Towards Rear-End Collision Avoidance: Adaptive Beaconing for Connected Vehicles

Feng Lyu, *Member, IEEE*, Nan Cheng, *Member, IEEE*, Hongzi Zhu, *Member, IEEE*, Haibo Zhou, *Member, IEEE*, Wenchao Xu, *Member, IEEE*, Minglu Li, *Senior Member, IEEE*, and Xuemin Shen, *Fellow, IEEE*

Abstract*— Connected vehicles have been considered as an effective solution to enhance driving safety as they can be well aware of nearby environments by exchanging safety beacons periodically. However, under dynamic traffic conditions, especially for dense-vehicle scenarios, the naive beaconing scheme where vehicles broadcast beacons at a fixed rate with a fixed transmission power can cause severe channel congestion and thus degrade the beaconing reliability. In this paper, by considering the kinematic status and beaconing rate together, we study the rear-end collision risk and define a danger coefficient ρ to capture the danger threat of each vehicle being in the rear-end collision. In specific, we propose a fully distributed adaptive beacon control scheme, called *ABC*, which makes each vehicle actively adopt a minimal but sufficient beaconing rate to avoid the rear-end collision in dense scenarios based on individually estimated ρ. With *ABC*, vehicles can broadcast at the maximum beaconing rate when the channel medium resource is enough and meanwhile keep identifying whether the channel is congested. Once a congestion event is detected, an NP-hard distributed beacon rate adaptation (DBRA) problem is solved with a greedy heuristic algorithm, in which a vehicle with a higher ρ is assigned with a higher beaconing rate while keeping the total required beaconing demand lower than the channel capacity. We prove the heuristic algorithm's close proximity to the optimal result and thoroughly analyze the communication overhead of *ABC* scheme. By using Simulation of Urban MObility (SUMO)-generated vehicular traces, we conduct extensive simulations to demonstrate the efficacy of our proposed *ABC* scheme. Simulation results show that vehicles can adapt beaconing rates according to the driving safety demand, and the beaconing reliability can be guaranteed even under high-dense vehicle scenarios.

***Index Terms*— V2X, rear-end collision avoidance, beacon congestion control, adaptive beaconing, safety-awareness.**

Manuscript received January 7, 2019; revised September 27, 2019; accepted December 16, 2019. Date of publication January 22, 2020; date of current version February 2, 2021. This work was supported in part by the National Natural Science Foundation of China under Grant 61420106010, Grant 91638204, and Grant 61772340, and in part by the Natural Sciences and Engineering Research Council (NSERC) of Canada. The Associate Editor for this article was P. Kachroo. *(Corresponding author: Nan Cheng.)*

Feng Lyu is with the School of Computer Science and Engineering, Central South University, Changsha 410083, China (e-mail: fenglyu@csu.edu.cn).

Nan Cheng is with The State Key Laboratory of ISN, Xidian University, Xian 710071, China, and also with the School of Telecommunications Engineering, Xidian University, Xian 710071, China (e-mail: nancheng@xidian.edu.cn).

Hongzi Zhu and Minglu Li are with the Department of Computer Science and Engineering, Shanghai Jiao Tong University, Shanghai 200240, China (e-mail: hongzi@cs.sjtu.edu.cn; li-ml@cs.sjtu.edu.cn).

Haibo Zhou is with the School of Electronic Science and Engineering, Nanjing University, Nanjing 210093, China (e-mail: haibozhouuw@gmail.com).

Wenchao Xu and Xuemin Shen are with the Department of Electrical and Computer Engineering, University of Waterloo, Waterloo, ON N2L 3G1, Canada (e-mail: w74xu@uwaterloo.ca; sshen@uwaterloo.ca).

Digital Object Identifier 10.1109/TITS.2020.2966586

I. Introduction

DRIVING safety has been the major concern in our daily life as unceasing traffic accidents now become the leading cause for death of young people. According to the most recent statistics [1], in the United States, traffic accidents alone account almost a quarter of all deaths among people in the age group of 15-24. Delayed reaction to the emergence situations is the major reason for accidents, which makes it necessary to build active and cooperative road safety applications, in order to prevent these extensive traffic crashes. Meanwhile, *connected vehicles*, empowered by V2X communications (broadly including vehicle-to-vehicle (V2V), vehicle-to-Road-Side-Unit (V2R), vehicle-to-pedestrian (V2P), etc.) [2], [3], have been envisioned as a promising solution for driving safety enhancement by enabling rapid message exchanging. Specifically, with periodically beaconing safety messages (or *beacons*) by each vehicle, vehicles can share their location, heading direction, braking status, velocity, etc., with neighboring vehicles, which can help to build many advanced road safety applications such as stop sign violation, intersection collision warning, emergency electronic brake lights, and so forth [4], [5]. Compared with other sensors such as camera and Light Detection and Ranging (LiDAR), V2X sensors can provide 360-degree situational awareness on the road with offering more excellent sensing range, through-objects view functionality, and around-corner viewing capability. Besides, V2X sensors are not affected or influenced by unexpected weather conditions, such as heavy rain, fog, and harsh sunbeams, which can work robustly in real driving environments.

However, to design an efficient and reliable beaconing scheme for connected vehicles, is quite challenging for the following three reasons. First, it is non-trivial to guarantee the safety demand for each vehicle with the limited available V2X bandwidth [6]–[9], especially under dense-vehicle conditions. On the one hand, if vehicles adopt aggressive beaconing rates, some vehicles may be sacrificed and have no required bandwidth to broadcast their moving status. On the other hand, if vehicles adopt moderate beaconing rates, the received moving status of neighboring vehicles may be out-of-date, resulting in delayed reactions to dangerous situations. In fact, vehicles in the moving are going to have different danger levels, calling for distinct beaconing rates to meet demands for their driving safety enhancement. Second, there is normally no global central unit in vehicular environments, making it very hard to achieve an optimal beaconing scheme. Alternatively, vehicles have to negotiate in a fully *distributed* way, to access the available bandwidth in real time. Third, as vehicles move fast and vehicular environments vary dramatically, the distributed beaconing scheme should minimize the communication overhead and react rapidly to the environment.

There have been several studies on beaconing control in the literature, which can be classified into transmit power control (TPC) and transmit rate control (TRC) two categories. TPC schemes [10]–[14] are proactive solutions, which adjust transmission powers proactively to prevent future channel congestions by predicting the vehicle distribution in advance. These solutions are sensitive to estimation errors, which are mainly caused by biased transmission model and imprecise prediction model, and however are very common in vehicular environments due to the highly dynamic mobility. Therefore, these solutions are unreliable in vehicular scenarios, which has been pointed out in the previous work [15]. In contrast, TRC schemes react to congestion events that have already happened, by controlling beaconing rates for vehicles. However, most current TRC schemes focus on achieving the max-min fairness under the constraint of bandwidth capacity, which lacks of safety-awareness. For instance, Linear MEssage Rate Integrated Control (LIMERIC) [16] and Periodically Updated Load Sensitive Adaptive Rate control (PULSAR) [17] consider equal fairness such that all vehicles within the congestion location takes the same level of beaconing rate adaptation. Such equal-fairness control schemes are able to achieve the maximum throughput gain while failing to satisfy safety demand for different danger levels. By taking driving context into consideration, another two TRC schemes [18], [19] are recently proposed, both of which formulated a network utility maximization problem to reply to the beacon rate adaptation. Particularly, each vehicle is associated with an utility function with the objective of maximizing the sum of utilities of all vehicles. However, their utility functions are defined based on the aggregated information such as the summation of velocities of one-hop neighbors and summation of relative distances to one-hop neighbors, which can hardly precisely capture the safety demand of individual vehicle. As a result, to the best of our knowledge, there is few beacon control schemes that can both efficiently manage the channel resource and adapt to different danger levels of every vehicle.

In this paper, we propose a novel safety-aware adaptive beacon control scheme, named as *ABC*, which adaptively adjusts beaconing rates for vehicles according to their rear-end collision threats. We first investigate a typical rear-end collision condition by considering the kinematic status of preceding-following vehicles and the beaconing rate together, and define a *danger coefficient* ρ for each vehicle to capture their rear-end collision threat, which also implicitly indicates the beaconing bandwidth requirement for the vehicle. We consider the beaconing activities under the context of the TDMA-based broadcast medium access control (MAC) protocol since it advances in ensuring certain delay when supports periodical broadcast. Then, with all bandwidth requirements and the total available channel capacity at the MAC layer, we formulate a *distributed beacon rate adaptation* (DBRA) problem, which is proved to be NP-hard. To solve it efficiently, we devise a heuristic greedy algorithm based on individual estimates of ρ. To be specific, vehicles with higher estimated ρ will be assigned with higher beaconing rates, expecting that more frequent beaconing are conducted for these vehicles to avoid rear-end collisions, while keeping the total required beaconing demand lower than the channel capacity. In *ABC*, each vehicle is safety-aware, i.e., the vehicle estimates its own danger coefficient ρ and collects the information of ρ of neighboring vehicles through beacon exchanges. Based on the collected beaconing status, a *close-loop* control mechanism is then employed, in which each vehicle keeps identifying whether the channel is congested or not. Once a vehicle detects a channel congestion, it adopts the greedy algorithm to solve the DBRA problem locally and broadcasts the beacon rate adaptation results to neighbors, in order to mitigate the channel congestion. When a vehicle receives multiple inconsistent beacon adaptation results from its neighbors, it will conservatively adopt the lowest beaconing rate to avoid channel congestions. We prove the heuristic algorithm's close proximity to the optimal result and thoroughly analyze the communication overhead of *ABC*.

At last, we implement our proposed *ABC* scheme based on Simulation of Urban MObility (SUMO)-generated vehicular traces, and conduct extensive simulations under various underlying road topologies and varied traffic densities to demonstrate its efficacy. Specifically, compared with two benchmark schemes, i.e., LIMERIC [16] and 802.11p [20], *ABC* can efficiently control the beaconing rates under the constraint of bandwidth limitation, and thus the rate of beacon transmission/reception collisions are greatly reduced. In addition, as beaconing rates are adapted in accordance with individual crash threat of each vehicle, *ABC* is able to satisfy each vehicle's safety demand with beaconing reliability guarantee.

We highlight our main contributions as follows:

- We investigate the relationship between the beaconing rate and the according rear-end collision risk, based on which, we define the danger coefficient ρ that captures the rear-end collision threat of each vehicle and describes the required beaconing bandwidth of each vehicle with respect to such collision threats.
- We propose a fully-distributed adaptive beacon control scheme, named as *ABC*, which can perform safety-aware beaconing rate adaptation for every vehicle under dynamic vehicular environments. Furthermore, we formulate the DBRA problem in the context of a TDMA-based broadcast MAC and prove it to be NP-hard, to solve which efficiently, we devise a heuristic algorithm based on real-time estimated value ρ.
- Performance analysis on the heuristic algorithm efficiency and on the communication overhead in *ABC* are carried out. In addition, we implement our proposed *ABC* scheme under the SUMO-generated traces and conduct extensive simulations to demonstrate its efficacy.

We organize the rest of this paper as follows. System model is presented in Section II and we investigate safety-aware beaconing rate adaptation in Section III. Section IV elaborates our *ABC* scheme design. Performance analysis and performance evaluation are carried out in Section V and Section VI, respectively. We review the related work in Section VII and conclude the future work in Section VIII.

II. System Model

In this paper, we consider a set of moving vehicles and RSUs, and they communicate via Dedicated Short Range Communications (DSRC) radios. To enhance driving safety, they are required to periodically broadcast beacons. Beaconing activities are considered in the context of a TDMA-based broadcast MAC.

A. Dedicated Short Range Communications (DSRC)

All nodes including both vehicles and RSUs in the vehicular environment, are equipped with a DSRC communication radio, to communicate with neighboring vehicles. The DSRC channel operates among 5.700 to 5.925 GHz frequencies with two optional bandwidths of 10 MHz and 20 MHz, which can provide the peak data rate up to 27 Mbps and 54 Mbps, respectively [21], [22]. A single DSRC radio can support one control channel (CCH) and multiple services channels (SCHs) by switching the radio among them every 50 ms. The CCH is essential and normally used to disseminate high-priority short messages (i.e., periodic and event-driven beacons) and control information (e.g., negotiations for SCHs usages). On the contrary, SCHs are utilized by non-safety applications for low-priority information dissemination. In this paper, we focus on periodical beaconing activities on the CCH since they are the most important for driving safety enhancement. In addition, as we consider resource allocation at MAC layer, we assume that radios in the network have the identical communication capability, i.e., with the same communication range R. Therefore, we can denote the network by an undirected graph $G(V, E)$, in which $V = \{1, 2, \ldots, n\}$ is the set of communicating nodes and E represents the link condition between any two nodes by a $n \times n$ matrix. Particularly, for two distinct nodes x and y, if they are within communication range with each other, i.e., $d_{xy} \leq R$, then $E_{xy} = 1$, otherwise $E_{xy} = 0$. We denote the one-hop neighbor set of node x by $\mathcal{N}_{\mathcal{OHS}}(x) = \{y \in V \mid y \neq x, d_{xy} \leq R\}$. To enhance driving safety, beacons broadcasted by x should be successfully received by all one-hop neighboring vehicles in $\mathcal{N}_{\mathcal{OHS}}(x)$, otherwise potential dangerous situations may arise.

B. TDMA-Based Broadcast MAC

We adopt a TDMA-based broadcast MAC to enable upper-layer periodical beaconing activities, since the TDMA-based MAC has been recently demonstrated in well guaranteeing reliable broadcast communication [23]–[25]. The 802.11p MAC is not considered due to its two major weaknesses when supporting periodical broadcast. First, it could result in unbounded delays when too many nodes contend for the channel simultaneously since 802.11p MAC works under a contention-based manner, in which before

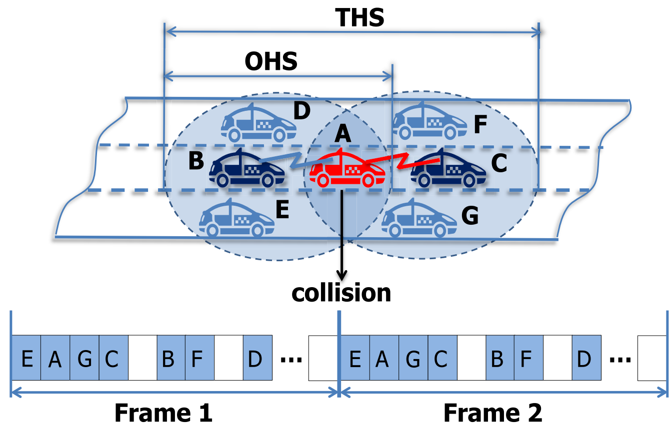


Fig. 1. Illustration of the TDMA-based broadcast MAC.

accessing the wireless medium, each node has to sense the channel to be free. Therefore, compared to the pre-defined frame and slot structure in the TDMA-based MAC, it is hard to guarantee the strict delay for periodical broadcasts. Second, to facilitate real-time response, RTS/CTS packets are removed in the broadcast mode of 802.11p MAC, which makes the *hidden terminal problem* inundant [20]. Besides, the core idea of our beaconing scheme is independent from the underlying MAC protocol, and it can be also applied in 802.11p to help dynamically decide the back-off time, size of contention window, etc.

1) Time-Slotted Channel Medium: In the TDMA-based MAC, the medium resource of control channel is represented by distinct time slots. As shown in Fig. 1, time is partitioned into consecutive frames, and each frame contains a fixed number (denoted by S) of fixed-duration time slots (denoted by the set $\mathcal{S}$). Vehicles synchronize the index of time slots with each other through a global positioning system (GPS) receiver (embedded in DSRC module). In the time-slotted channel, each vehicle applies for an unique time slot and broadcasts over the time slot every frame. By granting each vehicle with a determinate time slot can meet the stringent delay requirement for beacon-based safety applications.

2) Spatial Reuse TDMA Constraints: For a vehicle, the neighboring vehicles within its communication range, constitute its *one-hop set* (OHS). The union of two OHSs can constitute a *two-hop set* (THS), if those two OHSs overlap with each other. As shown in Fig. 1, the OHS of vehicle B and C form a THS as vehicle A locates in both two OHSs. In the THS, every vehicle can reach any other vehicle by at most two hops. Obviously, vehicles in the same OHS have to access different time slots to avoid transmission collisions. Additionally, in order to overcome the hidden terminal problem, vehicles in the same THS also have to access different time slots. To be specific, without RTS/CTS mechanisms, hidden terminal problems appear in a THS when two vehicles cannot hear from each other (e.g., locating in respective two OHSs) and decide to broadcast simultaneously. As an example in Fig. 1, as vehicle B and C are out of the communication range of each other, both of them could perceive the channel to be free and it is very likely that they broadcast simultaneously, resulting in message collisions at vehicle A. To cope with it, vehicles in the same THS are assigned with distinct time slots. We denote the THS (interference range) of vehicle x by $\mathcal{N}_{\mathcal{THS}}(x)$, and $\mathcal{N}_{\mathcal{THS}}(x) = \mathcal{N}_{\mathcal{OHS}}(x) \bigcup \{\mathcal{N}_{\mathcal{OHS}}(y), \forall y \in \mathcal{N}_{\mathcal{OHS}}(x)\}$. The time slot assignment in Fig. 1 is a valid allocation as vehicles in the same THS are associated with different time slots.

3) Time Slot Access and Collision Detection: To negotiate the time slot access in a fully distributed way, each vehicle (say vehicle x) includes the application data together with *frame information* i.e., $I(y)$ and $T(y)$ for $\forall y \in \mathcal{N}_{\mathcal{OHS}}(x)$, in each beacon, where $I(y)$ and $T(y)$ represents the vehicle ID of y and the time slot acquired by it, respectively. Therefore, each vehicle is able to perceive the time slot acquisition of THS by listening its OHS' beacons. If vehicle x wants to apply for a free time slot, it has to first listen to the channel (by receiving beacons) for S successive time slots to achieve the entire frame information, i.e, obtaining all $T(y)$ for $\forall y \in \mathcal{N}_{\mathcal{THS}}(x)$. After that, the vehicle chooses a time slot from the vacant time slot set (i.e., $\mathcal{S}$ - $T(y)$ for $\forall y \in \mathcal{N}_{\mathcal{THS}}(x)$) in a random way. Once the vehicle acquires a time slot successfully, it can use the same time slot in all subsequent frames unless a time-slot-collision happens. To detect the time-slot-collision in real time, at the end of every frame, each vehicle has to check the frame information received during previous S time slots. Particularly, for vehicle x, if all beacons received from y for $\forall y \in \mathcal{N}_{\mathcal{OHS}}(x)$, indicate that $x \in \mathcal{N}_{\mathcal{OHS}}(y)$ (i.e., vehicle y well received the beacon from vehicle x), it means no concurrent transmissions happen at the slot $T(x)$ within its THS; otherwise, vehicle x may collide with another vehicle at the time slot $T(x)$. Once a collision is detected by the vehicle, it has to release its original time slot and apply for a new one.

4) Beaconing Starving Problem: Considering a normal case under the TDMA-based broadcast MAC, where each beacon takes up 500 bytes [26] and the DSRC radio adopts a moderate transmission rate of 6 Mbps for reliable communication [21], then the data delivery requires about 0.67 ms. For driving safety, each vehicle in DSRC standard is required to periodically broadcast every 100 ms (i.e., normally the duration of each frame). Then, the number of time slots in each frame is limited to 150 (the guard period among slots and physical layer overhead are not even taken into account). In addition, as found in previous experimental study on DSRC communication in urban [21], the V2V communications are rather reliable within 300m regardless of the fast speed and complex environments. It means that vehicles within interference range, i.e., up to 1200 m, have to contend for the only 150 time slots. However, when meeting high-density scenarios such as at urban intersections, on bidirectional 8-lane highways, or for traffic at rush hours, vehicles will heavily aggregate within small areas, and the limited number of time slots is far from enough to meet their beaconing demands. We define this supply-demand imbalance as the *beaconing starving problem*, which may result in channel congestions and therefore degrade the beaconing reliability. Coping with the beaconing starving problem and meanwhile keeping vehicles safety-aware, is the main theme of this work.

III. Beacon Rate Control With Safety-Awareness

Before investigating the beacon rate adaptation, in this section, we delve into the prime goal of beaconing, i.e., how does it enhance driving safety. To this end, we consider the kinematic status and the beaconing rate together, to investigate the risk of encountering a rear-end collision, based on which we define a danger coefficient ρ to capture the danger threat of each vehicle being in the collision. We consider the rear-end collision situation in this paper, since it is the most common type of vehicle crashes, which alone accounts for more than 32% of all crashes according to the most recent report from U.S. Department of Transportation [27]. Other types of crashes can be incrementally added in, to form a general coefficient, being safety-aware for all types of crashes.

A. Danger Coefficient ρ

As shown in Fig. 2 (a), the following vehicle A (at the speed of V_f) moves after the preceding vehicle B (at a speed of V_p), with a following distance d. Through beaconing, vehicle B keeps reporting its moving status to vehicle A every T_{beacon} seconds (i.e., $\frac{1}{T_{\text{beacon}}}$ Hz). By sensing the moving status of vehicle B in real time, vehicle A can make a decision on acceleration or deceleration. Fig. 2 (b) demonstrates a risk of encountering a rear-end collision when vehicle B takes a sudden brake with $a_p m/s^2$. After receiving the reporting beacon, vehicle A can perceive the emergency rapidly and react to the situation after a delay T, where $T = T_{\text{beacon}} + T_{\text{reaction}}$, and T_{reaction} is the reaction time for a driver (or a response time of the automatic controlling system for autonomous vehicles). To avoid in collision with the preceding vehicle, vehicle A has to brake a little or fully, which is determined by the current kinematic status of two vehicles.

Definition 1(Danger Coefficient ρ): There are two vehicles A and B moving in the same lane, where A is the following vehicle while B is the preceding vehicle. If vehicle B decelerates suddenly at the maximum acceleration, after knowing the situation by receiving the beacon, vehicle A has to brake at ρ ($\rho \in$ (0, 1]) times the maximum acceleration, in order to avoid a collision with B. Then, vehicle B is said to be dangerous with a coefficient ρ in terms of encountering a rear-end collision.

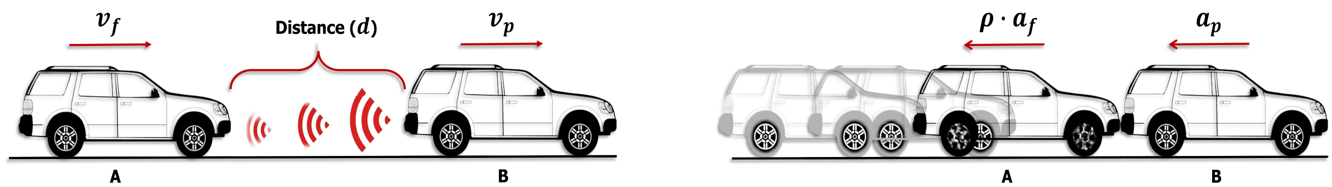
Therefore, as shown in Fig. 2, the kinematic relation of two vehicles satisfies

$$V_f(T_{\text{beacon}} + T_{\text{reaction}}) + (\frac{V_f^2}{2\rho a_f} - \frac{V_p^2}{2a_p}) = d, \qquad (1)$$

where a_f is the maximum acceleration of vehicle A. Then, the danger coefficient ρ can be represented by

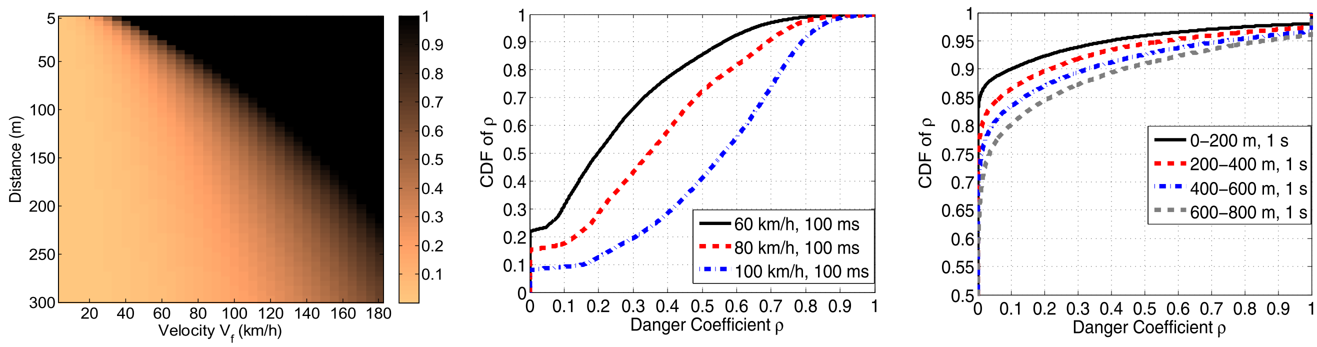
$$\rho = \frac{V_f^2}{2a_f(d - V_f(T_{\text{beacon}} + T_{\text{reaction}}) + \frac{V_p^2}{2a_p})}. \qquad (2)$$

By receiving beacons (including velocity, acceleration, moving direction, etc.) constantly from neighboring vehicles, each vehicle is able to update the moving status of the following vehicle and calculate the real-time danger coefficient ρ. The real-time danger coefficient of each vehicle can be also shared



(a) vehicle A moves after vehicle B normally. (b) a collision risk caused by a sudden deceleration of B

Fig. 2. Illustration of the kinematic status in rear-end collision situation.



(a) The danger coefficient ρ vs. distance and V_f (b) CDFs of ρ in different speed-limited lanes (c) CDFs of ρ at intersection zones

Fig. 3. Capturing danger threat through ρ.

among neighboring vehicles via beacon exchanges, which can be used to negotiate the beacon rate assignment in a fully distributed way.

B. Capturing Danger Threat

The danger threat of encountering a potential collision for each vehicle can be well captured through the danger coefficient ρ. In addition, based on the up-to-date beacon reception, the value of ρ can be updated in real time, which enables real-time beaconing resource allocation. To be specific, as shown Fig. 3 (a), we plot the value of ρ under the function of velocity V_f and distance d, where V_p, a_f, a_p, T_{beacon}, and T_{reaction} are empirically set to be 60 km/h, 8 m/s^2, 8 m/s^2, 1 s, and 0.5 s, respectively. It can be easily seen that the underlying *driving context* can be well captured by the variation of coefficient ρ. For example, the value ρ is quite small when the following vehicle moves slowly or is far away from the preceding vehicle, whereas it becomes relatively large when the following vehicle moves fast or is close to the preceding vehicle.

To further understand how ρ varies in realistic driving environments, we calculate vehicles' ρ in SUMO [28] every 100 ms, and the detail simulation setup can be found in the performance evaluation section. Fig. 3 (b) shows cumulative distribution functions (CDFs) of ρ of vehicles (beaconing every 100 ms) in different lanes, where each lane has a speed limit of 60, 80, and 100 km/h, respectively. It can be seen that *vehicles in faster lanes normally have larger ρ, which should be guaranteed with higher beaconing rates*. Particularly, the median ρ (i.e., with the CDF value of 0.5) is about 0.2 in 60 km/h-limit lane, while in the 80 and 100 km/h-limit lane, the median value increases to 0.35 and 0.55, respectively. Fig. 3 (c) shows CDFs of ρ of vehicles (beaconing every 1000 ms) at intersection zones, each of which locates at the respective distance zone, i.e., 0-200, 200-400, 400-600, and 600-800 m, away from the center of intersection area. It can be seen that smaller ρ prevail at intersection zones, which can be verified by two observations. First, the probability of $\rho = 0$ reaches up to 85% when vehicles are at intersection zones, whereas the probability decreases to as low as 10% when vehicles are far away from the intersection, as shown in Fig. 3 (b) (even though the beaconing rate is ten times larger than which in Fig. 3 (c)). Second, as the distance away from the intersection increases, the probability of $\rho = 0$ decreases accordingly, and the proportion is about 85%, 79%, 73% and 69% in respective intersection zones.

We can conclude that, *it is the intersection scenario that is urgently in need and suitable for applying the beacon congestion control, since the dense-vehicle condition makes more vehicles contending the channel, and smaller values of ρ make it possible to adapt the beaconing rates.*

C. Safety-Aware Beacon Rate Adaptation

Normally, vehicles can choose distinct time slots in a frame and broadcast with a rate of 1 beacon/frame to enable upper-layer safety applications. However, if the beaconing starving problem happens, beacon rate adaptation is in need to suppress the congestion event. In this work, *we propose a scheme to dynamically adapt the beaconing rate within a range* $[\alpha_{\min}, \alpha_{\max}]$ for every vehicle. Taking the coefficient ρ as a driving factor, the following rule should be complied with during the beaconing resource allocation.

Rule 1: In the set of $\mathcal{N}_{\mathcal{THS}}(x) \cup x$, for two vehicles i and j, the beaconing rate of i should be greater than or equal to the beaconing rate of j, if $\rho_i \geq \rho_j$, i.e.,

$$\alpha_i \geq \alpha_j, \quad \forall\{i, j | \rho_i \geq \rho_j, i, j \in \mathcal{N}_{\mathcal{THS}}(x) \cup x\}. \tag{3}$$

Additionally, in order to comply with the requirement of most safety applications [29], beaconing rates of vehicles should range from 1 Hz to 10 Hz. Therefore, we set the $\alpha_{\min}$ and $\alpha_{\max}$ to be 0.1 and 1 beacon/frame[1], respectively.

IV. ABC Scheme Design

A. Overview

We elaborate our *ABC* scheme design in this section. In *ABC*, vehicles can normally broadcast at the maximum beaconing rate when the channel medium resource is sufficient. Meanwhile, vehicles will collect beaconing status of neighbors through sending/receiving beacons, to keep identifying whether the channel is congested. If a vehicle identifies a congestion event, a distributed beacon rate adaptation (DBRA) problem is then formulated to adapt beaconing rates for vehicles, in order to suppress the congestion. As the DBRA problem is proved to be NP-hard, the vehicle solves the problem locally by the devised heuristic algorithm. Finally, the vehicle will inform other vehicles (within the interference range) of the rescheduled results, based on which vehicles can adapt beaconing rates accordingly to relieve the congestion. Considering the dynamic variation of ρ in the moving, when the vehicle' danger coefficient becomes larger than a threshold, it is allowed to increase its own beaconing rate independently, in order to minimize the risk of encountering a collision. In what follows, we elaborate key components of *ABC*: 1) online congestion detection; 2) distributed beacon rate adaptation; and 3) adaptation results informing. After that, we present the adaptive beacon control approach in *ABC*.

B. Online Congestion Detection

1) Collecting Beaconing Status: To keep vehicles well perceiving the channel condition (congested or not) within interference range, in our scheme, vehicles broadcast application data together with the beaconing status of themselves and their OHS neighbors. The beaconing status of each vehicle contains the information of the beaconing rate α and danger coefficient ρ. Specifically, for each vehicle (say vehicle x), it continuously updates its own danger coefficient based on newly received kinematic information, and then includes the up-to-date (α, ρ) list information of itself and OHS neighbors (collected directly from neighbors during previous S slots) in each beacon to broadcast out. By doing so, vehicle x is able to collect the real-time beaconing status of THS neighbors by receiving beacons from the OHS neighbors.

2) Detecting Congestion Events: To this end, vehicle x is capable of detecting congestion events in real time by checking the up-to-date beaconing status of THS neighbors.

Definition 2 (Beaconing Item Size): To model the beaconing resource usage, we define the *beaconing item size*, which is equal to α_i if the vehicle i has the beaconing rate of α_i beacon/frame ($\alpha_i \in (0, 1]$).

[1]The duration of each frame is normally set to be 100 ms.

Definition 3 (Time Slot Space): To model the medium resource for beaconing activities, we define the *time slot space* for each time slot, the value of which is 1 minus the sum of beaconing item sizes that the time slot is supporting, and the time slot space of a vacant time slot is 1.

Therefore, vehicle x would perceive a channel congestion event, if the beaconing rates of vehicles in its THS satisfy

$$\sum\nolimits_{i=1}^{|\mathcal{N}_{\mathcal{THS}}(x)|+1} \alpha_i > S, \tag{4}$$

where $|\mathcal{N}_{\mathcal{THS}}(x)|+1$ represents the number of vehicles in x' THS and x itself. By receiving beacons, the online congestion identification can be conducted at the end of each frame.

C. Distributed Beacon Rate Adaptation (DBRA)

In order to relieve the ongoing congestion, those vehicles who have involved in the congestion, have to adapt beaconing rates, where the following two constraints have to been complied with.

Constraint 1: (Periodical Beaconing Rate) As the broadcast is required to be periodical, the beaconing rate α_i of each vehicle within x' THS satisfies

$$\alpha_i = \frac{1}{t}, \quad t = 1, 2, 3, \ldots, 10, \forall i \in \mathcal{N}_{\mathcal{THS}}(x) \cup x, \tag{5}$$

i.e., beaconing every t frames while keeping silent during the other $t - 1$ frames.

Constraint 2 (Bandwidth Limitation): To avoid the channel congestion, the total beaconing bandwidth is restrained within the channel capacity,[2] i.e.,

$$\sum\nolimits_{i=1}^{|\mathcal{N}_{\mathcal{THS}}(x)|+1} \alpha_i \leq S. \tag{6}$$

1) Safety-Weighted Network Utility Maximization: The network utility depends on many variables such as delay, throughput, message collision probability and so forth. In our network utility, we incorporate the packet delay between communicating neighbors, which is the most important metric for delay-sensitive vehicular applications, as well as the safety benefit, i.e., a multiplicative weight denoted by ρ. The packet delay can be impacted by many factors, such as transmission data rate, the quality of wireless link, transmit power, etc [30]. For a vehicle in our case, if it is assigned with a beacon rate $\alpha = \frac{1}{t}$, i.e., beaconing every t frames while keeping silent during the other $t-1$ frames. Then, the delay performance of broadcast for the vehicle can be alternately represented by t, i.e., $1/\alpha$. In addition, as the network utility is generally related to the negative expected delay of each vehicle, the network utility contributed by the vehicle can be represented by α, since $\alpha \in (0, 1]$. Let $\boldsymbol{\alpha} = \{\alpha_i | i \in \mathcal{N}_{\mathcal{THS}}(x) \cup x\}$ be the vector of beaconing rate assignments for vehicles in the THS. With considering the danger threat, the danger coefficient ρ is added into the utility function to denote the importance of

[2]It should be noted that, it is generally difficult to schedule the time slot usage without any wasting and colliding at MAC layer, especially for moving vehicles with diverse beaconing rates [25]. Therefore, it is better to leave some redundant time slots for MAC layer scheduling. However, how to design and optimize MAC layer performance is out of the scope of this paper.

driving safety. Therefore, the safety-weighted network utility contributed by the vehicle i under the beaconing rates $\boldsymbol{\alpha}$ is

$$U_i(\boldsymbol{\alpha}) = \rho_i \cdot \alpha_i, \quad \forall i \in \mathcal{N}_{\mathcal{THS}}(x) \cup x. \tag{7}$$

The DBRA problem can be formulated as a maximization of the sum of the utilities contributed by all vehicles involved in the congested THS:

$$\begin{aligned} &\max \sum\nolimits_{i=1}^{|\mathcal{N}_{\mathcal{THS}}(x)|+1} \rho_i \cdot \alpha_i \\ &s.t. \alpha_i \in \{1/1, 1/2, 1/3, \ldots, 1/10\}, \\ &\quad \sum\nolimits_{i=1}^{|\mathcal{N}_{\mathcal{THS}}(x)|+1} \alpha_i \le S. \end{aligned} \tag{8}$$

If the objective function $\sum_{i=1}^{|\mathcal{N}_{\mathcal{THS}}(x)|+1} \rho_i \cdot \alpha_i$ can be maximized by adopting a specific $\boldsymbol{\alpha}$, the solution $\boldsymbol{\alpha}$ will be able to comply with the requirement in **rule 1**. It can be easily proved by the contradiction. Specifically, if $\boldsymbol{\alpha}$ is the optimal solution to the DBRA problem and (3) does not hold, there must exist $\alpha_i < \alpha_j$ while $\rho_i \ge \rho_j$. If the beaconing rates of i and j are exchanged with each other, a larger safety-weighted network utility to the DBRA problem can be achieved, which contradicts the maximizing property.

For each vehicle i, we can consider a class of beaconing rates, i.e., $\mathcal{C}_i = \{1/1, 1/2, 1/3, \ldots, 1/10\}$, in which it has to choose one item j as its beaconing rate. We introduce a binary variable x_{ij} in our problem formulation, and it takes on value 1 if the item j is chosen otherwise it takes on 0. Then, we can equally formulate the DBRA problem as follows

$$\begin{aligned} &max \sum_{i=1}^{|\mathcal{N}_{\mathcal{THS}}(x)|+1} \sum_{j \in \mathcal{C}_i} \rho_i \cdot \alpha_{ij} \cdot x_{ij} \\ &s.t. \sum_{i=1}^{|\mathcal{N}_{\mathcal{THS}}(x)|+1} \sum_{j \in \mathcal{C}_i} \alpha_{ij} \cdot x_{ij} \le S, \\ &\quad \sum_{j \in \mathcal{C}_i} x_{ij} = 1, i = 1, \ldots, |\mathcal{N}_{\mathcal{THS}}(x)| + 1, \\ &\quad x_{ij} \in \{0, 1\}, i = 1, \ldots, |\mathcal{N}_{\mathcal{THS}}(x)| + 1, j \in \mathcal{C}_i, \end{aligned} \tag{9}$$

where α_{ij} represents that the vehicle i chooses the j-th beaconing rate in the class $\mathcal{C}$.

We have the following theorem for the DBRA problem.

Theorem 1: The DBRA problem is NP-hard.

Proof: To prove the NP-hardness of the DBRA problem, we can devise a polynomial reduction from a classic NP-hard problem to our problem. Specifically, we can devise from the *multiple-choice knapsack problem (**MCKP**)* [31], which is a variant of the ordinary 0-1 knapsack problem. In the **MCKP** problem, there are m mutually disjoint classes $U_1, U_2, \ldots, U_m$ of items, which need to be packed into a knapsack with a total capacity C, and each item $j \in U_i$ has a profit p_{ij} with a weight cost c_{ij}; the object function is to maximize the profit sum without exceeding the capacity C when chooses exactly one item from each class. Our DBRA problem as formulated in (9) is equivalent to the problem, concluding the proof. ■

2) Heuristic Algorithm for DBRA: By adopting the dynamic programming (DP) algorithm, although the optimal result for our DBRA problem can be achieved, it requires a *pseudo-polynomial* level of time complexity, which is *unacceptable* to conduct online decision making. More specifically, to solve our problem, the DP algorithm requires a time complexity of $O(n \cdot S)$, where n and S denote the number of input vehicles and total capacity of all time slots, respectively. Traditionally, the complexity $O(n \cdot S)$ is a polynomial time in terms of input values n and S. However, for the input size, the value S requires 2^L bits to represent it and the time complexity becomes $O(n \cdot 2^L)$, which is an exponential time rather than a polynomial time in terms of input size. Therefore, in *ABC*, we devise a heuristic greedy algorithm to conduct beaconing rate adaptation for vehicles. Particularly, all vehicles $\mathcal{N}_{\mathcal{THS}}(x) \cup x$ are first guaranteed the minimum beaconing rate $\alpha_{\min}$. To assign the remaining medium resource, vehicles are then sorted by the danger coefficient ρ in descending order and the vehicle will be allocated with more beaconing resource until reaching $\alpha_{\max}$ if it has the largest ρ. The procedure will repeat until all medium resource is used up. The pseudocode of the greedy algorithm can be found in *Algorithm* 1. It should be noted that, due to the fast moving, the danger coefficient ρ of vehicles would vary continuously, where the previous adaptation results may cause unfairness after a period of time, e.g., when the vehicle leaves the intersection, its ρ may become large, suffering from potential dangers. In order to avoid this type of potential dangers, in the design of *ABC*, vehicles are allowed to increase beaconing rates independently if their danger coefficients reach up to a pre-defined threshold[3].

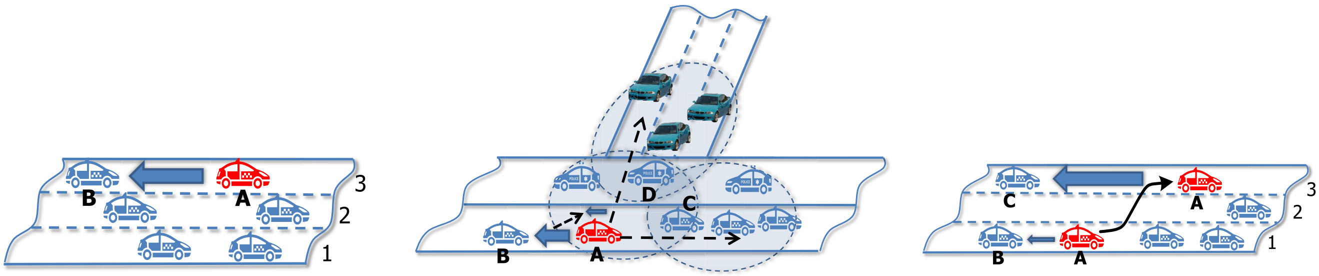
Algorithm 1 Heuristic Algorithm for DBRA at the Vehicle x

Input: S, $\alpha_{\min}$, $\alpha_{\max}$ and $\mathcal{N}_{\mathcal{THS}}(x) \cup x$
Output: $\boldsymbol{\alpha}$, *i.e.*, $\{\alpha_i | i \in \mathcal{N}_{\mathcal{THS}}(x) \cup x\}$
Initialize: $\boldsymbol{\alpha} = \mathbf{0}$
for $i \in \mathcal{N}_{\mathcal{THS}}(x) \cup x$ **do**
  $\alpha_i = \alpha_{\min}$
end for
Left_capacity=$S - \alpha_{\min} \cdot |\mathcal{N}_{\mathcal{THS}}(x) \cup x|$
$Sort(\mathcal{N}_{\mathcal{THS}}(x) \cup x)$ with $\downarrow \rho_i$
while Left_capacity>0 **do**
  $id \leftarrow (\mathcal{N}_{\mathcal{THS}}(x) \cup x)[0]$
  if Left_capacity $\ge \alpha_{\max} - \alpha_{\min}$ **then**
    $\alpha_{id} = \alpha_{\max}$
    Left_capacity$- = \alpha_{\max} - \alpha_{\min}$
    $\mathcal{N}_{\mathcal{THS}}(x) \cup x$=$\mathcal{N}_{\mathcal{THS}}(x) \cup x$-{id}
  else
    $\alpha_{id} = \alpha_{\min}$+Left_capacity
    Left_capacity=0
    break
  end if
end while
return $\boldsymbol{\alpha}$

D. Adaptation Results Informing

When the vehicle (say vehicle A) at the congested location achieves the DBRA results, it will then inform other vehicles

[3]The threshold setting does not affect how *ABC* works, and thus is conservatively set to be 0.5 in this paper.



(a) When the channel resource is sufficient (b) Encountering a congestion event (c) Driving safety demands increase

Fig. 4. Examples of adaptive beacon control.

within THS of the adaptation results. To do it, vehicle A first compares the adaptation results with its THS beaconing status. For those vehicles, whose current beaconing rates are larger than the adaptation result, A will include the informing information for them, i.e., containing a list of (vehicle ID, assigned beaconing rate), in its next beacon and broadcast out. After a neighbor (say vehicle B) receives the informing beacon, it will adjust itself beaconing rate to the allocated result if its original beaconing rate is larger than it. In addition, vehicle B will also compare the informing results with its OHS (who are out of the communication range of vehicle A) beaconing status and include informing information for those vehicles who are required to adapt beaconing rates, in its next beacon. There are two reasons making us disregard those vehicles whose current beaconing rates are smaller than the allocated results. First, although they have little impact on the current congested THS, additional congestions might be triggered in other THSs if their beaconing rates are improved. Second, as the number of vehicles in the THS might be quite large, informing all vehicles not only results in more communication cost but also prolongs the convergence to the stable state. To reach the stable state, the adaptation results have to be disseminated within the full THS. Considering the worst case, where the vehicle A is assigned with the minimum beaconing rate, the informing beacon can reach A's OHS within one second. Another one second may be required to cover all two-hop neighbors after assuming one of A' one-hop neighbors is also assigned with the minimum beaconing rate. Therefore, within at most two seconds, the congestion control can converge to the stable state.

E. Adaptive Beacon Control Approach

Fig. 4 illustrates how the proposed *ABC* scheme works. Specifically, in Fig. 4 (a), when vehicle A moves in the fast lane where the current traffic density is light, it can broadcast at the maximum beaconing rate to minimize the risk of being collided (in figures, the width of each arrow represents the size of beaconing rate). However, when vehicle A approaches an intersection shown in Fig. 4 (b), the channel is very likely to be congested since multiple sets of vehicles from different road segments merge together. In addition, the red traffic light can make vehicles slow down until they completely stop, which also aggravates the vehicle density. Once a congestion event is identified by vehicle A, it will solve the DBRA problem locally and broadcast out the adaptation results (shown by two long dashed arrows); its one-hop neighbors C and D will also broadcast the required adjustments to cover all vehicles within the congestion location. The short dashed arrow means that vehicle A adapts from the original large beacon rate (represented by the large blue arrow) to a new small beacon rate (represented by the small blue arrow). Note that, it is possible that one vehicle may receive multiple inconsistent beaconing adaptation results from different congestion locations. Under this case, the vehicle will conservatively adopt the lowest beaconing rate to relieve the congestion events. Another example is shown in Fig. 4 (c), where vehicle A leaves the intersection and initially moves in the slow lane. It then speeds up and changes to the fast lane, and therefore the danger threat ρ goes up. As the driving safety demand increases, its beaconing rate is also increased accordingly. *Algorithm* 2 gives the pseudocode of *ABC* scheme, which conducts adaptive beacon control at every vehicle.

V. Analysis on Efficiency and Overhead

In this section, we first analyze the efficiency of the heuristic algorithm by demonstrating its very slight gap to the optimal result. To evaluate the feasibility of the proposed *ABC* design, we then thoroughly analyze the communication overhead of the scheme.

A. Close Proximity to the Optimal Result

To begin with, we first sort vehicles by the danger coefficient in descending order, i.e., $\rho_i \geq \rho_j$ for $i < j$. Then, the i-th vehicle can be assigned with the maximum beacon rate, i.e., $\alpha_i = \alpha_{\max}$, if $\sum_{j=1}^{i} \alpha_{\max} \leq S-(|\mathcal{N}_{\mathcal{THS}}(x)|+1-i)\cdot\alpha_{\min}$, since the remaining $(|\mathcal{N}_{\mathcal{THS}}(x)| + 1 - i)$ vehicles can be guaranteed with the minimum beacon rate. We define the breaking item as the first vehicle that is not assigned with the maximum beaconing rate and the index b of the breaking item can be represented as

$$b=\arg\min_{i} \sum_{j=1}^{i} \alpha_{\max} > S-(|\mathcal{N}_{\mathcal{THS}}(x)|+1-i)\cdot\alpha_{\min}. \quad (10)$$

Therefore, the adaptation results calculated by the heuristic algorithm can be expressed as

$$\alpha_i = \begin{cases} \alpha_{\max} & i < b; \\ S - (|\mathcal{N}_{\mathcal{THS}}(x)| + 1 - b)\cdot\alpha_{\min} - \sum_{j=1}^{b-1}\alpha_j & i = b; \\ \alpha_{\min} & i > b. \end{cases} \quad (11)$$

Algorithm 2 Algorithm for ABC at the Vehicle x

Input: S, ρ_threshold, $\alpha_{\min}$ and $\alpha_{\max}$
Output: beaconing rate α_x

Initialize: channel_state = free, $\rho_x = 1$, $\mathcal{N}_{\mathcal{THS}}(x)$={}, $\mathcal{N}_{\mathcal{OHS}}(x) = \{\}$, $\alpha_x = \alpha_{\max}$
while at the end of each frame **do**
  Update $\mathcal{N}_{\mathcal{THS}}(x)and\mathcal{N}_{\mathcal{OHS}}(x)$
  Calculate ρ_x
  total_load = 0
  for $i \in \mathcal{N}_{\mathcal{THS}}(x)$ **do**
    total_load = total_load + α_i
  end for
  if total_load + $\alpha_x > S$ **then**
    channel_state = congested
    $\boldsymbol{\alpha} = DBRA(S, \alpha_{\min}, \alpha_{\max}, \mathcal{N}_{\mathcal{THS}}(x) \cup x)$
    $\alpha_x = \boldsymbol{\alpha}[x]$
    Inform results
  else
    channel_state = free
    if $\rho_x > \rho$_threshold **then**
      $\alpha_x = \alpha_{\max}$
    end if
  end if
  if Receive informing result list L_y **then**
    for $id \in L_y$ **do**
      if $id == x$and$L_y[id] < \alpha_x$ **then**
        $\alpha_x = L_y[id]$
      end if
    end for
    Reinform results
  end if
end while

We divide the S time slots into two groups, i.e., $\mathcal{S}_1 = \{1, 2, \ldots, b-1\}$ and $\mathcal{S}_2 = \{b, b+1, \ldots, S\}$, where the subgroup $\mathcal{S}_1$ is used to support the preceding $b-1$ vehicles with the maximum beaconing rate and the subgroup $\mathcal{S}_2$ is to guarantee the minimum beaconing rate for the rest of vehicles.

Lemma 1: By adopting our heuristic algorithm, the safety-weighted network utility contributed by the subgroup $\mathcal{S}_1$ can be the same as the optimal result.

Proof: We proof it by two steps. First, for vehicles $\{1, 2, \ldots, b-1\}$, we set them to be the maximum beaconing rate and to be served by the time slots in $\mathcal{S}_1$, which has maximized the network utility for the subgroup $\mathcal{S}_1$ since the time slots are fully utilized and assigned to those vehicles with the maximum danger coefficients. Second, without assigning time slots in $\mathcal{S}_1$ to those vehicles, no larger network utility can be achieved. It can be easily proofed by contradiction. If a time slot in $\mathcal{S}_1$ is assigned to a group vehicles in the set $\{b, b+1, \ldots, S\}$ and a larger network utility can be achieved, then there exists $i > j$ while $\rho_i > \rho_j$, which contradicts the descending order property. ■

For time slots in subgroup $\mathcal{S}_2$, there are totally $(|\mathcal{N}_{\mathcal{THS}}(x)| + 1 - (b-1)) \cdot \alpha_{\min}$ time slot spaces should be kept for vehicles $\{b, b+1, \ldots, |\mathcal{N}_{\mathcal{THS}}(x)| + 1\}$ to guarantee their minimum beaconing rates.

Definition 4: (Uncertain space) There is an uncertain space in subgroup $\mathcal{S}_2$, equaling $S - (b-1) - (|\mathcal{N}_{\mathcal{THS}}(x)| + 1 - (b-1)) \cdot \alpha_{\min}$, which could support one large-size (in terms of beacon rate) vehicle or a combination of small-size vehicles, leading to the knapsack complexity.

Lemma 2: The uncertain space cannot exceed the size $\alpha_{\max} - \alpha_{\min}$.

Proof: It can be easily proofed since if the uncertain space is larger than $\alpha_{\max} - \alpha_{\min}$, then another vehicle (i.e., b-th vehicle) can be allocated with the maximum beaconing rate, which contradicts the breaking item property of the b-th vehicle. ■

To this end, the gap to the optimal result can only appear at the usage of uncertain space, where the heuristic algorithm may fail to make full use of it and assign it to only one vehicle (with a large danger coefficient) while the DP algorithm can fully utilize it by dynamic combination. Considering the small size of it, our heuristic algorithm is capable of achieving very close proximity to the optimal result in practice. To further demonstrate it, we implement both the heuristic and DP algorithm and carry out both numerical results. We set the number of slots S to be 150 and vary the number of vehicles $|\mathcal{N}_{\mathcal{THS}}(x)| + 1$ (input size) from 50 to 450 with a step length of 50. In addition, the danger threat of each vehicle ρ_i is randomly chosen from 0 to 1. We calculate the value of safety-weighted network utility in Eq. (9) and log the running time of two algorithms by a normal laptop.

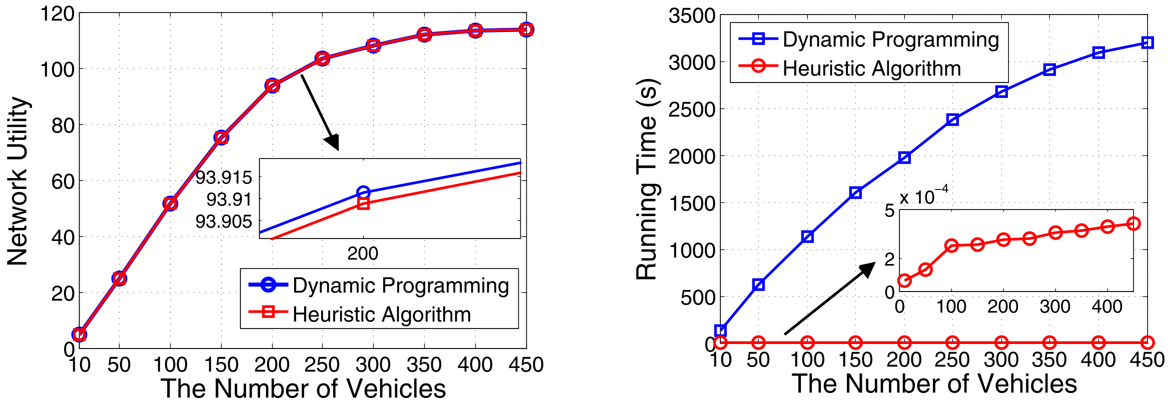
Fig. 5 shows the average results after running the simulation for 20 rounds. As shown in Fig. 5 (a), we can see that our heuristic algorithm can achieve very analogous safety-weighted network utility compared with that obtained by the DP algorithm. For instance, when the number of vehicles reaches 200, the network utility in heuristic and DP algorithm is about 93.90 and 93.91, respectively, which is a negligible performance gap. However, as shown in Fig. 5 (b), there is a huge gap between two algorithms in terms of the running time[4]. Particularly, no matter how many vehicles need to be scheduled, the required running time of the heuristic algorithm never exceeds 0.5 ms, which can well meet the real-time adaptation demand. In contrast, the required running time for the DP algorithm is about 130 s when the number of vehicles is only 10, and the time can reach above 3200 s when the input size is increased to 450.

B. Protocol Overhead Analysis

To conduct a fully distributed beacon congestion control, negotiations among neighboring vehicles is in need. The main overhead of *ABC* is the one-hop list of the beaconing status (α_i and ρ_i) in each beacon.[5] As $\alpha_i \in \{1/1, 1/2, 1/3, \ldots, 1/10\}$, it can be labeled by other ten values, e.g., $\{1, 2, 3, \ldots, 10\}$, and thus $\lceil \log_2 10 \rceil = 4$ bits are

[4]Compared with the DP algorithm which has a time complexity of $O(n \cdot 2^L)$, our heuristic algorithm can achieve the result with a polynomial time complexity of $O(nlogn)$.

[5]The vehicle ID of one-hop neighbors has been contained in each beacon by the TDMA MAC as indicated in the system model section.



(a) Network utility vs. input size

(b) Running time vs. input size

Fig. 5. Efficiency of the heuristic algorithm.

required to identify each beaconing rate, where the symbol $\lceil . \rceil$ is ceil function. Similarly, $\lceil \log_2 101 \rceil = 7$ bits are sufficient to label each danger coefficient with the value range of $\{0, 1, 2, 3, \ldots, 100\}$ (in order of magnitude -2). Let V_{OHS} denote the maximum number of OHS neighbors, and then the maximum overhead (in bits) is

$$overhead = V_{\mathrm{OHS}} \times (4 + 7). \tag{12}$$

As the area of an OHS covers a circle area within the radius R, on a road, the value of V_{OHS} can be calculated by

$$V_{\mathrm{OHS}} = \left(\frac{2R}{length_{vehicle} + distance_{safety}}\right) \times L, \tag{13}$$

where $length_{vehicle}$, $distance_{safety}$ and L represent the vehicle length, safety following distance and number of lanes on the road, respectively. Specifically, $length_{vehicle}$ is normally 3-5 meters for sedans. In normal driving conditions, drivers should drive at least 2 seconds behind the preceding vehicle to avoid crashes; given a normal speed of 60 km/h in urban environments, the $distance_{safety}$ can be obtained as $distance_{safety} \approx 35$ m. Considering a normal case where $R = 300$ and $L = 6$, then the value of V_{OHS} can be calculated $V_{\mathrm{OHS}} = (\frac{600}{5+35}) \times 6 = 90$. Then, the overhead in this case is $overhead = 90 \times 11 = 1620$ bits ≈ 123 bytes. Considering the packet size of each beacon being normally smaller than 500 bytes [26], including such extra 123 bytes of coordination information in each beacon is *acceptable*, since the total size is far smaller than the payload of MAC layer data unit (normally about $1,500$ bytes). In addition, we can consider an extreme case, when the $distance_{safety}$ is only about 5 meters. Then, the overhead is $overhead = 360 \times 11 = 3960$ bits ≈ 495 bytes, which can still be well implemented even though this case rarely happens in real driving scenarios.

VI. Performance Evaluation

A. Methodology

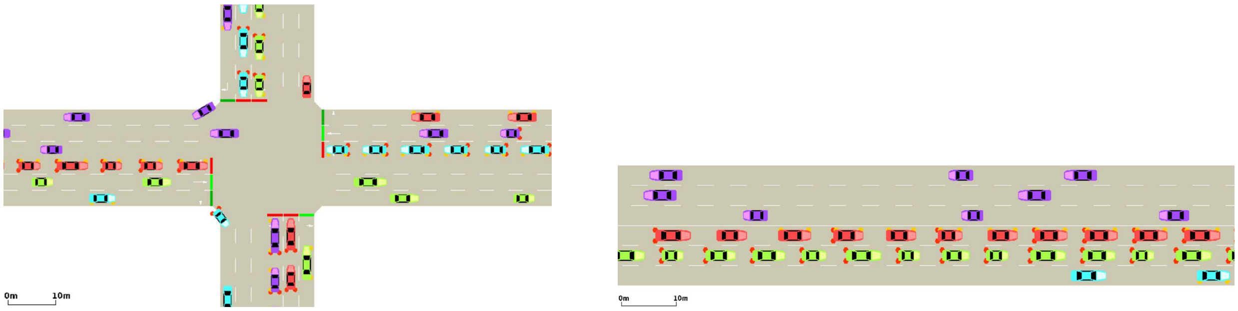
1) Simulation Setup: We adopt SUMO to emulate real driving scenarios, since it allows building intermodal traffic systems (including road topologies, traffic lights, moving vehicles, etc.). Table I summarizes the main simulation parameters.

TABLE I
Simulation Parameters

Parameters	Urban
Road length	$5\ km$
Number of road segments	4
Number of lanes on each road	6
Speed limit in lanes (in km/h)	$[60, 100]$
Maximum speed of vehicles (in km/h)	$[80, 240]$
Acceleration of vehicles (in m/s^2)	$[1.0, 5.0]$
Deceleration of vehicles (in m/s^2)	$[3.0, 10.0]$
Transmission range	$300\ m$
Frame duration	$100\ ms$
Number of slots (per frame)	150
Loaded vehicles	$800 - 1080$
Simulation time	1000 frames

More specifically, we create a typical urban road topology, constituted by four bidirectional 6-lane road segments, each of which is 5 km long, and they merge together at the center forming an intersection. In each direction, three lanes are set with speed limits of 60, 80, and 100 km/h, respectively. At the intersection, traffic lights are configured at each inbound road segment (i.e., entering the intersection), and the durations of green light, yellow light and red light are set to be 20 s, 3 s, and 20 s, respectively. To simulate normal traffic conditions, we generate vehicles at the open end of each road segment with a rate of 10 vehicles/lane/minute. For their roadworthiness, we set up the maximum velocity ranging from 80 to 240 km/h, acceleration capability ranging from 1 to 5 m/s^2, and deceleration capability ranging from 3 to 10 m/s^2, which are randomly determined within the range when vehicles are generated. Vehicles are driven under the the LC2013 lane-changing and Krauss car-following model [28], which can conduct normal lane-change and overtaking events when necessary. When a vehicle is generated, it will randomly choose a destination road segment and will disappear from the system after reaching the destination. Snapshots of the simulated scenarios are shown in Fig. 6, in which different colors of vehicles represent distinct roadworthiness sets.

With the generated SUMO trace (1000 frames of trace are chosen), we implement our *ABC* scheme over them by



(a) at intersection (b) on multi-lane road

Fig. 6. Snapshots of the simulated scenario.

Python with about 500 lines of code. As we study MAC activities, we consider all transmissions successful within communication range unless time slot usage collisions happen. The transmission range R is set to be 300 m according to the DSRC experiment study [21], which verifies that V2V communication can be rather reliable within the distance. In addition, each frame lasts 100 ms consisting 150 time slots, in order to compliant with the 100 ms delay requirements for most safety applications [29].

2) Benchmark Schemes: We compare the proposed *ABC* with two reasonable benchmark schemes as follows:

- **Conventional 802.11p [20]:** In broadcast mode of IEEE 802.11p, all vehicles broadcast with a rate of 1 beacon/frame, and there is no any congestion control mechanism.
- **LIMERIC [16]:** In LIMERIC, once a congestion event is identified, vehicles within the interference range will adapt to the same beaconing rate under the medium resource limit. Note that, this scheme normally works in a different system model like us, and here we just adopt its congestion control idea as a benchmark scheme, i.e., treating all vehicles equally when a congestion event is identified.

3) Performance Metrics: We define the following five metrics to compare performance of all beaconing schemes:

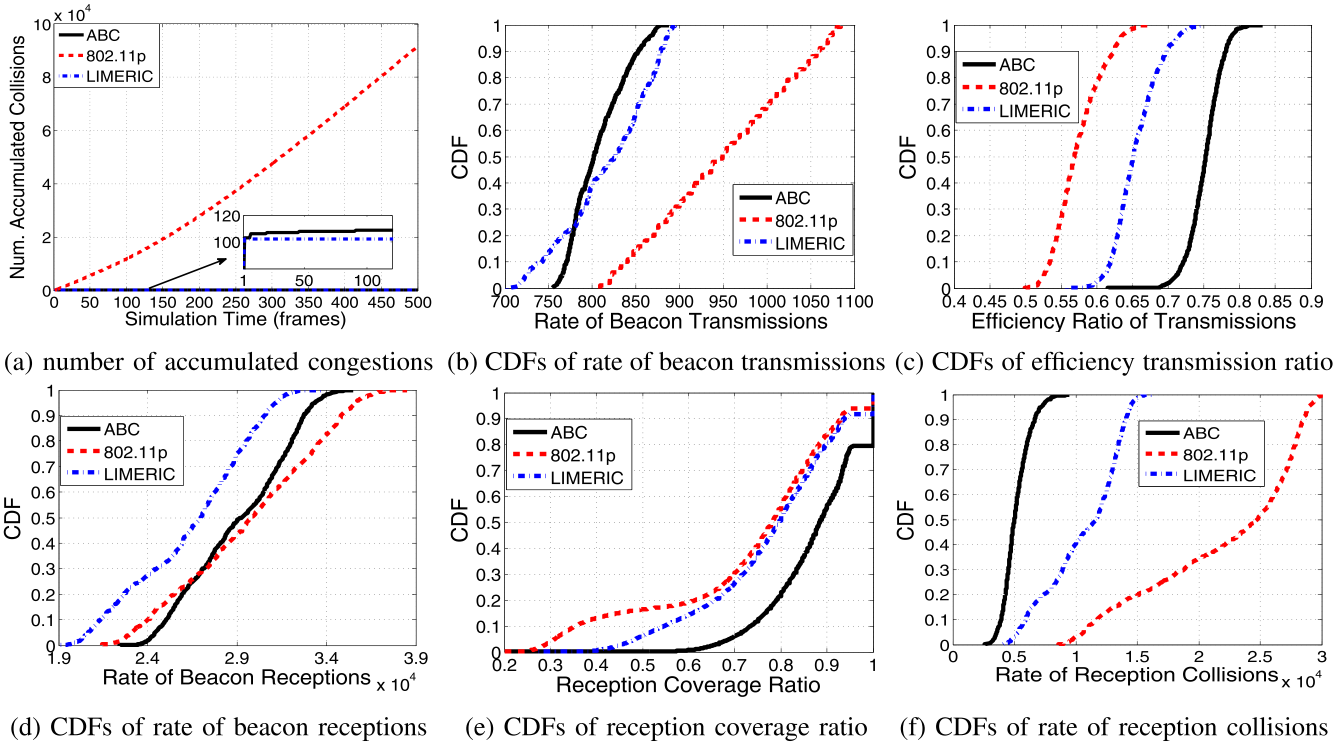
1) **Rate of beacon transmissions** refers to the average number of transmitted beacons per frame.
2) **Efficiency ratio of transmissions** refers to the number of successful transmissions to the total number of transmissions. When a vehicle transmits a beacon at a time slot and no concurrent transmission happens within its interference range, then the transmission is counted as a successful transmission.
3) **Rate of beacon receptions** refers to the average number of successfully received beacons per frame.
4) **Reception coverage ratio** refers to the number of successful receptions at a vehicle to the total number of transmissions by its OHS neighbors in a frame, measuring whether the vehicle can successfully receive all beacons from neighboring vehicles.
5) **Rate of reception collisions** refers to the average number of reception collisions per frame. Particularly, if a receiver receives more than one beacon at a single time slot, then the number of concurrent receptions are counted as the number of reception collisions.

B. Performance Comparison

We first examine the overall performance (results of all vehicles together), by checking the CDF results of all metrics.

1) Efficiency of Beacon Rate Control: By checking the number of accumulated congestions as shown in Fig. 7 (a), we can easily see that congestion events can be successfully suppressed in *ABC* and LIMERIC schemes by adopting beacon rate control. Specifically, without any congestion control in 802.11p, the channel congestion will flood within the network, reaching up to $20,000$ times at only 150-th frame. To understand how control activities happen, we then check the CDF results of rate of beacon transmissions as shown in Fig. 7 (b), in which we can see that the beacon transmission rates are effectively reduced in both LIMERIC and *ABC* schemes. Particularly, the median beacon transmission rate is about 825 and 800 transmissions/frame in LIMERIC and *ABC* scheme, respectively, while the rate can be as high as 950 transmissions/frame in 802.11p. Besides, the maximum beacon transmission rate in 802.11p reaches up to $1,080$ transmissions/frame, which however is no more than 900 in both *ABC* and LIMERIC schemes.

With suppressing congestion events properly, massive messages collisions can be efficiently relieved. Particularly, as shown in Fig. 7 (c), in 802.11p, the median ratio of efficiency transmission is only 0.56 while in LIMERIC and *ABC*, the value can be enhanced to 0.65 and 0.75, respectively. Moreover, in *ABC*, more than 98% ratios are larger than 0.7, whereas in LIMERIC and 802.11p, the proportion drops down to 10% and 0, respectively. It means that in *ABC*, when a vehicle broadcasts a beacon, the probability that all neighboring vehicles can successfully receive the bacon, is able to reach about 70%. Fig. 7 (f) shows CDFs of reception collision rates, which can further indicate the importance of beacon congestion control. Specifically, the median rate of reception collisions is only about $5,000$ collisions/frame in *ABC*, while the rate increases significantly in LIMERIC and 802.11p, to the value of $12,000$ and $25,000$, respectively. In addition, in *ABC*, all reception collision rates are smaller than $10,000$ collisions/frame, while in LIMERIC and 802.11p, more than 60% and 99% rates are larger than this value.



(a) number of accumulated congestions (b) CDFs of rate of beacon transmissions (c) CDFs of efficiency transmission ratio

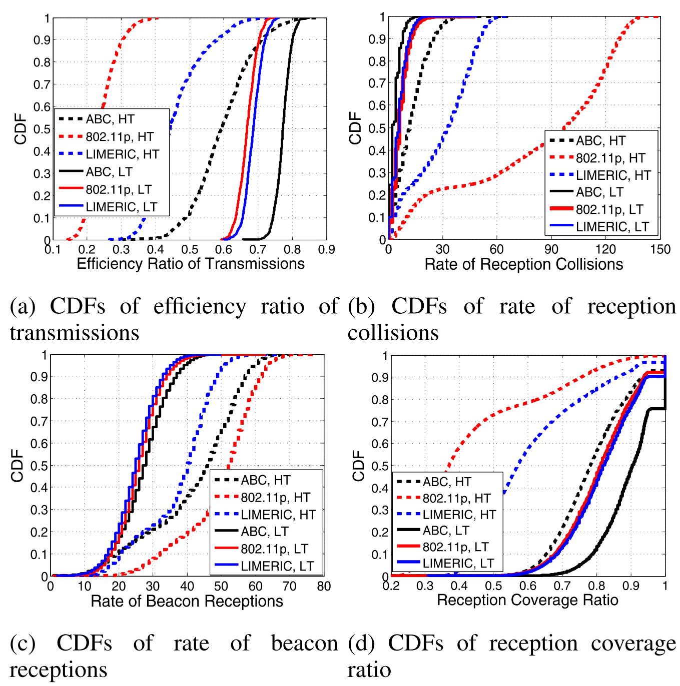
(d) CDFs of rate of beacon receptions (e) CDFs of reception coverage ratio (f) CDFs of rate of reception collisions

Fig. 7. Overall performance results.

2) Slight Degradation in Rx Throughput: As shown in Fig. 7 (d), we can see that when the vehicle density becomes heavy,[6] 802.11p can sometimes achieve the largest beacon reception rates. Specifically, the median reception rate in LIMERIC and *ABC* is about 26, 000 and 29, 000 receptions/frame, respectively, while the value can increase slightly to 29, 500 in 802.11p. It is reasonable for this phenomenon as transmission rates are reduced in both *ABC* and LIMERIC schemes. In 802.11p, although massive reception collisions would happen, maximum transmission rates of all vehicles can still maintain the Rx throughput. Slight degradation in Rx throughput is *acceptable* in the vehicular network, since its goal is to guarantee each vehicle's driving safety by enhancing the beaconing reliability, rather than maximize the throughput with sacrificing some vehicles' safety demands. However, as shown in Fig. 7 (e), the probability of the reception coverage ratio larger than 0.8 is about 45% and 50% in 802.11p and LIMERIC, respectively, while the probability can be enhanced to 80% in *ABC*. It indicates that vehicles are better aware of the nearby environment with adopting our proposed scheme, as vehicles can successfully receive beacons from most neighboring vehicles.

C. Working Robustly Under Dynamic Road Traffic

According to the number of vehicles in the THS, we divide vehicles into two groups, i,e., $|\mathcal{N}_{\mathcal{THS}}(x)| + 1 < 150$ (under light traffic (LT)) and $|\mathcal{N}_{\mathcal{THS}}(x)| + 1 \geq 150$ (under heavy traffic (HT)). As shown in Fig. 8, we then examine the performance under different density conditions, where solid lines are LT results while dashed lines are HT results. From Fig. 8 (a) and (b), it can be seen that *ABC* is capable of achieving the most obvious efficacy in congestion control under HT conditions. Particularly, the median ratio of efficiency transmissions reach 0.61 in *ABC* while the value decreases below to 0.25 in 802.11p. On the contrary,

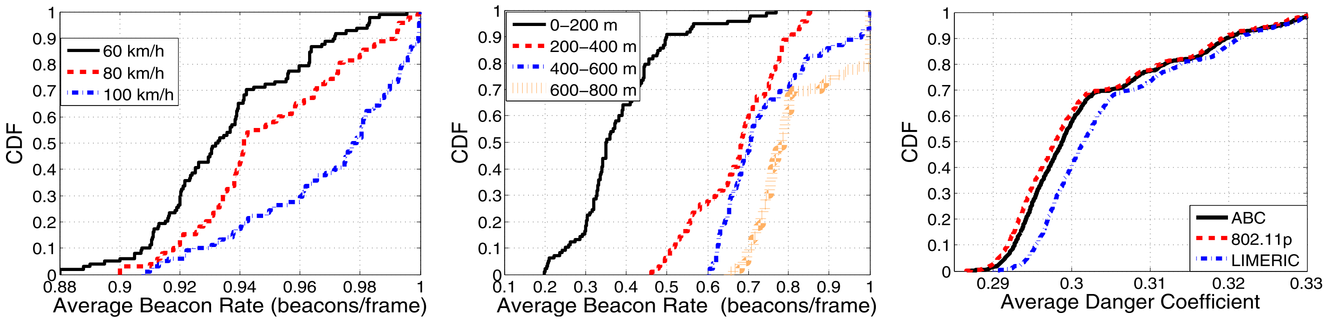


(a) CDFs of efficiency ratio of transmissions (b) CDFs of rate of reception collisions

(c) CDFs of rate of beacon receptions (d) CDFs of reception coverage ratio

Fig. 8. Performance of vehicles under LT and HT conditions.

[6]Note that, the rate of reception can indirectly indicate the vehicle density.



(a) average beacon rate in different lanes (b) average beacon rate at intersection zones (c) CDFs of average danger coefficients

Fig. 9. Safety-aware beacon rate adaptation results.

the median reception collision rate in *ABC* is about 15 collisions/frame/vehicle, whereas the rate increases dramatically to 100 in 802.11p. Furthermore, when in LT conditions, in both figures, *ABC* can guarantee the best performance, i.e., achieving the highest ratio of efficiency transmissions and the lowest rate of reception collisions. Fig. 8 (c) shows CDFs of rates of beacon receptions, and it can be seen that *ABC* outperforms 802.11p under LT conditions whereas performs a little worse than it under HT conditions. We can conclude that, when in LT conditions, the higher efficiency ratio of transmissions in *ABC* ensures a better Rx throughput performance, while in HT conditions, the large number of vehicles and their maximum beaconing rates in 802.11p enforce the larger Rx throughput performance. However, in both density conditions, the reception coverage ratio can be well enhanced in *ABC*, which can be seen from Fig. 8 (d). For instance, when in HT conditions, the median reception coverage ratio is about 0.38, 0.58, and 0.79 in 802.11p, LIMERIC, and *ABC*, respectively.

D. Safety-Aware Beacon Rate Adaptation

With adopting *ABC*, Fig. 9 (a) shows CDFs of average beacon rate of vehicles in different lanes, and it can be seen that vehicles in fast lanes are assigned with higher beacon rates due to their possible higher danger coefficients. For instance, in the respective 60, 80, and 100 km/s-limit lane, the median value of the average beacon rate is about 0.93, 0.94, and 0.98 beacons/frame. In addition, Fig. 9 (b) shows CDFs of average beacon rate of vehicles at different intersection zones, i.e., with respective 0-200, 200-400, 400-600, and 600-800 m away from the intersection center area, and we can make the following two statements. First, with the distance away from the intersection increasing, the average beacon rates of vehicles increase accordingly; for example, the median beacon rate can increase from 0.35 in the range of 0-200 m to 0.68, 0.7, and 0.8 in other respective ranges. Second, the intersection is the main scenario where the beacon congestion is controlled due to the heavy-density vehicles. Specifically, compared with results in Fig. 9 (a) (far away from the intersection) where all beacon rates are larger than 0.88, the percentage of beacon rates larger than this value is about 0, 0, 15% and 30% in respective ranges at intersection areas.

Furthermore, Fig. 9 (c) shows CDFs of average danger coefficients achieved by adopting different schemes. Obviously, 802.11p can achieve the smallest danger coefficients as all vehicles broadcast at the maximum beacon rates. However, we can observe that our proposed *ABC* can achieve very close safety-aware performance to 802.11p as two curves are quite close with a negligible gap, but as demonstrated above, 802.11p suffers from serious packet loss due to channel congestion which can result in potential dangers. On the other hand, we can see that there is an obvious performance gap between *ABC* and LIMERIC, with the respective median average danger coefficient of 0.299 and 0.302. It is reasonable as in *ABC*, beacon rates are assigned according to the underlying driving contexts while beacon rates are equally assigned in LIMERIC. Therefore, *ABC* can control beacon rates to avoid massive message collisions under congested channel conditions, and meanwhile is able to conduct safety-aware beacon rate adaptation for vehicles.

VII. Related Work

A. Transmit Power Control (TPC)

There have been several researches on TPC approaches to avoid future channel congestions, among which, D-FPAV [11] is one of the most cited solutions. Particularly, complying with constraints of guaranteeing max-min fairness and without exceeding the channel load threshold, vehicles can run the D-FPAV algorithm to calculate their allowed maximum Tx powers. Since the original D-FPAV design suffers from the heavy packet overhead, Mittag et al. [14] devised an upgraded version, which can reduce two orders of magnitude in overhead. Shah *et al.* [10] proposed an transmission power control approach, named as AC3, which allows vehicles to select their transmission powers automatically in response to local channel congestions. In specific, they introduced a notion of marginal contributions, which aggregated from vehicles and finally resulted in a potential channel congestion, and under the principles of cooperative game theory, the vehicle should reduce the most transmit power if it has the highest marginal contribution. Besides, joint rate-power control algorithms for safety message broadcast are also proposed in some works. For example, Egea-Lopez *et al.* [13] defined that vehicles could transmit packets with different levels of power and each level mapped with a distinct beaconing rate. In addition, in the work [32], the required minimum Tx rates are first calculated in order to comply with the tracking error demand; Tx powers of vehicles are then enlarged until the Channel Busy Ratio (CBR) reaches up to a pre-defined threshold. For these proactive approaches, precise models are essential to conduct prediction for future traffic density, channel load, etc, which however are difficult to be guaranteed due to fast speed, time-varying traffic, etc, in dynamic vehicular environments, and therefore these solutions may be unstable. For instance, the recent proposal [15] has studied TPC approaches and pointed out that their accuracies are deeply influenced by the quality of the transmission and prediction model, leading to serious instability issue. In addition, previous studies [33] have also concluded that to well reach the stable stage, message rate control is the most efficient method. Therefore, we focus on TRC techniques in this paper.

B. Transmit Message Rate Control (TRC)

For TRC schemes, LIMERIC [16] and PULSAR [17] are two highly cited works and have many techniques in common. Particularly, with continuous feedback from neighbors (beaconing rate in use) as input, a linear control algorithm is designed in LIMERIC [16], while in PULSAR [17], the authors devised an iteration algorithm named as AIMD (i.e., additive increase multiplicative decrease), which depends on a binary feedback from THS (congested or not), to adjust beaconing rates for vehicles. However, they didn't take the driving context into consideration: all vehicles adapt to the same beaconing rate. Such equal fair resource allocations are likely to achieve the maximum throughput, but cannot guarantee the best safety benefit for the transportation system. There are two recent proposals [18], [19] on the vehicular network congestion control, both of which model a Network Utility Maximization (NUM) problem for beacon rate adapting. Specifically, Egea-Lopez *et al.* [18] defined a notion of "fairness" for beacon rate adaptation with targeting at the throughput maximization. They then proposed a FABRIC algorithm to solve the dual of the NUM problem, in which the scaled gradient projection scheme is adopted. Similarly, in the context of a slotted p-persistent broadcast MAC, Zhang *et al.* [19] also formulated a NUM problem for beacon rate adaptation, by taking the velocity and relative position into consideration. In both piece of works, network utility is optimized while driving safety demands of vehicles are not preferentially treated. The same issue is also existed in the scheme of DBCC (i.e., distributed beacon congestion control) [34], in which the authors assign beaconing medium resource according to vehicles' link qualities rather than their driving contexts. In the work [35], each vehicle broadcasts beacon interval requests and the road side unit as a centralized controller allocates channel resources according to the requests from all vehicles, which is formulated to an optimization problem and then transformed into a maximum weighted independent set problem. Since a centralized controller is required and it takes time to converge to the optimal result, it fails to meet the distributed and real-time demands of beacon exchanging. Our preliminary work has shown the advantage of conducting beacon congestion control according to safety demand of individual vehicles [36]. In this paper, we further improve it by giving complete system model and detailed problem formulation, and carrying out performance efficiency analysis and comprehensive performance comparison.

VIII. Conclusion and Future Works

In this paper, we have proposed a distributed adaptive beacon control scheme, named *ABC*, to conduct safety-aware beacon rate adaptation for vehicles under highly-dynamic vehicular environments. Three novel techniques have been integrated in *ABC*: 1) online congestion detection; 2) distributed beacon rate adaptation; and 3) adaptation results informing. Performance analysis on the efficiency of the devised algorithm and on the communication overhead of the scheme have been provided. Finally, we have implemented our proposed *ABC* scheme under SUMO-generated traces and conducted extensive simulations to demonstrate its efficacy. By adopting *ABC*, the beaconing reliability can be guaranteed even when the vehicle density becomes quite heavy, and meanwhile, vehicles can adapt sufficient beaconing rates according to the driving safety demand to avoid the rear-end collision. For our future work, we will consider more crash models, e.g., run-off-road collisions or head-on collisions, and incorporate their danger weights into our beacon congestion control framework.

References

[1] U.S. Mortality Causes and Prevention Methods. *Top 10 Causes of Death for Americans Ages 15 to 24*. Accessed: Dec. 2018. [Online]. Available: https://www. verywellhealth.com/top-causes-of-death-for-ages-15-24-2223960

[2] N. Lu, N. Cheng, N. Zhang, X. Shen, and J. W. Mark, "Connected vehicles: Solutions and challenges," *IEEE Internet Things J.*, vol. 1, no. 4, pp. 289–299, Aug. 2014.

[3] J. E. Siegel, D. C. Erb, and S. E. Sarma, "A survey of the connected vehicle landscape—Architectures, enabling technologies, applications, and development areas," *IEEE Trans. Intell. Transp. Syst.*, vol. 19, no. 8, pp. 2391–2406, Aug. 2018.

[4] W. Xu *et al.*, "Internet of vehicles in big data era," *IEEE/CAA J. Autom. Sinica*, vol. 5, no. 1, pp. 19–35, Jan. 2018.

[5] X. Cheng, R. Zhang, and L. Yang, "Wireless toward the era of intelligent vehicles," *IEEE Internet Things J.*, vol. 6, no. 1, pp. 188–202, Feb. 2019.

[6] N. Cheng *et al.*, "Big data driven vehicular networks," *IEEE Netw.*, vol. 32, no. 6, pp. 160–167, Nov. 2018.

[7] D. Yu *et al.*, "Stable local broadcast in multihop wireless networks under SINR," *IEEE/ACM Trans. Netw.*, vol. 26, no. 3, pp. 1278–1291, Jun. 2018.

[8] S. M. O. Gani, Y. P. Fallah, G. Bansal, and T. Shimizu, "A study of the effectiveness of message content, length, and rate control for improving map accuracy in automated driving systems," *IEEE Trans. Intell. Transp. Syst.*, vol. 20, no. 2, pp. 405–420, Feb. 2019.

[9] X. Cheng *et al.*, "Space/aerial-assisted computing offloading for IoT applications: A learning-based approach," *IEEE J. Sel. Areas Commun.*, vol. 37, no. 5, pp. 1117–1129, May 2019.

[10] S. A. A. Shah, E. Ahmed, J. J. P. C. Rodrigues, I. Ali, and R. M. Noor, "Shapely value perspective on adapting transmit power for periodic vehicular communications," *IEEE Trans. Intell. Transp. Syst.*, vol. 19, no. 3, pp. 977–986, Mar. 2018.

[11] M. Torrent-Moreno, J. Mittag, P. Santi, and H. Hartenstein, "Vehicle-to-vehicle communication: Fair transmit power control for safety-critical information," *IEEE Trans. Veh. Technol.*, vol. 58, no. 7, pp. 3684–3703, Sep. 2009.

[12] F. Goudarzi and H. Asgari, "Non-cooperative beacon power control for VANETs," *IEEE Trans. Intell. Transp. Syst.*, vol. 20, no. 2, pp. 777–782, Feb. 2019.

[13] E. Egea-Lopez and P. Pavon-Marino, "Fair congestion control in vehicular networks with beaconing rate adaptation at multiple transmit powers," *IEEE Trans. Veh. Technol.*, vol. 65, no. 6, pp. 3888–3903, Jun. 2016.

[14] J. Mittag, F. Schmidt-Eisenlohr, M. Killat, J. Härri, and H. Hartenstein, "Analysis and design of effective and low-overhead transmission power control for VANETs," in *Proc. 5th ACM Int. Workshop Veh. Inter-NETworking (VANET)*, 2008, pp. 39–48.

[15] M. Sepulcre, J. Mittag, P. Santi, H. Hartenstein, and J. Gozalvez, "Congestion and awareness control in cooperative vehicular systems," *Proc. IEEE*, vol. 99, no. 7, pp. 1260–1279, Jul. 2011.

[16] G. Bansal, J. B. Kenney, and C. E. Rohrs, "LIMERIC: A linear adaptive message rate algorithm for DSRC congestion control," *IEEE Trans. Veh. Technol.*, vol. 62, no. 9, pp. 4182–4197, Nov. 2013.

[17] T. Tielert, D. Jiang, Q. Chen, L. Delgrossi, and H. Hartenstein, "Design methodology and evaluation of rate adaptation based congestion control for vehicle safety communications," in *Proc. IEEE Veh. Netw. Conf. (VNC)*, Nov. 2011, pp. 116–123.

[18] E. Egea-Lopez and P. Pavon-Marino, "Distributed and fair beaconing rate adaptation for congestion control in vehicular networks," *IEEE Trans. Mobile Comput.*, vol. 15, no. 12, pp. 3028–3041, Dec. 2016.

[19] L. Zhang and S. Valaee, "Congestion control for vehicular networks with safety-awareness," *IEEE/ACM Trans. Netw.*, vol. 24, no. 6, pp. 3290–3299, Dec. 2016.

[20] *Standard Specification for Telecommunications and Information Exchange Between Roadside and Vehicle Systems—5 GHz Band Dedicated Short Range Communications (DSRC) Medium Access Control (MAC) and Physical Layer (PHY) Specifications*, Standard ASTM E2213, ASTM, 2018. [Online]. Available: http://www.astm.org/Standards/E2213.htm

[21] F. Lyu *et al.*, "Characterizing urban vehicle-to-vehicle communications for reliable safety applications," *IEEE Trans. Intell. Transp. Syst.*, to be published, doi: 10.1109/tits.2019.2920813.

[22] X. Shen, X. Cheng, L. Yang, R. Zhang, and B. Jiao, "Data dissemination in VANETs: A scheduling approach," *IEEE Trans. Intell. Transp. Syst.*, vol. 15, no. 5, pp. 2213–2223, Oct. 2014.

[23] H. A. Omar, W. Zhuang, and L. Li, "VeMAC: A TDMA-based MAC protocol for reliable broadcast in VANETs," *IEEE Trans. Mobile Comput.*, vol. 12, no. 9, pp. 1724–1736, Sep. 2013.

[24] X. Jiang and D. H. C. Du, "PTMAC: A prediction-based TDMA MAC protocol for reducing packet collisions in VANET," *IEEE Trans. Veh. Technol.*, vol. 65, no. 11, pp. 9209–9223, Nov. 2016.

[25] F. Lyu *et al.*, "SS-MAC: A novel time slot-sharing MAC for safety messages broadcasting in VANETs," *IEEE Trans. Veh. Technol.*, vol. 67, no. 4, pp. 3586–3597, Apr. 2018.

[26] "Dedicated short range communications (DSRC) message set dictionary," DSRC Committee, Soc. Automot. Eng., Warrendale, PA, USA, Tech. Rep. J2735 200911, Nov. 2009.

[27] NHTSA. *2016 Summary of Motor Vehicle Crashes*. Accessed: Sep. 2018. [Online]. Available: https://crashstats.nhtsa.dot.gov/Api/Public/ViewPublication/812580

[28] DLR Institute of Transportation Systems. *Sumo: Simulation of Urban Mobility*. Accessed: Sep. 2017. [Online]. Available: http://www.dlr.de/ts/en/desktopdefault.aspx/tabid-1213/

[29] "Vehicle safety communications project: Task 3 final report: Identify intelligent vehicle safety applications enabled by DSRC," CAMP Vehicle Saf. Commun. Consortium, Nat. Highway Traffic Saf. Admin., US Dept. Transp., Washington, DC, USA, Tech. Rep. DOT HS 809 859, Mar. 2005.

[30] J. He, L. Cai, J. Pan, and P. Cheng, "Delay analysis and routing for two-dimensional VANETs using carry-and-forward mechanism," *IEEE Trans. Mobile Comput.*, vol. 16, no. 7, pp. 1830–1841, Jul. 2017.

[31] H. Kellerer, U. Pferschy, and D. Pisinger, "The multiple-choice knapsack problem," in *Knapsack Problems*. Berlin, Germany: Springer, 2004, pp. 317–347.

[32] C.-L. Huang, Y. Fallah, R. Sengupta, and H. Krishnan, "Adaptive intervehicle communication control for cooperative safety systems," *IEEE Netw.*, vol. 24, no. 1, pp. 6–13, Jan. 2010.

[33] A. Autolitano, C. Campolo, A. Molinaro, R. M. Scopigno, and A. Vesco, "An insight into decentralized congestion control techniques for VANETs from ETSI TS 102 687 V1.1.1," in *Proc. IFIP Wireless Days (WD)*, Nov. 2013, pp. 1–6.

[34] F. Lyu *et al.*, "DBCC: Leveraging link perception for distributed beacon congestion control in VANETs," *IEEE Internet Things J.*, vol. 5, no. 6, pp. 4237–4249, Dec. 2018.

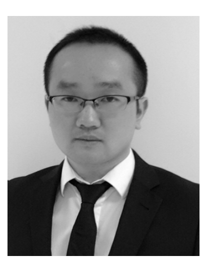
[35] L. Sun, A. Huang, H. Shan, and L. Cai, "Adaptive beaconing for collision avoidance and tracking accuracy in vehicular networks," *J. Commun. Inf. Netw.*, vol. 2, no. 2, pp. 30–45, Jun. 2017.

[36] F. Lyu *et al.*, "ABC: Adaptive beacon control for rear-end collision avoidance in VANETs," in *Proc. 15th Annu. IEEE Int. Conf. Sens., Commun., Netw. (SECON)*, Jun. 2018.

Feng Lyu (Member, IEEE) received the B.S. degree in software engineering from Central South University, Changsha, China, in 2013, and the Ph.D. degree from the Department of Computer Science and Engineering, Shanghai Jiao Tong University, Shanghai, China, in 2018. From September 2018 to December 2019 and October 2016 to October 2017, he worked as a Post-Doctoral Fellow and was a Visiting Ph.D. Student, respectively, with the BBCR Group, Department of Electrical and Computer Engineering, University of Waterloo, Canada. He is currently a Professor with the School of Computer Science and Engineering, Central South University. His research interests include mobile networking and computing, big data driven service design, and space-air-ground integrated networks. He is a member of the IEEE Computer Society, Communication Society, and Vehicular Technology Society.

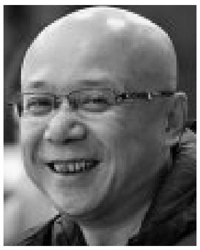
Nan Cheng (Member, IEEE) received the B.E. and M.S. degrees from the Department of Electronics and Information Engineering, Tongji University, Shanghai, China, in 2009 and 2012, respectively, and the Ph.D. degree from the Department of Electrical and Computer Engineering, University of Waterloo, in 2016. He worked as a Post-Doctoral Fellow with the Department of Electrical and Computer Engineering, University of Toronto, and with the Department of Electrical and Computer Engineering, University of Waterloo, from 2017 to 2018. He is currently a Professor with the School of Telecommunication Engineering, Xidian University, Shaanxi, China. His current research focuses on space-air-ground integrated systems, big data in vehicular networks, and self-driving systems. His research interests also include performance analysis, MAC, opportunistic communication, and application of AI for vehicular networks.

Hongzi Zhu (Member, IEEE) received the Ph.D. degree in computer science from Shanghai Jiao Tong University in 2009. He was a Post-Doctoral Fellow with the Department of Computer Science and Engineering, The Hong Kong University of Science and Technology, and with the Department of Electrical and Computer Engineering, University of Waterloo, in 2009 and 2010, respectively. He is currently an Associate Professor with the Department of Computer Science and Engineering, Shanghai Jiao Tong University. His research interests include vehicular networks, and mobile sensing and computing. He is a member of the IEEE Computer Society, Communication Society, and Vehicular Technology Society. He received the Best Paper Award from IEEE Globecom 2016. He was a leading Guest Editor for the *IEEE Network Magazine*. He is an Associate Editor for the IEEE TRANSACTIONS ON VEHICULAR TECHNOLOGY.



Haibo Zhou (Member, IEEE) received the Ph.D. degree in information and communication engineering from Shanghai Jiao Tong University, Shanghai, China, in 2014. He is currently an Associate Professor with the School of Electronic Science and Engineering, Nanjing University. His research interests include resource management and protocol design in cognitive radio networks and vehicular networks.

Wenchao Xu (Member, IEEE) received the B.E. and M.E. degrees from Zhejiang University, Hangzhou, China, in 2008 and 2011, respectively, and the Ph.D. degree from the University of Waterloo, Canada, in 2018. In 2011, he joined Alcatel Lucent Shanghai Bell Co. Ltd., where he was a Software Engineer for telecom virtualization. He is currently a Research Associate with the Department of Computing, The Hong Kong Polytechnic University. His interests include wireless communications with emphasis on resource allocation, network modeling, and AI applications.



Minglu Li (Senior Member, IEEE) received the Ph.D. degree in computer software from Shanghai Jiao Tong University in 1996. He is currently a Full Professor and the Director of the Network Computing Center, Shanghai Jiao Tong University. He has published more than 350 articles in academic journals and international conferences. His research interests include vehicular networks, big data, cloud computing, grid computing, and wireless sensor networks. He served as a PC member for more than 50 international conferences, including IEEE INFOCOM from 2009 to 2016 and IEEE CCGrid in 2008. He also served as a General Co-Chair of IEEE SCC, IEEE CCGrid, IEEE ICPADS, and IEEE IPDPS, and a Vice Chair of IEEE INFOCOM. He was the Chairman of Technical Committee on Services Computing (TCSVC) from 2004 to 2016, Technical Committee on Distributed Processing (TCDP) from 2005 to 2017, and the IEEE Computer Society in Great China region.

Xuemin (Sherman) Shen (Fellow, IEEE) received the Ph.D. degree in electrical engineering from Rutgers University, New Brunswick, NJ, USA, in 1990. He is currently a University Professor with the Department of Electrical and Computer Engineering, University of Waterloo, Canada. His research focuses on network resource management, wireless network security, social networks, 5G and beyond, and vehicular ad hoc and sensor networks.

He is a registered Professional Engineer of Ontario, Canada, an Engineering Institute of Canada fellow, a Canadian Academy of Engineering fellow, a Royal Society of Canada fellow, a Chinese Academy of Engineering foreign fellow, and a Distinguished Lecturer of the IEEE Vehicular Technology Society and Communications Society. He received the R.A. Fessenden Award in 2019 from IEEE, Canada, James Evans Avant Garde Award in 2018 from the IEEE Vehicular Technology Society, Joseph LoCicero Award in 2015, and Education Award in 2017 from the IEEE Communications Society. He has also received the Excellent Graduate Supervision Award in 2006 and Outstanding Performance Award five times from the University of Waterloo, and the Premier's Research Excellence Award (PREA) in 2003 from the Province of Ontario, Canada. He served as the Technical Program Committee Chair/Co-Chair for the IEEE Globecom'16, the IEEE Infocom'14, the IEEE VTC'10 Fall, and the IEEE Globecom'07, the Symposia Chair for the IEEE ICC'10, the Tutorial Chair for the IEEE VTC'11 Spring, and the Chair for the IEEE Communications Society Technical Committee on Wireless Communications. He is the Editor-in-Chief of the IEEE INTERNET OF THINGS JOURNAL and the Vice President on Publications of the IEEE Communications Society.