ABC: Adaptive Beacon Control for Rear-End Collision Avoidance in VANETs

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***Abstract*—Vehicular ad hoc network (VANET) has been widely recognized as a promising solution to enhance driving safety, by keeping vehicles well aware of the nearby environment through frequent beacon message exchanging. Due to the dynamic of transportation traffic, especially for those scenarios where the density of vehicles is high, the naive beaconing scheme where vehicles send beacon messages at a fixed rate with a fixed transmission power can cause severe channel congestion. In this paper, we investigate the risk of rear-end collision model and define a danger coefficient ρ to characterize the danger threat of each vehicle being in a rear-end collision. We then propose a fully-distributed beacon congestion control scheme, referred to as *ABC*, which guarantees each vehicle to actively adapt a minimal but sufficient beacon rate to avoid a rear-end collision based on individual estimates of ρ. In essence, ABC adopts a TDMA-based MAC protocol and solves a NP-hard optimal distributed beacon rate adapting (DBRA) problem with a greedy heuristic algorithm, in which a vehicle with a higher ρ will be assigned with a higher beacon rate while keeping the total required beacon demand lower than the channel capacity. We conduct extensive simulations to demonstrate the efficiency of ABC design in different traffic density and a large variety of underlying road topologies.**

***Index Terms*—vehicular ad hoc networks; adaptive beacon control; beacon congestion control; rear-end collision avoidance**

I. INTRODUCTION

Driving safety is becoming urgent due to a large number of traffic crashes every year, which not only result in considerable financial loss but also imperil people's life. As reported in the most recent traffic safety facts by U.S. Department of Transportation, in 2015, there were estimated 22,144 and 2.18 million vehicle occupants in U.S. who died and were injured respectively in motor vehicle traffic crashes [1]. The inability of drivers to react in time is the major reason, which poses an urgent demand to build active driving safety applications. Vehicular Ad-Hoc Networks (VANETs) show great promise in enhancing driving safety by enabling information exchanges through vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) communications (or V2X communications in general) [2]–[5]. Periodical broadcasting of safety messages (or *beacons*), containing the information of location, speed, heading direction, and braking status of each vehicle, can enable a wide variety of advanced road safety applications. Being updated with such information, drivers can take actions in time to avoid potential dangers.

To design a *safety-aware* beaconing scheme in VANETs, however, is very challenging due to three reasons. First, given the limited available bandwidth for V2X communications, how to guarantee the safety requirement of each vehicle, especially for dense traffic scenarios, is not trivial. On one hand, if aggressive beaconing rates are adopted, it is very likely that some vehicles have no required bandwidth to send their status information. On the other hand, if moderate rates are used, the status of neighboring vehicles may be out-of-date, causing delayed reactions to avoid potential crashes. In addition, each vehicle on road may have different safety threats, calling for distinct beaconing rates. Second, the lack of a global central unit in VANETs makes an optimal beaconing scheme very hard to achieve. In VANETs, vehicles have to negotiate to assign the available bandwidth in a fully *distributed* way in real time based on the information exchanged within their neighborhood. Third, due to the high mobility of vehicles, the durations of V2X communications are very short. It is very important to minimize the communication overhead of a distributed beaconing scheme. Moreover, as the environment (e.g., the channel utility and the number of related vehicles) changes very fast, such a distributed beaconing scheme should also react fast to keep the pace.

In the literature, there have been several beacon control studies in VANETs, which can be classified into two categories, i.e., transmit power control (TPC) and transmit rate control (TRC). TPC-based schemes [6]–[8] are proactive solutions, which heavily rely on the prediction of the spatial distribution of the neighboring vehicles and adjust the transmission power of each vehicle accordingly to prevent future channel congestions. Such schemes are sensitive to estimation errors and therefore unreliable [9], [10]. In contrast, TRC-based schemes consider the max-min fairness given the limited available bandwidth. For example, LIMERIC [11] and PULSAR [12] aim to achieve local fairness such that all vehicles within the carrier sense range of a channel congestion should take the same beacon rate control. Such max-min or equal fairness beacon schemes cannot satisfy the distinct safety requirement

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of vehicles. Two recent TRC-based schemes [13], [14] model the beacon rate control problem as a network utility maximization problem where each vehicle is associated a utility function and the objective is to maximize the sum of utilities of every vehicle. However, such utility functions are defined based on aggregated information such as the sum of relative distances and velocities with one-hop communication neighbors, which cannot precisely capture the safety requirement of individual vehicles. In addition, both schemes rely on a slotted p-persistent broadcasting MAC [15], which could result in uncertain delays and the broadcast storm problem if not carefully controlled. As a result, to the best of our knowledge, there is no successful safety-aware beacon control scheme in VANETs.

In this paper, we demonstrate a novel beacon rate control scheme, called *ABC*, which adaptively adjust beacon rates among neighboring vehicles according to the rear-end collision threat of each vehicle. We first investigate the rear-end collision model considering the kinematic status of two adjacent vehicles in a lane and define a *danger coefficient* ρ for each vehicle to characterize the rear-end collision threat and therefore the beacon bandwidth requirement of this vehicle. We then formulate the *distributed beacon rate adapting* (DBRA) problem given all bandwidth requirements and the total available channel capacity. Given the proved NP-hardness of the DBRA problem, we devise a heuristic greedy algorithm, where vehicles with higher ρ estimates will be assigned with higher beacon rates, expecting immediate actions could be taken for these vehicles to avoid such collisions, while keeping the total required beacon demand lower than the channel capacity. In ABC, each vehicle will estimate its own danger coefficient ρ and collect the information of ρ of neighboring vehicles through beacon exchanges. When a vehicle identifies a channel congestion event, it will adopt the greedy algorithm to locally solve the DBRA problem and broadcast the beacon rate suppression result to neighbors. When a vehicle receives multiple inconsistent beacon control results from its neighbors, it will adopt the lowest beacon rate. We implement the ABC scheme over generated vehicular mobility trace, and conduct extensive simulations in different traffic densities and road topologies to evaluate the performance of ABC. Compared with two candidate beaconing schemes, i.e., 802.11p [16] and LIMERIC [11], the simulation results demonstrate the efficiency of ABC design.

We highlight our major contributions made in this paper as follows:

- We are the first to investigate the relationship between the beacon rate and the rear-end collision threat and define an effective indicator, i.e., the danger coefficient ρ, to capture the rear-end collision threat of each vehicle and describe the required beacon bandwidth of each vehicle with respect to such collision threats.
- We formulate the DBRA problem in the context of TDMA-based broadcasting MAC and prove its NP-hardness. We also devise a heuristic greedy algorithm to solve the DBRA problem. Furthermore, we propose a beacon control scheme, referred to as ABC, to dynamically adapt the beacon rate for each vehicle in a fully distributed way.
- We conduct extensive simulations on the proposed scheme and the results demonstrate that ABC outwits the 802.11p standard and the state-of-the-art scheme called LIMERIC.

The remainder of this paper is organized as follows. System model is given in Section II. We investigate crash-avoidance beacon congestion control in Section III. Section IV elaborates ABC protocol design. We conduct extensive simulations to evaluate the performance of ABC in Section V. We review the related work in Section VI before the conclusion and future work in Section VII.

II. SYSTEM MODEL

The VANET under consideration contains a set of RSUs and moving vehicles, and they communicate via DSRC radios. We will consider beacon activities in the context of a TDMA-based broadcast MAC.

A. Dedicated Short Range Communications (DSRC)

All entities in the network are equipped with a DSRC communication radio. In DSRC standards, there are one CCH and multiple SCHs with two optional bandwidths of 10 MHz and 20 MHz [17] [18]. The CCH is essential and used to transmit high-priority short messages (such as periodic or event driven safety messages) and control information (such as negotiations for SCHs usages). In contrast, SCHs are used for transmission of non-safety messages. In this paper, we only investigate the dissemination of periodic safey messages, i.e., beacons, on the CCH, which is most related to driving safety. We consider that all radios have the identical communication capability and the same communication range R. Thus, the network can be represented by a undirected graph $G(V, E)$, where $V = \{1, 2, ..., n\}$ denotes the set of vehicular nodes and E is a $n \times n$ matrix to represent link conditions between any two nodes. In the matrix E, for two distinct nodes i and j, if distance between them is within communication range, i.e., $d_{ij} \leq R$, $E_{ij} = 1$, otherwise $E_{ij} = 0$. We denote the set of neighbors of node i by $N_{cch}(i) = \{j \in V \mid j \neq i, d_{ij} \leq R\}$. For each vehicle in the system, its beacons should be well received by all neighboring vehicles, or it might result in potential dangerous driving situations.

B. TDMA-based Broadcast MAC

We apply the TDMA-based broadcast MAC [19]–[21], which was recently proposed for reliable broadcasts, to examine beacon congestion control. We adopt TDMA-based broadcast MAC rather than 802.11p MAC due to two major weaknesses of 802.11p supporting periodical broadcast. First, the basic MAC method of 802.11p is contention-based (each node has to sense the channel to be free before it use it), which may result in possible unbounded delays, and thus cannot satisfy the real-time requirement of safety applications in VANETs. Second, in broadcast mode of 802.11p protocol,

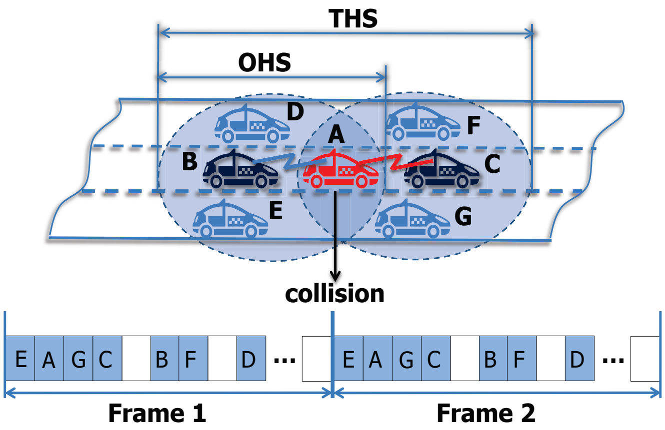

Fig. 1: Illustration of the TDMA-based broadcast MAC.

RTS/CTS packets are removed to facilitate real-time response, which leaves the *hidden terminal problem* unsolved [16].

In TDMA-based broadcast MAC, time is partitioned into frames consisting of a constant number of equal-length time slots and synchronized among nodes. Each node is assigned with a distinct slot and once a node obtains a slot successfully, it can use the same slot in all subsequent frames until a transmission collision is detected. In the time-slotted channel, by guaranteeing each node to access the channel at least once in each frame, the stringent time requirement of safety applications can be guaranteed. Neighboring vehicles within the communication range of a vehicle constitute the *one-hop set* (OHS) of this vehicle, and if two OHSs overlap with each other, the union of these two OHSs is referred to as a *two-hop set* (THS), in which each vehicle can reach any other vehicle in at most two hops. Figure 1 illustrates an example where the respective OHSs of vehicle B and vehicle C form one THS with vehicle A locating in between. Obviously, vehicles in the same OHS should select different time slots to avoid transmission collisions. Moreover, vehicles in the same THS should also choose distinct time slots for communication in order to overcome the hidden terminal problem. Since there is no RTS/CTS mechanisms in the broadcast mode, the hidden terminal problem can arise in a THS when two vehicles, locating in each of the two OHSs respectively, cannot hear with each other and decide to broadcast in parallel. As shown in the above example, vehicle B wants to broadcast and at the same time vehicle C also wants to broadcast. As vehicle B is not within the communication range of vehicle C, vehicle B perceives the channel to be free and starts to transmit even though vehicle C has already started the transmission. As a result, there is a collision happened at vehicle A. To avoid this problem, all vehicles in the same THS have to be assigned with distinct time slots. The slot occupation shown in Figure 1 is a valid example, where vehicles in the same THS choose distinct time slots for transmissions.

Beacon Starving Problem. The number of time slots per frame on the channel is denoted by S. Considering a normal case, where the size of beacons is about 500 bytes [22] and DSRC radios adopt a moderate transmission rate 6 Mbps, then the data transmission needs about $0.67\ ms$. As the DSRC standard requires beacons broadcasted every $100\ ms$ (the duration of each frame), the size of S would not exceed 150 in each frame. As shown in the empirical study on urban V2V communication [17], the communication of DSRC could be reliable throughout about $300\ m$ in urban, which means that, vehicles within $1200\ m$ (within THS) have to contend for the 150 slots. However, in the dense scenarios such as bidirectional 8-lane highways or urban intersections, the density of vehicles will heavily aggregate and as a result, the number of time slots S is far from enough to support the high density vehicles [1]. We define this as the *beacon starving problem*, which would cause the channel congested and is also the main motivation of this paper.

III. CRASH-AVOIDANCE BEACON CONGESTION CONTROL

In this section, we take the rear-end collision model as an instance to investigate how beacon rate affects the collision risk, based on which we can design congestion control scheme in the rest of the paper. We learn the rear-end collision model since it is the most common type of motor vehicle crash, and other types of crash, e.g., side-impact collision, can be easily incrementally added in based on our congestion control framework.

A. Danger Coefficient ρ

Figure 2 (a) shows a normal vehicle-following case, where a following vehicle A runs after the preceding vehicle B and they have a respective velocity V_f and V_p, and there is a distance d between two vehicles. The DSRC radio of B keeps reporting its kinematic status to A every T_{beacon} seconds (i.e., a frequency of $\frac{1}{T_{beacon}}$ Hz) and based on this vehicle A decides to accelerate or decelerate. Figure 2 (b) illustrates a rear-end collision risk cased by a sudden deceleration of B and the corresponding acceleration is $a_p\ m/s^2$. By receiving beacons from the vehicle B, vehicle A could perceive the emergency and react to the situation after a delay T, i.e., $T = T_{beacon} + T_{reaction}$, where $T_{reaction}$ is the reaction time of the driver. To avoid the potential rear-end collision, vehicle A has to brake a little or fully based on the kinematic relations of two vehicles.

Definition 1: *(Danger coefficient) Considering two vehicles A and B move in a same lane and A is the following vehicle while B is the preceding vehicle, if vehicle B decelerates suddenly with the maximum acceleration, after knowing the situation, vehicle A has to take ρ ($\rho \in (0, 1]$) times of maximum acceleration to brake in case to collide with B. Then, vehicle B is said to be dangerous with a coefficient ρ in terms of encountering a collision.*

As in the above example, the maximum acceleration of A is a_f, and the kinematic relation should satisfy

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

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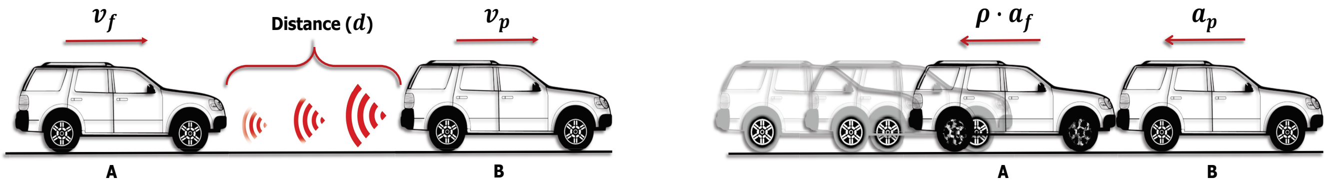
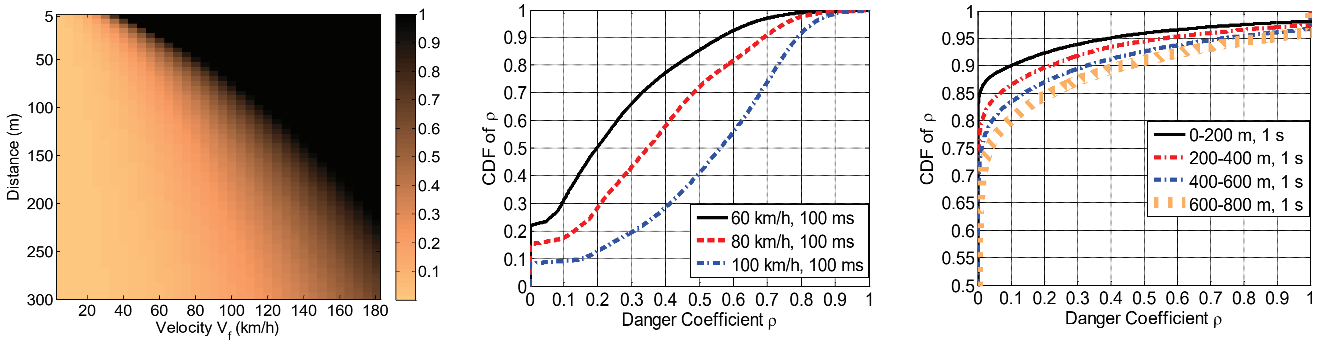
[1] The time slot needs for event driven safety messages and control information are not even counted.



(a) vehicle A following the ahead vehicle B normally (b) a collision risk caused by a sudden deceleration of B

Fig. 2: Illustration of kinematic status in rear-end collision model.



(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.

Then the danger coefficient ρ is achieved, i.e.,

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

B. Capturing Danger Threat

The coefficient ρ can well explain the *driving context* in terms of safety, for instance, when $\rho = 0$, there will be no potential collision since V_A is smaller than V_B or there is no any vehicle chasing after the vehicle B. In contrast, when $\rho = 1$, the vehicle A has to brake immediately with the maximum acceleration once receives the beacon. Figure 3 (a) shows the danger coefficient ρ as the function of distance d and velocity V_f, when a_f, a_p, V_p, T_{beacon} and $T_{reaction}$ is set to be 8 m/s^2, 8 m/s^2, 60 km/h, 1 s, 0.5 s, respectively. We can see that it is reasonable to adjust the beacon rate based on the value ρ, since the value is highly related to the driving context, where the value is very small at the low speed and far distance while the value becomes very large when the speed is fast and the distance gets small. Therefore, those vehicles with the small value of ρ can reduce beacon rates to save the channel resource and on the contrary, vehicles with the high value of ρ should increase the beacon rate to avoid the potential dangers. To further understand how ρ behaves in realistic driving scenarios, we calculate its values in the SUMO [23], which has been widely applied to generate vehicle traces and the detail simulation setup is presented in the performance evaluation section. Figure 3 (b) shows cumulative distribution functions (CDFs) of ρ in different lanes, which have the respective speed limit 60 km/h, 80 km/h and 100 km/h. In addition, each vehicle broadcasts a beacon every 100 ms, and we can see that *vehicles in faster lanes will experience higher values of ρ and should be assigned with higher beacon rates*. For instance, the median value ρ (i.e., with the CDF value of 0.5) in the 80 km/h-limit lane is 0.2, whereas the value can be 0.35 and 0.55 in the 100 km/h-limit lane and 120 km/h-limit lane, respectively. Figure 3 (c) shows CDFs of ρ in intersection zones, which have different distance ranges away from the intersection area, i.e., $0 - 200$ m, $200 - 400$ m, $400 - 600$ m and $600 - 800$ m, respectively. We can disclose that lower values of ρ prevail at intersections and it can be inferred from two observations. First, the proportion of $\rho = 0$ can reach up to 85% when vehicles in intersection zones [2], while the proportion can drop down to about 20% in the results of Figure 3 (b) (far away from the intersection). Second, the proportion of $\rho = 0$ will decrease as the distance range away from the intersection increases and the value would be 85%, 79%, 73% and 69%, respectively. *Exquisitely, it is the intersection that urgently needs beacon congestion control due to the high vehicle density as multiple sets of vehicles move together.*

C. ρ-Based Beacon Rate Adaptation

We denote $N_{cch}^2(x)$ as the set of THS of vehicle x and $N_{cch}^2(x) = N_{cch}(x) \bigcup \{N_{cch}(y), \forall y \in N_{cch}(x)\}$. When time slot is enough, each of vehicles in $N_{cch}^2(x)$ can occupy a distinct time slot and broadcast at the time slot every frame, i.e., with the beacon rate 1 beacon/frame. However, when meets beacon starving problem, i.e., $S < |N_{cch}^2(x) + 1|$, multiple vehicles would broadcast at the same time slot and thus cause massive transmission collisions. To solve such a problem, *we propose a scheme to adaptively change the beacon rate α_i for each individual vehicle i within a range*

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[2] Although each beacon is transmitted every 100 ms, which the rate is ten times faster than the setting in Figure 3 (b).

$[\alpha_{min}, \alpha_{max}]$. Considering the danger coefficient, beacon rate adaptation has to comply with the following rule.

Rule 1: For two vehicles i and j in the set of $N^2_{cch}(x) \cup x$, if $\rho_i \geq \rho_j$, then the beacon rate of i should be greater or equal than the beacon rate of j, i.e.,

$$\alpha_i \geq \alpha_j, \forall \{i, j | \rho_i \geq \rho_j, i, j \in N^2_{cch}(x) \cup x\}. \tag{3}$$

In addition, according to the vehicle safety communications report of U.S. Department of Transportation [24], the beacon rate of safety applications can be range from 1 Hz to 10 Hz. Thus the α_{min} and α_{max} can be set to be 0.1 and 1 beacon/frame, respectively. To this end, one specific time slot can support one vehicle with beacon rate 1 beacon/frame or two vehicles with beacon rate 0.5 beacon/frame, or so forth.

IV. ABC PROTOCOL DESIGN

A. Overview

In this section, we elaborate ABC protocol design. In ABC, vehicles first leverage beaconing status exchange among neighbors through sending/receiving beacons, to online detect congested channel conditions. Once a congestion is detected by a vehicle, vehicles in its THS should adapt their beacon rates to suppress the congestion. We then formulate the distributed beacon rate adapting (DBRA) problem in the context of the TDMA broadcast MAC, which is proved to be NP-hard; a greedy heuristic algorithm is then proposed to solve the problem. Finally, the vehicle informs all other vehicles within its interference range of the adapting results and they adapt their beacon rates accordingly.

B. Online Congestion Detection

Beaconing Status Exchange. To let each vehicle well perceive channel load in its interference range, in ABC, in addition to application data, each vehicle also broadcasts beaconing status of itself and its one-hop neighbors, and the beaconing status includes the information of the beacon rate α and danger coefficient ρ. In specific, for a vehicle x, based on received kinematic information of the behind following vehicle, it continuously updates itself danger coefficient and then includes (α_i,ρ_i) information of itself and its one-hop neighbors (collected directly from neighbors during previous S slots) in each beacon and broadcasts to all its neighbors. By receiving beacons, vehicle x can achieve the beaconing status of each neighbor, say vehicle y, and the neighbors of y.

Detecting Congested Channel Condition. With beaconing status of vehicles in THS, each vehicle can online detect congested condition.

Definition 2: *(Item size)* For a vehicle with a beacon rate of α_i beacon/frame, the *item size* of the vehicle is α_i, $\alpha_i \in (0.1, 1]$.

Definition 3: *(Slot capacity)* For a specific time slot, the *capacity* C of the time slot is 1 minus the sum of item sizes it support and the capacity of a free time slot is $C = 1$.

Thus, if the channel is currently saturated, their beacon rates must be

$$\sum\nolimits_{i=1}^{|N^2_{cch}(x)|+1} \alpha_i > S, \tag{4}$$

where $|N^2_{cch}(x)| + 1$ means vehicle x itself and the number of its THS.

C. Distributed Beacon Rate Adapting (DBRA)

When the channel is perceived to be congested, every vehicle which contributes to the congestion has to adapt beacon rate to prevent the ongoing congestion. Two constraints have to be followed.

Constraint 1: *(Periodical beacon rate)* As the beaconing is required to be periodical, the α_i should satisfy

$$\alpha_i = \frac{1}{t}, t = 1, 2, 3, ..., 10, \forall i \in N^2_{cch}(x) \cup x, \tag{5}$$

i.e., broadcast at a specific time slot every t frames and keep silent during other $t - 1$ frames.

Constraint 2: *(Bandwidth limitation)* To prevent channel congestions, beacon bandwidth should not exceed the slots that the system can totally support [3], i.e.,

$$\sum\nolimits_{i=1}^{|N^2_{cch}(x)|+1} \alpha_i \leq S. \tag{6}$$

The **DBRA** problem can be summarized as a resource allocation problem under a limited resource condition and more dangerous vehicles should be assigned with more resources. The DBRA problem can be equivalently formulated as follows

$$\begin{aligned} max \quad & \sum\nolimits_{i=1}^{|N^2_{cch}(x)|+1} \rho_i * \alpha_i \\ s.t. \quad & \alpha_i = \frac{1}{t}, t = 1, 2, 3, ..., 10, \\ & \sum\nolimits_{i=1}^{|N^2_{cch}(x)|+1} \alpha_i \leq S. \end{aligned} \tag{7}$$

Let $\boldsymbol{\alpha} = \{\alpha_i | i \in N^2_{cch}(x) \cup x\}$ be the vector of beacon rate assignments for vehicles in the THS. After maximizing the value $\sum_{i=1}^{|N^2_{cch}(x)|+1} \rho_i * \alpha_i$, the solution $\boldsymbol{\alpha}$ can satisfy the requirement in **rule 1**, which can be easily proofed by contradiction. If $\boldsymbol{\alpha}$ is the optimal solution to the problem DBRA and Eq. (3) does not hold, then there exists $\alpha_i < \alpha_j$ while $\rho_i \geq \rho_j$. If we change the beacon rate of i and j with each other, then a bigger value of the objective function in DBRA problem can be achieved, which contradicts the maximizing property.

For the DBRA problem, we have the following theorem.

Theorem 1. *The DBRA problem is NP-hard.*

Proof. We prove the NP-hardness by devising a polynomial reduction from a classic NP problem, *multiple-choice knapsack problem (**MCKP**)* [26], to our problem. The MCKP problem is a variant of the ordinary 0-1 Knapsack Problem and can be described as follows. Considering m mutually disjoint classes $N_1, N_2, ..., N_m$ of items to be packed into a knapsack with a total capacity C. Each item $j \in N_i$ has a profit p_{ij} and a weight cost c_{ij}. The problem is to maximize the profit

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[3] Note that, some time slot redundancy should be kept for MAC layer assigning, since it is hard for MAC layer to schedule the usage of time slots for vehicles with diverse beaconing rates [25] without wasting and colliding. However, the MAC design and optimization is out of the scope of this paper.

sum when chooses exactly one item from each class without exceeding the capacity C in the corresponding weight cost sum. By introducing the binary variables x_{ij}, which take on value 1 if item j is chosen in class N_i otherwise it is set to be 0, the problem can be formulated as

$$\begin{aligned}(MCKP) \qquad max \quad & \sum_{i=1}^{m} \sum_{j \in N_i} p_{ij} * x_{ij} \\ s.t. \quad & \sum_{i=1}^{m} \sum_{j \in N_i} c_{ij} * x_{ij} \leq C, \\ & \sum_{j \in N_i} x_{ij} = 1, i = 1, ..., m, \\ & x_{ij} \in \{0, 1\}, i = 1, ..., m, j \in N_i.\end{aligned} \tag{8}$$

The reduction takes an instance of the MCKP problem as input, and we construct an instance of the DBRA problem as follows. There are $|N_{cch}^2(x)| + 1$ classes, i.e., $N_1, N_2, ..., N_i$, and each class has 10 choices. For jth choice, $j = 1, 2, ..., 10$, in N_i, it has a safety profit $\rho_i * \frac{1}{j}$ and a time slot cost $\frac{1}{j}$. Under the time slot cost sum constraint, choosing exactly one item from each class such that the objective function is maximized is equivalent to the MCKP problem, which is NP-hard. Therefore, the DBRA problem is a NP-hard problem, which concludes the proof. ■

Heuristic Algorithm for DBRA. Although the MCKP problem can be solved by using dynamic programming (DP), the *pseudo-polynomial* time complexity is *unacceptable* for on-line decision making. To this end, in ABC, we adopt greedy heuristics to assign beacon rate for each vehicle. In specific, all vehicles are first assigned with the minimum beacon rate α_{min}; for the remaining medium resource, vehicles are first ranked according to the danger coefficient ρ and the vehicle with the largest ρ is then assigned with more medium resource until reaching α_{max}; this procedure repeats until there is no medium resource left. Note that, since vehicles keep moving and the danger coefficient values of ρ would dynamically vary, the DBRA results might cause unfair after some time, e.g., the vehicle leaves the intersection and ρ of the vehicle increases to a big value. In the design of ABC, we allow each vehicle to increase beacon rate independently when the danger coefficient ρ reaches up to a threshold, which is not detailed due to the space limitation.

D. Informing Adapting Results

After computing the DBRA results at the vehicle (congestion location, say vehicle A), A has to inform other vehicles of the results. As A has all beaconing status of its THS, it can compare the beacon rate between DBRA results and the beaconing status of each vehicle in its THS. It will include the information (vehicle ID, assigned beacon rate) of all vehicles, whose current beacon rate is bigger than the results assigned by DBRA, in its next beacon and broadcast to its neighbors. Once a neighbor (say vehicle B) receives the informing beacon, B will first compare its own beacon rate with the assigned result; if its own beacon rate is bigger than the assigned result, it will adjust its beacon rate to the assigned result. In addition, B will also compare the informing results with beaconing status of its OHS (who cannot hear the informing result directly from A) and include information of vehicles that need to be informed, in its next beacon and then broadcast out. We ignore those vehicles whose current beacon rate is smaller than assigned results due to the following two reasons. First, although those vehicles have little impact on channel congestion of this THS, it might trigger more congestions in other THSs after increasing their beacon rate; they can improve self beacon rates independently based on their danger coefficients. Second, due to the large number of the THS, informing all vehicles in the THS not only causes more communication cost but also might result in delays of convergence.

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)	$[60, 100]$
MaxSpeed 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	100 s

V. PERFORMANCE EVALUATION

A. Methodology

Simulation setup. We conduct simulations over SUMO, which allows constructing intermodal traffic systems including road conditions, vehicles and traffic lights, to evaluate the performance of ABC protocol. We consider a typical urban road network, where a 4-way intersection locates at the center and connects to four bidirectional 6-lane roads of 5 km long, respectively. Each of the three lanes in one direction is given a speed limit of 60 km/h, 80 km/h and 100 km/h, respectively. Traffic lights are set at each inbound road segment at the intersection with the duration of green light being 20 s. Vehicles are generated at the open end of each road segment with a rate 10 vehicles/lane/minute to mimic normal traffic conditions in a city. vehicles have different performance parameters in terms of maximum velocity (ranging from 80 km/h to 240 km/h), acceleration ability (ranging from 1 m/s^2 to 5 m/s^2), and deceleration ability (ranging from 3 m/s^2 to 10 m/s^2). Ten different sets of vehicle parameters are configured according to the main types of vehicles on the market. Vehicles are driven under the Krauss car-following model and the LC2013 lane-changing model. Each vehicle randomly chooses a performance parameter configuration, a destination road segment and a lane when enters the system, and it will disappear from the system after passing the intersection and reaching the end of another road segment. In all simulations, the transmission range R is set to be 300 m according to the observation in the measurement-based work [17], that V2V communication can be reliable within 300 m regardless of the channel conditions. In addition, each frame lasts 100 ms to satisfy the delay requirement of safety applications [24] and each frame consists of 150 time slots. The overall simulation system is written by Python and Table I summarizes the simulation parameters.

Candidate protocols. We compare our ABC protocol with two reasonable alternative protocols as follows:

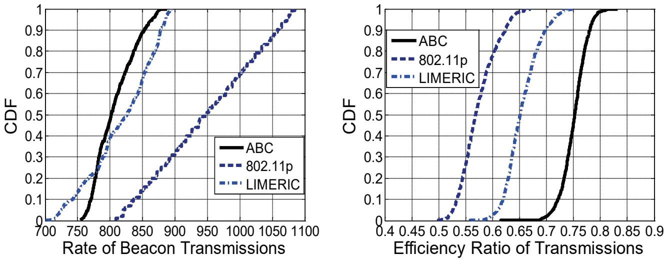
- **Conventional 802.11p [16]:** IEEE 802.11p standard has been dedicated by the Federal Communications Commission (FFC) as the physical and MAC layer for VANET communications in many countries. In broadcast mode of 802.11p protocol, each vehicle broadcasts every frame without any congestion control schemes.
- **LIMERIC [11]:** Even though this scheme works under different system model and does not consider danger coefficient, we borrow its congestion control idea that treats all nodes equally regardless of the driving context, as another benchmark. In LIMERIC, when detects a congestion, vehicles are assigned with the same beacon rate without exceeding the medium resource limit.

Performance metrics. We consider the following four metrics to evaluate the performance of ABC and above candidate protocols:

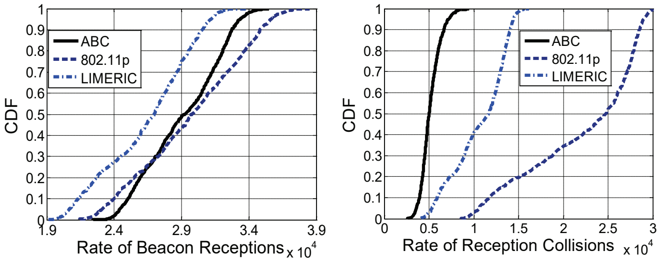
1) **Rate of beacon transmissions** refers to the average number of beacon transmissions per frame.
2) **Efficiency ratio of transmissions** refers to the number of successful transmissions to the total number of transmissions. A successful transmission means when a node broadcast a beacon, there is no other concurrent transmission happening at the same time slot within its THS.
3) **Rate of beacon receptions** refers to the average number of successfully received beacons per frame.
4) **Rate of reception collisions** refers to the average number of reception collisions per frame happened at receivers. For example, if a vehicle simultaneously receives more than two beacons at a time slot, then the number of this simultaneous receptions is counted as the number of reception collisions.

B. Overall Performance

Efficiency of rate control. We first examine the overall performance (i.e., results of all vehicles together), and Figure 4 plots the CDF results of the whole system. From Figure 4 (a), we can easily observe that with congestion detection and control schemes, the rate of beacon transmissions will be effectively reduced in ABC and LIMERIC schemes. For instance, the median rate of beacon transmissions is about 800, 825 and 950 transmissions/frame in ABC, LIMERIC and 802.11p, respectively; in addition, the maximum rate in ABC and LIMERIC is no more than 900 while it will reach 1080 in 802.11p.



(a) rate of beacon transmissions (b) efficiency ratio of transmissions



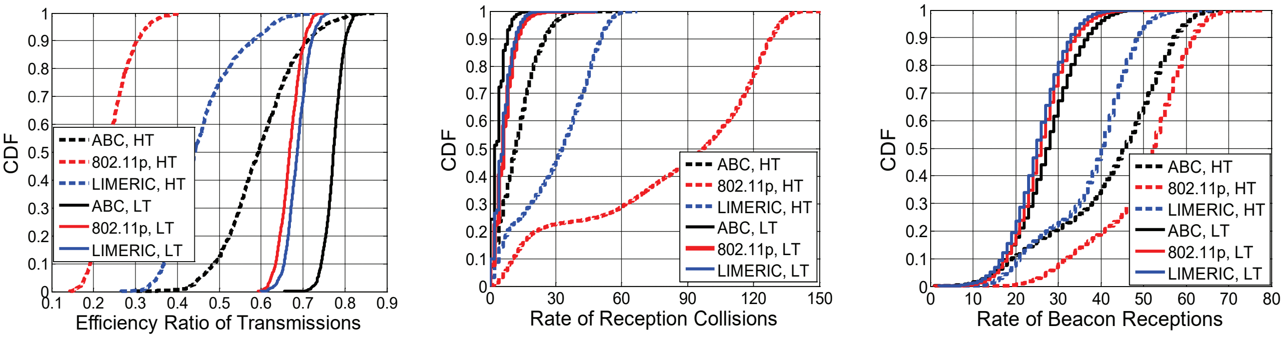
(c) rate of beacon receptions (d) rate of reception collisions

Fig. 4: Overall CDF results of all vehicles together in the system.

Easing messages collisions. With proper congestion controls, efficiency transmission ratio can be well enhanced and rate of reception collisions will be greatly reduced as shown in Figure 4 (b) and (d). Specifically, the median value of efficiency transmission ratio in 802.11p is about 0.56 while the value can reach up to 0.65 and 0.75 in respective LIMERIC and ABC schemes; moreover, more than 98% of the ratios are bigger than 0.7 in ABC, whereas the proportion would drop to below 10% and 0 in LIMERIC and 802.11p, respectively. On the other hand, the median rate of reception collisions would increase from 5000 collisions/frame in ABC to 12000 and 25000 in respective LIMERIC and 802.11p; in addition, all rates in ABC are smaller than the value 10000 collisions/frame while more than 60% rates in LIMERIC and 99% in 802.11p are bigger than the value. The main reason that the control efficacy of LIMERIC is not as obvious of ABC lies in two folds. First, for those vehicles with big danger coefficients, they are very likely to meet low vehicle densities while they are assigned with the average beacon rate which is below the maximum beacon rate they can use. Second, on the contrary, for those vehicles with small danger coefficients, they are very likely to meet high vehicle densities while they are assigned with the average beacon rate where the control is far from enough to suppress the congestion.

Slight degradation in Rx throughput. In addition, from Figure 4 (c), we find that 802.11p can sometimes achieve the best performance of rate of beacon receptions when the vehicle density is relatively high [4], and for example, the median reception rate is about 26000, 28000 and 285000 receptions/frame in LIMERIC, ABC and 802.11p, respectively.

[4] Note that, the values of the reception rate can indirectly represent the vehicle density.



(a) CDFs of efficiency ratio of transmissions

(b) CDFs of rate of reception collisions

(c) CDFs of rate of beacon receptions

Fig. 5: Performance of vehicles under heavy traffics (HT) and light traffics (LT).

This phenomenon is reasonable since transmission rates are reduced in LIMERIC and ABC shcemes and although massive reception collisions would encounter in 802.11p, its maximum transmission rates of all vehicles still can improve the Rx throughput.

C. *Impact of Dynamic Traffics*

With the overall performance guaranteed, we then investigate the performance of vehicles under different density conditions. We divide the vehicles into two groups based on the number of their THS, i,e., $|N^2_{cch}(x)| + 1 < 150$ (vehicles under light traffics) and $|N^2_{cch}(x)| + 1 \geq 150$ (vehicles under heavy traffics), and Figure 5 shows the performance results of vehicles under two respective density conditions. From Figure 5 (a) and (b), we can see that very obvious efficacy of congestion control in ABC will appear when meets heavy traffics. For instance, the median efficiency ratio of transmissions can be improved from 0.25 in 802.11p to 0.61 in ABC and the median rate of reception collisions can be decreased from 100 collisions/frame/vehicle in 802.11p to 15 in ABC; moreover, ABC can also achieve the supreme performance under light traffics in terms of higher efficiency transmission ratios and lower reception collision rates as solid line results in figures. Figure 5 (c) plots the CDFs of the rate of beacon receptions, and we can observe that ABC can outperform 802.11p under light traffics and would be a litter worse than it under heavy traffics. This can well explain in Figure 4 (c), why the performance in ABC can behave better within small values (e.g., $\leq$ 27000 receptions/frame) and on the contrary behave worse at big values (e.g., $>$ 27000 receptions/frame) compared with which in 802.11p.

VI. RELATED WORK

A. *Transmit Power Control (TPC)*

Several studies have focused on Tx power adaptation to prevent future congestion. One of the most cited solutions is D-FPAV [6]; vehicles run D-FPAV cooperatively to calculate the max Tx power for each individual vehicle under two constraints, i.e., not exceeding the channel load threshold and guaranteeing max-min fairness. Due to the heavy packet overhead in the original D-FPAV design, Mittag et al. [7] proposed a revised version of previous D-FPAV scheme, which could reduce overhead by two orders of magnitude by adopting a segment-based power adjustment approach. Besides, some works propose joint rate-power control algorithm for broadcast of safety messages. For example, in the work [8], based on the estimated tracking error of vehicles, Huang et al. calculated the minimum required Tx rate, and in the second step, Tx power is extended until the channel load reaches a defined Channel Busy Ratio (CBR) threshold. As those proactive solutions require highly accurate models for prediction, it cannot be very practicable in actual deployments compared with reactive congestion controls, i.e., TRC techniques, which react to congestion that has actually occurred. Beyond that, recent proposals [9], [10] have investigated TPC approaches and disclosed that TPC has serious issues in instabilities and its accuracy depends on the quality of the transmission model. Moreover, some previous work, e.g., [27], concluded that message rate control is the most effective method in terms of reachability.

B. *Transmit Message Rate Control (TRC)*

LIMERIC [11] and PULSAR [12] are two famous rate control schemes. In LIMERIC [11], Bansal et al. used a linear control based on continuous feedback (beaconing rate in use) from neighbors, while in PULSAR, Tielert et al. used an additive increase multiplicative decrease (AIMD) iteration with binary feedback (congested or not) from one and two-hop neighbors. However, both two works show limitations in some aspects. Specifically, regarding fairness, none of them consider this accurately: LIMERIC aims to achieve fairness such that all the nodes converge to the same message rate, and PULSAR claims targeting local fairness, i.e., all vehicles within Carrier Sense (CS) range of a congested location should participate in congestion control. However, the fairness of congestion control in VANETs is to guarantee each vehicle's safety benefits, and max-min or equal fair distributions of channel resource might not surely guarantee the best possible safety benefits for the system. In addition, in LIMERIC, even though it is shown to converge to a unique equal rate for each vehicle, the rate is below the optimal rate and there is a trade-off between the convergence speed and the distance to the optimal value. Proposals [13], [14] are two recent congestion control schemes and both of them model the problem of controlling the beaconing rate on each vehicle as a Network Utility Maximization (NUM) problem. In the work [13], based on NUM model, Egea-Lopez et al. formally applied the notion of fairness of beaconing rates allocation and proposed the FABRIC algorithm, which utilized a particular scaled gradient projection algorithm to solve the dual of the NUM problem. Zhang et al. in the work [14], took driving context, i.e., relative position and velocity, into consideration and formulated the NUM problem of adapting beacon rates under a slotted p-persistent vehicular broadcast MAC; a distributed algorithm is then proposed to solve the problem.

VII. CONCLUSION AND FUTURE WORK

In this paper, we have analyzed the broadcast requirements for safety applications in VANETs and disclosed the necessary of beacon congestion control to avoid control channel being blocked. To this end, we have investigated the role of beacon rate in rear-end crash model and defined a danger coefficient ρ to well capture the danger threat of each vehicle to the system. Based on this indicator, we have proposed a distributed beacon congestion control scheme, named ABC, to dynamically adapt beacon rate for each vehicle. In ABC, we have integrated three novel techniques: 1) online congestion detection; 2) distributed beacon rate adapting; 3) informing adapting results. At last, we have conducted extensive simulations and the results demonstrate the efficiency of ABC. For our future work, we will consider more crash model, e.g., head-on collisions or run-off-road collisions, and integrated their danger weights into our congestion control framework.

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