Adaptive Vehicle Platooning with Joint Network-Traffic Approach

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***Abstract*—The Intelligent Transportation System has become one of the most globally researched topics, with Connected and Autonomous Vehicles(CAV) at its core. The CAV applications can be improved by the study of vehicle platooning immune to real-time traffic and vehicular network losses. In this work, we explore the need to integrate the Network model and Platooning system model for highway environments. The proposed platoon model is designed to be adaptive in length, providing the node vehicles to merge and exit. This overcomes the assumption that all the platoon nodes should have a common source and destination. The challenges of the existing platoon model, such as relay selection, acceleration threshold, are addressed for highly modular platoon design. The presented algorithm for merge and exit events optimizes the trade-off between network parameters such as communication range and vehicle dynamic parameters such as velocity and acceleration threshold. It considers the network bounds like SINR and link stability and vehicle trajectory parameters like the duration of the vehicle in the platoon. This optimizes the traffic throughput while maintaining stability using the PID controller. The work tries to increase the vehicle inclusion time in the platoon while preserving the overall traffic throughput.**

***Index Terms*—Adaptive Platoon, V2V channel, Highway, Stability, Vehicle Dynamics, PID**

I. Introduction

The Intelligent Transportation System (ITS) improves road efficiency by solving problems such as traffic congestion, exhaust emissions leading to environmental pollution, route guidance to name a few [1]. Platooning provides an effective solution, in which autonomous vehicles in the same lane are grouped as single unit, move at the same speed and maintain a small constant headway distance from preceding vehicles [2]. Platooning of connected and autonomous vehicles (CAV) is promising due to its potential to benefit the road traffic significantly, e.g., enhancing highway safety, improving traffic capacity and smoothness, and reducing fuel consumption [3]. To reap the full benefits of platooning, one must ensure that each vehicle in the platoon, there must exist a seamless communication between the platoon nodes.

Autonomous platooning is comprised of two main subsystems Vehicular Network model and Adaptive Cruise Control. Vehicular connectivity have to solve challenges such as time delay, packet loss to maintain the link connectivity. Our previous work [4] on the effect of dynamic environment and relative motion of the transreceivers on the SINR has been extended for vehicular network environment. The paper elaborates the platooning architecture and proposes an algorithm for adaptive source and destination of its nodes which can be applied beyond spatio-temporal constraints. While organizing the vehicular geometry formations, it also considers the network architecture reducing the SINR in inter platoon communication. The simulations demonstrate performance evaluation of the proposed adaptive platoon model.

In literature, there has been a lot of work in vehicle platooning and its adaptive nature [5] - [9]. In [5] the platoon is adaptive to node properties of homogeneity, [6] study a controller for adaptive platoon size ,in [7], the platoon velocity and control is adaptive because of the fuzzy controller. In the above works, the purpose of *adaptivity* is in terms cruise control or the platoon environment. However, in the existing work, the proposed overcomes the a very common assumption that all the nodes in the platoon have common source and destination. Although [8] discusses a merging scenario for single vehicle and a platoon respectively, however it assumes an existing communication link and the effects on stability margins of the platoon. In the recent work [9] elaborates on merging of a target platoon with using stable Distributed Model Predictive Control (DPMC) controller, it assumes the destination and traffic throughput criteria for the merging scenario. The proposed algorithm is simulated for highway environments which considers the platoon geometry, effects of non-linear acceleration on the stability and vehicle spacing and effects of communication range on vehicle merging probability with traffic safety and steady flow.

II. System Model

Inspired by [3], the proposed platoon system model is divided in four main subsystems of a) Vehicle Dynamics(VD) b) Information Flow Topology (IFT) c) Inter vehicle spacing (IVS) and d) Controller. These subsystems analyse the data using Joint Network Traffic(JNT) approach which maintains the network Quality of Service(QoS) and platooning driving experience. Section III elaborates more the advantages of this approach. In our proposed work, the platoon is adaptive in terms of length and the flexibility in the source and destination of individual vehicles. As seen in the Fig. 1, the leader communicates with the followers as well as the non-platoon neighboring vehicles. This communication can either exist as

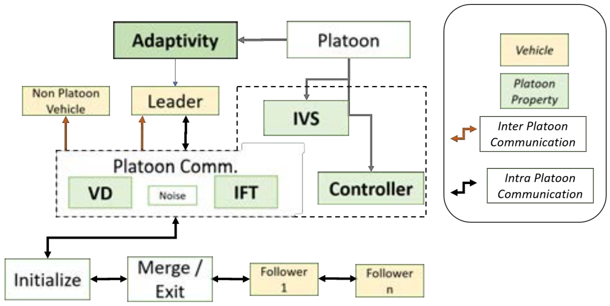

Fig. 1: Adaptive Platoon

bidirectional or unidirectional based on the subsystems and desired error margin spectrum availability trade off. The events which enable the flexibility of source and destination take place in two stages of Initialization and either merging of new vehicle in to the platoon, or an exit of an existing platoon member is implemented as per algorithm in section IV. If the vehicular network architecture consists of dense nodes, Rode Side Units and Bases tations, the SINR drops, degrading the QoS. To solve this issue by reducing the active links [10] has proposed a Predecessor-Follower(PF) architecture which has been implemented in this work. The PF reduces the interference of the active links, power requirements due to less range, more bandwidth availability for the complex protocols. The error margins of PF model such as increased delay and stability margin are considered while working on the platoon Controller [3].

A. Assumptions

The proposed architecture assumes V2V direct communication which enhances the system capacity, increases spectral efficiency and reduces latency. The leader has the capacity for Inter and Intra Platoon communication. The message frame can be divided based on the works of [2]. As per [11], CAV is aimed for a safe driving approach by using Constant Time Headway Policy (CTHP). However, CTHP increases the headway distance leading to reduced vehicle throughput. As the proposed work assumes highway environment, the Constant distance spacing policy is preferred. The stability margin proves that Inter vehicle Spacing (IVS) error is less than 0.2 m which maintains the driving safety. This can further be supported by increase in available spectrum and switching to bi-directional communication in the PF mode.

Although the platoon is assumed to be homogeneous, the leader has the ability of inter and intra-platoon communication with its destination as the last one. This will assume a constant leader of the platoon. The adaptivity is limited only to the followers. The goal of the adaptive algorithm is to optimize the vehicle inclusion time in the platoon with maximum flexibility in source and destination. It is assumed that the vehicle platooning advantages will result in increased vehicle throughput over the highway.

III. Joint Network Traffic Approach

A. JNT

The CAV have two main subsystems which need to work in coordination:1)Vehicular Network model and 2) Adaptive Cruise Control (ACC) [11]. ACC is primarily a control system that monitors inter vehicle spacing, velocity and acceleration. The Vehicular Networks can be classified as (Vehicle-to-vehicle) V2V or (Vehicle-to-infrastructure) V2I communications is responsible for exchange information related to autonomous vehicle and Infotainment services. Although these are two separate systems, their efficient interdependence is critical for Platooning systems. The VD and IVS is monitored by the Controller affect the IFT uplink and downlink connectivity of the network architecture. Joint Network Traffic Approach deals with both communication and control of a vehicle traffic.

B. Traffic Approach

The vehicle trajectory has a spatial dependence on neighboring conditions like road topology, meteorological conditions and traffic flow. For a suitable algorithm performance, these parameters are estimated for a better driving experience and increased vehicle throughput on the highway. Traffic forecasting is a process of analyzing traffic conditions on urban roads such as flow, speed, and density, mining traffic patterns, and predicting the trends of traffic on roads [12], [13], [14].

In [2], for multi-node network, the upper bound on on number of nodes is function of the average SNR. However, for adaptive platoons the motion of the nodes due to merge and exit needs to be considered in V2V communication model.

C. Network Approach

The Network Architecture defines the inter-platoon and intra-platoon communication. A strict node geometry in platoons undermines the network architecture. Thus equal importance shall be given to both the subsystems.

5G ultra-reliable low latency (URLLC) standards can be met by Millimeter Wave (mmWave) technology for autonomous vehicles. However, the mmWave signals suffer from high pathloss and interference, especially in the dynamic environments of AVs. One approach to solve this issue is by using multihop communication with RSU infrastructure [15] or neighboring vehicles [16] as intermediate relays. However, we proposed network approach aims to reduce the long range active links and the overhead of relay selection. Although this increase the time delay, the adaptive platoon structure would remain highly modular. The system would need no surplus time to restructure if the relay node decides to exit the platoon. Assume the network is represented by a set of vehicles $V_{p,n}$ which indicate the platoon id,p, and vehicle id, n=1 to N, respectively. Vehicle $V_{p,1}$ is the platoon leader. A communication link L [0,1] between $V_{p,m}$ and $V_{p,n}$ is based on the SINR threshold and availability of resources. The parameters for routing protocol can be seen in the works of [17]. The node will switch to next resource if the SINR for $N_{res} \geq SINR_{Th}$

$$SINR_{V1,V2,t}^{(V)} = \frac{P_{V1,V2}G_{V1,V2}}{\sigma_N^2 + \sum_{v_i} P_{V1,n}G_{V1,n}}, \forall v_i \in \mathcal{N} \quad (1)$$

From [18], where $P_{V1,V2}$ is average energy symbol, $g_{V1,V2}$ refers to the channel gain from vehicle V1 to V2, which follows a Rayleigh distribution.

IV. Adaptive Platoon System Model

A. VD

The Vehicle Dynamics are non-linear in real-time environments which may be result of internal factors (sudden throttle or brakes, engine and power train losses) or due to external factors (road typologies or meteorological conditions). The proposed system can be stable even in case of non-linear velocities and the error margin approaches to zero for any length. This has been elaborated further in the Controller in section IV D.

B. IFT

The Information Flow Topology defines the protocol and message structure. The existing adaptive platoon has to control two main communication links .

1) Controller IFT: The controller information flow is responsible to main basic platoon characteristics like Stability, IVS, Safety and better driving experience. The proposed algorithm requires only the position of the preceding vehicle. This information can be obtained merely by on board sensor and there is no overhead communication required by the IFT. However for better accuracy the IFT can send the position and velocity. The proposed simulation shows the effect of these parameters.

2) Adaptive IFT: It is designed to be high priority IFT channel where messages are sent during an event of merge or exit, and at regular intervals to update the leader and followers of the surrounding events

C. Adaptivity

τ is vehicle reaction time delay,which is joint sum of sensor reaction time, the data fusion and processing time and the transmission delay between two vehicles wand scales based on the length of platoon. The messages are sent every Δt. $T_{SD} = T_e T_a / T_a$ is the spectrum division of resources allocated by platoon leader for inter T_e and intra T_a platoon communication. The platoon controller has been inspired by the works of [11] [19] and [20] and modified for adaptive structure.

1) Initialisation: Initialise Platoon Id used in inter platoon communication, path is trajectory from source to destination used to maintain the common distance $d_m t$ during Adaptive Algorithm. - d_v, For IVS, safe headway distance, $hw = pos_{v1} - pos_{v2}$, $e_{v,i}$ is the error in target and current velocity for a given car at instant t. The ego(merging) vehicle will establish link with Platoon leader within range R. The range will affect the probability of the event as shown in Fig.2. Based on $pos, S, D, d_{seg}, d_{merge}$ the Leader sends the Acknowledgement along with d_{merge} as seen in the Algorithm. For the exit

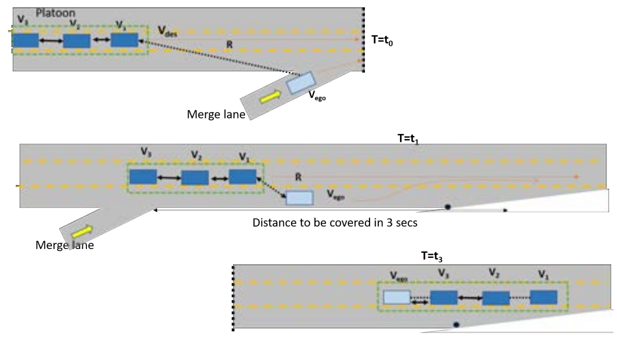

Fig. 2: Merging event of an Ego vehicle to an Adaptive Platoon

event, the communication between ego (exiting) vehicle takes place using Adaptive IFT channel, which follows bi-drectional PF topology

2) Merge: This is initiated by the an AV external to the platoon who wishes to merge. After the Initialization communication between Leader and the vehicle, the concerned vehicle merges the platoon preferable as the last node. After a successful merge, the platoon leader is updated with total length and follower ids. The objective is to reduce the d_{merge} to 0 and increase the merging probability of ego vehicle in the platoon. Before merging the vehicle can sense the environment, connected and unconnected vehicles by either Image Processing [21] or LIDAR [22]. This is fed to the vehicle mobility model to decide the trajectory. One of the important challenge is the short time duration, high velocity and non linear acceleration of vehicles and ego vehicles.

3) Exit: As the vehicle approaches it exit, The vehicle preceding the ego vehicle should decelerate to create a safe space. The ego vehicle needs to check the prospect lane for clear traffic before changing the lane. After successful exit, the platoon needs to be updated, the string stability should be adjusted by resetting the vehicle spacing.

The Ego vehicle is the node initiating the merge request external to platoon, or one of the follower initiating an exit request from the Leader. Frequent merges can reduce the traffic throughput due to constant deceleration and switching periods. Thus the total distance between source S and destination D, d_D is divided into multiple segments of length d_{seg}. Higher d_D/d_{seg} will increase platoon inclusion time while lower values will reduce the Adaptivity delay given by $t_{avg} - t_{total}$. This d_{seg} is predefined based on traffic patterns and probabilities of exit and merge traffics which is currently out of scope for this paper and should be greater than 1.

The vehicle can merge or exit the platoon at safe velocity v_s within the switching time t_{sw}. v is the instantaneous velocity of the platoon and a_m is the maximum acceleration or deceleration the platoon can sustain while maintaining the stability. This transition between two velocities(v and v_s) requires time t_{tr}. Thus the total time required by the adaptivity algorithm is t_{adp} and the time required to cover one segment is t_{total}. The adaptivity in source and destination comes at the cost of increased delay t_δ in vehicle traffic throughput,

Algorithm 1 IFT Model for Adaptive Platoons

Initialise $v_s, a_m, t_{sw}, P_{id}, S, D, d_D, d_{seg}, T_{ratio}, R$
while *Initialisation* **do**
  if *Merge/Exit (M/E) Request* **then**
    $Leader \leftarrow Ego_m(v, pos, Dest)$
    $Ego_m \leftarrow Leader(Ack, v_s, d_{(M/E)}, V_{id})$
    $Platoon \leftarrow Leader((M/E)cmd, d_{(M/E)})$
    $d_{merge} = f(R, v_p, acc_p, acc_{ego})$
  end
end
while *Merge or Exit* **do**
  if $v - v_s < a_m$ **then**
    $a = v - v_s$
  end
  $t_{tr} = abs(v_s - v)/a$
  $d_{sw} = v_s * t_{sw}$
  $t_{adp} = t_{tr} + t_{sw} + t_{tr}$
end

D. Controller

The following is a controller design for a specific platoon, hence the in ego node $P_{p,n,t}$, p=1. The position and velocity of vehicle v at time t is given by $pos_{n,t}$, $v_{n,t}$ where n=1, is the leader node, N is the platoon length. $e_v(n,t)$ and $e_p(n,t)$ is the velocity and position error between the desired and actual values. Since the IFT for platoon stability considers only the positions, where hw is the constant headway distance between two vehicles which has been set at 3 m and 10 m for the two test cases and Gaussian distributed noise N with variance 0.01 for every PF transmission.

$$e(n,t) = pos_{n,t} - pos_{n-1,t-\Delta t} - hw + N \tag{2}$$

$$K_{cor}(n,t) = k_p e_v + k_i \sum_{i=0}^{n} e + k_d \frac{e_{t-1} - e_t}{\Delta t} \tag{3}$$

where K_{cor} is the update correction, kp, kd, ki are the gains. After PID tuning the values these constants are 0.5,0.0045 and 0.45 respectively. The instantaneous position is used to calculate the required velocity and acceleration.

$$pos_{n,t} = pos_{n-1,t} + K_{cor} \tag{4}$$

$$v_{n,t} = pos_{n,t-1} - pos_{n,t-1}/\Delta t \tag{5}$$

V. Performance Evaluation for Adaptivity

A. Effect of VD and Range

Consider an event where an ego vehicle with acceleration a_e has communicated with platoon with max acceleration a_p over the range R. The goal of the adaptive algorithm is to reduce the merging distance $d_{merge} = pos_e - pos_p$ to increase the platoon inclusion time of the vehicle while maintaining safe VD of the platoon and ego vehicle. This is indicated by

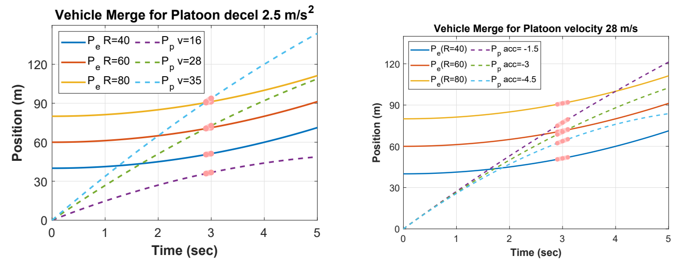

Fig. 3: Relative positions of Ego and Platoon vehicles for different VD modes. a) Varying v and R. b) Varying a and R

highlighted red points with minimum d_merge Fig. **??**a shows the variation in merge time for platoon safe deceleration at $a_p = -2.5m/s^2$ with R and $a_e = 2.5m/s^2$. As seen in Fig 2, the merge distance is covered in 3 secs. For a longer range R, the platoon gets enough time to decelerate under safe headway distance between intra platoon vehicles at the cost of SINR and energy consumption. d_merge also reduces with lower platoon velocity $P_v$at the cost of reduced traffic throughput. A detailed In [21], the centralised architecture for lane merge scenario has been elaborated.

B. Effect of non linear VD on platoon IVS

For a platoon of length 15, with variable acceleration a of leader 0,1,0 and resulting rise in velocity from 10 m/s to 30 m/s over a period of 20 seconds. The platoon followers starts with 0 initial velocity, constant headway distance, unidirectional communication with minimum links, reduced data in IFT since it requires only the positions. Although these advantages come at the cost ofinitial stabilizing period with maximum space error of 1.2 m, for a constant headway distance of 10 m. After the controller reaches the stability, the non linear VD results in spacing error of less than 0.1 m, within safety margin, increases traffic throughput ... The headway distance can further be reduced to improve the traffic throughput.

Similar error reduction was also implemented by [23]. Using the PID controller, the error reduces over time t by setting correction constants kp,ki,kd. For the given simulation, the values of kp,ki and kd are 0.8,0.1 and 0.05 in eq.(2).

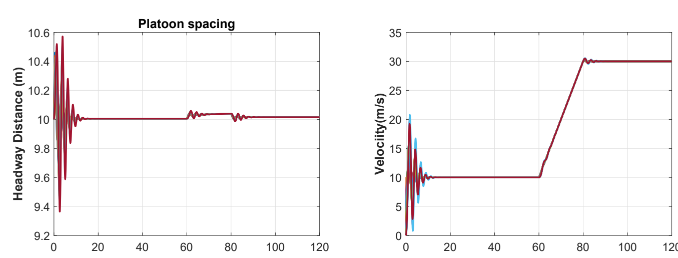

Fig. 4: Stability for a platoon of 5 vehicles when subjected to non linear velocity. a) Variation in headway distance for a constant value of 10m b) Variation in velocity after $a = 1m/s^2$ from 60 s to 80 s.

In terms of vehicle kinematics, position, velocity and acceleration can be important parameters to describe the trajectory. For the platoon using PF strategy, the proposed cooperative awareness can be maintained effectively merely using the position sensor data. The transmission delay introduces headway error ripples across the platoon which gradually reduces to zero as seen in Fig. 4. Although this stability margin increases with the length of platoon, the strong effects are limited only during initialisation stage. The effect of this stable error margin on traffic flow is used as a threshold in deciding the length of the platoon and acceleration threshold a_m. The velocities for 5 vehicles in platoon is calculated using Eq.3-5.

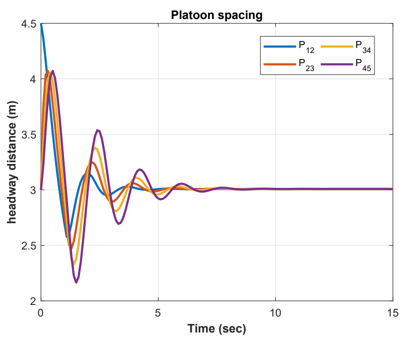

Fig. 5: Inter Vehicle Platoon spacing

The above Fig. 5 the shows the headway distance of vehicles 1 to 5, based on their positions, $pos_{n,i} - pos_{n,i+1}$. The expected headway distance is assumed to be 3 meters. As the length of the platoon increases, the transmission delay causes a butterfly effect to scale the error. However the error was approximately same for 20 vehicles when compared with the [2].

C. Time Segmentation for Adaptive Algorithm

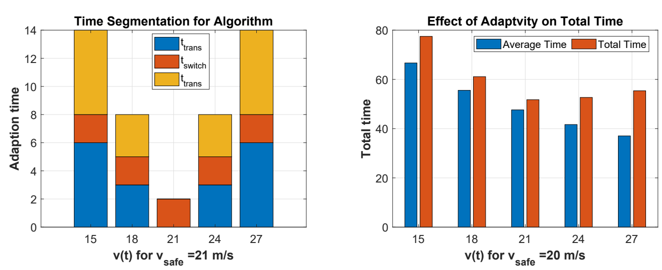

Fig. 6: Comparison of t_{tr} and t_{sw} time segments in the Algorithm

In the event of merge or exit, the Platoon travelling at velocity $v(t)$ has to reduce its velocity to v_s for the traffic safety. Based on the Adaptive Algorithm from section IV, the Fig. 6, compares the delay introduced in the total time required for the Platoon while moving at constant velocity v_{avg} without the algorithm, and while including a merge or exit event during the given segment d_{seg} In Fig. 6a, for an acceleration of $1m/s^2$, $v_s = 21m/s$ and constant $t_{sw} = 2s$. It is assumed that the neighbouring lane is free and the vehicle can switch the lane as soon as $v = v_s$ within $t_{sw}s$. The time required for transition between the velocities and actual merging or exit time called as t_{tr}. The best case scenario is when $v = v_s$ and $t_{tr} = 0$, however, for maximum traffic throughput, $v > v_s$. In Fig. 6b, it can be seen that over a $d_{seg} = 1000m$, for $v_s = 20m/s$ and $a = 1m/s^2$, it is obvious that with the increase in platoon velocity the total or the average time reduces gradually. However it is worth noting that the algorithm introduces a minimum delay when $v = v_s$ of approximately 3 s without severely hampering the traffic throughput. For the extreme velocities, t_{tr} increases due to acceleration.

The proposed approach has many properties, concluded as follows: In real world traffic flow, unforeseen events can go beyond road junctions and lane merging have to addressed with complex network and vehicular traffic model which can be further researched in future.

VI. Conclusion

In this paper, a system model for platooning under the Joint Network Traffic model has been discussed. The platoon stability is preserved when the Vehicle Dynamics consider a nonlinear model with variable acceleration. The Information Flow Transfer assumes minimum bandwidth for the controller, and the system performs based on the positions of the preceding vehicles using PF topology and constant headway policy. The cooperative platooning is implemented based on V2V underlay communication with no requirement of Road sided units and minimum long-range active links for the followers. Further, we introduce an adaptive source destination for different nodes in the platoon to overcome the common assumption. While presenting this, we propose an Adaptive Algorithm that presents different merge and exit scenarios along the highway. The performance evaluation based on communication range, Vehicle Dynamics such as acceleration, instantaneous velocity, permitted safe velocity, and controller stability are simulated using Matlab. The PID-based controller shows the stability margin safe enough for Constant Headway Distance Policy. The merge events indicate that neighboring nodes can be included in the platoon. The proposed Adaptive Algorithm shows that inclusion time in platoons and flexibility in their source and destination can be implemented with marginal effects on the overall traffic throughput.

VII. ACKNOWLEDGMENT

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