Journal Paper

Optimal Rate-Adaptive Data Dissemination in Vehicular Platoons

Early Access Article

Kai Li*
Wei Ni
Eduardo Tovar*
Mohsen Guizani

*CISTER Research Centre

CISTER-TR-190909

2019/09/18

Optimal Rate-Adaptive Data Dissemination in Vehicular Platoons

Kai Li*, Wei Ni, Eduardo Tovar*, Mohsen Guizani

*CISTER Research Centre

Polytechnic Institute of Porto (ISEP P.Porto)

Rua Dr. António Bernardino de Almeida, 431

4200-072 Porto

Portugal

Tel.: +351.22.8340509, Fax: +351.22.8321159

E-mail: kaili@isep.ipp.pt, Wei.Ni@data61.csiro.au, emt@isep.ipp.pt

https://www.cister-labs.pt

Abstract

In intelligent transportation systems, wireless connected vehicles moving in platoons can improve roads' throughput. For managing driving status of the platoon, a lead vehicle transmits driving information to following autonomous vehicles by using multi-hop data dissemination. We study a novel data dissemination protocol which investigates a chain-based transmit rate control to reduce data dissemination latency. The optimal resource allocation algorithm is formulated to minimize the total dissemination latency of the platoon under guaranteed bit error rates, and can be judiciously reformulated and solved using standard optimization techniques. A novel dynamic programming algorithm is presented to solve the platooning resource allocation optimization, which uses backward induction to significantly reduce the resource allocation complexity. In addition, we interpret the vehicular platoon as one-dimensional Markov chain, and derive a closed form of dissemination latency. Simulations are carried out to evaluate the performance of the proposed dynamic programming algorithm. The numerical results show that our algorithm achieves optimal solutions with cutting off the complexity by orders of magnitude, while improving dissemination rate in the vehicular platoon.

Optimal Rate-Adaptive Data Dissemination in Vehicular Platoons

Kai Li, *Member, IEEE*, Wei Ni, *Senior Member, IEEE*, Eduardo Tovar, and Mohsen Guizani, *Fellow, IEEE*

***Abstract*— In intelligent transportation systems, wireless connected vehicles moving in platoons can improve roads' throughput. For managing driving status of the platoon, a lead vehicle transmits driving information to following autonomous vehicles by using multi-hop data dissemination. We study a novel data dissemination protocol which investigates a chain-based transmit rate control to reduce data dissemination latency. The optimal resource allocation algorithm is formulated to minimize the total dissemination latency of the platoon under guaranteed bit error rates, and can be judiciously reformulated and solved using standard optimization techniques. A novel dynamic programming algorithm is presented to solve the platooning resource allocation optimization, which uses backward induction to significantly reduce the resource allocation complexity. In addition, we interpret the vehicular platoon as one-dimensional Markov chain, and derive a closed form of dissemination latency. Simulations are carried out to evaluate the performance of the proposed dynamic programming algorithm. The numerical results show that our algorithm achieves optimal solutions with cutting off the complexity by orders of magnitude, while improving dissemination rate in the vehicular platoon.**

***Index Terms*— Vehicular platoon, data dissemination, latency, transmit rate, dynamic programming.**

I. Introduction

IN THIS section, we introduce research background on forming vehicular platoons, and motivation of fast data dissemination in the vehicular platoon.

A. Vehicular Platoons

Vehicular communication is expected to be an important facet of future intelligent transportation systems. Technological advances in the vehicle-to-vehicle communication have enabled the formation of vehicular platoons, where a lead vehicle can be driven automatically or manually, and a number of autonomous vehicles follow the lead vehicle's driving pattern (e.g., Safe Road Trains for the Environment project [1], and SafeCop project [2]). For the sake of driving safety, the autonomous following vehicle is required to keep a small distance to the preceding vehicle [3]–[5]. Particularly, Land Transport Authority in Singapore plans to build dedicated lanes on highway for the vehicular platoon to enhance traffic management and roads' throughput [6]. "The Automated Highway System" is developed by The US Department of Transportation to enable a platoon of vehicles driving on the highway [7].

Figure 1 presents formation of a vehicular platoon, where the lead vehicle periodically disseminates the cruise control messages to the following autonomous vehicles. The lead vehicle decides driving status of the platoon, e.g., acceleration or deceleration, moving directions, and driving speed, which can warn the following vehicles about emergencies on the road, such as car accidents, obstacles, or traffic violations [8], [9]. The cruise control packets that contain information on its driving speed and position are disseminated by the lead vehicle who manages the platoon to adjust the driving status of the following autonomous vehicles. The following vehicle in the platoon receives the data packets from the preceding vehicle and forwards them to the next-hop vehicle. By doing this, the cruise control packets from the lead vehicle are disseminated to all the vehicles. Note that the critical control messages need to be delivered to each of the following vehicles, with confirmed reception of the messages. In terms of inter-vehicle communication, the vehicle in the platoon disseminates the cruise control packets to the adjacent following vehicle. This is because one-hop broadcasts provide high reliability to the vehicle-to-vehicle transmission, which does not interfere other platooning vehicles' communication [10], [11].

Real-time data dissemination in the vehicular platoon is necessary to ensure driving safety of the vehicles. A number of considerations make the fast data dissemination in vehicular platoons non-trivial. First, the cruise control information is required to be delivered to every vehicle in the platoon, and data reception at each following vehicle depends on the reception of its preceding vehicle. However, due to the mobility of the vehicles, time-varying wireless fading channels cause packet loss of the disseminated cruise control messages. The packet loss at the following vehicle can greatly prolong the data dissemination latency in vehicular platoons since the dropped packets need to be retransmitted by the preceding vehicle. Additionally, this packet loss can result

Manuscript received July 4, 2017; revised March 26, 2018, November 29, 2018, and July 21, 2019; accepted August 28, 2019. This work was supported in part by the National Funds through the Portuguese Foundation for Science and Technology (FCT/MEC) and co-financed by the European Regional Development Fund (ERDF) under the PT2020 Partnership, within the Real-Time and Embedded Computing Systems Research Centre (CISTER) Research Unit, under Grant CEC/04234 and in part by Portuguese Foundation for Science and Technology/Ministry of Education and Science (FCT/MEC) and the European Union (EU) Electronic Components and Systems for European Leadership (ECSEL) Joint Undertaking (JU) through the H2020 Framework Programme, within the project ECSEL/0002/2015, under Grant 692529-2 (SAFECOP). The Associate Editor for this article was B. Chen. *(Corresponding author: Kai Li.)*

K. Li and E. Tovar are with the Real-Time and Embedded Computing Systems Research Centre (CISTER), 4249-015 Porto, Portugal (e-mail: kaili@isep.ipp.pt; emt@isep.ipp.pt).

W. Ni is with the Digital Productivity and Services Flagship, Commonwealth Scientific and Industrial Research Organization (CSIRO), Sydney, NSW 2122, Australia (e-mail: wei.ni@csiro.au).

M. Guizani is with the Department of Computer Science and Engineering, Qatar University, Doha 61780, Qatar (e-mail: mguizani@ieee.org).

Digital Object Identifier 10.1109/TITS.2019.2939292

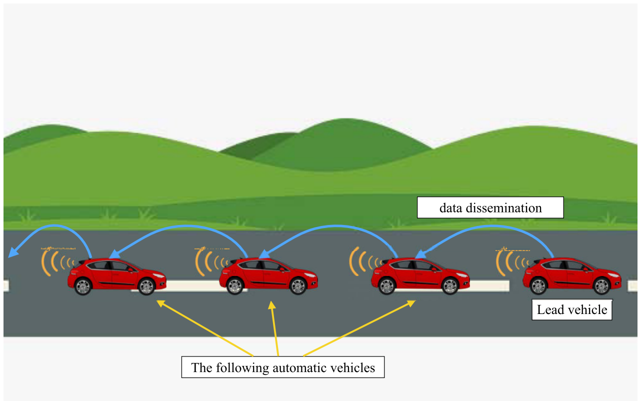

Fig. 1. The vehicular platoon contains a number of autonomous vehicles, where the lead vehicle disseminates the driving control information to the following vehicles.

in fatal accidents since the driving states of the following vehicles are not timely updated. Second, transmission latency for each vehicle can be reduced by using a high transmit rate. However, increasing the transmit rate at the preceding vehicle also increases bit error rate (BER) at the receiver vehicle given a certain Signal-to-Noise Ratio (SNR). In this case, the data dissemination latency increases since the vehicles in the platoon with high BER need a longer time due to data retransmissions. Therefore, data dissemination latency performance can substantially degrade if the transmit rate of the platooning vehicles is not properly allocated.

B. Research Motivation

An optimal rate-adaptive scheme is proposed for fast data dissemination in vehicular platoons while guaranteeing the data delivery at each vehicle. Specifically, we optimize the transmit rate (i.e., modulation) of the platoon vehicles such that the expected total latency of the platoon control message delivery is minimized under a guaranteed BER. A new dynamic programming algorithm, namely LADA, is developed to solve the optimal transmit rate allocation problem at a low time-complexity linear to the platoon's size. Furthermore, we interpret the vehicular platoon as one-dimensional Markov chain to derive the data dissemination latency, where the ith state indicates the first i vehicle in the platoon that has successfully received the disseminated data packet. The packet transmitted from the ith vehicle to the $(i+1)$th vehicle with a selected transmit rate is formulated as state transition, which traverses all the vehicles in the platoon. Moreover, the transition probability from the ith state to the $(i+1)$th state depends on the channel and the modulation-coding scheme (MCS) over the link between the ith and the $(i+1)$th vehicle. The ith state can also transmit to itself in the case that the transmission from the ith vehicle to the $(i+1)$th vehicle is unsuccessful. The modeling of the data dissemination in the platoon by using a Markov chain facilitates quantifying the steady-state delay of the data delivery over a platoon. Therefore, the length of the platoon with data delivered and the average latency of data dissemination can be analyzed using a steady-state analysis in Markov chain, which will be investigated in Section V.

Some initial ideas and results of the proposed algorithm have been reported in our recent work [12], but no details were provided on problem formulation and derivation. In this paper, we derive the closed-form expression for the average end-to-end transmission latency of a platoon, and formulate the min-max problem of the expression to optimize the transmit rates of the platoon. We also reveal the optimal subproblem structure of the problem to qualify the use of dynamic programming to solve the problem. All this was not provided in [12]. Moreover, in [12], the average latency was analyzed under a simplified scenario with identical fading across all hops of the platoon. In this paper, we generalize the analysis to capture different fading at different hops, and new results are provided to reveal the impact of platoon size and packet size on the latency. This is also new, and was not provided in [12].

This paper is organized as follows. The related work on vehicular data dissemination is presented in Section II. Section III presents the communication protocol and system model of the vehicular platoon. In Section IV, we formulate the optimal rate-adaptive data dissemination problem. The practical solution using dynamic programming is presented. Section V analyzes the data dissemination latency using the Markov chain model. Section VI demonstrates the simulations and numerical results. Section VII concludes the article.

II. Literature Review

Various position-based communication protocols have been designed for vehicle ad hoc networks (VANET) to reduce transmission latency. A number of urban infrastructure based routing protocols considering traffic information are studied in [13]–[15]. The signals of traffic lights on the road and traffic patterns that are constrained by roads and obstacles are synthetically utilized to determine how packets could be forwarded. A communication protocol is presented to reduce transmission latency in vehicular networks [16]. The global network topology information including vehicles' speed, spatial distribution, link delay and connectivity, is utilized by the data sender vehicle to find the most time-efficient path before data transmission. In [17], a geography-based communication protocol is studied to select road intersections through which a packet must pass to reach a gateway to the Internet. Geographical forwarding is used to transfer packets between any two intersections on the path, reducing the path's sensitivity to individual vehicle movements. Unfortunately, the data dissemination protocols in literature assume the driving and communication information of all the vehicles have been globally known. This is not true in the vehicular platoon since only local channel information is available to the vehicle.

Some recent protocols [19]–[29] are developed for vehicular communications with local channel information. In [20], two sending vehicles driving in opposite directions disseminate their data with the help of network coding. The dissemination completion time is analyzed for the two encountering sender vehicles, which provides insight on the impact of the opposite direction on the data dissemination. Probabilistic models that account for vehicle density and multi-hop data delivery are

TABLE I
COMMUNICATION PROTOCOLS IN VANET

References	Require global geographical info	Require infrastructures/mobility info	Adaptive communication	Network structure
[13]–[18]	yes	yes	no	vehicle-to-infrastructure (V2I)
[19]	no	yes	yes	V2I
[20]–[23]	no	no	no	multihop vehicle-to-vehicle (V2V)
[24], [25]	no	yes	no	multihop V2V
[26]	no	no	yes	single-hop V2V
[27]	no	yes	no	delay-tolerant V2V
[28], [29]	no	yes	no	V2I
LADA	no	no	yes	multihop V2V

studied to analyze data dissemination reliability [21]. The models are used for addressing system design issues, such as a proper setting of the forwarding probability at each vehicle, so that a given probability to receive the disseminated data can be guaranteed to all vehicles. A comparative study [22] on existing approaches for performance modeling of data dissemination in VANETs is discussed. Different analytical models designed for the data dissemination in VANETs are analyzed based on various performance metrics and environment assumptions. It is also noted that performance modeling of data dissemination in VANETs is sophisticated due to a range of assumptions on road network layout, vehicular mobility, and networking (including density criteria and communication techniques). However, the dissemination latency due to improper allocation of vehicles' transmit rates is not considered in [20]–[22].

A data transmission scheme is studied to bundle retransmissions to high speed vehicles in a two-hop vehicle network [19]. The authors in [23] present a protocol that uses fuzzy logic to evaluate whether a wireless link between vehicles is good or not by considering available bandwidth, link quality, and relative vehicle movement. Their protocol also employs a fuzzy constraint Q-learning algorithm based on an on-demand distance vector protocol for multi-hop networks. An adaptive approach for data dissemination is studied in [26], where each vehicle adjusts local parameters using local information (i.e., inter-arrival time, number of redundant messages) about the messages received from neighboring vehicles. In [27], a vehicle-assisted multi-hop data delivery protocol is studied based on the idea of carry and forward, where vehicles carry the packet when the next hop is not available and forward the packet to the new receiver that moves into its vicinity. In [28], Wang *et al.* considered a highway scenario where two roadside units (RSUs) are deployed at a distance, and vehicles are sparsely distributed on the road between the RSUs. The average transmission delay of road condition information is analyzed to obtain the proper deployment of the RSUs under a specific delay constraint. The deployment of RSUs in a road grid scenario is studied by considering the tradeoff between the data delivery delay and the cost of the deployment [29]. An analytical framework is presented, which estimates the data delivery delay between vehicles, and calculates deploying benefits of RSUs at an intersection. However, the placement and maintenance of the roadside units on highways can have a high cost. On the other hand, connection setup time between a vehicle and a roadside unit is limited due to high mobility of vehicles, which downgrades wireless bandwidth utilization.

In this work, we minimize the data dissemination latency in the vehicular platoon by adapting transmit rate while guaranteeing data delivery. Moreover, we present a rate-adaptive data dissemination algorithm that derives the optimal transmit rate allocation by conducting backward induction in dynamic programming. We also interpret the vehicular platoon as one-dimensional Markov chain to quantify the data dissemination latency over time-varying channels. Table I generalizes the communication protocols in the literature review.

III. SYSTEM MODEL

The vehicular platoon of interest has N autonomous vehicles. The platoon control messages can contain intermittent speed control information, such as acceleration and deceleration, or emergency driving control information, such as collision warning, emergency braking, or lane changing. The packets are generated at the lead vehicle in response to changes of road conditions. A Poisson distribution of the packet generation with rate λ_c is taken as an example here. However, the proposed rate-adaptive dissemination algorithm is generic, and can work with other packet generation schemes. There is no collision between vehicles in the same platoon, as it is important to guarantee critical platoon control messages to be delivered to each of the vehicles. A vehicle does not transmit unless it has correctly received the information from the preceding one. Given collision-free packet (re)transmissions opportunities, the proposed algorithm can minimize the end-to-end data dissemination latency with guaranteed BER.

The transmit rate of vehicle i ($i \in [0, N-1]$) is r_i, and $r_i \in \{\rho_1, \rho_2, \ldots, \rho_M\}$; where ρ_1, ρ_2, and ρ_3 indicate BPSK, QPSK, and 8PSK, respectively, and $r_i \geq 4$ corresponds to 2^{r_i} QAM. ρ_M is the highest-order modulation. Suppose that the BER requirement of vehicle i is ϵ_i. Given Nakagami-m fading channel model, ϵ_i can be given by [30]

$$\epsilon_i \approx \frac{0.2}{\Gamma(m)}\left(\frac{m}{\bar{\gamma}_i}\right)^m\Big[\frac{\Gamma(m, b_{r_i}\gamma_{i,i+1}(r_i))}{(b_{r_i})^m} - \frac{\Gamma(m, b_{r_i}\gamma_{i,i+1}(r_i+1))}{(b_{r_i})^m}\Big], \quad (1)$$

$$b_{r_i} = \frac{m}{\bar{\gamma}_i} + \frac{3}{2(2^{r_i}-1)}, \quad (2)$$

where $\Gamma(\cdot)$ is the Gamma function [31], and $\bar{\gamma}_i$ is the average SNR. $\gamma_{i,i+1}(r_i)$ is the SNR of the link when i uses r_i, as given

by

$$\gamma_{i,i+1}(r_i) = \frac{\|\mathbf{h}_{i,i+1}\|^2 P_i(r_i)}{\sigma_0^2}, \tag{3}$$

where $P_i(r_i)$ denotes the transmit power, $\|\mathbf{h}_{i,i+1}\|$ is the channel gain, and σ_0 is the variance of background noise. For illustration convenience, the variable (r_i) in $P_i(r_i)$ and $\gamma_{i,i+1}(r_i)$ is suppressed in the rest of the paper.

According to [32]–[34], Rayleigh fading channel model, a special case of the Nakagami-m model with $m = 1$, is considered in this work because a signal is likely to be reflected by a number of surrounding vehicles. The transmit power at vehicle i is given by [35]

$$P_i \approx \frac{\kappa_2^{-1} \ln \frac{\kappa_1}{\epsilon_i}}{\|\mathbf{h}_{i,i+1}\|^2}(2^{r_i} - 1), \tag{4}$$

where κ_1 and κ_2 are channel-dependent constants. The successful packet transmission probability at vehicle i can be given by

$$\begin{aligned}\eta_i &= \mathbb{P}(\gamma_{i,i+1} \geq \bar{\gamma}_i | \gamma_{i-1,i} \geq \bar{\gamma}_{i-1}) \\ &= \mathbb{P}(\frac{\|\mathbf{h}_{i,i+1}\|^2 P_i}{\sigma_0^2} \geq \bar{\gamma}_i),\end{aligned} \tag{5}$$

where $\bar{\gamma}_i = 2^{\bar{r}_i} - 1$.

In the platoon, vehicle i uses a channel probing method to acquire $h_{i,i+1}$, and sends to the lead vehicle through inter-vehicle control message exchange before data dissemination. Consequently, by running the proposed rate-adaptive dissemination algorithm that is discussed in Section IV, the lead vehicle obtains the optimal r_i $(i \in [0, N-1])$ and disseminates them together with the data packet. As such, the following vehicle i is aware of r_i once the disseminated data packet is decoded. In addition, note that the latency of the control message exchange is neglected in our model due to the tiny size of the link information, compared to the payload of the data packet. Moreover, the length of r_i information in the data packet decreases with the increase number of transmitting vehicles as the packet transmitted from vehicle i only needs to enclose r_j, where $j \in [i+1, N-1]$.

IV. Rate-Adaptive Data Dissemination for Platoon

In this section, we first minimize the data dissemination latency from the lead vehicle to the tail considering the transmit power constraint of the vehicles. The optimal transmit rate allocation is formulated as a Min-Max problem, and efficiently solved by a new dynamic programming approach.

A. Problem Formulation

The goal of our formulation is to optimize r_i adapting time and channel fading, thereby minimizing the data dissemination latency in the platoon. Let P_{max} denote the maximum allowable transmit power that the wireless transceiver of a vehicle can support. Based on (4), the highest transmit rate of the transceiver, denoted by r_{max}, depends on P_{max} which is known apriori, and $r_i \leq r_{max}$.

Particularly, P_{max} specifies the maximum allowable transmit power subject to antenna, chip or regulatory requirements. Due to (4), the highest transmit rate, denoted by r_{max}, is known. Note that r_i can not be higher than r_{max} that is limited by P_{max}, otherwise, the wireless transceiver is not able to function properly as the required P_i is higher than P_{max}. Moreover, we define the transmission latency of the platooning vehicle, which is

$$\begin{cases} T_0 = \dfrac{L}{r_0} \\ T_1 = \dfrac{L}{r_1} \\ \dots \\ T_{N-1} = \dfrac{L}{r_{N-1}} \end{cases} \tag{6}$$

where T_i is the data transmission time at i, and L is the packet length. The average latency when a packet is successfully transmitted to the tail vehicle is given in (7), shown at the bottom of this page, where Z is the maximum number of retransmissions. Especially, Z is fixed in the formulation since we focus on optimizing r_i to minimize the latency of data dissemination.

To ensure the formulation is realistic, the successful packet transmission probability of any vehicle in the platoon needs to be greater than 0. Otherwise, the dissemination latency would be infinite no matter how to optimize the transmit rates for the vehicles. Moreover, each data packet needs to be successfully delivered to the tail of the platoon, which gives $\sum_{i=0}^{N-1} \eta_i = 1$. Therefore, the problem of minimizing the average data dissemination latency with a guaranteed BER under the power constraints can be formulated as:

$$\begin{aligned}\textbf{P1:} \quad & \min_{r_i \in [\rho_1, \rho_M]} \left\{ \max_{i_x \in [1, N-1]} \mathbb{E}(T) \right\} \\ & \textit{subject to}: \ P_i \leq P_{max}, \quad \forall i \in [0, N-1]\end{aligned} \tag{8}$$

where the expectation of the dissemination latency, i.e., $\mathbb{E}(T)$, is taken over the randomness of the wireless channels of all the vehicles. Note that this optimization has two interpretations.

$$\begin{aligned}\mathbb{E}(T) &= \frac{1}{(i+1)}\Big[\frac{ZL}{r_0}(1-(1-\eta_0)^Z)(1-\eta_1)^Z + \frac{ZL}{r_1}(1-(1-\eta_0)^Z)(1-(1-\eta_1)^Z)(1-\eta_2)^Z \\ &\quad + \frac{ZL}{r_2}(1-(1-\eta_0)^Z)(1-(1-\eta_1)^Z)(1-(1-\eta_2)^Z)(1-\eta_3)^Z + \ldots + \frac{ZL}{r_i}\prod_{i'=0}^{i}(1-(1-\eta_{i'})^Z)(1-\eta_{i+1})^Z\Big] \\ &= \frac{1}{(i_x+1)}\sum_{i=1}^{i_x}\Big[\Big[\sum_{i'=0}^{i-1} T_{i'}Z + \sum_{z=1}^{Z} zT_i(1-\eta_i)^{z-1}\eta_i\Big]\Big[\prod_{i'=0}^{i}(1-(1-\eta_{i'})^Z)\Big](1-\eta_{i+1})^Z\Big]\end{aligned} \tag{7}$$

This article has been accepted for inclusion in a future issue of this journal. Content is final as presented, with the exception of pagination.

First, $\mathbb{E}(T)$ can be thought of as a resource allocation of the transmit rate for each vehicle. Thus, minimizing the $\mathbb{E}(T)$ can be regarded as maximizing r_i under the constraints of the average transmit power and the BER requirement. Second, the platoon's size (number of vehicles), also affects the dissemination latency. The optimization explores the delay when the packets are disseminated to the tail vehicle, which gives $\max_{i_x \in [1,N-1]} \mathbb{E}(T)$. Thus, the formulation of **P1** can potentially be used as a surrogate for minimizing the average latency of dissemination over N vehicles in the network.

Lemma 1: The complexity of the minimizing dissemination latency in **P1** is NP-hard.

Proof: we prove that the optimization in **P1** is NP-hard via reducing the 0-1 Knapsack problem to a special case of **P1**. Specifically, let $\eta_{i,m} = e^{-\nu_i \sigma_0^2 \bar{\gamma}_{i,m}/P_{i,m}}$, where $\bar{\gamma}_{i,m} = 2^{\bar{r}_{i,m}} - 1$ and $m \in \{1, M\}$. We have $P_{i,m} \approx \frac{\kappa_2^{-1} \ln \frac{\kappa_1}{\epsilon_i}}{\|\mathbf{h}_{i,i+1}\|^2} \bar{\gamma}_{i,m}$. Hence, an equivalent formulation of **P1** can be given by

$$\textbf{P2:} \quad \min_{x_{i,m} \in [0,1]} \Big\{ \max_{i_x \in [1,N-1]} \frac{1}{(i_x+1)} \sum_{i=1}^{i_x} \Big[\Big[\sum_{i'=0}^{i-1} T_{i'} Z + \sum_{z=1}^{Z} z T_i (1 - \sum_{m=1}^{M} x_{i,m} \eta_{i,m})^{z-1} \sum_{m=1}^{M} x_{i,m} \eta_{i,m} \Big] \Big[\prod_{i'=0}^{i} (1 - (1 - \sum_{m=1}^{M} x_{i',m} \eta_{i',m})^{Z}) \Big] (1 - \sum_{m=1}^{M} x_{i'+1,m} \eta_{i'+1,m})^{Z} \Big] \Big\}$$

$$subject\ to: \sum_{m=1}^{M} x_{i,m} P_{i,m} \le P_{max}, \quad \forall i \in [0, N-1] \tag{9}$$

$$\sum_{m=1}^{M} x_{i,m} = 1, \quad \forall i \in [0, N-1] \tag{10}$$

Basically, **P2** can be described as follows. There are M items with their values $\{\upsilon_1, \upsilon_2, \ldots, \upsilon_M\}$, which are transmission rate at the vehicle and N knapsacks. The items to be put in knapsacks are $\Big[\sum_{i'=0}^{i-1} T_{i'} Z + \sum_{z=1}^{Z} z T_i (1 - \sum_{m=1}^{M} x_{i,m} \eta_{i,m})^{z-1} \sum_{m=1}^{M} x_{i,m} \eta_{i,m} \Big] \Big[\prod_{i'=0}^{i} (1 - (1 - \sum_{m=1}^{M} x_{i',m} \eta_{i',m})^{Z}) \Big] (1 - \sum_{m=1}^{M} x_{i'+1,m} \eta_{i'+1,m})^{Z}$ whose size is prorated by $\eta_{i,m}$. The goal of **P2** is to decide which items to be packed to minimize the maximum overall value and satisfies the average power condition (see constraint (9)). This way, the optimal placement of items in knapsacks is reduced to such an instance of **P1**. Since **P2** is obviously an NP-hard problem, so is **P1**. ■

B. Latency-Aware Dissemination Algorithm

Given the high complexity of the rate-adaptive data dissemination problem in a vehicular platoon, we propose a latency-aware dissemination algorithm based on the technique of dynamic programming. Our algorithm allocates the transmit rate of the platooning vehicles with an optimized joint control policy.

In order to find the best transmit rate for each of the vehicles, we represent the transmit rate allocation for the vehicles as a graph. Figure 2 illustrates the graph associated with a two dimensional path search with a platoon size of N, where each vehicle can use one of M available modulation schemes. Each edge in the graph reflects a possible transition from one transmit rate of the vehicle to a one of another vehicle, and has an associated transition probability that is η_i shown in (5). Note that the transmit rate of the vehicle needs to be reallocated in order to retransmit the data if a non-ACK message is received from the following vehicle.

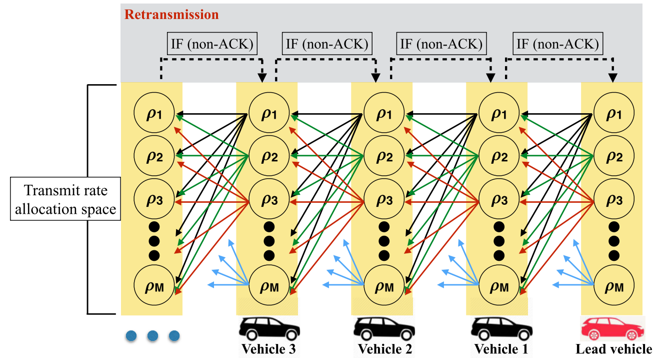

Fig. 2. Transmit rate allocation in the vehicular platoon.

Due to lossy channels, taking actions $r_i \in [\rho_1, \rho_M]$ can result in two cases: 1) vehicle i successfully transmits the data to its following vehicle, and the transmission time at the vehicle is $T_i = \{T_i + T_{i-1} | r_{i-1}\}$; 2) the data is not successfully transmitted, and $T_i = T_{i-1}$. The subproblem of minimizing the dissemination latency can be recursively formulated for each of the vehicles, which is

$$T_i(r_i) = \min_{r_j} \Big\{ \sum_{j=1}^{i} T_j(r_j) \Big| T_{j-1}(r_{j-1}), \quad P_j \le P_{max} \Big\}, \quad \forall i \in [1, N] \tag{11}$$

Then, based on Bellman equation, we recursively solve $T_i(r_i)$ at vehicle i by using the optimized outcomes of preceding subproblems at $(i-1)$. Particularly, $r_i^\star$, i.e., the optimal transmit rate at vehicle i, is derived by all solutions to the preceding subproblems of υ_{i-1} for minimizing the data dissemination latency, which is

$$r_i^\star = \text{argmin}\{ \sum_{i=0}^{N-1} T_i(r_i) | P_i \le P_{max} \}. \tag{12}$$

As the tradeoff obtained in **P1**, the platooning vehicle that is allocated with an excessively high transmit rate costs a small transmission time, but experiencing a high BER (or packet loss) and consuming a large transmit power. On the other hand, the vehicle with an excessively low transmit rate costs a long transmission time, but experiencing small packet loss and consuming a small transmit power.

Based on this tradeoff, we aim to find the optimal transmit rate for each of the platooning vehicles (namely, $\boldsymbol{r}^\star = [r_0^\star, r_1^\star, r_2^\star \ldots, r_{N-1}^\star]$) to minimize the dissemination latency in the vehicular platoon. The optimal solution to **P1** is the transmit rate allocation for all the vehicles.

Algorithm 1 Latency-Aware Dissemination Algorithm (LADA)

```
Initialize: P_i, r_i = ρ_M, T_i(0) = 0, T_i(r_i) = ∞, T_total = 0, and N.
Dynamic Programming
Initialization: T_i(r_i) = ∞ and T_i(0) = 0.
for i → N do
    for r_i → [ρ_1, ρ_M] do
        T_i(r_i) ← min_{r_j} { Σ_{j=1}^{i} T_j(r_j) | T_{j-1}(r_{j-1}), P_j ≤ P_max }
        Save the results of T_i(r_i)
        r* is updated.
    end for
end for
The optimal transmit rate allocation →
    r_i* ← argmin{ Σ_{i=0}^{N-1} T_i(r_i) | P_i ≤ P_max }.
Backward induction
Initialization: r_i ← r_i*.
for i decreases from N to 1 do
    Transmit Power: P_i* ≤ P_max.
    Trace backward: T_total = T_total + T_i(r_i*)
end for
Transmit Power Optimization
P_i* ← (4), where transmit rate is r_i*.
```

A new Latency-Aware Dissemination Algorithm (LADA) is proposed to derive the optimal solutions by conducting backward induction in dynamic programming [36], where rate allocation is optimized offline and implemented in real time via a lookup table that is stored at the lead vehicle. Specifically, the value function and corresponding policy function are calculated in every decision iteration. Moreover, the algorithm iterates over uncertainty spaces, and LADA solves each subproblem in one iteration, where the optimized results are stored in a table. The proposed LADA is presented in Algorithm 1.

In terms of the complexity, the optimal solution to the subproblems in LADA is iteratively solved by using the dynamic programming techniques. Specifically, the optimal solution for each subproblem is solved in a bottom-up fashion. Essentially, the complexity of LADA depends on the number of subproblems to be solved. Since $r_i^\star$ in (12) is obtained by recursively solving the Bellman equation, the complexity for each subproblem using (11) is $\mathcal{O}(1)$. Therefore, the overall complexity of completing $r_i^\star$ allocation for the platoon is $\mathcal{O}(NM^2)$, where the backward induction requires M^2 elementary computations.

V. Data Dissemination Latency Analysis

In this section, we analyze the latency of data dissemination in the vehicular platoon by using one-dimensional Markov chain [37]. Suppose the data arrival rate at vehicle i is λ_i, and the processing rate at the vehicle i is μ_i. The data dissemination in the vehicular platoon is formulated as a one-dimensional Markov chain, where the platooning vehicle

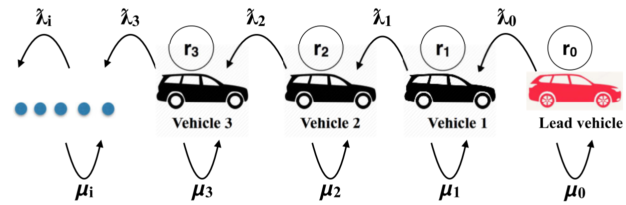

Fig. 3. State transition diagram of vehicles with a transmit rate r_i, where the data arrival rate is λ_i and the processing rate is μ_i.

seems to be a server with infinite buffer. Moreover, the vehicle stores the received data packets in the data queue, and always processes and sends out the packet that is at the first place in the queue. The state transition diagram is shown in Figure 3. When all vehicles in the platoon are steady, we have the transition matrix, as given by

$$\mathbf{T} = \begin{bmatrix} \lambda_0 & -\mu_1 & 0 & 0 & 0 & \cdots & 0 & 0 \\ -\lambda_0 & (\mu_1+\lambda_1) & -\mu_2 & 0 & 0 & \cdots & 0 & 0 \\ 0 & -\lambda_1 & (\mu_2+\lambda_2) & -\mu_3 & 0 & \cdots & 0 & 0 \\ \cdot & 0 & -\lambda_2 & \cdot & & & & \\ \cdot & \cdot & 0 & \cdot & & & & \\ \cdot & \cdot & \cdot & & \cdot & & & \\ \cdot & \cdot & \cdot & & & \cdot & & \end{bmatrix} \tag{13}$$

Let Π_i denote the probability of the disseminated data packet to i. Given $\mathbf{T}$ of (13), we can have the steady state of platooning vehicles, which is

$$\Pi_i = \lim_{t\to\infty} \Pi_i(t). \tag{14}$$

Moreover, from queuing theory, we know that

$$\sum_{\forall i \in [0,+\infty]} \Pi_i = 1. \tag{15}$$

We further consider a case in a more general setting, where the platooning vehicles, with packet arrival rate λ_i and processing rate μ_i, experience independent channel fading. In this case, the arrival probability of data packets and ACK probability at vehicle i adhere to an independent Poisson process with intensity λ_i, and an exponential process with intensity μ_i, respectively. Moreover, μ_i gives the ACK probability at vehicle i, which is equal to the successful reception probability of the packet during time $\tau_i = \frac{L}{\lambda_i}$. According to Loynes' theorem [38], for the one-dimensional Markov chain, if the arrival process and the service process of a queue are strictly stationary, then the queue is stable if and only if the average processing rate is greater than the average arrival rate of the queue, which gives $\mu_i \geq \lambda_i$.

According to the steady Markov chain with the transition rate $\mathbf{T}$, the balance equation for a steady-state N-vehicle platoon can be obtained by

$$-(1-\Pi_i)\mu_i + \Pi_{i-1}\lambda_{i-1} = 0, \quad \forall i \tag{16}$$

$$\Pi_0 + 1 - \frac{\lambda_0}{\mu_1}\Pi_0 + 1 - \frac{\lambda_1}{\mu_2} + \frac{\lambda_0}{\mu_1}\frac{\lambda_1}{\mu_2}\Pi_0 + \ldots + 1 - \frac{\lambda_{N-1}}{\mu_N} + \frac{\lambda_{N-1}\lambda_{N-2}}{\mu_N\mu_{N-1}} - \ldots + \Pi_0\prod_{n=0}^{N-1}(\frac{\lambda_n}{\mu_{n+1}}) = 1 \tag{19}$$

$$\Pi_0 = \frac{\frac{\lambda_1}{\mu_2} - 1 - \frac{\lambda_1\lambda_2}{\mu_2\mu_3} + \frac{\lambda_2}{\mu_3} - 1 + \ldots + (-1)^N \prod_{n=1}^{N-1}\frac{\lambda_n}{\mu_{n+1}} + (-1)^{N-1}\prod_{n=2}^{N-1}\frac{\lambda_n}{\mu_{n+1}} + \ldots + \frac{\lambda_{N-1}}{\mu_N} - 1}{-\sum_{i=1}^{N-2}(\frac{\lambda_i\lambda_{i+1}}{\mu_{i+1}\mu_{i+2}}) + \sum_{i=1}^{N-3}(\frac{\lambda_i\lambda_{i+1}\lambda_{i+3}}{\mu_{i+2}\mu_{i+3}\mu_{i+4}}) + \ldots + (-1)^N\prod_{n=1}^{N-1}\frac{\lambda_n}{\mu_{n+1}} + \sum_{i=1}^{N-1}(\frac{\lambda_i}{\mu_{i+1}}) - N} \tag{20}$$

where $i = [1, +\infty)$,

$$\begin{cases} -(1-\Pi_1)\mu_1 + \Pi_0\lambda_0 = 0 \\ -(1-\Pi_2)\mu_2 + \Pi_1\lambda_1 = 0 \\ \quad\cdots \\ -(1-\Pi_i)\mu_i + \Pi_{i-1}\lambda_{i-1} = 0 \\ \quad\cdots \\ -(1-\Pi_N)\mu_N + \Pi_{N-1}\lambda_{N-1} = 0 \end{cases} \tag{17}$$

Furthermore, (17) can be rewritten as

$$\begin{cases} \Pi_1 = \frac{\mu_1 - \Pi_0\lambda_0}{\mu_1} = 1 - \frac{\lambda_0}{\mu_1}\Pi_0 \\ \Pi_2 = \frac{\mu_2 - \Pi_1\lambda_1}{\mu_2} = 1 - \frac{\lambda_1}{\mu_2}\Pi_1 \\ \quad\cdots \\ \Pi_i = \frac{\mu_i - \Pi_{i-1}\lambda_{i-1}}{\mu_i} = 1 - \frac{\lambda_{i-1}}{\mu_i}\Pi_{i-1} \\ \quad\cdots \\ \Pi_N = \frac{\mu_N - \Pi_{N-1}\lambda_{N-1}}{\mu_N} = 1 - \frac{\lambda_{N-1}}{\mu_N}\Pi_{N-1} \end{cases} \tag{18}$$

It can be observed that the probability decreases with increasing the number of vehicles in the platoon.

By substituting (18) to (15), we can obtain the formula when the vehicles are in steady states for N vehicles, as shown in (19), shown at the top of this page. Moreover, the LHS of (19) contains $\Big(1 - \frac{\lambda_0}{\mu_1} + \frac{\lambda_0\lambda_1}{\mu_1\mu_2} - \frac{\lambda_0\lambda_1\lambda_2}{\mu_1\mu_2\mu_3} + \ldots + \prod_{n=0}^{N-1}(\frac{\lambda_n}{\mu_{n+1}})\Big)\Pi_0$, which can be used to transform (19). Hence, we have the closed-form expression for Π_0, as given in (20), shown at the top of this page. Consequently, we are able to obtain the probability that the data packet is received by any vehicle i in the platoon based on (18), which can be reformulated using Π_0.

Furthermore, we investigate the amount of successfully disseminated data packets given the steady state of all the platooning vehicles. Specifically, let ω denote the number of data packets in the platoon. The average number of data packets transmitted by the lead vehicle can be computed by

$$\mathbb{E}(\omega) = \sum_{i=0}^{N-1} i \prod_{n=0}^{i}\frac{\lambda_n}{\mu_n}(1 - \frac{\lambda_i}{\mu_i}). \tag{21}$$

Assume that t_i is the time that packet i is generated by the lead vehicle, and packet i spends $W_i \geq 0$ units of time in the platoon, and then it reaches the tail vehicle at time $t_i^{\mathrm{d}} = t_i + W_i$. We have the average transmission latency at any vehicle i based on *Little's Law*, which is

$$\tau_i = \frac{1}{\mu_i - \lambda_i}. \tag{22}$$

Therefore, the average latency of the data dissemination is

$$\mathbb{E}(T) = \mathbb{E}(\omega)\sum_{i=0}^{N-1}\tau_j. \tag{23}$$

In a special case, the identical fading channel of the platooning vehicles is considered, where η_i has an identical probability distribution. We have $\lambda_i = \lambda_c$ and $\mu_i = \mu_c$, where λ_c is the data arrival rate and μ_c are the data processing rate. By substituting this into (19) and following the above analysis steps, we obtain the average latency in the special case, as shown in [12].

VI. Simulations and Performance

MATLAB simulations are carried out to evaluate the proposed LADA in terms of the amount of disseminated packets, data dissemination latency, and data dissemination rate.

A. Simulator Configuration

Payload of the data packet has 32 bytes, i.e., $L = 256$, unless otherwise specified. The noise power at the vehicles is normalized as $\sigma_0^2 = 1$. κ_1 and κ_2 in (4) are set to 0.2 and 3, respectively. The average channel gain of the link between two platoon vehicles has $\nu_i = 1$. The highest modulation scheme $\rho_M = 8$, and the number of vehicles increases from 5 to 50, i.e., $N \in [5, 50]$. Target ϵ at the platooning vehicles is configured to 0.05%, i.e., the transmitted bits have an error no more than 0.05, however, this value can be configured depending on the traffic type and data quality-of-service (QoS) requirements. Since a communication frame is typically up to 10 ms, we assume that the channels of the platooning vehicles experience Block fading.

We compared LADA with two other dissemination algorithms that are suitable in our context setting with the fixed transmit rate, i.e., the lowest data rate protocol (LDRP), and power-constrained data rate protocol (PCDRP). The LDRP data dissemination algorithm fixes the transmit rate of all the transmissions in the platoon with the lowest transmit rate. The PCDRP allocates the vehicles with the highest transmit rate that is restricted by P_{max}. Moreover, we also simulate a rate-adaptive algorithm NFDRP that is extended from [39] for comparison. In NFDRP, the data rate r_i is exclusively allocated to vehicle i for data transmission based on $\eta_{i,i+1}$. Namely, the vehicle ($i \in [0, N-1]$) with a high $\eta_{i,i+1}$ selects ρ_M as the modulation scheme. Otherwise, the vehicle selects ρ_1.

We also carry out a comparison study between the proposed algorithm and the optimal rate-adaptive solution that is implemented by directly applying the standard optimization techniques to solve **P1**. The optimal solution provides a lower

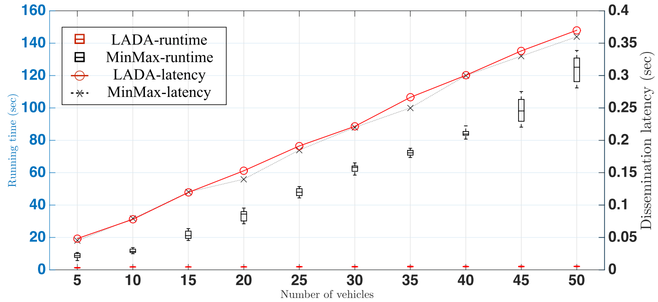

Fig. 4. Comparison between the Min-Max formulation and LADA in terms of runtime and dissemination latency.

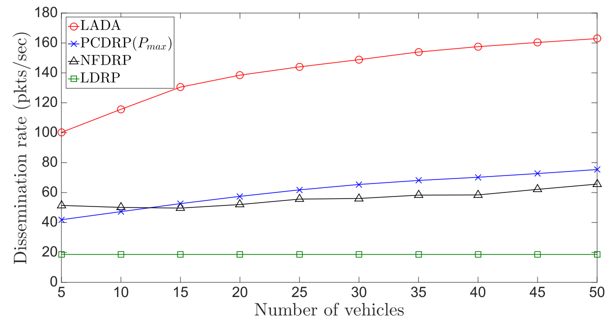

Fig. 5. Data dissemination rate with regards to the number of vehicles in the platoon.

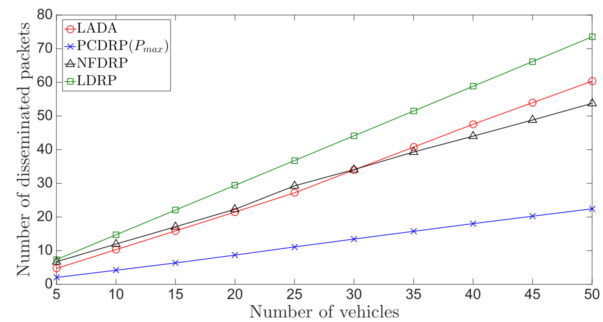

Fig. 6. Amount of disseminated packets with regards to the number of vehicles in the platoon.

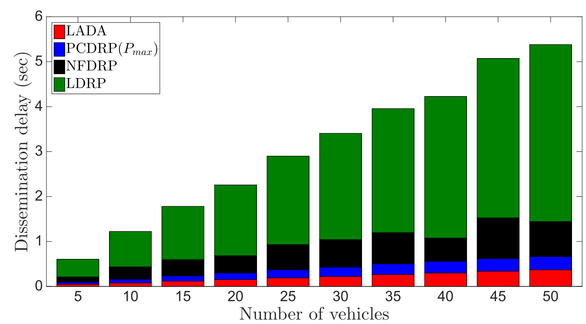

Fig. 7. Dissemination latency with regards to the number of vehicles in the platoon.

bound to the dissemination latency of any rate-adaptive algorithms applicable to the vehicular platoon setting. Comparisons between our algorithm and the optimal solution are meaningful and conclusive in terms of confirming the effectiveness of the proposed algorithm.

B. Simulation Results

1) Validation of the LADA: We assess the performance of LADA when it operates as the platoon enlarges from 5 to 50. This initial comparison makes us aware of the runtime difference between the Min-Max formulation (Problem **P1**) and LADA. The experiments are constructed using MATLAB and a state of the art optimization solver in a 2.7 GHz Intel core processor with 8 GB of memory.

Figure 4 shows that LADA performs more efficiently than the Min-Max formulation on runtime while LADA approaches the optimal transmit rate allocation in **P1** in terms of dissemination latency. The error bar with runtime performance shows the standard deviation over 50 runs. The difference between the Min-Max formulation and LADA on runtime grows as the number of vehicles increases. The results also confirm that LADA that utilizes backward induction in dynamic programming can be applied to real-time vehicular platoon due to its low complexity.

2) Platoon Size: In this case, we compare the dissemination rate, dissemination latency, and the number of disseminated packets, with respect to the number of platooning vehicles. Particularly, the dissemination latency defines as time span for the delivery of a data packet to all the platooning vehicles. We also define the dissemination rate as a ratio of the number of successfully disseminated packets to the overall time consumption on the dissemination. Figure 5 plots the performance of data dissemination of LDRP, PCDRP, NFDRP, and the proposed LADA with an increasing platoon size. In addition, LADA achieves 50.9%, 87.6%, and 64% higher dissemination rate than the PDCRP, LDRP, and NFDRP, respectively. The optimal solutions for the Min-Max formulation in Problem **P1** is not plotted due to computational intractability, as discussed earlier.

In Figure 6, it is observed that the amount of disseminated packets of LADA, PCDRP, LDRP, and NFDRP grows with the platoon size. Specifically, LDRP achieves the most disseminated packets since the lowest transmit rate, ρ_i, at the vehicle leads to the highest η_i in (5). PCDRP gives the lowest packet delivery since a high transmit rate at the vehicle causes a high BER. The performance of NFDRP is similar to LADA since both of them allocate the transmit rate adaptively. Moreover, LADA achieves a similar number of successfully disseminated packets as LDRP with a difference about 16.7% at the maximum. The reason is that the transmit rate at some vehicles using LADA can be higher than that with LDRP in order to minimize the average dissemination latency. This issue can be also confirmed by Figure 7, which shows the dissemination latency of the platoon. As observed, PCDRP has the smallest dissemination latency, and LADA approaches PCDRP with a gap of around 0.2 second. Moreover, LADA achieves faster data dissemination than LDRP, and LADA also outperforms NFDRP with 1.2 seconds of the dissemination latency.

3) Data Packet Size: In this case, we compare the dissemination rate, the number of disseminated packets, and latency

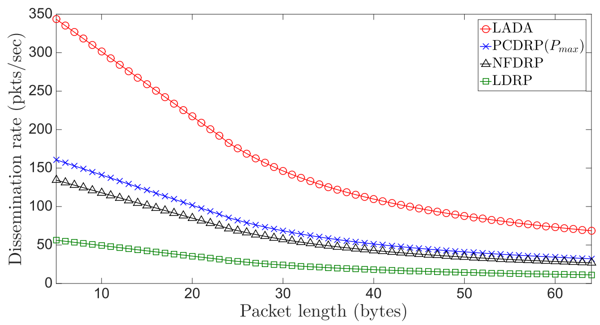

Fig. 8. Data dissemination rate with respect to the packet size.

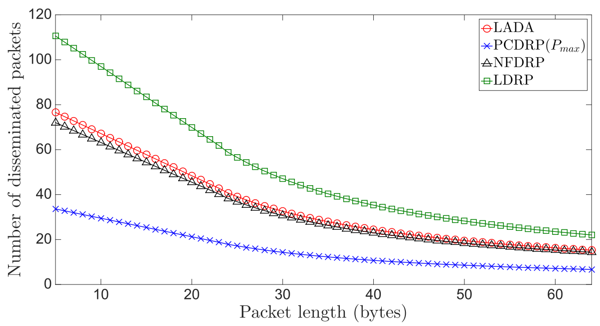

Fig. 9. Number of disseminated packets with different rate allocation algorithms.

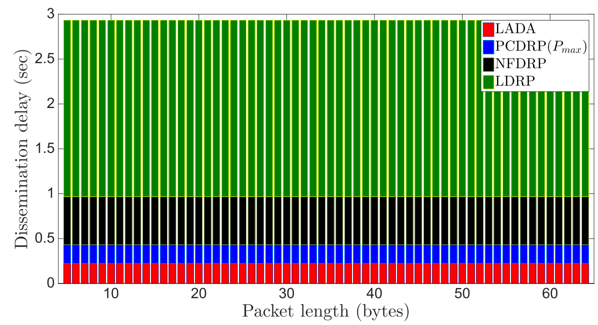

Fig. 10. Dissemination latency with regards to the packet size.

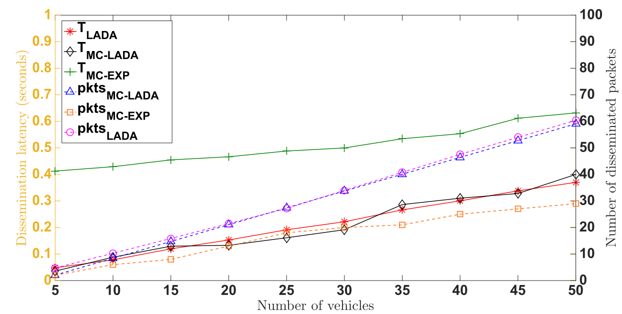

Fig. 11. Number of disseminated packets and latency with LADA and one-dimensional Markov chain model.

given a platoon of 30 vehicles and the data packet size from 5 bytes to 65 bytes. LADA outperforms PCDRP, LDRP, and NFDRP on the maximum dissemination rate by around 56.3%, 85.6%, and 60%, respectively, as shown in Figure 8.

In Figure 9, it can be observed that the two adaptive allocation algorithms, LADA and NFDRP, provide similar numbers of disseminated packets. LADA disseminates 28.2% more packets than LDRP when the packet size is 5 bytes. However, with an increasing packet size, the gap decreases significantly to 25%. Moreover, LADA achieves 51.9% more packets than PCDRP. In terms of dissemination latency, it is observed in Figure 10 that the latency of all the algorithms maintains no matter how large the data packet has. This is because the platoon size is fixed, and the packet size does not affect the lower bounded $\mathbb{E}(T)$ according to (7). Moreover, LADA achieves smaller dissemination latency than PCDRP, LDRP, and NFDRP for about 0.1, 2.7, and 0.8 seconds, respectively.

4) Dissemination Latency With Queueing Analysis: Figure 11 studies the dissemination latency and the number of packets with LADA and one-dimensional Markov chain model (in Section V) in regards to the platoon size. In particular, we consider two Markov chain models that are suitable in our context setting. The first model, referred to as "MC-LADA", utilizes the $r_i^\star$ in LADA to generate λ_i. The second model, referred to as "MC-EXP", generates λ_i at the vehicles in terms of the exponential distribution.

In Figure 11, the proposed LADA approaches the numerical calculation of MC-LADA model in terms of latency and disseminated packets. This is reasonable because the optimal solution, $r_i^\star$, that is utilized by MC-LADA model minimizes the average dissemination latency. Therefore, the performance of MC-LADA also confirms validity of LADA. We also see that LADA is able to achieve a significant lower dissemination latency than the MC-EXP model. The reason is that LADA adapts r_i of each vehicle i to minimize $\sum_{i\in[0,N-1]} \tau_i$, i.e., maximizing λ_{i+1} of its following vehicle $(i+1)$, thereby achieving a minimized dissemination latency.

VII. Conclusion

In this paper, we focus on the fast data dissemination problem for managing a platoon of autonomous vehicles. The problem is first formulated as a Min-Max optimization with the objective of minimizing the average dissemination latency. Then, a rate-adaptive data dissemination scheme that applies dynamic programming is proposed to produce an optimal rate allocation policy for the problem. Furthermore, the vehicular platoon is formulated by using a one-dimensional Markov chain model to quantify the dissemination latency. Simulation results show that the proposed LADA can reduce the computational complexity by orders of magnitude with negligible degradation of dissemination latency, compared to the state-of-the-art solver. LADA can also significantly improve the dissemination rate, compared to the algorithms without rate control in the literature.

References

[1] E. Chan, "Overview of the SARTRE platooning project: Technology leadership brief," SAE Tech. Paper 2012-01-9019, 2012.

[2] P. Pop, D. Scholle, H. Hansson, G. Widforss, and M. Rosqvist, "The SafeCOP ECSEL project: Safe cooperating cyber-physical systems using wireless communication," in *Proc. IEEE Euromicro Conf. Digit. Syst. Design (DSD)*, Aug. 2016, pp. 532–538.

[3] D. Jia, K. Lu, J. Wang, X. Zhang, and X. Shen, “A survey on platoon-based vehicular cyber-physical systems,” *IEEE Commun. Surveys Tuts.*, vol. 18, no. 1, pp. 263–284, 1st Quart., 2016.

[4] J. Cheng, J. Cheng, M. Zhou, F. Liu, S. Gao, and C. Liu, “Routing in Internet of vehicles: A review,” *IEEE Trans. Intell. Transp. Syst.*, vol. 16, no. 5, pp. 2339–2352, Oct. 2015.

[5] L. Li, D. Wen, and D. Y. Yao, “A survey of traffic control with vehicular communications,” *IEEE Trans. Intell. Transp. Syst.*, vol. 15, no. 1, pp. 425–432, Feb. 2014.

[6] C. Tan and K. Tham. (Nov. 2014). *Autonomous Vehicles, Next Stop: Singapore*. [Online]. Available: https://www.lta.gov.sg/ltaacademy/doc/J14Nov_p05Tan_AVnextStepSingapore.pdf

[7] R. A. Ferlis. (Aug. 2007). *The Dream of an Automated Highway*. [Online]. Available: https://www.fhwa.dot.gov/publications/publicroads/07july/07.cfm

[8] K. Li, Y. Emami, and E. Tovar, “Privacy-preserving control message dissemination for PVCPS,” in *Proc. 18th ACM/IEEE Int. Conf. Inf. Process. Sensor Netw. (IPSN)*, Apr. 2019, pp. 301–302.

[9] C.-H. Wang, C.-T. Chou, P. Lin, and M. Guizani, “Performance evaluation of IEEE 802.15.4 nonbeacon-enabled mode for Internet of vehicles,” *IEEE Trans. Intell. Transp. Syst.*, vol. 16, no. 6, pp. 3150–3159, Jun. 2015.

[10] K. Li, L. Lu, W. Ni, E. Tovard, and M. Guizani, “Secret key agreement for data dissemination in vehicular platoons,” *IEEE Trans. Veh. Technol.*, to be published.

[11] K. Li, L. Lu, W. Ni, E. Tovar, and M. Guizani, “Cooperative secret key generation for platoon-based vehicular communications,” in *Proc. IEEE Int. Conf. Commun. (ICC)*, May 2019, pp. 1–6.

[12] K. Li, W. Ni, E. Tovar, and M. Guizani, “LCD: Low latency command dissemination for a platoon of vehicles,” in *Proc. IEEE Int. Conf. Commun. (ICC)*, May 2018, pp. 1–6.

[13] C. T. Barba, M. A. Mateos, P. R. Soto, A. M. Mezher, and M. A. Igartua, “Smart city for VANETs using warning messages, traffic statistics and intelligent traffic lights,” in *Proc. IEEE Intell. Vehicles Symp. (IV)*, Jun. 2012, pp. 902–907.

[14] J. J. Chang, Y.-H. Li, W. Liao, and I.-C. Chang, “Intersection-based routing for urban vehicular communications with traffic-light considerations,” *IEEE Wireless Commun.*, vol. 19, no. 1, pp. 82–88, Feb. 2012.

[15] N. Alsharif, S. Céspedes, and X. Shen, “iCAR: Intersection-based connectivity aware routing in vehicular ad hoc networks,” in *Proc. Int. Conf. Commun. (ICC)*, Jun. 2013, pp. 1736–1741.

[16] M. A. Togou, A. Hafid, and L. Khoukhi, “SCRP: Stable CDS-based routing protocol for urban vehicular ad hoc networks,” *IEEE Trans. Intell. Transp. Syst.*, vol. 17, no. 5, pp. 1298–1307, May 2016.

[17] H. Saleet, R. Langar, K. Naik, R. Boutaba, A. Nayak, and N. Goel, “Intersection-based geographical routing protocol for VANETs: A proposal and analysis,” *IEEE Trans. Veh. Technol.*, vol. 60, no. 9, pp. 4560–4574, Nov. 2011.

[18] Y. Zhu, Y. Wu, and B. Li, “Trajectory improves data delivery in urban vehicular networks,” *IEEE Trans. Parallel Distrib. Syst.*, vol. 25, no. 4, pp. 1089–1100, Apr. 2014.

[19] M. J. Khabbaz, H. M. K. Alazemi, and C. M. Assi, “Delay-aware data delivery in vehicular intermittently connected networks,” *IEEE Trans. Commun.*, vol. 61, no. 3, pp. 1134–1143, Mar. 2013.

[20] F. Liu, Z. Chen, and B. Xia, “Data dissemination with network coding in two-way vehicle-to-vehicle networks,” *IEEE Trans. Veh. Technol.*, vol. 65, no. 4, pp. 2445–2456, Apr. 2016.

[21] R. Fracchia and M. Meo, “Analysis and design of warning delivery service in intervehicular networks,” *IEEE Trans. Mobile Comput.*, vol. 7, no. 7, pp. 832–845, Jul. 2008.

[22] M. Chaqfeh, A. Lakas, and S. Lazarova-Molnar, “Performance modeling of data dissemination in vehicular ad hoc networks,” in *Proc. IEEE/ACM 17th Int. Symp. Distrib. Simulation Real Time Appl.*, Oct. 2013, pp. 135–141.

[23] C. Wu, S. Ohzahata, and T. Kato, “Flexible, portable, and practicable solution for routing in VANETs: A fuzzy constraint Q-learning approach,” *IEEE Trans. Veh. Technol.*, vol. 62, no. 9, pp. 4251–4263, Nov. 2013.

[24] M. Al-Rabayah and R. Malaney, “A new scalable hybrid routing protocol for VANETs,” *IEEE Trans. Veh. Technol.*, vol. 61, no. 6, pp. 2625–2635, Jul. 2012.

[25] N. Kumar and J.-H. Lee, “Peer-to-peer cooperative caching for data dissemination in urban vehicular communications,” *IEEE Syst. J.*, vol. 8, no. 4, pp. 1136–1144, Dec. 2014.

[26] M. Bakhouya, J. Gaber, and P. Lorenz, “An adaptive approach for information dissemination in vehicular ad hoc networks,” *J. Netw. Comput. Appl.*, vol. 34, no. 6, pp. 1971–1978, Nov. 2011.

[27] J. Zhao and G. Cao, “VADD: Vehicle-assisted data delivery in vehicular ad hoc networks,” *IEEE Trans. Veh. Technol.*, vol. 57, no. 3, pp. 1910–1922, May 2008.

[28] Y. Wang, J. Zheng, and N. Mitton, “Delivery delay analysis for roadside unit deployment in vehicular ad hoc networks with intermittent connectivity,” *IEEE Trans. Veh. Technol.*, vol. 65, no. 10, pp. 8591–8602, Oct. 2016.

[29] J. He, Y. Ni, L. Cai, J. Pan, and C. Chen, “Optimal dropbox deployment algorithm for data dissemination in vehicular networks,” *IEEE Trans. Mobile Comput.*, vol. 17, no. 3, pp. 632–645, Jul. 2017.

[30] M.-S. Alouini and A. J. Goldsmith, “Adaptive modulation over Nakagami fading channels,” *Wireless Pers. Commun.*, vol. 13, nos. 1–2, pp. 119–143, 2000.

[31] I. S. Gradshteyn and I. M. Ryzhik, *Table of Integrals, Series, and Products*. New York, NY, USA: Academic, 2014.

[32] B. Blaszczyszyn, P. Muhlethaler, and Y. Toor, “Performance of MAC protocols in linear VANETs under different attenuation and fading conditions,” in *Proc. IEEE Int. Conf. Intell. Transp. Syst. (ITSC)*, Oct. 2009, pp. 1–6.

[33] Q. Wang, P. Fan, and K. B. Letaief, “On the joint V2I and V2V scheduling for cooperative vanets with network coding,” *IEEE Trans. Veh. Technol.*, vol. 61, no. 1, pp. 62–73, Jan. 2012.

[34] E. Giordano, R. Frank, G. Pau, and M. Gerla, “CORNER: A radio propagation model for VANETs in urban scenarios,” *Proc. IEEE*, vol. 99, no. 7, pp. 1280–1294, Jul. 2011.

[35] T. He, X. Wang, and W. Ni, “Optimal chunk-based resource allocation for OFDMA systems with multiple BER requirements,” *IEEE Trans. Veh. Technol.*, vol. 63, no. 9, pp. 4292–4301, Nov. 2014.

[36] T. H. Cormen, *Introduction to Algorithms*. Cambridge, MA, USA: MIT Press, 2009.

[37] W. J. Stewart, *Probability, Markov Chains, Queues, and Simulation: The Mathematical Basis of Performance Modeling*. Princeton, NJ, USA: Princeton Univ. Press, 2009.

[38] R. M. Loynes, “The stability of a queue with non-independent inter-arrival and service times,” *Math. Proc. Cambridge Philos. Soc.*, vol. 58, no. 3, pp. 497–520, 1962.

[39] A. Fu, E. Modiano, and J. N. Tsitsiklis, “Optimal transmission scheduling over a fading channel with energy and deadline constraints,” *IEEE Trans. Wireless Commun.*, vol. 5, no. 3, pp. 630–641, Mar. 2006.

Kai Li (S’09–M’14) received the B.E. degree from Shandong University, China, in 2009, the M.S. degree from The Hong Kong University of Science and Technology, Hong Kong, in 2010, and the Ph.D. degree in computer science from the University of New South Wales, Sydney, Australia, in 2014.

From 2010 to 2011, he was a Research Assistant with the Mobile Technologies Centre, The Chinese University of Hong Kong. He was a Visiting Research Assistant with the ICT Centre, CSIRO, Australia, from 2012 to 2013. He was a Post-Doctoral Research Fellow with the SUTD-MIT International Design Centre, Singapore University of Technology and Design, Singapore, from 2014 to 2016. He is currently a Senior Research Scientist and a Project Leader with the Real-Time and Embedded Computing Systems Research Centre (CISTER), Portugal. He serves as an Associate Editor for IEEE ACCESS journal, the Demo Co-Chair for the ACM/IEEE IPSN 2018, and a TPC Member of EWSN’19, the IEEE PerCom’19, Globecom’18, MASS’18, VTC-Spring’18, Globecom’17, VTC’17, and VTC’16.

Wei Ni (M'09–SM'15) received the B.E. and Ph.D. degrees in electronic engineering from Fudan University, Shanghai, China, in 2000 and 2005, respectively.

He was a Post-Doctoral Research Fellow with Shanghai Jiao Tong University from 2005 to 2008, the Deputy Project Manager at the Bell Labs R&I Center, Alcatel/Alcatel-Lucent, from 2005 to 2008, and a Senior Researcher at Devices Research and Development, Nokia, from 2008 to 2009. He is currently a Team Leader at Commonwealth Scientific and Industrial Research Organization (CSIRO), Sydney, Australia, and an Adjunct Professor with the University of Technology Sydney (UTS). He also holds adjunct positions at the University of New South Wales (UNSW) and Macquarie University (MQ). His research interests include stochastic optimization, game theory, graph theory, and their applications to network and security. He has been serving as the Vice Chair for the IEEE NSW VTS Chapter and an Editor for the IEEE TRANSACTIONS ON WIRELESS COMMUNICATIONS since 2018 and served as the Secretary for the IEEE NSW VTS Chapter from 2015 to 2018, the Track Chair for VTC-Spring 2017, the Track Co-Chair for the IEEE VTC-Spring 2016, and the Publication Chair for BodyNet 2015. He also served as the Student Travel Grant Chair for WPMC 2014, a Program Committee Member for CHINACOM 2014, and a TPC Member of the IEEE ICC'14, ICCC'15, EICE'14, and WCNC'10.

Eduardo Tovar was born in 1967. He received the Licentiate, M.Sc., and Ph.D. degrees in electrical and computer engineering from the University of Porto, Porto, Portugal, in 1990, 1995, and 1999, respectively. He is currently a Professor with the Computer Engineering Department, School of Engineering (ISEP), Polytechnic Institute of Porto (IPP), where he is also involved in research on real-time distributed systems, wireless sensor networks, multiprocessor systems, cyber-physical systems, and industrial communication systems. He heads the Research Unit, Real-Time and Embedded Computing Systems Research Centre (CISTER), an internationally renowned research center focusing on RTD in real-time and embedded computing systems. He is deeply involved in research on real-time distributed systems, multiprocessor systems, cyber-physical systems, and industrial communication systems. Since 1991, he has authored or coauthored more than 150 scientific and technical articles in the area of real-time and embedded computing systems, with an emphasis on multiprocessor systems and distributed embedded systems. He was for five years, until December 2015, a member of the Executive Committee of the IEEE Technical Committee on Real-Time Systems (TC-RTS). He is currently the Vice-Chair of ACM SIGBED (ACM Special Interest Group on Embedded Computing Systems). He has been consistently participating in top-rated scientific events as a member of the Program Committee, as the Program Chair, or as the General Chair. He has been the Program Chair/Co-Chair of ECRTS 2005, the IEEE RTCSA 2010, the IEEE RTAS 2013, or the IEEE RTCSA 2016, all in the area of real-time computing systems. He has also been the Program Chair/Co-Chair of other key scientific events in the area of architectures for computing systems and cyber-physical systems as is the case of ARCS 2014 or the ACM/IEEE ICCPS 2016 or in the area of industrial communications (IEEE WFCS 2014).

Mohsen Guizani (S'85–M'89–SM'99–F'09) received the B.S. (Hons.) and M.S. degrees in electrical engineering and the M.S. and Ph.D. degrees in computer engineering from Syracuse University, Syracuse, NY, USA, in 1984, 1986, 1987, and 1990, respectively. He served as the Associate Vice President for Graduate Studies at Qatar University, the Chair of the Computer Science Department, Western Michigan University, and the Chair of the Computer Science Department, University of West Florida. He also served in academic positions at the University of Missouri–Kansas City, the University of Colorado at Boulder, Syracuse University, and Kuwait University. He is currently a Professor with the Department of Computer Science and Engineering, Qatar University. He is the author of nine books and more than 500 publications in refereed journals and conferences. His research interests include wireless communications and mobile computing, computer networks, mobile cloud computing, security, and smart grid. He is a Senior Member of ACM. He also served as a member, the chair, and the general chair for a number of international conferences. He was a recipient of the Teaching Award multiple times from different institutions as well as the Best Research Award from three institutions, the 2017 IEEE ComSoc Recognition Award for his contribution to wireless communications. He was the Chair of the IEEE Communications Society Wireless Technical Committee and the TAOS Technical Committee. He served as the IEEE Computer Society Distinguished Speaker from 2003 to 2005. He currently serves on the editorial boards of several international technical journals and the Founder and the Editor-in-Chief for the *Wireless Communications and Mobile Computing* journal (Wiley). He guest edited a number of special issues in IEEE journals and magazines.