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An Infrastructure-Assisted Message Dissemination for Supporting Heterogeneous Driving Patterns

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***Abstract*— With the advances of Internet of Things (IoT) technologies, individual vehicles can now exchange information to improve traffic safety, and some vehicles can further improve safety and efficiency by coordinating their mobility via cooperative driving. To facilitate these applications, many studies have been focused on the design of inter-vehicle message dissemination protocols. However, most existing designs either assume individual driving pattern or consider cooperative driving only. Moreover, few of them fully exploit infrastructures, such as cameras, sensors, and road-side units (RSUs). In this paper, we address the design of message dissemination that supports heterogeneous driving patterns. Specifically, we first propose an infrastructure-assisted message dissemination framework that can utilize the capability of infrastructures. We then present a novel beacon scheduling algorithm that aims at guaranteeing the timely and reliable delivery of both periodic beacon messages for cooperative driving and event-triggered safety messages for individual driving. To evaluate the performance of the protocol, we develop both theoretical analysis and simulation experiments. Extensive numerical results confirm the effectiveness of the proposed protocol.**

***Index Terms*—Heterogeneous driving pattern, beacon, event-triggered message, infrastructure-assisted, protocol, analytical model**

I. Introduction

In recent years, the advances of Internet of Thing (IoT) have greatly promoted the development of intelligent transport systems (ITS). Specifically, by the aid of the advanced sensing, vehicular communication and computing technologies, an individual vehicle can quickly detect traffic anomalies and then notify neighboring vehicles so as to improve traffic safety. Moreover, a group of vehicles with common interests can drive in a cooperative manner, namely *cooperative driving*, which can further improve transportation efficiency and traffic safety [1]–[3]. For example, the E.U.-sponsored SARTRE project demonstrated that a group of trucks can adopt cooperative driving and move with a speed of 90 km/h and only 6 meters between adjacent vehicles [1]. To support the cooperative driving pattern, vehicles in the same group shall periodically sense their kinetic status (e.g. speed, position, acceleration) and broadcast such information to other vehicles in the same group, and then each vehicle can adopt a suitable control law to achieve a certain objective, such as maintaining a constant inter-vehicle spacing [4], [5].

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Clearly, the heterogeneous driving patterns consisting of both cooperative driving and individual driving will prevail on roads in the near future. To facilitate the scenarios, a critical challenge is how to quickly and reliably deliver messages, including both event-triggered messages for vehicles driving individually, and periodic messages for vehicles driving cooperatively. To provide *inter-vehicle communication* (IVC), most existing studies are based on the IEEE 802.11p/ITS-G5 protocol [1], the current defacto vehicular networking standard. Using this protocol, event-triggered messages (e.g. safety warnings) can be disseminated according to a contention-based *carrier-sense multiple access with collision avoidance* (CSMA/CA) scheme, while periodic messages can be sent by using the beacon mechanism, which is a schedule-based time-division multiple access (TDMA) scheme.

Since IEEE 802.11p provides the basic functionality for IVC, many message dissemination schemes have been developed in the past few years [6]–[8]. Although these studies are fundamentally important, there are two major issues that have not been fully addressed. First, most existing message dissemination schemes ignore the impact of emerging hybrid traffic scenarios, i.e., on the same road, some vehicles are driving individually while others are driving cooperatively in multiple groups. Second, most existing studies design distributed communication schemes among vehicles, which cannot fully utilize the advanced capability of infrastructure, such as sensors/cameras deployed along the road, and road side units (RSUs) for communications.

In this study, we consider the realistic heterogeneous traffic flow which consists of both cooperative driving and individual vehicles in a connected environment, as shown in Fig. 1. Typically, a cooperative driving system (CDS) consists of several members and one leader (e.g. platoon leader) which manages and controls certain type of cooperative driving such as vehicle platooning or clustering. On the other hand, infrastructure can be deployed along the road, including RSUs for vehicular communication and sensors/cameras that can collect local traffic status [9]. Based on these facts, we systematically investigate how to support reliable message dissemination in a hybrid traffic scenario by fully utilizing the context awareness of roadside sensors as well as the vehicle-to-infrastructure (V2I) communication that combines both centralized and distributed approaches. Specifically, we

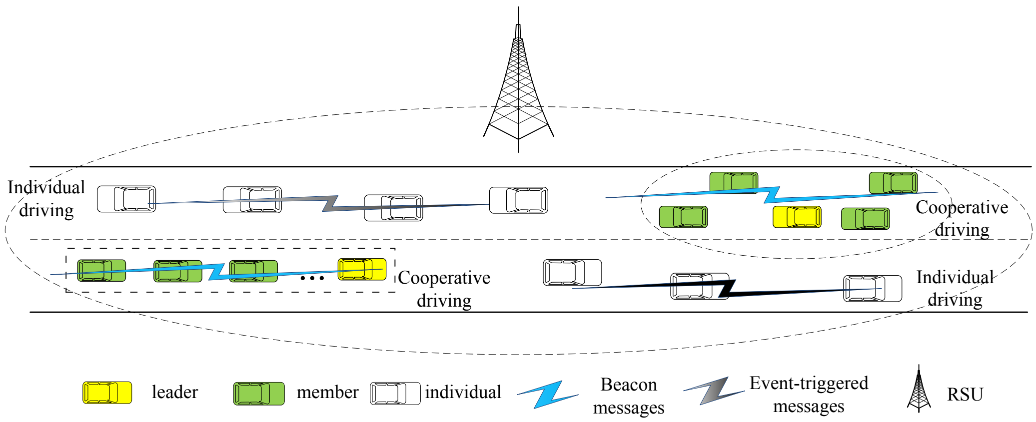

Fig. 1. An example for hybrid traffic with both cooperative driving and individual driving.

propose different message dissemination strategies for both cooperative driving vehicles and individual vehicles. Our main contributions in this paper are as follows:

- We propose a general framework for Infrastructure-assisted Beacon and Safety message Dissemination (IBSD) that takes advantages of centralized and decentralized approaches to support the heterogeneous driving pattern.
- Based on the collected traffic dynamics and communication situations, we select RSUs as the coordinators to arrange beacon schedule for multiple CDSs in bidirectional roads to avoid communication collisions.
- We adopt the TDMA-like MAC mechanism for the CDS beaconing to improve transmission reliability, while utilize CSMA-based MAC protocols for the safety message to maximize the channel utilization.
- We validate the efficiency of the proposed infrastructure-assisted message dissemination algorithms by analytical model and extensive simulation experiments under various traffic scenarios with different vehicular networking settings.

The rest of this paper is organized as follows. In Section II, we first discuss related work about message dissemination schemes in vehicular ad-hoc networks. In Section III, we present the infrastructure-assisted message dissemination framework and the main assumptions and specifications, then we propose a comprehensive dissemination scheme for both periodical beaconing messages and event-triggered safety messages in Section IV, and we theoretically analyze the performance of the proposed scheme in Section V. Finally, in Section VI, we validate our design and analysis through extensive simulation experiments, before concluding the paper in Section VII.

II. Related Work

In this section, we discuss related work about periodical beacon dissemination and event-triggered safety message dissemination in vehicular networking.

To improve the performance of information exchange in vehicular networking, many beacon dissemination schemes have been proposed which can be classified into two categories: centralized scheme and distributed scheme. The main idea for typical centralized beaconing scheme is that vehicles are grouped into a cluster in which the cluster head is responsible for allocating TDMA slots to other cluster members [8], [10], [11]. In [8], the authors proposed a contention-free broadcast protocol for periodic safety messages in vehicular networks. The time slot reservation schedule managed by the cluster head can dynamically adjust with traffic situations. Moreover, the overhead is reduced by using single reservation request for a periodic medium access during a vehicles cluster session. In [10], the authors presented a cluster-based TDMA scheduling protocol for Vehicular Ad-Hoc Networks (VANETs), in which the collision-free intra-cluster communications were organized by the cluster head using a TDMA scheme.

In the distributed beacon dissemination scheme, the beacon sending rate and frequency are adjusted by vehicles according to the channel condition or some other requirements of specific applications. Also, the slot allocation is always self-configured when TDMA-based beacon scheme is applied. The authors of [12] developed an algorithm named Dynamic beaconing (DynB), with which each vehicle decreases/increases its beacon rate if the channel load is higher/lower than the desired one. In [13], the authors developed a linear rate-control algorithm, called LIMERIC, which is configurable by means of two parameters that control fairness, stability, and steady state convergence. In [14], a distributed transmission power control approach was proposed to maximize the minimum value over all transmission power levels assigned to nodes under a maximum load constrain.

Recently, some beaconing strategies have been designed specifically for typical cooperative driving applications e.g., platooning. For instance, the authors in [15] proposed the VeSOMAC protocol in which the MAC slots in a highway platoon are time ordered based on the vehicles locations, to minimize the multi-hop delivery delay of ITS safety messages. A bitmap vector packet headers is designed in this paper for exchanging relative slot timing information across the 1-hop and 2-hop neighbor vehicles. Simulation shown that VeSOMAC can offer better vehicle safety through smaller and bounded packet latency. In [16], the authors evaluated the co-existence of periodic and event-driven data traffic in a safety-critical platooning application. An event-based safety message dissemination strategy was proposed to support vehicle platooning application. [17] proposed a dynamic information dissemination protocol named "Jerk" for platooning which exploits vehicle dynamics to send beacons only when needed. The protocol showed that the beaconing frequency can be less than 10Hz when the control qualities do not change. In this way the channel load can be reduced and thus may improve the delivery of safety messages.

Another type of message dissemination is the event-triggered safety message dissemination, which is normally contention-based. In the literature, existing schemes can be divided into two categories: infrastructure-free and infrastructure-based. Due to the implementation simplicity, most current studies on the safety message dissemination assume an infrastructure-free VANET. In these studies, a source vehicle broadcasts the safety message to destination vehicles through the relay vehicles in its communication range. Thus, a typical problem is how to select an optimal set of relay vehicles, while another classic problem is how to broadcast messages. Specifically, in a delay-based approach, a different waiting delay is assigned to each receiving vehicle before rebroadcasting the packet, and the vehicle with the shortest waiting delay acquires the opportunity in rebroadcasting the packet [6], [18], [19]. In probabilistic-based broadcasting, each vehicle rebroadcasts a packet according to its assigned rebroadcast probability [20]–[22].

In an infrastructure-based VANET, RSUs are deployed on the roadside to collect and delivery messages, which can improve the message delivery ratio and reduce delivery delay. For instance, [23] considers a model in which future trajectories of vehicles can be acquired so that certain roadside units are selected as relays to forward packets to the destination vehicles. In [24], the authors formulated the coexisting problem of packet forwarding and buffer allocation as a knapsack problem, and then designed centralized and distributed algorithms.

Although the aforementioned protocols are important to support efficient and reliable message dissemination among vehicles, few of which consider the realistic heterogeneous driving patterns consisting of diversities of cooperative driving and individual driving. Moreover, the IoT related technologies, such as the context awareness of roadside sensors and V2I communication, have not been fully utilized in the literature. Motivated by these facets, we design an infrastructure-assisted beacon/safety message dissemination scheme in this paper.

III. Message Dissemination Framework

This section describes the proposed message dissemination framework and the main assumptions and specifications. To facilitate further discussions, we first summarize the symbols and notations in Table I.

TABLE I
SYMBOLS AND NOTATIONS.

IVC	inter-vehicle communication
RSU	road-side unit
CDS	cooperative driving system
TS	TDMA-based period
TC	contention-based period
CCHI	control channel interval
S	inter-RSU distance
R_V	V2V transmission range
R_I	V2I transmission range
α	vehicle acceleration
ε	communication channel quality
F	beaconing frequency of member
k_m	number of slots for beaconing of member
T_t	duration for TDMA-based period in CCHI
T_c	duration for CSMA-based period in CCHI
T_{CCH}	duration of a CCHI

A. Infrastructure-assisted Message Dissemination Framework

For a typical hybrid traffic shown in Fig. 1, the message dissemination objective in this paper is to provide reliable beacons for cooperative driving vehicles and effective event-triggered messages for individual vehicles, respectively. To this end, we take advantage of RSUs deployed along the roadside. The main idea for message dissemination is: based on the current situation awareness by collecting local traffic/VANET information, RSUs dynamically adjust radio resource allocation for both beacons and event-triggered message dissemination, then periodically broadcast the optimal allocation to local vehicles. Accordingly, the vehicles within the RSU's coverage will cooperatively reschedule their message dissemination.

Fig. 2 demonstrates a general framework to support message dissemination in heterogeneous driving patterns with the help of RSUs. Specifically, local situation awareness at RSU is achieved by collecting information in two ways: V2X-communication based information which may include kinetic status of the CDS and local channel quality, and sensor-based (e.g. camera) information such as traffic density estimation. Consequently, both types of information can capture the local traffic/VANET situation from both microscopic and macroscopic perspectives.

Since we choose IEEE 802.11p/ITS-G5 protocol families, in which all messages are disseminated in control channel intervals (CCHIs), we adopt the TDMA-like MAC mechanism for the CDS beaconing to improve transmission reliability, while utilize CSMA-based MAC protocols for the safety message to maximize the channel utilization. Accordingly, two issues regarding resource allocation should be carefully addressed: how to timely allocate the suitable time division for cooperative driving and individual driving, respectively, and how to schedule beaconing sequence among multiple CDSs. The details in message dissemination design will be presented in the follow section.

B. System Assumptions and Specifications

The specifications and assumptions for the system are summarized as follows.

1) Each vehicle is equipped with the communication module which integrates IEEE 802.11p/ITS-G5 protocols and a GPS (Global Positioning System) receiver, as well as on-board sensors to detect the vehicles kinetic status.

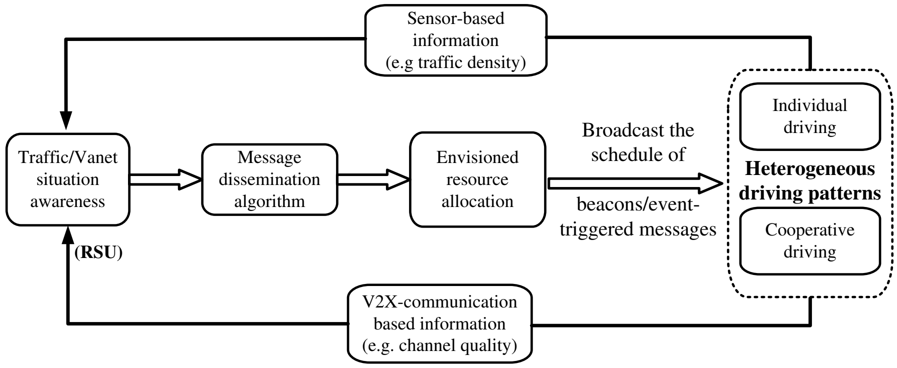

Fig. 2. RSU-assisted message dissemination framework for heterogeneous driving patterns.

2) All vehicles within the same CDS can connect with each other, and the impact of CDS length is ignored to simplify the theoretical analysis.
3) RSUs are uniformly distributed along the road with the gap S and the corresponding fixed V2I transmission range R_I.
4) Roadside sensors are deployed along the road within the RSU's coverage to guarantee timely collecting local traffic information and reporting to the RSU.

IV. Beacon And Safety Message Dissemination

In this section, we illustrate in detail the proposed infrastructure-assisted time allocation scheme for cooperative driving and event-based safety messages dissemination scheme for individual vehicles, wherein a more common scenario with multiple CDSs and a number of individual vehicles on a road is considered.

We adopt the TDMA-like MAC mechanism for the CDS beaconing to improve transmission reliability, while utilize CSMA-based MAC protocols for the safety message to maximize the channel utilization. The main ideas of our method are: 1) CDSs' beacons are assigned at appropriate time slots by RSUs in a centralized manner to avoid beacon collision among adjacent CDSs and maximize the channel utility at the same time. 2) Time duration for each CDS is adaptively allocated by the RSU's periodical broadcasting according to the current channel quality and the traffic dynamics. 3) For individual vehicles, safety message sending time is dynamically regulated in a distributed manner to avoid the collision with the CDSs' beacons.

A. Frame Structure

For convenience, we define *slot* as unit time duration for single beacon/message dissemination, and *beaconing block* as time duration for a CDS beaconing process. It shall be noted that beaconing block is composed of several continuous slots and cannot be split. In addition, different CDSs may have different beaconing blocks in dynamic traffic situations.

Based on the aforementioned main ideas, a CCHI is divided into a TDMA-based period (TS) for beacon dissemination and a contention-based period (TC) for safety message dissemination, as shown in Fig. 3. TS contains one slot reserved for RSU's broadcasting (beacon scheduling message) and several beacon blocks for CDSs beaconing. The periodical broadcasting message from the RSU specifies the beacon scheduling information for all CDSs within the communication coverage, including the start slot and end slot of each CDS, real-time geographical position, and the moving direction. The TC period employs the CSMA protocol, mainly used for event-based safety message dissemination and the newly coming CDS to send a request message to the RSU for joining in the centralized beacon block schedule.

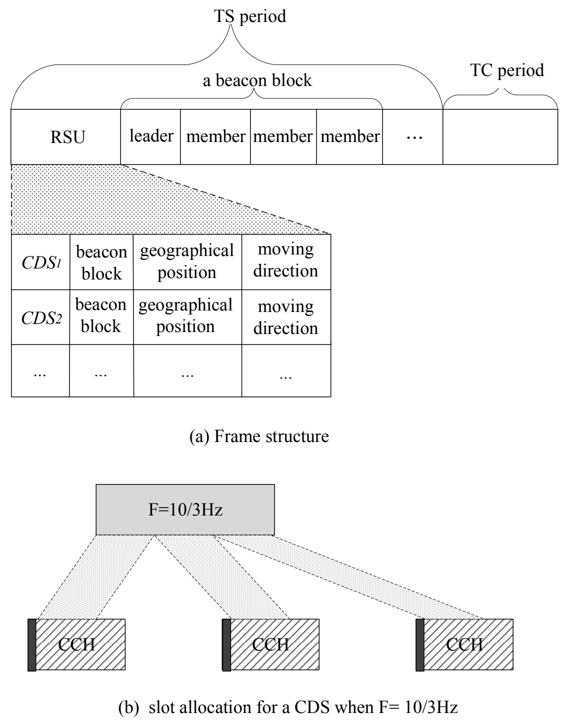

Fig. 3. Frame structure.

The system working process is as follows. When a CDS runs outside of any RSU's coverage, it implements a self-configuring slot allocation algorithm and adaptively arranges TS to avoid the collision with neighboring CDSs, which has been discussed in our previous work [25]. In case the CDS enters the coverage of an RSU and receives the first broadcast message from the RSU, the leader will create a request message which contains moving direction, geographical position, velocity setting, number of members, etc., and send the message to the RSU via the sensor within the communication range. If successful, it will periodically receive the beacon scheduling message from the RSU which includes its ID and the allocated beaconing block in TS period. Otherwise, it should resend the request message. Similarly, when the CDS leaves the RSU's coverage and cannot receive the periodical message from the RSU for several consecutive CCHIs, it will send a leaving message to the RSU via roadside sensors to report its current position. Accordingly, the RSU removes its record from the beacon scheduling message.

B. Centralized Time Allocation for Cooperative driving

To avoid communication collision among neighbouring CDSs, in [25], we set up a series of rules to let the leader rearrange the TDMA-based period and temporarily choose the slots next to overlapping slots. However, due to lack of the central coordinator for the time slot allocation, the leader can only adjust its time slot when it detects communication collisions surroundings, which may lead to a sharp dropping of beacon reception ratio.

To solve this problem, we select RSU as the centralized coordinator of time slots allocations for each CDS within its coverage. In more detail, based on the collected both V2X-communication based information and sensor-based information, the RSU is supposed to decide the sequence of time allocation and the corresponding beaconing block for each CDS.

1) Scheduling Beaconing Block for CDSs: We set up a series of rules to regulate the time sequence of CDSs' beacons within the coverage of RSU.

(a) To avoid beacon collision, all neighbouring CDSs within the V2V transmission range are allocated with non-overlapping slots.
(b) To maximize the channel utilization, any two CDSs out of each other's communication range can be allocated with the same slot.
(c) The RSU preferentially allocate the most front available slot of the TS period for the CDS, which guarantees the minimum length of TS.
(d) Rescheduling Trigger: when one CDS within the RSU's coverage meets the one outside, the former will keep its beaconing slots unchanged. If the gap between any two CDSs within the coverage of RSU is approaching or leaving certain threshold value (normally a bit larger than V2V communication range), the RSU will reschedule the related CDSs time slot to avoid beaconing collision in the new situation.

Fig. 4 describes a typical scenario in which CDS A follows B on the east direction, C drives to the west direction. A and B are in each other's communication range. To simplify the demonstration, we assume all CDSs keep the constant and same speed within the RSU's coverage.

Initially, A and C out of each other's communication range are allocated at the beginning of TS period based on Rule (b) and (c), as shown in Fig. 4 (a). As B is in the communication range of the front CDS A, it is allocated the following slots behind A according to Rule (a). Once A drives in the communication range of C, i.e. approaching event, the RSU will delay C's beacon block to avoid slot overlapping from A. The following Fig. 4 (b)-(e) illustrate the beacon block scheduling process regulated by the rules we set up.

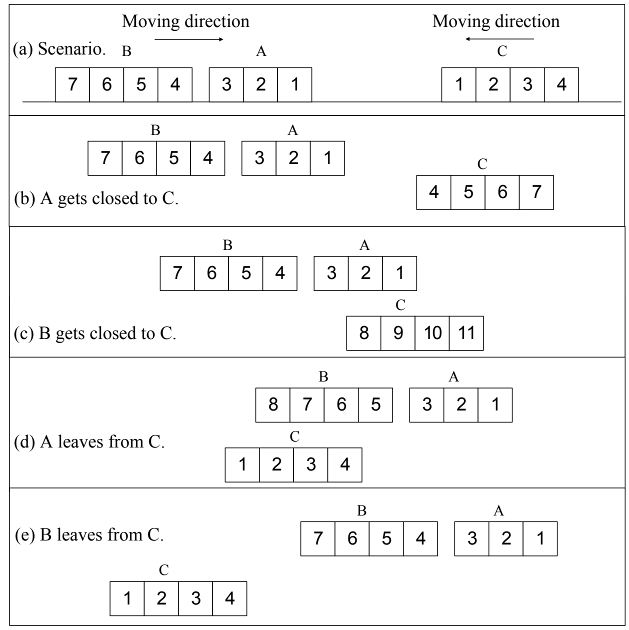

Fig. 4. An example of beaconing block schedule.

2) Beaconing Block Estimation: Based on the context of current traffic dynamics and vehicular communication, RSU is supposed to estimate a suitable beaconing block for each CDS within its coverage.

In a typical CDS, a vehicle drives cooperatively with its neighbours, in which the vehicle may obtain local information from the neighbours via IVC communication.

Moreover, the recent work showed that the globally achievable leaders information plays a critical role for the stability of cooperative driving [5], and furthermore, and the acceleration of the leader affects the dynamics of traffic flow and that such information helps stabilize traffic flow under a small perturbation [26]. Therefore, the leader's beacon is set as a fixed higher frequency (normally 10Hz beaconing frequency is suitable for a typical CDS [4], [27]) and starts transmitting at the beginning of beaconing block.

For the slot allocation of members, the beaconing frequency F of members can be dynamically adjusted based on the current local channel quality ε and the CDS dynamics, i.e. acceleration α, to guarantee the CDS performance and alleviate channel congestion at the same time. Consequently, the beacon block duration of each CDS can be estimated by $T = 1 + \frac{10F}{\text{Number of members}}$.

To evaluate local channel quality, we adopt the similar method proposed in [28], [29] by means of three metrics: (1) number of neighbors estimated by local roadside sensors, (2) the collisions on the channel observed by the leader, and (3) the Signal to Noise Ratio (SNR) on the channel measured by the leader. Based on these metrics which capture the quality of the channel in the past, present, and future, the RSU can derive a metric of the overall channel quality ε which is a linear combination of the three metrics, ranging in the interval [0,1] (lower values describing a better channel10/ quality).

Accordingly, the RSU estimates an adaptive beaconing frequency for the ensured CDS based on current α and ε. Specifically, we define three states of beaconing frequency in $\{F_{min},\ F_{def},\ F_{max}\}$. In general, the bigger α is, the higher F is demanded. On the other hand, excessive number of beacons may lead to serious packet collision as well as channel overload, and accordingly, degrades the packet transmission ratio. As a result, there is a tradeoff to decide F, probably remaining a fixed value or even being reduced. In this paper, We adopt the same rules in [25] to decide beaconing frequency:

(a) In state F_{min}, the state shall be switched to F_{def} if $\alpha_L < \alpha <= \alpha_H$ and $\varepsilon <= \varepsilon_H$, to F_{max} if $\alpha > \alpha_H$ and $\varepsilon <= \varepsilon_H$.
(b) In state F_{def}, the state shall be switched to F_{min} if $\alpha <= \alpha_L$ and $\varepsilon > \varepsilon_L$, to F_{max} if $\alpha > \alpha_H$ and $\varepsilon <= \varepsilon_H$.
(c) In state F_{max}, the state shall be switched to F_{min} if $\varepsilon > \varepsilon_H$, to F_{def} if $\alpha <= \alpha_H$ and $\varepsilon_L < \varepsilon <= \varepsilon_H$.

It shall be noted that, for a CDS member, beacon dissemination with the frequency F means each beacon is sent by the member every $10/F$ CCHI. For instance, 10/3 Hz means each member sending only one beacon every three CCHI, as illustrated in Fig. 3(b).

C. Algorithm for Beaconing Block Schedule

As mentioned in Section IV-B, in case of any two CDSs i and j approaching or leaving to each other's transmission range, they will rearrange their beaconing blocks. Accordingly, the CDSs within the single-hop range of them have to reschedule their beaconing blocks to match this rearrangement. As a result, the possible CDSs to be involved in the beaconing block reschedule are within the multi-hop range of both CDS i and j, as shown in Fig. 5. With the knowledge of the locations of all CDSs, the RSU can easily obtain the multi-hop neighbors of any CDS within the RSU's coverage.

The procedure of beaconing block schedule is as follows. First, the RSU obtains the both multi-hop neighboring CDSs sets $\mathcal{N}_i^m$ and $\mathcal{N}_j^m$ for CDS i and j (including themself). It shall be noted that $\mathcal{N}_i^m$ and $\mathcal{N}_j^m$ could be the same set in the approaching event between CDS i and j. Second, the RSU goes through the two subsets within single transmission range R_V from both $\mathcal{N}_i$ and $\mathcal{N}_j$, respectively, denoted by $\mathcal{N}_{i,k}^s, k \in \mathcal{N}_i^m$ and $\mathcal{N}_{j,k}^s, k \in \mathcal{N}_j^m$, then identifies the ones with the longest total beaconing blocks, denoted as $\bar{\mathcal{N}}_i^s$ and $\bar{\mathcal{N}}_j^s$. Third, the RSU first allocates the beacon blocks of CDSs in $\bar{\mathcal{N}}_i^s$ and $\bar{\mathcal{N}}_j^s$ at the beginning of TS period, in which the CDSs are ordered by the length of beaconing blocks. Last, the remaining CDSs in $\mathcal{N}_i^m - \bar{\mathcal{N}}_i^s$ and $\mathcal{N}_j^m - \bar{\mathcal{N}}_j^s$ are allocated the slots according to the rules set up in section IV-B1.

The pseudo-code for beaconing blocks scheduling algorithm is as Algorithm 1.

Algorithm 1 scheduling algorithm of beacon blocks

Input: CDS i and j with approaching/leaving event
Output: The beacon blocks reschedule for all related CDSs.

```
Obtain the multi-hop neighboring CDSs sets N_i^m and N_j^m for CDS i and j.
Order CDSs in N_i^m and N_j^m by the geographical position.
for each CDS k ∈ N_i^m do
    Obtain single-hop neighboring CDSs set N_{i,k}^s
    L_k^s = Σ_{m ∈ N_{i,k}^s} L_m
    if T_t < L_k^s then
        T_t = L_k^s
        N̄_i^s = N_{i,k}^s
    end if
    clear N_{i,k}^s and L_k^s
end for
Calculate N̄_j^s in the same way.
RSU allocates the beacon blocks of CDSs in N̄_i^s and N̄_j^s at the beginning of TS period.
The remaining CDSs in N_i^m − N̄_i^s and N_j^m − N̄_j^s are allocated the slots according to the rules set up in section IV-B1
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D. Safety Message Dissemination for Individual Vehicles

In general, safety message dissemination of individual vehicles is event-triggered. Due to the coexistence of beacons and safety messages, the envisioned safety message dissemination scheme for individual vehicles is to not only guarantee the safety message transmission performance, but also avoid impairing the beaconing process of the CDS.

As stated previously, safety messages are supposed to be disseminated within the TC period. To do that, individual vehicles need to estimate the start time of TS and its duration T_t. In case of no RSU's assistance, the individual vehicle overhears the packets from neighbors and obtains the packet type (This can be identified based on the different packet length of beacons and safety messages), analyzing the corresponding received packet temporal distribution. The duration of T_t can be approximately estimated by the unique distribution profile.

In the infrastructure-assisted slot allocation scheme, an individual vehicle can timely receive the locations and beacon blocks of the CDSs surroundings from the periodical broadcast of the RSU. Thus, it can calculate the available TS period within its communication range. Accordingly, those messages generated during T_S period will be delayed to TC period for dissemination.

Although the RSU can provide an optimal beaconing block schedule for CDSs to minimize the TS period and improve the channel utilization, there still exists a relationship between the number of CDSs and safety message transmission ratio of individual vehicles, which will be analyzed in the next section.

V. Analytical Model for Performance Evaluation

In this section, we theoretically analyze the system performance of the proposed IBSD scheme. Specifically, we first analyze the performance of the algorithm for beaconing

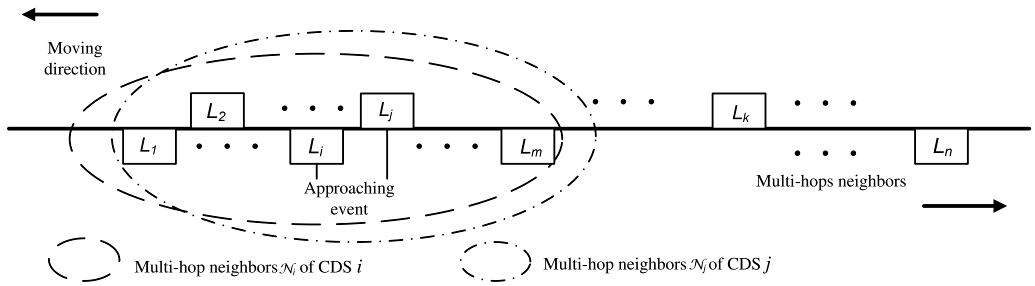


Fig. 5. Distribution of CDSs in the RSU coverage.

TABLE II
SYMBOLS AND NOTATIONS FOR THE ANALYTICAL MODEL.

PTR	Beacon/safety message transmission ratio
PRR	Beacon/safety message reception ratio
v_c	average velocity of CDS
φ	duration of a slot for beaconing
ϱ	duration of backoff slot
λ_c	number of CDSs per meters
λ_d	number of individual vehicles per meters
λ_s	safety message generation rate
P_i	safety message transmission ratio for an individual vehicle
P_{lr}	beacon reception ratio for leader
P_{mr}	beacon reception ratio for member
P_{ir}	safety message reception ratio for an individual vehicle
P_{uns}	probability that an individual vehicle transmits in a randomly slot under unsaturated situation with our scheme
N_c^m	number of CDSs within multi-hop range
N_c^s	number of CDSs within single-hop range
L_i	duration of beaconing block of CDS i
L_i^s	total beaconing blocks for all CDSs within single-hop range of CDS i

block schedule proposed in Section IV-C in terms of channel resource occupancy and the event occurrence which reflect the RSU working overload. Then we investigate the safety message dissemination performance of individual vehicles in terms of message transmission ratio. Lastly, we analyze the message reception ratio for both beacon and safety message dissemination.

Traffic flow distribution models have been developed since the 1960s, and some representatives include exponential distribution, normal distribution, gamma distribution, and log-normal distribution [30]. Nevertheless, the distributions of individual vehicles and CDSs in a hybrid traffic scenario are still not clear at the current stage because cooperative driving has been evaluated mainly in simulation or in testing environment. To simplify the analysis in the remaining part of this section, we assume that the CDSs and individual vehicles in either direction follow Poisson distribution with the mean value of λ_c and λ_d, respectively, and that safety messages generated from individual vehicles are subject to a Poisson distribution with average λ_s in the time domain [1]. In addition, we assume the length of beaconing block L_i for a CDS i is independent and identically distributed with mean μ and standard deviation σ, and independent of the CDS spatial distribution. The symbols and notations in this section are summarized in Table II.

A. Performance Analysis of Beaconing Block Schedule and Safety message dissemination

We first analyze beaconing block schedule performance of CDS. It is easy to conclude that the distance between any two adjacent CDSs at the time t follows an exponentially distributed with density $2\lambda_c$. Thus the expected number of CDSs within the single-hop range can be given by:

$$\mathbb{E}(N_c^s) = 2\lambda_c R_V \tag{1}$$

Accordingly, for any CDS i, the total beaconing blocks of all single-hop neighboring CDSs L_i^s is subject to compound Poisson distribution. We can further estimate the expected value of L_i^s:

$$\mathbb{E}(L_i^s) = \mathbb{E}(N_c^s)\mathbb{E}(L_i) = 2\mu\lambda_c R_V \tag{2}$$

and the variance of L_i^s

$$\mathbb{V}ar(L_i^s) = 2(\sigma^2 + \mu^2)\lambda_c R_V \tag{3}$$

which can be considered as the average indicators of the shortest T_t, i.e. the longest available T_c for individual vehicle message dissemination. However, due to spatially uneven distribution of L_i^s at any time t, it is impossible for individual vehicle to obtain the longest T_c at each beaconing block reschedule timestep. Moreover, larger variance of L_i^s will lead to the deterioration of available T_c allocation for individual vehicles. On the other hand, based on Eq. (3), it can be concluded that reducing V2V communication range and variance of L_i will potentially improve the efficiency of beaconing block schedule.

Next, we evaluate the event occurrence which may reflect the RSU working overload. Let N_c^m denote the number of CDSs within multi-hop range, then the expected value of N_c^m can be easily calculated by:

$$\mathbb{E}(N_c^m) = \frac{1}{e^{-2\lambda_c R_V}} \tag{4}$$

For any CDS i, the expected number of events caused by CDS i when passing through the RSU's coverage is

$$\mathbb{E}(N_i^e) = 4\lambda_c R_I \tag{5}$$

Assuming all CDSs drive approximately at the constant speed v_c, then the expected event occurrence at unit time can be approximately calculated by:

$$\mathbb{E}(N^e) = \frac{\mathbb{E}(N_i^e)\mathbb{E}(N_c^m)}{2R_I/v_c} = \frac{2\lambda_c v_c}{e^{-2\lambda_c R_V}} \tag{6}$$

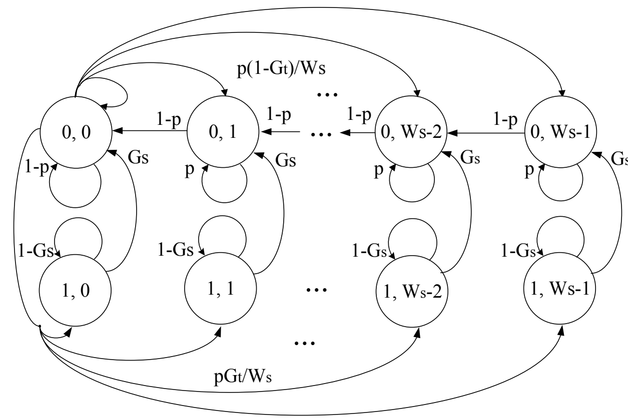


Fig. 6. Markov chain for the channel contention.

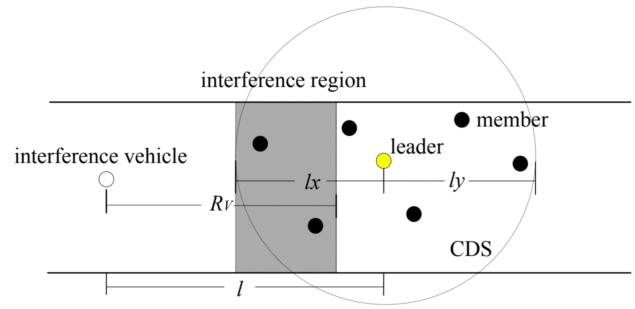


Fig. 7. Illustration of interfered region.

Finally, we analyze safety message transmission ratio (PTR) for individual vehicles, which can be calculated by the probability that no other vehicles within transmission range send packets at the same time slot. For an arbitrary individual vehicle, the contention process can be characterized by a two-dimensional Markov chain as illustrated in Fig. 6, in which each state variable is represented by $\{s(t), b(t)\}$, where $s(t) \in \{0, 1\}$ represents that the vehicle has a safety message ready for transmission during non-TC or TC period, and $b(t) \in \{0, 1, 2, ..., W_e - 1\}$ represents the backoff time counter. The transition probability of the Markov chain can be derived as follow:

$$\begin{cases} P\{0, k|0, k+1\} = 1 - p, k \in [0, W_s - 2] \\ P\{0, k|0, k\} = p \\ P\{0, k|0, 0\} = p(1 - G_t)/W_s \\ P\{1, k|0, 0\} = pG_t/W_s \\ P\{0, k|1, k\} = G_s \\ P\{1, k|1, k\} = 1 - G_s \end{cases} \tag{7}$$

where apart from the first line, $k \in \{0, 1, 2, ..., W_s - 1\}$. G_t and G_s are supposed to be constant and independent values. G_t is the probability that a safety message is generated in non-TC period, while G_s is the probability that the safety message is ready to send. Since the safety messages are generated uniformly over time, $G_t = \frac{T_t + T_{SCH}}{T_{CCH} + T_{SCH}}$, and $G_s = \frac{T_c}{T_{CCH} + T_{SCH}}$. Let $b_{i,k} = \lim_{t \to \infty} P\{s(t) = i, b(t) = k\}$, and T'_{ss} denotes the average service time, Thus the probability that an individual vehicle transmits in a randomly chosen slot time can be calculated as

$$P_{uns} = b(0, 0)(1 - e^{-\lambda_s T'_{ss}}) \tag{8}$$

P_i can be calculated as

$$P_i = (1 - P_{uns})^{2R_V \lambda_d} \tag{9}$$

According to Eq. (2), we can roughly derive the relationship between the transmission ratio of individual vehicles and the number of CDS moving in the RSU coverage. Based on the relationship, we can know the block schedule capacity of the RSU under a specific transmission ratio of individual vehicles. Thus, we can limit the number of CDSs in the coverage of RSU when a higher safety message transmission ratio is needed.

B. Beacon/safety message Reception Ratio

Due to potential simultaneous broadcasts (failure of random back-off) and the presence of hidden nodes, not every targeted receiver can receive the broadcast message successfully. Beacon/safety message reception ratio (PRR) is defined as the ratio of the number of vehicles successfully received the Beacon/safety message to the number of target nodes. P_{lr} for leader indicates the proportion of members which receive the beacons from the leader. It is assumed that the leader locates at 0, and the position of given effective interference source vehicle X, Y and Z is within $(-l_x - R, -l_x]$, $(-l_x, l_y]$, and $(l_y, l_y + R]$, as illustrated in Fig. 7. P_{lr} can be derived as:

$$P_{lr} = \int_{-l_x - R}^{-l_x} \int_{-l_x}^{l_y} \int_{l_y}^{l_y + R} (1 - \frac{\bar{N}_{IR}}{N_m}) P(X = x) P(Y = y) P(Z = z) dx dy dz \tag{10}$$

where $\bar{N}_{IR}$ is the mean number of vehicles within the interfered region (IR), N_m is the number members, and $P(X = x)$ is the probability that an effective interference source locates at $-x$ which can be expressed as: $P(X = x) = \bar{r}_x \lambda_d e^{x \lambda_d \bar{r}_x}$, in which $\bar{r}_x$ is the average transmission rate within $(-x, -l_x)$. P(Y=y) and P(Z=z) can be calculated in the same way [31]. Similarly, we can also obtain P_{mr} and P_{ir}.

VI. Numerical Results

In this section, we first describe the experiment settings, then evaluate the performance for the proposed IBSD protocol.

A. Simulation Settings

In our experiments, we choose the Veins simulator [32], which combines OMNeT++ for event-driven network simulation and SUMO for the generation of traffic environment and vehicle movement. For the traffic scenario, we consider a 10-kilometer bidirectional highway segment with 4 lanes in either direction (one for CDS), on which the traffic flow is composed of several CDSs and individual vehicles. Specifically, we choose *platoon*, the typical cooperative driving application, as the representative of CDS. In addition, the individual vehicles are moving with speeds from 12m/s to 41m/s and

TABLE III
PARAMETERS SETTING OF IVC.

Parameter	Value
Phyical/Mac protocol	IEEE802.11p
Path loss model	Free-space (α=2)
Fading Model	Nakagami-m (m=3)
Transmission power	20 dBm
Safety message rate λ_s	5 packets/sec
Beacon frequency for leader	10 Hz
Beacon slot time φ	0.5 ms
Min.CW for safety message	3
CW for beacon	15
CSMA/CA time slot ϱ	13 μs
Data rate	6 Mb/s
Beacon size	200 bytes
Safety message size	512 bytes
ε_L	0.3
ε_H	0.7
α_L	1 m/s^2
α_H	2 m/s^2

TABLE IV
TRAFFIC RELATED PARAMETERS

Parameter	Value	Parameter	Value
Vehicle length	5 m	Max. acceleration	2.5 m/s^2
Max. λ_c	0.02 CDSs/m	Max. deceleration	6 m/s^2
Intra-platoon spacing	10 m	Average speed	25 m/s
Max. λ_d	0.32 vehicles/m	Max. speed	41 m/s

their positions are subject to Poisson distribution, as specified in Table IV. The system parameters for communication model is specified in Table III. It shall be noted that Free-Space path loss model ($\alpha = 2.0$) and Nakagami-m fading model [33] are employed here. The appropriate transmitting power is set to meet the requirement of the communication range with R_V=300m for each vehicle and R_I=1000m for RSU. The threshold gap for any two CDSs to active the RSU beaconing block scheduling is set as 310m.

B. Performance of Beacon Dissemination

We first evaluate the beaconing performance of the proposed IBSD scheme in a stable traffic scenario where we assume that all vehicles move steadily and F is set as 5 by the RSU, i.e. identical beaconing blocks for all platoons. Fig. 8 show the PTR and PRR of beaconing versus λ_d. We can see from the two figures that PTR and PRR of beaconing are almost close to 1 with IBSD. We also compare IBSD with ABSD proposed in [25], and we can see the IBSD outperforms ABSD. This is because, in ABSD, individual vehicles should take several CCHI to estimate the duration of TS period, and the estimation may be not very accurate in a poor channel condition, which will lead to a higher probability of collision with the beacons from the CDS. However, in IBSD, the RSU broadcasts the beacon block scheduling in real-time. Individuals can easily acquire the accurate value of TS duration in its communication range. Thus, safety messages from individual vehicles have rather low probability to collide with the CDS beacons with IBSD scheme. We also compare the performance of beacon dissemination with and without the IBSD/ABSD scheme, as well as ATB proposed in [28]. The results show the beaconing

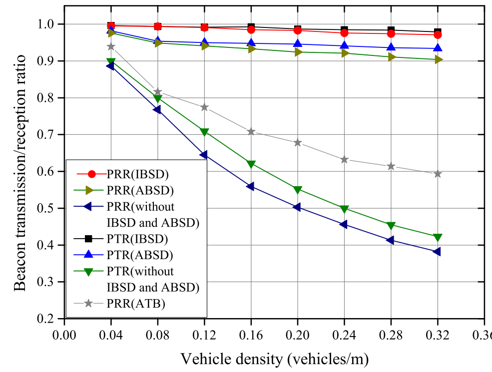
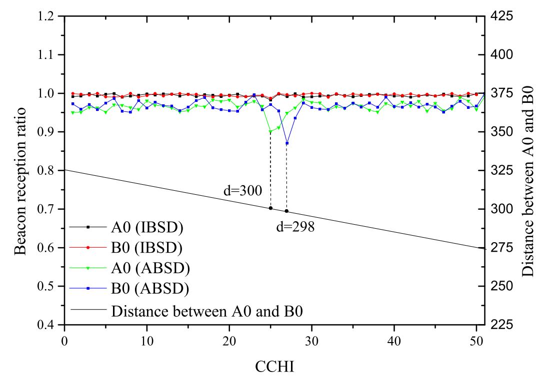
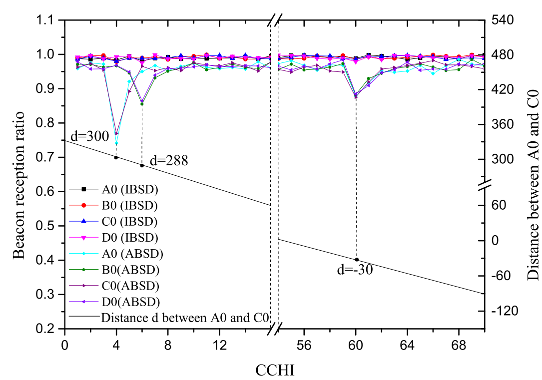


Fig. 8. beacon transmission/reception ratio versus λ_d.



(a) Beacon reception ratio when two CDSs in the same direction are approaching

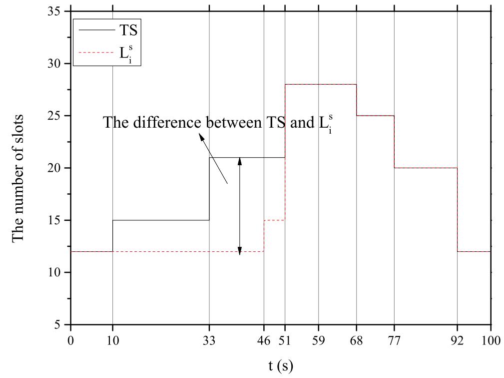


(b) The PRR of leaders when 4 CDSs in the bidrection encounter.

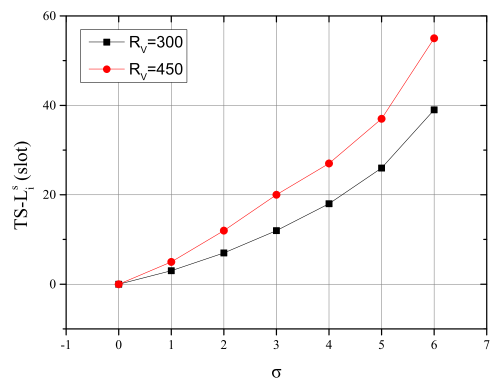
Fig. 9. The PRR of leaders in multiple CDSs.

performance degrade sharply without the help of the two schemes, which could seriously influence the stability of CDS.

Next, we investigate the communication performance when two CDSs are approaching. Fig. 9(a) displays the PRR of leader in traffic scenario that platoon B is approaching platoon A on the same direction, and the speed difference between $B0$ and $A0$ is 10m/s. We can see that the PRRs of both leaders with the IBSD scheme keep a steady and high level in all



(a) The dynamics of TS period and L_i^S



(b) The difference between TS period and L_i^S with different set of σ and R_v.

Fig. 10. Performance of beaconing block schedule.

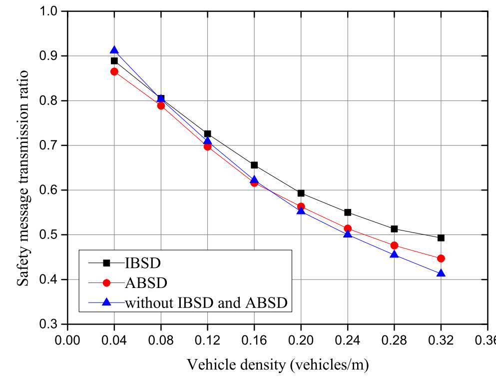


Fig. 11. Safety message transmission ratio versus λ_d.

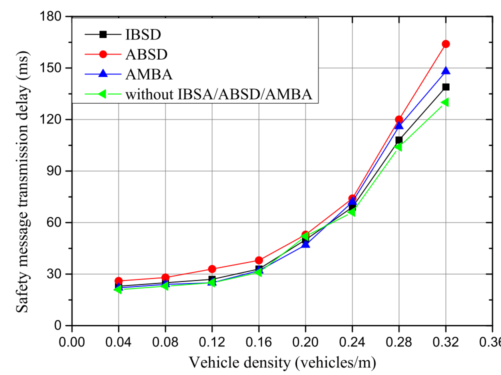


Fig. 12. Safety message transmission delay versus λ_d.

the time. In contrast, the PRRs of the leaders with the ABSD scheme drop about 10% during a short transition period (about 4 CCHIs) . This is because, for IBSD scheme, the RSU as the coordinator reschedules the beaconing blocks of the two platoons in advance to avoid packet collisions, while during the transition period of ABSD scheme, some packets from leaders will collide with safety messages from individual vehicles.

In Fig. 9(b), we then consider a more general traffic scenario wherein platoon B follows A on the eastward direction, and platoon D follows C on the westward direction. In addition, all vehicles move with the constant speed of $30m/s$, and the distance between $A0$ and $B0$ (or $C0$ and $D0$) is $330m$. Similar to Fig. 9(a), the PRRs of the four leaders with the IBSD scheme keep a steady and high level in all the time. For ABSD, The PRRs of leaders are about 95% most of the time. The anomaly happens at about CCHI=4, 6 and 60 when the approaching/leaving event happens. These are mainly caused by the packet collision with individual vehicles when the distributed beacon block adjustment in ABSD is executed. Then all PRRs can be recovered quickly, in about 4 CCHI.

Fig. 10(a) shows the difference between the actual allocated TS period by beaconing block schedule algorithm and theoretical minimum beaconing blocks L_i^S for a given CDS i. We can see that the length of TS period is larger than L_i^S in several timestep. This is because L_i^S is spatially uneven distributed at any time t, and the beacon block allocated by the RSU for the given CDS might be in the end of the TS period. Fig. 10(b) shows that with the increasing of σ and R_V, the difference between TS period and L_i^S is enlarged. The results well match our analysis in section V-A.

C. Performance of Safety Message Dissemination

In this section, we evaluate the performance of safety message dissemination of individual vehicles. Fig. 11 shows the safety message transmission ratio versus vehicle density λ_d. We can observe that the PTRs of three schemes are very close in case of sparse distribution of individual vehicles. However, with the traffic density increasing, PTR of IBSD is better than the ones of other two schemes, which verifies the efficiency of our proposed method.

Fig. 12 shows the safety message transmission delay increase with the growth of λ_d, which is due to the high probability of channel contention and collisions in dense traffic condition. Moreover, compared to the adaptive and mobility based algorithm (AMBA) proposed in [33], IBSD/ABSD has the similar performance of transmission delay. The reason is that, although the individual vehicles can transmit the safety messages only during the TC period, the collision probability

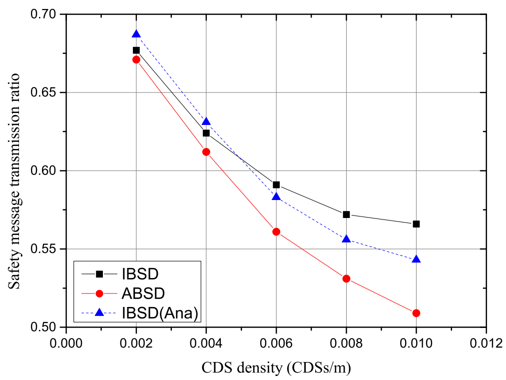


Fig. 13. Safety message transmission ratio versus λ_c.

is lower because all the platoon beacons are disseminated in the TS period. We also can notice that the IBSD outperform ABSD. This is because the duration of TS period can always keep small with the help of beaconing block scheduling in IBSD.

Fig. 13 shows the relationship between the CDS density λ_c and safety message transmission ratio. It is assumed that the CDS density varies from 0.002 to 0.01 CDSs/m and the density of individual vehicles is set as a constant value 0.12 vehicles/m. We can see that the PTR of safety message dissemination decreases slight when CDS density increases from 0.004 to 0.01. Also, we can notice that IBSD has higher PTR than ABSD. The reason is that the TS period can keep a smaller value in IBSD (i.e. larger TC period) compared to the distributed slots allocation in ABSD. What's more, we can see that the simulation results match well with the analytical results.

To summarize, the simulation results verify the efficiency of IBSD on solving the problem of overlapping slots occupation among CDSs. Moreover, it provides the individual vehicles an accurate value of TS period duration so that the probability of collision between the beacon for CDSs and the safety message from individual vehicles can be reduced significantly. With respect to the distributed slot allocation of ABSD, A higher and more stable beacon transmission ratio and reception can be achieved with IBSD.

VII. Conclusion

In this paper, we have systematically investigated message dissemination scheme to support the heterogeneous driving patterns which consist both reliable cooperative driving and individual driving. Specifically, we first propose an infrastructure-assisted message dissemination framework that can utilize the capability of infrastructure as well as ability of context awareness of roadside sensors. We then present a novel beaconing block schedule algorithm that aims at guaranteeing the timely and reliable delivery of both periodic beacon messages for cooperative driving and event-triggered safety messages for individual driving. To evaluate the performance of the protocol, we develop both theoretical analysis and simulation experiments. Extensive numerical results confirm the effectiveness of the proposed protocol.

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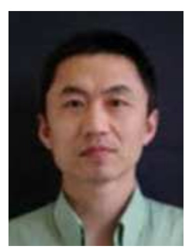

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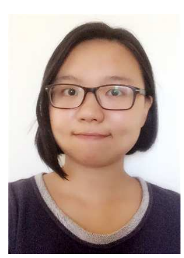

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