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Efficient Broadcast Mechanism for Cooperative Collision Avoidance Using Power Control

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***Abstract*—Improving driver's safety has been an active research area in wireless communication. In particular, the vehicle cooperative collision avoidance (CCA) is one of the most important issues in safety applications. A variety of broadcast protocols has been proposed for vehicular network. However, there is only a few of them dedicatedly designed for the CCA system. In this paper, we propose a novel broadcast mechanism for CCA using the power control technique. The power control rule is based on the safe distance between vehicles. Simulation results show that our approach can significantly reduce the delivery delay and avoid car collision.**

Keywords-vehicular networks; power control; cooperative collision avoidance

I. INTRODUCTION

Traffic accidents have been taking thousand of lives each year, exceeding any deadly disease or natural disasters in many countries. Numerous factors, such as bad weather conditions and mechanical failures, may lead to a traffic accident. In particular, the inability of drivers to react in time to emergency events often creates to a series of car crashes, i.e. the chain car collision. As shown in Fig. 1a, three vehicles A, B, and C are driving on a highway platoon. When vehicle A brakes suddenly, vehicle B can start to decelerate after a *driver reaction time*, i.e. the duration when an event is observed and when the driver actually applies the brake, to avoid a collision with A. However, due to the line-of-sight limitation from B, vehicle C may not decelerate until its driver has seen the rear brake light of vehicle B. Studies show [1] that the driver reaction time could range from 0.75 to 1.5s, which means that a trailing vehicle may keep running for a long distance before reacting to an accident ahead. For instance, at a speed of 70 mph, vehicle C may pass through 75 to 150 ft before being decelerated. Consequently, a single emergency event often leads to a string of secondary crashes. Clearly, such an undesirable situation can be substantially avoided or lessened if drivers can be warned earlier.

The Cooperative Collision Avoidance (CCA) is an important class of safety applications in Intelligent Transport Systems (ITS), which aims at offering earlier warning to drivers using vehicle-to-vehicle (V2V) communication [2]. As the example shown in Fig. 1b, once vehicle A confronts an accident, it can directly send out a warning message to C or quickly forward the warning message hop-by-hop to C whenever their distance is beyond the transmission range. As a result, vehicle C can obtain more chance to stop safely, in contrast to counting on the rear brake lights of vehicle B.

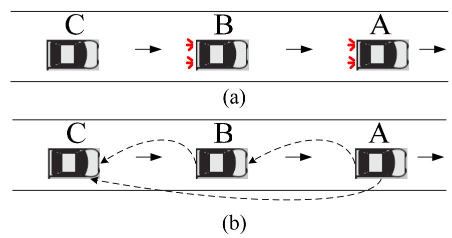

Figure 1. (a) alerted by rear brake lights; (b) alerted by warning messages.

However, due to the severe interference in wireless communication, the deliver delay could be intolerably large, especially when many vehicles have to transmit or forward their warning messages. The delay would result in a longer time to response to the emergency event. The interference problem would become more significant in density traffic roads or multi-lane environments.

In this paper, we present a new broadcast mechanism for the CCA system, named PC-CCA. The PC-CCA employs the power control (PC) technique to reduce the physical interference incurred by delivering warning messages. The power control technique has been considered as an effective way to lessen interference in the wireless environments. By reducing the transmission power of each vehicle, the broadcast radius can be smaller, implying fewer warning messages being forwarded and fewer nodes being interfered.

The rest of this paper is organized as follows. In Section II, we review recent researches related to broadcasting in the Vehicular Ad Hoc Network (VANET) and the CCA system. Section III presents the proposed broadcast mechanism. In Section V, we conduct simulation results. Conclusion is remarked in the last section.

II. RELATED WORK

VANET Broadcast has been studied in several articles, such as in [3, 4, 5, 6, 7]. Xu *et. al.* [3] discussed a vehicle-

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to-vehicle location-based broadcast protocol, where each vehicle generates a warning message at a constant rate. The optimum transmission probability at MAC layer for each message is then identified to reduce the packet collision probability. In [4], the authors propose a multi-hop broadcast protocol based on slot reservation MAC. Considering the scenario that not all vehicles will be equipped with wireless transceivers, forwarding in sparsely connected ad hoc network consisting of highly mobile vehicles is studied in [5]. Motion properties of vehicles are exploited in [6] to help with message relay. In [7], the authors proposed efficient protocols to reduce the amount of messages being forwarded. Compared with MANET broadcast, the above protocols concern the mobility of vehicles to achieve more efficient message forwarding. However, these protocols are not specifically for safety applications (e.g. CCA system), where more emphasis should be paid on the emergency of warming messages.

Several application challenges in the CCA system, such as stringent delay requirement, coexisting abnormal vehicles, and different emergency levels, have been identified in [8]. The authors also designed a protocol comprising congestion control policies, service differentiation mechanism, and methods for emergency warning dissemination. In [9], a broadcast scheme based on a client-server platform is proposed. The rebroadcast probability of each relaying vehicle is changed dynamically according to the number of vehicles insides the transmission zone. The purpose is to avoid relaying redundant warming messages so as to reduce delivery delay. However, this protocol requires each vehicle to acquire information in its two hops range. The control overhead may lead to additional delivery delay.

In order to perform forwarding without prior knowledge about neighbors, Biswas *et. al.* propose two *context-aware* protocols [10], named the naive broadcast (NB) and intelligent broadcast with implicit acknowledgment (I-BIA), for the CCA system. In both protocols, when an emergency event occurs, the source vehicle broadcasts a warming message first, and then a recipient will forward the message only if the direction-of-arrival (DoA) of the message is in front of itself. This mechanism ensures that the warming message will be eventually delivered to all vehicles behind the source vehicle and any vehicle which is not endangered will not forward the message. The I-BIA can further avoid redundant retransmission by setting a waiting time to see if there is any vehicle behind a recipient having received the same message. Similarity, three context-award protocols, named weighted p-persistence broadcasting, slotted 1-persistence broadcasting, and slotted p-persistence broadcasting, are proposed in [11]. In these protocols, vehicles which are farther away from the previous broadcaster will transmit with higher priority (higher probability or earlier time). The purpose is to avoid redundant retransmissions from intermediate vehicles. A similar protocol is presented in [12] for multi-lane highway.

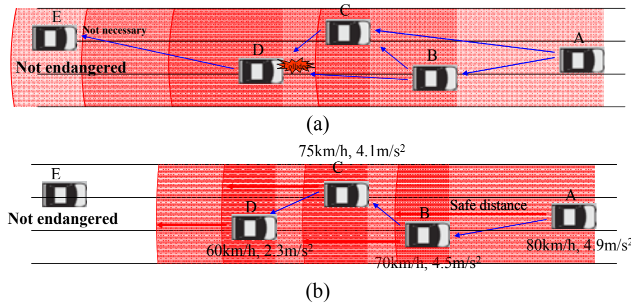

Figure 2. (a) CCA without power control; (b) CCA with power control.

Although the above protocols can make use of directional or other geographic information to reduce overall delay, the local delay may not meet the requirement for each individual vehicle. Consequently, chain car collision may still occur if even the overall delay is low. To solve this problem, a *risk-aware* protocol is presented in [13]. In this protocol, vehicles are classified into several clusters according to the features of their movement. Then, an emergency level is defined for each vehicle based on the order in its cluster. The emergency level reflects the risk of a vehicle to meet an emergency situation in the platoon. The medium access delay of each vehicle is then set as a function of its emergency level to promptly disseminate warning message. However, the order in cluster cannot explicitly reflect the risk, because in real situation many factors, such as intercar space and velocity, are inconsistent from vehicle to vehicle. Besides, the interference is still severe if the physical transmission range is large. To the best of our knowledge, there is no research using power control technique to improve the CCA system.

III. Proposed Broadcat Mechanism

In this section, we present our broadcast mechanism for the CCA system. First of all, the basic concept is described. After that, we formally model the safe distance between vehicles in vehicular network environment. The power control rule is then summarized in the last part.

A. Basic Concept

The interference may occur when more than one vehicle has to forward the same message within a short period. An example is shown in Fig 2a. Once vehicles B and C received a warning message from A, because they can not be aware of each other, they may forward the message at the same time to the vehicles behind, resulting in a signal collision at vehicle D. The PC-CCA employs the power control technique to physically reduce the interference. As shown in Fig. 2b, by reducing the transmission power, vehicle D can avoid receiving messages simultaneously from both B and C, since only vehicle B receives the message from A at the first place.

The major problem is how to guarantee the delivery to all vehicles which are endangered as long as the transmission power is shrunk. To tackle this problem, our protocol will dynamically adjust the transmission radius based on the *safe distance* between vehicles. As shown in

Fig. 2b, under the given velocities and deceleration rates, we assume that the safe distance between vehicles A and B is d, which means that vehicle B is potentially endangered if its distance to A is shorter than d. In other words, to avoid being collided by vehicle B, the transmission radius of A should be at least d.

Using the power control technique can also avoid transmitting to vehicles which are not endangered. As shown in Fig. 2a, vehicle E is far away from the platoon, i.e. it is out of the safe distance to D. But, if vehicle D always transmits at the maximum transmission power, vehicle E will eventually receive a warning message from D even if it is not endangered. In contrast to Fig. 2b, if vehicle D shrinks its power according to its safe distance to E, vehicle E will never be disturbed and it can avoid relaying useless messages to the vehicles behind any further. In other words, the covered area can be confined into a smaller zone to avoid redundant bandwidth usage.

B. *Modeling Safe Distance*

Before presenting our power control rule, the safe distances between vehicles in vehicular network environments should be carefully modeled. As shown in Fig. 3, three vehicles C_{i+1}, C_i and C_{i-1} are on a highway platoon, where C_{i-1} is in front of C_i and C_{i+1} is behind C_i. Assuming that C_{i-1} is the vehicle confronted an accident, we aim to formulate the safe distance $S_{i,i+1}$ that C_{i+1} should be kept from C_i. The safe distance $S_{i,i+1}$ is then used to model the necessary transmission radius $T_{i,i+1}$ between C_i and C_{i+1} and broadcast radius B_i of C_i. Other symbols used in our model are listed in Table 1. Note that we assume each vehicle can obtain its current position and the UTC time from a Global Positioning System (GPS).

TABLE I. SYMBOLS

Symbols	Meanings
V_i	Velocity of C_i;
D_i	Deceleration rate (regular or emergency deceleration) of C_i;
δ	Average driver reaction time;
L	Car length;
t_i	UTC time when C_i applies emergency braking or receives a warming message from C_{i-1} at network queue;
$\Delta_{i-1,i}$	$\Delta_{i-1,i} = t_i - t_{i-1}$: delivery delay from C_{i-1} to C_i;
$d_{i-1,i}$	Distance between the position of C_i at t_i and the position of C_{i-1} at t_{i-1};
M_i	Moving distance of C_i after t_i;
$S_{i,i+1}$	Safe distance between C_{i+1} and C_i at time t_i;
$T_{i,i+1}$	Transmission radius from C_i to C_{i+1} at time t_i;
B_i	Broadcast radius of C_i at time t_i;

First of all, we need to estimate the moving distance M_i for C_i. The M_i represents the distance that C_i has to run through after C_{i-1} confronted an accident. The model of M_i has three cases, corresponding to the cases of soft brake, medium brake, and hard brake in Fig. 2.

Case 1: C_i stops safely

Case 2: C_i collides with C_{i-1} after (or when) C_{i-1} stopped;

Case 3: C_i collides with C_{i-1} before C_{i-1} stops;

In case 1, C_i applies a hard brake so that it can stop safely before colliding with C_{i-1}. Therefore, after C_i received a warning message from C_{i-1}, it will move at the original velocity V_i during the driver reaction time δ and then move at the decelerated velocity for a period of V_i/D_i before stopping. Let $l(V, D, t)$ stand for the moving distance of a vehicle with velocity V and deceleration rate D during a period of time t. That is,

$$l(V,D,t) = Vt - \frac{D}{2}t^2 \cdot$$

The moving distance of C_i after t_i can be represented as

$$M_i = \delta V_i + l(V_i, D_i, V_i / D_i) = \delta V_i + \frac{V_i^2}{2D_i} \cdot$$

In case 2, since C_i collided with C_{i-1} after (or when) C_{i-1} stopped, its moving distance is depending on the moving distance of the vehicle ahead, i.e. M_{i-1}. Therefore, assuming that the distance between the position of C_i at t_i and the position of C_{i-1} at t_{i-1} is $d_{i-1,i}$, the moving distance of C_i after t_i is the moving distance of C_{i-1} (i.e. M_{i-1}) plus their distance $d_{i-1,i}$. Note that the car length L should be subtracted. That is, the M_i in this case can be given by

$$M_i = d_{i-1,i} + M_{i-1} - L \cdot$$

Case 3 further has three subcases: 3.1, 3.2 and 3.3. Let t_x denote the moving time of C_i before collided and $\chi_{i-1,i}$ temporally denote the moving distance in this case. In subcase 3.1, C_i collides with C_{i-1} before both of them decelerate, which means that

$$\chi_{i-1,i} = t_x V_i,$$

where t_x satisfies that

$$t_x V_i + L = d_{i,i-1} + t_x V_{i-1} \cdot$$

In subcase 3.2, C_i collides with C_{i-1} before C_{i-1} decelerates and after C_{i-1} decelerated, which means that

$$\chi_{i-1,i} = t_x V_i,$$

where t_x satisfies that

$$t_x V_i + L = d_{i,i-1} + \delta V_{i-1} + l(V_{i-1}, D_{i-1}, t_x) - (\delta - \Delta_t) \cdot$$

In subcase 3.3, C_i collides with C_{i-1} after both of them decelerated, which means that

$$\chi_{i-1,i} = \delta V_i + l(V_i, D_i, t_x - \delta),$$

where t_x satisfies that

$$\delta V_i + l(V_i, D_i, t_x - \delta) + L = \\ d_{i,i-1} + \delta V_{i-1} + l(V_{i-1}, D_{i-1}, t_x - (\delta - \Delta_t)).$$

Combining the above cases, we have the following function for the moving distance M_i:

$$M_i = \min \begin{Bmatrix} \delta V_i + \frac{V_i^2}{2D_i} \\ d_{i-1,i} + M_{i-1} - L, \\ \chi_{i-1,i} \end{Bmatrix}$$

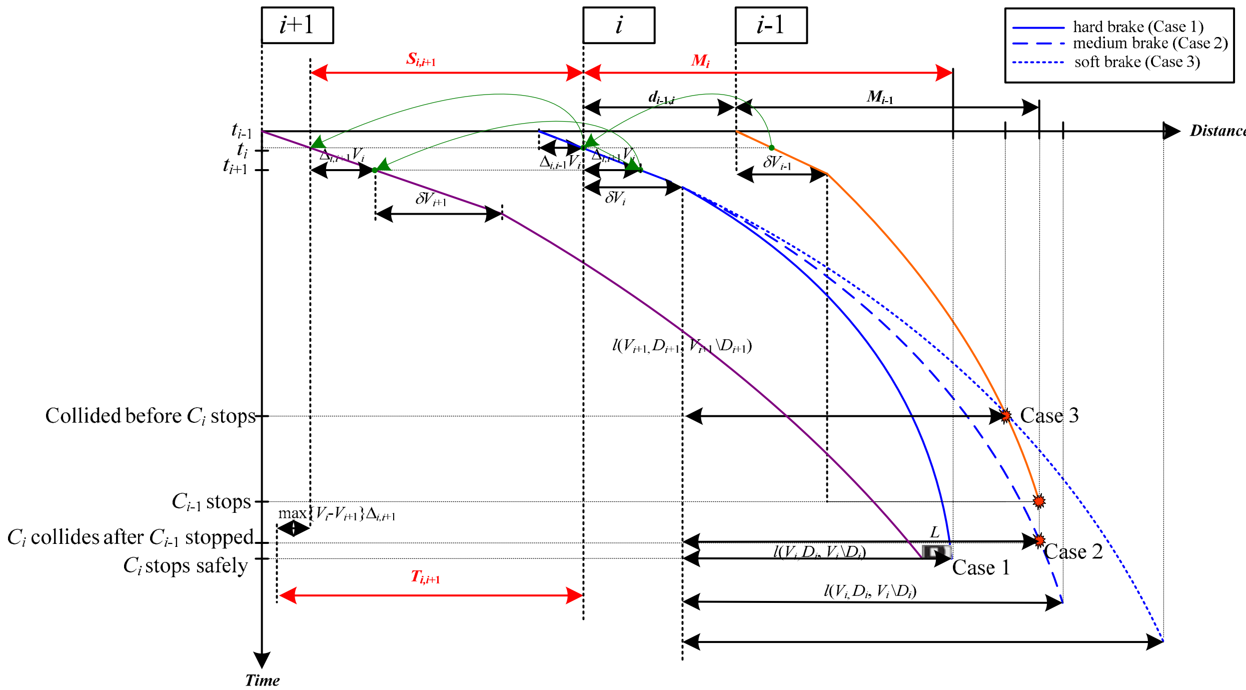

Figure 3. Safe distance and Transmission radius

Based on the moving distance M_i, we can now model the safe distance $S_{i,i+1}$ between C_i and C_{i+1} for C_i. Assuming that C_i can obtain the velocity V_{i+1} and deceleration D_{i+1} of vehicle C_{i+1}, it can know that C_{i+1} will move for a distance of $l(V_{i+1}, D_{i+1}, V_{i+1}/D_{i+1})$ after reacting the warning message from itself. On the other hand, before reacting to the warning message, C_{i+1} has to move for a distance of δV_{i+1} during the driver reaction time. Furthermore, there is a propagation delay $\Delta_{i,i+1}$ so that C_{i+1} has to move at the original velocity V_{i+1} for a distance of $\Delta_{i,i+1}V_{i+1}$. As a result, the safe distance $S_{i,i+1}$ between C_i and C_{i+1} can be modeled as

$$S_{i,i+1} = (\Delta_{i,i+1} + \delta)V_{i+1} + l(V_{i+1}, D_{i+1}, V_{i+1}/D_{i+1}) + L - M_i \,.$$

C. Powr Control Rule

As mentioned above, to send a warning message to C_{i+1}, the transmission radius of C_i should be at least the safe distance $S_{i,i+1}$. Furthermore, because the velocities of C_i and C_{i+1} are not always the same, vehicle C_{i+1} may not receive any message from C_i if their distance was enlarged during the message propagation, i.e. the duration $\Delta_{i,i+1}$. For this reason, the transmission radius of C_i to C_{i+1} should add the enlarged gap. That is,

$$T_{i,i+1} = S_{i,i+1} + \Delta_{i,i+1}\max\{V_i - V_{i+1}, 0\} \,.$$

Now, assume that C_i can be aware of the statuses of all vehicles behind. The broadcast radius of C_i can be set as

$$B_i = (1+\varepsilon)\max_{C_j \in P_i}\left\{ T_{i,j} \mid d_{i,j} \le T_{i,j} \right\},$$

where P_i is the set of vehicles behind C_i and $\varepsilon \ge 0$ is a factor to cope with the possible wireless channel fading.

However, if the statues of the trailing vehicle are unknown, we can estimate the safe distance, transmission power broadcast radius, respectively, by

$$\hat{S}_i = (\tau + \delta)V_{\max} + l(V_{\max}, D_r, V_{\max}/D_r) + L - M_i \,,$$

$$\hat{T}_i = \hat{S}_i + \tau \max\{V_i - V_{\min}, 0\} \,,$$

and

$$\hat{B}_i = (1+\varepsilon)\hat{T}_i \,,$$

where $V_{\max}$ denotes the maximum velocity (or upper speed limit), $V_{\min}$ denotes the minimum velocity (or lower speed limit), and D_r is the regular deceleration. Note that the optimal value of ε can be turned by simulation or some rational function. The above models are also applicable to any vehicle C_i in a platoon. In such a case, the C_{i-1} presents the vehicle that has received a warning message from a vehicle ahead (e.g. C_{i-2}).

IV. SIMULATIONS

In this section, we conduct simulations to evaluate the proposed mechanism. We use the ns-2 network simulator [14] to simulate a highway scenario, where 50 vehicles driving on a highway platoon toward the same direction. Vehicle emergency situations are created by forcing the vehicle at the front of the platoon (i.e. vehicle 0) to rapidly decelerate (8m/s^2), which triggers a CCA process by initiating a warning message. Any vehicle behind will decelerate at the regular rate (4.9m/s^2) whenever it has received a warning message for a driver reaction time, randomly chosen from 0.75s to 1.5s.

The transmission medium is IEEE 802.11 MAC. The broadcast throughput is throughput is 1Mbps and the maximum transmission range is 250m. We will compare the cases with and without the power control mechanism. In order to evaluate the performance under the same base, we employ the naive broadcast [10], a direction-ware broadcast protocol for CCA, to forward any warning message at the network layer. Other parameters used in our simulation are listed in Table 2, which are mostly adapted from [10]. Note that to add dynamics in our test vehicle speed and inter-car spacing have 10% variations. Besides, we assume the maximum speed (V_{max}) and minimum speed (V_{min}) are available to each vehicle so that each vehicle C_i can estimate its broadcast radius B_i. The channel fading factor ε is set as 0.1 in our test. All results are averaged from 10 runs.

TABLE II. PARAMETERS SETTINGS

Parameters	Values
Number of vehicles on each lane	50
Vehicle length	4m
Vehicle speed	32m/s ± 10%
Regular deceleration	4.9/m/s/s
Emergency deceleration	8/m/s/s
Inter-car spacing	[9.6 – 28.8] m ± 10%
Driver's reaction time	[0.75 – 1.5] s
Radio model	Two ray ground
MAC protocol	IEEE 802.11 DCF
Broadcast protocol	Naïve broadcast
Message size	20 bytes
Random wait time	[0 –10] ms
Simulation runs	10

Fig. 4 shows the number of collided vehicles under varied average inter-car spacing. We can see that there are no more than a half of collisions being avoided if each vehicle always transmits or forwards at the maximum transmission radius. Contrarily, by using the power control technique, the possibility of a car collision can be greatly reduced especially when the inter-car spacing is reasonably large.

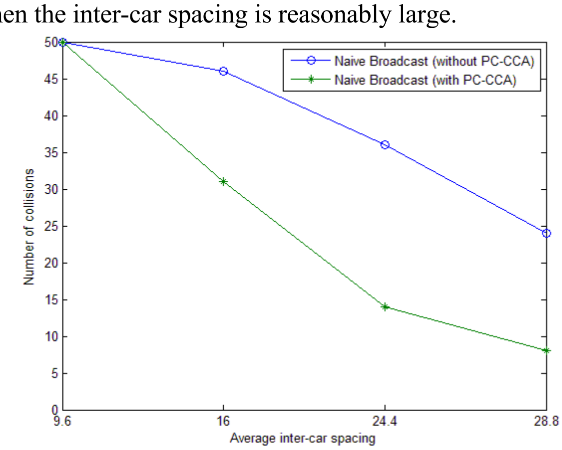

Figure 4. Number of collided vehicles under varied inter-car spacing

Such an impressive improvement is primarily the consequence of the reduced delivery delay. As shown in Fig. 5, with an average inter-car space of 28.8 m, the maximal delay required to delivery a warning message all vehicles can be confined in 8 ms if the PC-CCA is used. By contrast, the delivery delay without the PC-CCA increases drastically to the trailing vehicles, implying that more vehicles are not able to receive a warning message in time and brake safely.

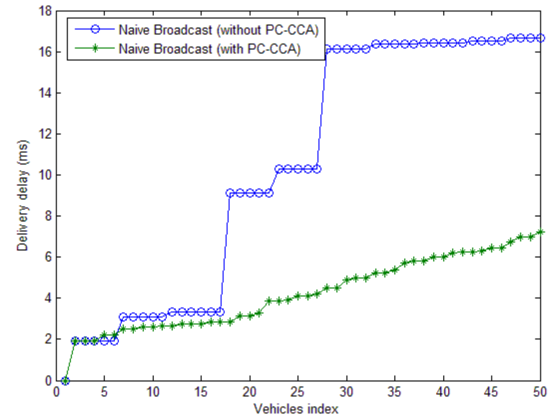

Figure 5. Delivery delay for each vehicle in the platoon (inter-car spacing: 28.8 m ± 10%)

V. CONCLUSION

In this paper, we have proposed an efficient broadcast mechanism for the CCA system using power control technique. The main idea for controlling power is based on the safe distance between vehicles. Simulation results show that our mechanism indeed helps to reduce delivery delay and car crashes.

ACKNOWLEDGMENT

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