACC), either of which can be applied to govern the motion of vehicles in the simulation. PLEXE is the most promising endeavour to establish a common simulation platform for platooning experiments. In addition to PLEXE, there is VENTOS developed by Amoozadeh et. al. [16] which again combines SUMO and OMNET++. This platform, in addition to car-following models for ACC and CACC, also offers a platoon management protocol model that supports manuevers such as merge, split, entry, follower leave and platoon leader leave. However, our intentions are to make use of VISSIM and NS3 for traffic and network simulations respectively. This will allow one to carry out much more precise modelling of both the road infrastructure and the vehicle dynamics, in case it is intended to create platoons of a specific type of vehicle, and simulate platooning with the full WAVE protocol stack available in NS3. Therefore, the afore-mentioned simulation tools therefore do not satisfy our requirements. There has been some platooning research where simulations were carried out using VISSIM for traffic simulations such as [22], which modelled the ACC and CACC strategies in a Dynamic Link Library coded in C++ and incorporated them in VISSIM's External Driver Behaviour Module. [23] also uses VISSIM to study the effect of platooning on roadway capacity. However, the platoon is modelled as a chain of vehicles travelling at the same speed and no ACC or CACC algorithms were implemented. Furthermore, in both the VISSIM related platoon simulations there is no network simulator involved and the communication has not been simulated. An exhaustive review of other available V2X simulators has been provided in [8].

III. SIMULATOR DESIGN

In this section, we describe the simulation design and architecture. Fig 1 shows the basic simulator coupling idea. VISSIM and MATLAB communicate with each other via VISSIM's COM interface, which allows access to most attributes of the traffic simulation such as vehicle speeds, positions, signal phase information, etc. through MATLAB. Both VISSIM and MATLAB were installed on a Windows OS, since VISSIM only runs on a Windows platform. On the other hand, NS3 has been developed for Linux. To couple VISSIM/MATLAB with NS3, we setup a Linux virtual machine, installed NS3 on it and linked the host machine (with Windows) to the virtual machine via a virtual network. We then applied sockets API for communication of data between MATLAB and NS3. More information regarding the simulator can be obtained from [8].

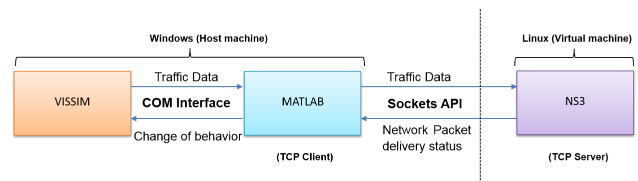


Fig. 1: Block diagram of the simulation environment.

A. Modelling the Platoon CACC algorithm

In order to demonstrate the capability of the simulation platform to model platoon control algorithms, we consider the control strategy proposed by Rajamani [10] for longitudinal control of a platoon. The equation for the acceleration is given in Eq. 1.

$$\ddot{x}_{i\_\text{des}} = (1-C_1)\ddot{x}_{i-1} + C_1\ddot{x}_l - (2\xi - C_1(\xi + \sqrt{\xi^2-1}))\omega_n\dot{\epsilon}_i - (\xi + \sqrt{\xi^2-1})\omega_n C_1(\dot{x}_i - \dot{x}_l) - \omega_n^2\epsilon_i, \quad (1)$$

where

$$\epsilon_i = x_i - x_{i-1} + L_i,$$

$$\dot{\epsilon}_i = \dot{x}_i - \dot{x}_{i-1},$$

and

$$L_i = l_{i-1} + g_{i\_\text{des}}$$

In platooning the main goal is to obtain a desired acceleration $\ddot{x}_{i\_\text{des}}$ for each platoon member, calculated from the speed and acceleration of the leader ($\dot{x}_l$, $\ddot{x}_l$) along with the position, speed and acceleration of preceding platoon member (x_{i-1}, $\dot{x}_{i-1}$, $\ddot{x}_{i-1}$). ξ is the controller damping ratio, while ω_n is the controller bandwidth. The control algorithm is coded in MATLAB which, via the COM interface, modifies the velocity of the platoon members based on the calculated acceleration.

B. Communication simulation

WAVE [24] is one of the two main protocols which are currently being envisioned for V2V communications. We considered the NS3's protocol stack for WAVE to model the communication amongst platoon members. The advantage of using this module is that it already contains models for the IEEE 802.11p and IEEE 1609.4 as part of the WAVE MAC layer. However, to holistically simulate a VANET, not only does does one need an accurate model of the communication protocol, but also an accurate representation of the mobility of the communicating entities. In addition, there also needs to be an appropriate propagation loss model that can capture the attenuation due to the vehicular environment including the effects of shadowing caused by the platoon members.

In order to simulate mobility, we applied the waypoint mobility model in NS3. This mobility model provides functionality to define waypoints (time, location pair). From these pairs the nodes calculate the direction and speed of movement. Therefore, in order to move from point to point, a node requires an origin and a destination waypoint. Since we want to run the simulations online and prefer not to use waypoint traces generated beforehand, we decided to run the VISSIM simulations one simulation step in advance. Each simulation step is 0.1 seconds. By doing this, we are able to provide both origin and destination to NS3, which improves the accuracy of the node mobility. However, this means that the control action (as calculated by the CACC algorithm) is not implemented at the exact time at which the packet is received by the vehicle but is delayed slightly (approximately 0.1 seconds).

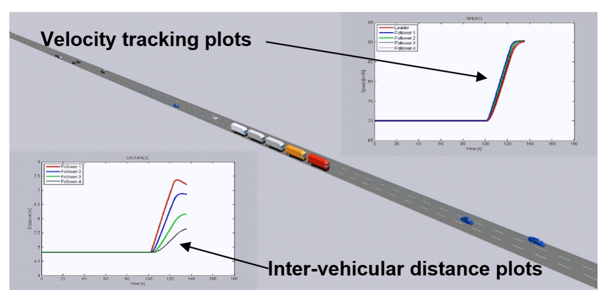


Fig. 2: Platoon simulations

Although there are some models which take into account environmental/physical factors such as buildings, length of vehicles, etc. to model the channel, we felt they will not be able to correctly represent the Line-of-sight (LOS) and Obstructed Line-of-sight (OLOS) communication for VANETs which also takes into account the shadowing effects caused by other vehicles. Therefore, to model propagation loss, we considered the Three Log Distance Propagation Loss model with Nakagami - m fading. Abbas et al. [25] conducted channel measurements for highway and urban scenarios to gather data on average received power, packet delivery ratio and packet inter-arrival times for both LOS and OLOS cases. They also compared the results to a channel model based on Nakagami - m fading and showed that there is a strong

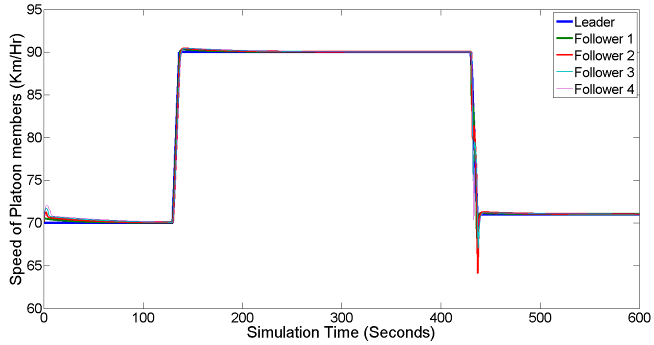


Fig. 3: Five vehicle Platoon velocity tracking

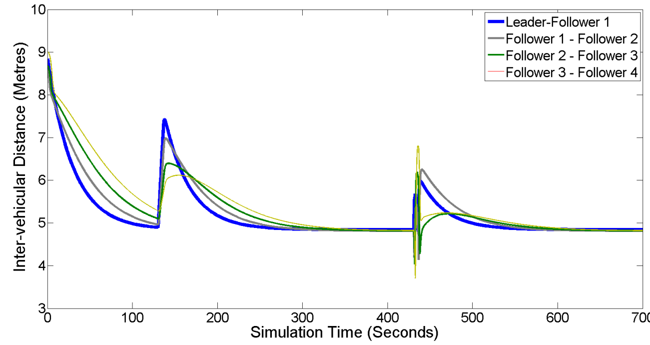


Fig. 4: Platoon inter-vehicular distance

coincidence between the averaged received power from the LOS/OLOS and the Nakagami model. There is also small difference between the packet reception probability between the two models. The afore-mentioned combination has also been applied to model the channel in [26] for communication amongst a convoy of vehicles.

In the network simulations, each vehicle is configured to broadcast 1000 byte long messages at 10 Hz (10 messages/sec) with each vehicle broadcasting within 0.1 seconds, irrespective of the platoon length. The first broadcast of each vehicle takes place with random offset based on a uniform distribution. The message transfer rate has been chosen to be 6 Mbps, which is a supported data rate for WAVE communication [27] over the Control Channel [28]. The control channel will be used by vehicles in a network for beacon broadcasts [29]. Also, a TX power level of 23 dBm is considered along with an Energy Detection Threshold of -87 dBm. The transmit power level is within the specified power range [27] for On-Board Unit (OBU) devices.

Controller Parameter	Definition	Value
C_1	Weight Factor	0.5
ξ	Damping Ratio	1.7
ω_n	Controller Bandwidth	0.4 Hz
g_{i_des}	Desired Gap	5 m
l_{i-1}	Previous Vehicle Length	10.22 m

TABLE I: Controller Parameters

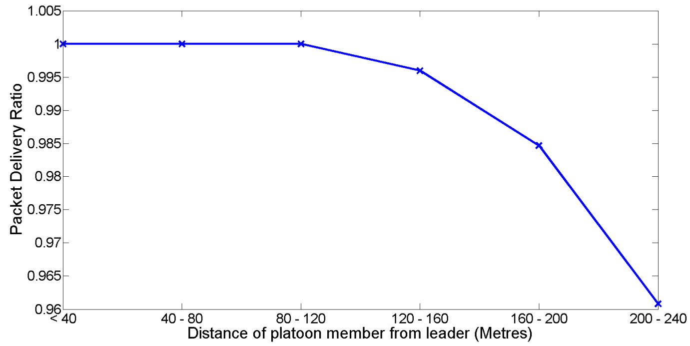
In order to simulate platooning communication we created a `Platoon` class. In case of multiple platoons, each object of the class will represent an individual platoon. The network simulations are initially configured by creating nodes and not attaching the NS3 socket objects to them. As we are only simulating communication amongst the platoon members, the sockets will be attached to only those many number of nodes as there are members of the platoon. In future simulations, sockets will also be attached to vehicles within a predefined neighbourhood of the platoon so as to gather data on platoon communication performance in the presence of dense traffic with vehicles also capable of V2V communication. The user can define as an input the size of the platoon that they would like to experiment with which will be communicated to NS3 for the object creation. In addition to the socket attachment, the class is also going to be responsible for initializing the mobility model with origin waypoints and will contain methods for initializing the beacon broadcasts by every platoon vehicle.

IV. SIMULATION SETUP AND RESULTS

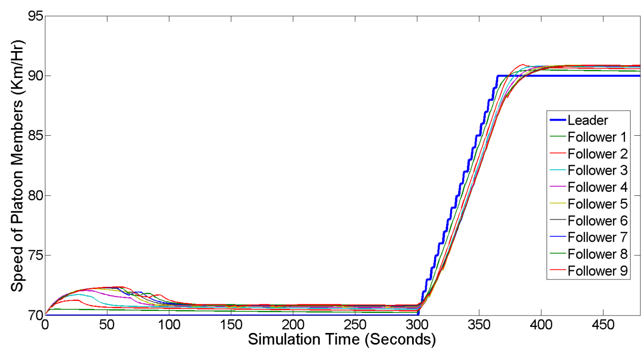
We carried out two kinds of simulations on the integrated simulation platform. In the first scenario we simulated a 5 vehicle platoon for a time period of 1000 seconds.

We changed the velocity of the leader from 70 km/hr to 90 km/hr with an acceleration of 0.93 m/s^2 400 seconds into the simulation and made to decrease back to 70 km/hr at the same rate, at around 700 simulation seconds. The control objective for the CACC algorithm is to track this velocity while maintaining a constant inter-vehicular gap of 5m. The first set of simulations were to done to observe the efficacy of the control algorithm. The controller parameters have been mentioned in Table I while the velocity tracking and the inter-vehicular gap plots have been shown in Fig. 3 and Fig. 4. The length of the vehicle in the simulations has been chosen to be 10.22m which is the default length of Heavy Goods Vehicles (HGV) in VISSIM. This length can be modified in the simulations to match dimensions of specific vehicles/trucks, if necessary.

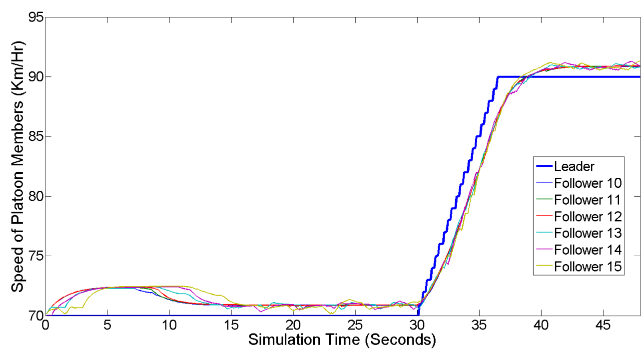
The second set of simulations were carried out to gather data on packet delivery ratio for platoons of different lengths. In these simulation, the network simulation results were recorded for 50 seconds which included the time during which the leader vehicle increased its speed. This ratio is for the packet broadcasted by the leader. In Fig. 5a we have shown the packet delivery ratio for a platoon of 16 vehicles while Fig. 5b and Fig. 5c display the velocity tracking of the leader by the followers. Fig.6a, 6b, 6c and 6d show the same metrics for a 25 vehicle platoon. In the packet delivery plots (Fig.5a and Fig.6a) the x-axis represents the distance of the platoon member from the leader while the y-axis represents the ratio. In addition, in Fig. 7, we have shown the packet delivery ratio for simulations carried out with platoons of arbitrary lengths. In the future, the `Platoon`



(a) Packet delivery ratio as a function of distance of platoon member from the leader



(b) Leader velocity tracking by the first 9 followers



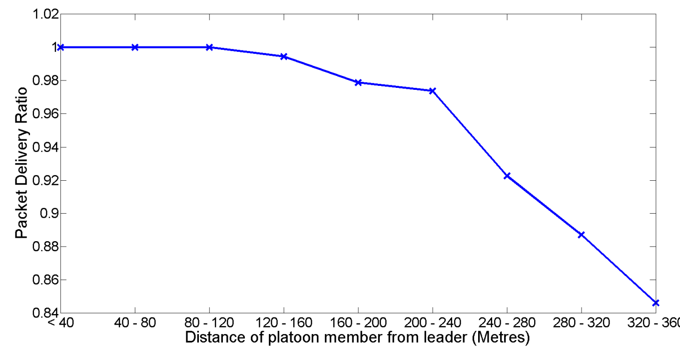
(c) Leader velocity tracking by the last 6 followers

Fig. 5: Packet delivery ratio and speed tracking plots for a 16 vehicle platoon.

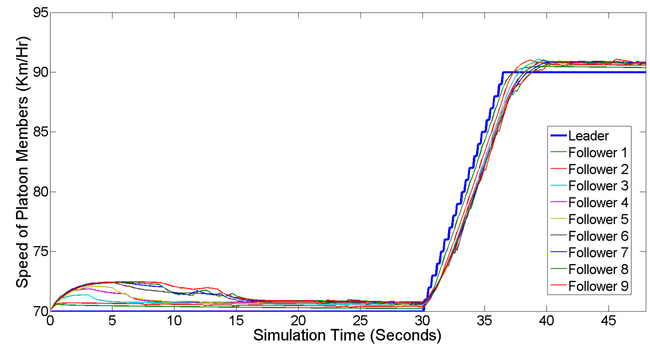
class will also be extended with methods for adding and removing vehicles from the platoon based on some platoon management protocol.

V. CONCLUSIONS

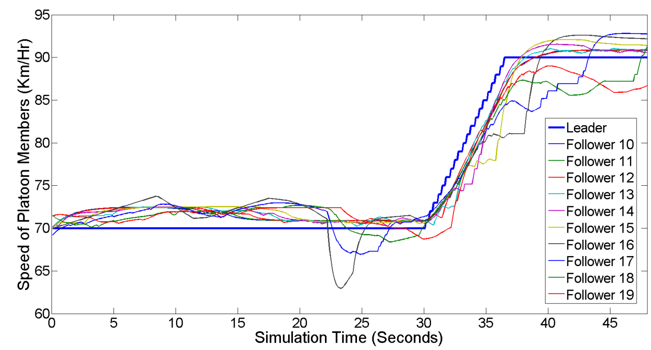
In addition to simulation of platooning, the aim of this work is to demonstrate the capability of the simulator to be able to model and test multiple V2X applications. To this end, we considered the example of platooning of vehicles since it is envisioned to be one of the earliest application use-case for V2V. As the realization of a highly robust and fault tolerant platoon involves an interplay of communication



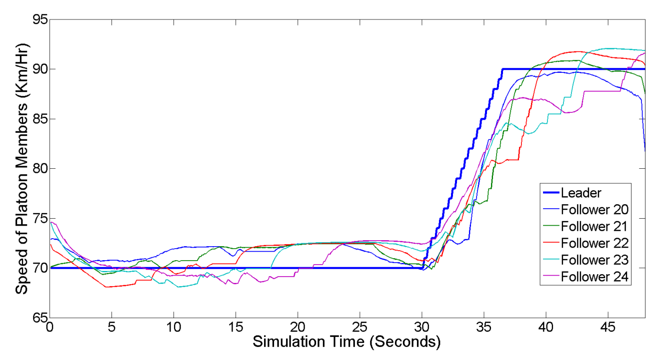
(a) Packet delviery ratio as a function of distance of platoon member from the leader



(b) Leader velocity tracking by the first 9 followers



(c) Leader velocity tracking by Vehicles 10-19



(d) Leader velocity tracking by the last 5 followers

Fig. 6: Packet delivery ratio and speed tracking plots for a 25 vehicle platoon.

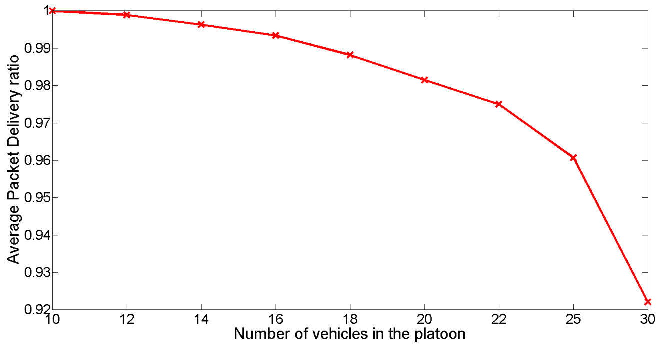


Fig. 7: Packet delivery ratios for platoons with different number of vehicles.

protocol and control algorithm, each needs to be thoroughly verified for its intended effect before being actually applied on any kind of vehicle. Therefore, this platform can be taken advantage of, without having to resort to mathematical models of traffic and the communication network or to code control algorithms in a lower level language to test on a more hardware-centric platform. Our next step towards platoon simulations will be to gather data regarding Packet delivery (amongst platoon members) when other non-platoon vehicles in the vicinity are also capable of V2X and will be broadcasting packets. In addition, we also aim to apply principles of High-Level Architecture (HLA) and use a Run-Time Infrastructure (RTI) to connect the three simulators and also to split up Large scale traffic and network simulations into smaller parts, using the RTI to exchange data among them.

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