Work-in-Progress: Age of Information-Aware CACC for Vehicle Platooning*

Gulabi Mandal, Anik Roy, Ayantika Chatterjee, Soumyajit Dey
Indian Institute of Technology Kharagpur
{gulabi007@kgpian,anikroy@kgpian,ayantika@atdc,soumya@cse}.iitkgp.ac.in

Abstract

Future intelligent transportation will involve significant fleet based autonomy driven by cost and efficiency concerns. To achieve such goals, usual control theoretic methods for Cooperative Adaptive Cruise Control (CACC) for vehicle platooning needs to be aware of non-idealities like packet drops and delays during exchange of periodic time-critical vehicle state information through Inter-Vehicle Communication (IVC). This paper performs an evaluation of existing CACC techniques in typical urban environments. We demonstrate the degradation in IVC quality resulting from packet losses owing to obstacle shadowing caused by large urban buildings. We characterize the impact of such packet losses on time-critical vehicular operations. We next propose a novel Age-of-Information (AoI)-aware CACC for time-critical control data updates in safety applications based on the data age. Through simulations, we show that our proposed controller performs better than usual CACC schemes in a dense urban environment.

1 Introduction

Vehicle platooning is a cooperative driving application of Intelligent Transportation Systems (ITS) with the prominence of improving road safety and traffic efficiency by grouping vehicles to form a string with small inter-vehicle spacing. The platoon coordination is maintained by the Cooperative Adaptive Cruise Control (CACC), which requires periodic and reliable exchange of time-critical vehicle state information, such as position, speed, and other in-vehicle sensor data, for control computation. The periodic exchange of vehicle data is realized by the wireless IVC standard IEEE 802.11p Dedicated Short Range Communication (DSRC), which enables direct Vehicle-to-Vehicle (V2V) and Vehicle-to/from-Infrastructure (V2I) communication [1].

Platooning in urban environments makes economic sense as established in works like [2]. In an urban environment, unforeseen events such as sudden deceleration of the lead vehicle, i.e., the Platoon Leader (PL) can cause the inter-vehicle spacing among the Platoon Members (PMs) to reduce drastically, which increases the risk of accidents. Therefore, the CACC in each vehicle must get fed with state information via frequent, timely, and reliable broadcast message exchanges. The dissemination of time-critical messages among the PMs heavily relies on the Line of Sight (LOS) V2V communication signal strength. However, buildings in an urban scenario, especially at intersections, can obstruct the LOS communication among the PMs and attenuate the communication signal strength at the receiving PM [3]. This may lead to packet loss and communication delays, which forces the CACC in the receiving PM to use previous or outdated vehicle state information to compute control inputs. The use of stale information may cause the platoon vehicles to react inappropriately by compromising the platoon stability during sudden deceleration [4].

To improve packet transmission reliability in a CACC-based platoon, the work in [3], [5] proposed an increase in the number of data exchange and re-transmission techniques to mitigate communication errors. Even if such methods improve communication-related delay, they do not guarantee better CACC performance in terms of reduced spacing error. The works reported in [2], [4] have conducted a complete study on the CACC control design to achieve platoon stability. However, the scenarios considered are simplistic (free highway) compared to a realistic urban environment. The work reported in [6] considers a Decentralised Model Predictive Control (DMPC) that relies on optimization techniques to reduce spacing and speed errors in platooning. Although this work enhances the controller's performance, its performance gets hampered during safety-critical applications due to stale data usage and persistent packet losses.

Hence, there is a need for a metric that quantifies the freshness of the vehicle state information shared among PMs. In this regard, the Age of Information (AoI) is a metric that uses "data age" to characterize the freshness of the vehicle state information for control inputs [7]. Hence, we propose a decentralized Age of Information (AoI)-Aware CACC, which considers the practical issues of wireless communication in the platooning application. The key contributions of this work are as follows, **1.** A motivational analysis of the network effect on platooning in an urban scenario has been performed. **2.** The basic outline of a control theoretic solution method has been discussed. **3.** The proposed AoI-aware control solution has been evaluated through simulation

*This work has been done in the High-Performance Real-Time Computing (HiPRC) Lab of Computer Science and Engineering department of Indian Institute of Technology, Kharagpur. We acknowledge the generous grants received from "IHUB NTIHAC Foundation - IIT Kanpur" and "Meity Grant No. AAA.22/8/2021-CSRD-Meity" for partially supporting this work.

for an urban scenario. The rest of this paper is organized as follows. In section II, we explain in detail our system and obstacle model. In section III, we discuss our motivating example and problem formulation. Section IV presents our proposed solution methodology for the AoI-aware CACC controller design. In Section V, we present the experimental results while in Section VI we conclude with future work.

2 System and Obstacle Model

System Model: The system model consists of an n vehicle platoon $\{V_0, V_1, ..., V_{n-1}\}$, where the vehicle V_i broadcasts a beacon message containing its state information, i.e., position, speed, and acceleration values, at every k^{th} discrete time instance. Vehicle V_0 is the PL. We have modeled the discrete-time state-space model of the i^{th} vehicle with respect to a sampling time T_s as $x_i[k+1] = Ax_i[k] + Bu_i[k]$, where the state vector is denoted by $x_i[k] = [s_i[k]\ v_i[k]\ a_i[k]]^T$ and the control input is denoted by $u_i[k]$. The parameters $s_i[k]$, $v_i[k]$ and $a_i[k]$ are position, velocity and acceleration values of the i^{th} vehicle at the k^{th} sampling instance. The system state transition matrices are $A = \begin{bmatrix} 1 & T_s & \frac{1}{2}T_s^2 \\ 0 & 1 & T_s \\ 0 & 0 & 1-\frac{T_s}{\tau} \end{bmatrix}$ and $B = [0\ \ 0\ \ \frac{T_s}{\tau}]^T$, where τ is the inertial delay of longitudinal vehicular dynamics.

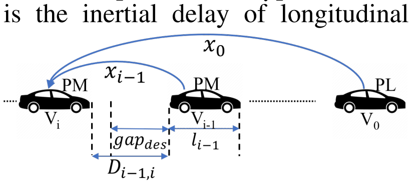


Figure 1: PLF topology

Platoon topology defines the way in which a platoon vehicle uses the state information received from other platoon vehicles to maintain close form and coordination. Our platoon follows the *Predecessor Leader Following (PLF)* topology, as depicted in Fig. 1, where the i^{th} vehicle computes $u_i[k]$ by using the state information received from the leader vehicle and predecessor $(i-1)^{th}$ vehicle. The control input $u_i[k]$ for the i^{th} vehicle's plant is computed using the discretized CACC rule [8] given as,

$$u_i[k] = \alpha_1 a_{i-1}[k] + \alpha_2 a_0[k] + \alpha_3(v_i[k] - v_{i-1}[k]) + \alpha_4(v_i[k] - v_0[k]) + \alpha_5(s_i[k] - s_{i-1}[k] + l_{i-1} + gap_{des}) \quad (1)$$

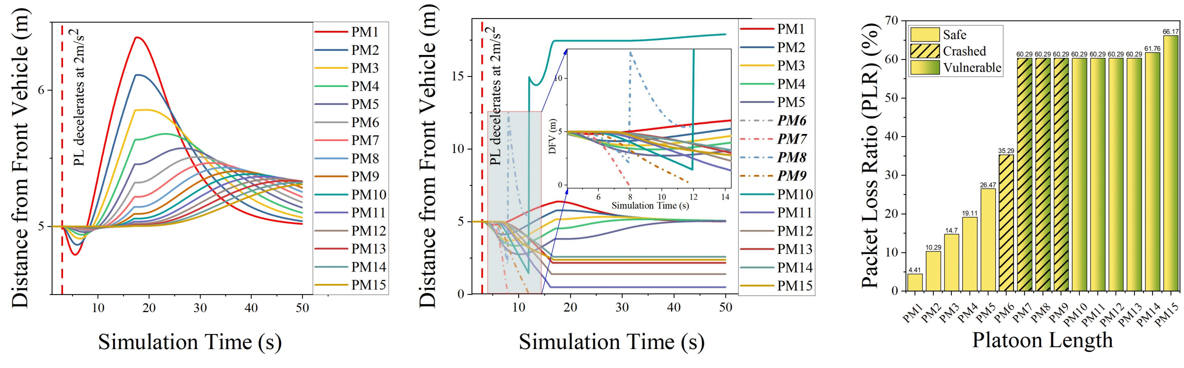
Here, the state information ($s_{i-1}[k]$, $v_{i-1}[k]$ and $a_{i-1}[k]$) received by the i^{th} vehicle from the preceding $(i-1)^{th}$ vehicle is used to determine $u_i[k]$, as shown in Fig. 1. The parameters l_{i-1} and gap_{des} are the length of the $(i-1)^{th}$ vehicle and the desired inter-vehicle gap respectively. The α_i parameters in the discrete CACC equation are $\alpha_1 = 1 - C_1$, $\alpha_2 = C_1$, $\alpha_5 = -\omega_n^2$, $\alpha_3 = -(2\xi - C_1(\xi + \sqrt{\xi^2 - 1}))$, $\alpha_4 = -C_1(\xi + \sqrt{\xi^2 - 1})$. Here, C_1 is the weighing factor between the PL and the preceding vehicle accelerations, ξ is the damping ratio and the ω_n is the bandwidth of the CACC [8].

Controller algorithms for platooning must ensure the fundamental property of string stability, which states that errors due to disturbances, such as sudden braking, occurring at the platoon head must be dampened (not amplified) towards the platoon tail. Let the spacing error between vehicle V_i and its predecessor V_{i-1} be δ_i, it is calculated as $\delta_i = gap_{des} - D_{i-1,i}$, where $D_{i-1,i}$ is the actual DFV of V_i (refer Fig. 1). Let $H(s) = \frac{\delta_i}{\delta_{i-1}}$ be the transfer function that relates the spacing errors between consecutive PMs. A platoon is said to be string-stable if $||H(s)||_\infty \leq 1$ and $h(t) > 0\ \forall t \geq 0$ [9]. Here, $h(t)$ is the Laplace inverse of $H(s)$. The attenuation in errors towards the tail is ensured by the condition on $H(s)$ while the condition on $h(t)$ ensures that the errors have the same sign. The PLF topology-based CACC control algorithm works towards maintaining string stability under *constant spacing* policy, i.e., the controller ensures that the inter-vehicle spacing is fixed regardless of the cruising speed. However, in a practical scenario, the string stability is affected by imperfections in the control input, which in turn affects the platoon performance. The platoon performance is determined by the deviation of δ_i from its optimal value which is zero.

Obstacle Model: The wireless transmissions involved in platoon communication encounter path loss which is the attenuation of signal power. This signal attenuation is characterized by path loss models. The path loss can be represented by the path loss exponent α, whose value ranges from 2 to 4. In our work, we incorporate a free space path loss model with a path loss coefficient $\alpha = 2$ [10]. The *obstacle shadowing* due to each building that obstructs the LOS communication between the transmitter and receiver is modeled as $L_{obs}(dB) = \beta n + \gamma d_m$ [10]. L_{obs} depends on the number of times n the building's boundary is intersected by the LOS communication path and the total length d_m of the building's intersection. The calibration factor β, given in *dB/wall*, represents the signal attenuation due to the exterior wall of a building, and the factor γ, given in *dB/m*, roughly approximates the internal structure of a building. Due to the path loss and the obstacle shadowing, the overall received signal power at the receiving vehicle is obtained as $P_{Rx}(dB) = P_{Tx}(dB) + G_{Rx}(dB) + G_{Tx}(dB) - PL(dB) - \sum L_{obs}(dB)$ [10]. Here, P_{Rx} and P_{Tx} are the received signal power and the transmitted signal power, while G_{Tx} and G_{Tx} are the antenna gains of the transmitting vehicle and the receiving vehicle. The data transmitted by the sender vehicle is successfully received by the receiver vehicle if $P_{Rx}(dB) \geq P_{min}(dB)$, where P_{min} is the minimum signal power required for successful data reception. Severe attenuation in the received signal power due to buildings, especially in a dense urban environment, causes the $P_{Rx}(dB) < P_{min}(dB)$, which leads to unsuccessful data reception or packet drops.

3 Motivation & Problem Formulation

Motivating Example: We consider a preliminary simulation scenario that involves a comparative study of the platoon's performance when the PL decelerates at 2 m/s^2 around an intersection (a) having LOS communication with the PL and (b) having Non-Line of Sight (NLOS) communication with PL due to obstruction by a building at the corner as shown in Fig. 3 for a platoon length of $n = 16$ vehicles. Initial platoon velocity is $27.77 m/s^2$. The system parameter values are inertial delay $\tau = 0.5s$, desired gap $gap_{des} = 5m$, vehicle length $l_{i-1} = 5m$ and sampling time $T_s = 0.1s$. The obstacle shadowing model used in our simulations have $\beta = 9\ dB/wall$ and $\gamma = 0.4\ dB/m$ [10]. Both in Fig. 3 (a) and (b), the solid *blue lines* indicate successful packet reception and the *red lines* indicate dropped packets due to shadowing during the PL

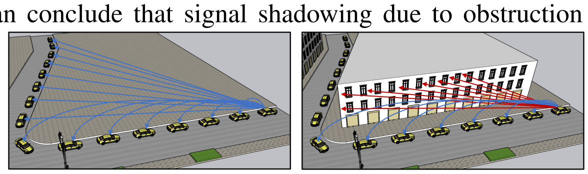


(a) (b) (c)

Figure 2: Comparison of DFV among platoon members when the leader decelerates at 2 m/s^2 under (a) LOS communication with PL, (b) NLOS communication with PL, and (c) the packet loss encountered by each PM on PL broadcast under NLOS communication

broadcast. Fig. 2(a) shows the Distance from the Front Vehicle (DFV) profile of PMs under LOS communication in an unobstructed scenario. We can observe a decrease in the DFV among PMs closer to the platoon head due to PL deceleration, and this effect dampens as we move toward the tail of the platoon. The LOS communication path with the PL enables the successful reception of messages with PL states by all the PMs in every instance. The successful reception of time-critical PL messages helps the entire platoon to decelerate effectively and gradually come to a halt. On the other hand, from the obstruction scenario shown in Fig. 2(b), we can observe that the PMs (PM 6, 7, 8, and 9) undergo collisions, indicated by *dotted lines* (DFV profiles of rest of the PMs are plotted with *solid lines*). As the PL decelerates, the DFV for PM7 and PM9 encounter an under-shoot leading to collisions with their front vehicles, PM6, and PM8, respectively. The sudden DFV under-shoot among PMs 7 and 9 is due to their high Packet Loss Ratio (PLR), shown in Fig. 2(c). The PLR in figure 2(c) represents the ratio of the number of lost PL packets by a PM to the total number of sent packets by PL. We can observe an abrupt increase in PLR among PMs labeled as *vulnerable* in Fig. 2(c), and PMs 7 and 9 are present in this group. As discussed earlier, the effect of PL deceleration is more prominent at the platoon head than towards the platoon tail. As the PM6 starts decelerating, it causes the first vulnerable vehicle PM7 to collide. The vehicles that collide get removed from the simulation. Therefore, a brief overshoot in the DFV can be observed in the case of PM8. However, the PM8's vehicle controller tries to bridge its DFV with its next predecessor vehicle, which is PM5 here. However, the PM9's DFV value is constantly decreasing and this eventually leads to a collision with its front vehicle, PM8. The vehicles PM 6, 7, 8, and 9 are labeled as the *crashed* in Fig. 2(c). The remaining platoon vehicles are labeled as *safe* in Fig. 2(c).

Problem Formulation: Based on the simulation results, we can conclude that signal shadowing due to obstruction by a building can severely cause platoon instability due to PL packet loss in a PLF topology. The CACC present in each PM is heavily dependent on the time-critical fresh PL data packet during PL deceleration. The CACCs in the PMs must be aware of the PL packet losses. To this end, we utilize the idea of measuring the *Age of Information*(AoI) in order to figure out whether the data packets received from the PL are fresh or not. The AoI is evaluated by measuring the time elapsed since the last data packet was received. We propose a novel CACC that is aware of the drop in the PL packet received based on the AoI of the received data. In the next section, we describe the proposed AoI-aware control scheme.



(a) (b)

Figure 3: PMs around an intersection having (a) LOS communication with the PL due to no obstruction and (b) NLOS communication with PL due to obstruction by a building at the corner

4 Solution Methodology

The proposed AoI-aware CACC control strategy addresses the control problem that arises due to the NLOS communication with PL in an urban platooning scenario. Fig 4 gives an overview of the proposed control solution that runs in each i^{th} vehicle V_i in the platoon. At each k^{th} time instance V_i receives states of every j^{th} vehicle in the platoon

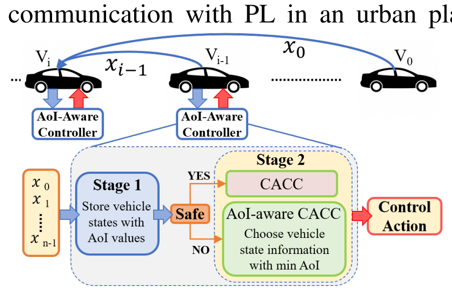


Figure 4: Overview of the proposed AoI-aware CACC scheme

i.e. $x_j = [s_j\ v_j\ a_j]^T$ $(j \neq i, j \in [0, n-1])$ (omitting the time instance-based indexing used in Sec. 2). These are used as input to our control solution (blue arrows in Fig. 4). It outputs an AoI-aware control action for V_i at every k^{th} time instance, i.e. $u_i[k]$ (red arrows in Fig. 4). In the first stage of the control strategy, it computes the AoIs of the data received from every j^{th} vehicle (V_j), i.e. AoI_j. If the data from V_j is received at k_0^{th} sampling iteration then at k^{th} sampling iteration, $AoI_j = (k - k_0)T_s$. Therefore, if the data from $V_{j'}$ is received at the current time instance $AoI_{j'}$ is reset to 0. On the other hand, for any j^{th} vehicle that does not broadcast data packets at the current sampling iteration the AoI_j is incremented with the sampling period T_S i.e. $AoI_j = AoI_j + Ts$. In the second stage, the AoI-aware CACC is applied depending on the inter-vehicle spacing error δ_i (see Sec. 2). If δ_i is equal to its optimal value i.e., $\delta_i = 0$, then the platoon is considered safe. In such cases, the stored PL state information x_0 is used for control calculation (see Eq. 1). Incorrect control computation due to the usage of stale PL data can cause the δ_i to decrease below the optimal value. In such a situation instead of using the PL state data, the proposed control strategy considers the state information of any vehicle other than the predecessor vehicle, that registers a minimum AoI among vehicles $\{V_1, \ldots, V_{i-2}\}$, i.e. $u_i[k] = \alpha_1 a_{i-1}[k] + \alpha_2 a_{j_{min}}[k] + \alpha_3(v_i[k] - v_{i-1}[k]) + \alpha_4(v_i[k] - v_{j_{min}}[k]) + \alpha_5(s_i[k] - s_{i-1}[k] + l_{i-1}[k] + gap_{des})$ s.t. $j_{min} = \arg\min_{\forall j \in [1, i-2]} AoI_j$. This ensures that whenever an unsafe situation is likely to arise, the control action of V_i at that sampling iteration is calculated using the freshest state information that is received from a PM other than the predecessor. Deriving a stability guarantee while using switched control law is something we plan as future work.

5 Experimental Results

In order to evaluate the performance of the proposed AoI-aware CACC, we simulate a platoon of length $n = 16$ with $gap_{des} = 5m$ cruising at $27.77 m/s$ speed in a realistic dense urban scenario as shown in Fig. 5.

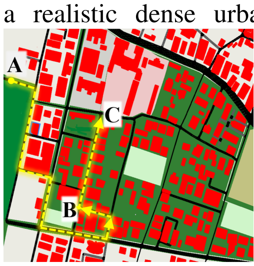


Figure 5: Dense urban area from OpenStreetMap

The platoon cruise mode starts at point A, and the deceleration of PL starts from point B onwards. The route ends at point C. We conduct these simulations in PLEXE [8] and SUMO road traffic simulator. The dense urban scenario is based on real-world geo-data imported from the OpenStreetMap (OSM) for the city of Kolkata, India, as shown in Fig 5. We have imported the outlines of the building and street information into the road traffic simulator SUMO. The simulation is conducted for $100s$ in a Region Of Interest (ROI) of $3km^2$, as illustrated in Fig 5. We incorporate the same set of system and obstacle shadowing parameter values as that used in Sec. 3.

We now observe the effect due to PL deceleration at a rate of $2\ m/s^2$ from the simulation time of 50s onwards. In Fig. 6(a) the *dotted lines (PM 7, 8, 9, and 10)* represent the vehicles that undergo collision due to packet losses encountered by the PMs in receiving time-critical PL state information. Due to such packet losses, their DFV value decreases to zero leading to collisions. PMs towards the tail of the platoon (*PMs 12, 13, 14, and 15*) have non-converging spacing errors δ_is which indicate that the platoon string stability is not maintained. On the other hand, in Fig. 6(b), the proposed AoI-aware CACC can keep all vehicles not only safe from collision but also reduce spacing errors. The improvement in the DFV values for the proposed method is mainly due to the fresh data updates sent to the controller based on the AoI metric as discussed in Sec 4. Also, it takes roughly 35s for the vehicles to converge towards a zero spacing error δ_i and thus ensure a stable platoon string.

6 Conclusion and Future Work

We have demonstrated the efficacy of our proposed strategy of using AoI as the metric to feed the freshest data into

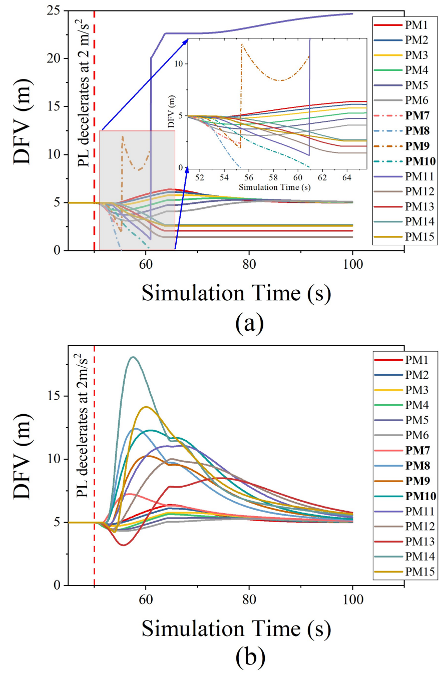


Figure 6: Comparison of DFV among PMs during PL deceleration at $2\text{m}/s^2$, for (a) CACC, and (b) AoI-aware CACC-based platoon of length 16

the controller during safety-critical applications under severe packet loss conditions. Our proposed technique is simple, effective, and compatible with the existing controller scheme. In the future, we plan to extend the platoon control mechanism described here to design a generic platooning algorithm that can handle complex scenarios in terms of increased channel load conditions due to traffic congestion. We intend to evaluate it under various urban network scenarios and derive control theoretic performance as well as stability guarantees while budgeting network resources.

7 References

[1] Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications Amendment 6: Wireless Access in Vehicular Environments. *IEEE Std 802.11p-2010*, 2010.

[2] A. Khalifa et al. Vehicles platooning in urban environment: Consensus-based longitudinal control with limited communications capabilities. In *ICARCV*. IEEE, 2018.

[3] C. Sommer et al. How shadowing hurts vehicular communications and how dynamic beaconing can help. In *IEEE INFCOM*, 2013.

[4] C. Lei et al. Impact of packet loss on CACC string stability performance. In *ITST*, 2011.

[5] M. Kim et al. Age of Information Based Beacon Transmission for Reducing Status Update Delay in Platooning. *IEEE TVT*, 2022.

[6] A. Ibrahim et al. Multi-layer multi-rate model predictive control for vehicle platooning under IEEE 802.11p. *Transportation Research Part C: Emerging Technologies*, 2021.

[7] Z. Zhou et al. Maintaining Real-Time Data Freshness in Wireless Powered Communication Networks. In *RTSS*, 2020.

[8] M. Segata et al. Plexe: A platooning extension for Veins. In *IEEE VNC*, 2014.

[9] V. Lesch et al. An Overview on Approaches for Coordination of Platoons. *IEEE T-ITS*, 2022.

[10] C. Sommer et al. A computationally inexpensive empirical model of IEEE 802.11p radio shadowing in urban environments. In *WONS*, 2011.