An Efficient Collision Avoidance Strategy for ITS Systems

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***Abstract*— In this paper, we develop an efficient vehicle collision avoidance strategy for intelligent transport systems. The proposed strategy first clusters vehicles according to the features of their movement (e.g., direction of movement, inter-vehicle distance, and relative velocity). To enhance the responsiveness of the proposed CCA system, a risk-aware MAC protocol is designed. In the proposed scheme, an emergency level is defined for each vehicle based on its order in its respective 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 set as a function of its emergency level in a way that enables vehicles in emergency situations to promptly disseminate warning messages to neighboring vehicles and to accordingly minimize chain collisions. The proposed CCA system is dubbed Cluster-based Risk-Aware CCA (C-RACCA). The performance of the proposed C-RACCA system is evaluated via simulations and encouraging results are obtained.**

I. INTRODUCTION

Intra-platoon Cooperative Collision Avoidance (CCA) systems form an important aspect of vehicular ad-hoc networks' (VANET) safety applications. The importance of CCA systems stems from the relatively long time a driver takes since the observation of an emergency event till the application of the brake. This reaction time typically ranges from $0.75s$ to $1.5s$ [1]. In case of a dense platoon traveling at high speeds, the damage becomes significant. The success of any CCA system hinges, however, on its responsiveness to emergency scenarios and the reliability of its disseminated information. To cope with the former, the used Medium Access Control (MAC) protocols should ensure reduced medium access delay for vehicles in emergency situations. For this purpose, in this paper we propose an efficient CCA strategy based on a risk-aware MAC protocol tailored for VANET networks. In the proposed CCA system, we first cluster the vehicles according to the features of their movement using information such as the direction of their movement, inter-vehicle distance, and relative speed. For each vehicle in a particular cluster we associate an emergency level. The emergency level indicates the likelihood of a vehicle to experience an accident in the platoon. The medium access delay of each vehicle, termed also as the waiting time or contention window, is set as a function of its emergency level in a way that grants for vehicles, with high risk to encounter accidents, the ability to deliver safety warning messages with the shortest delivery latencies. The proposed CCA strategy is called Cluster-based Risk-Aware CCA (C-RACCA).

The remainder of this paper is structured as follows. Section II highlights some research work pertaining to MAC protocols in the context of VANET networks. Section III presents the C-RACCA system. It describes the clustering operation and the proposed risk-aware MAC protocol. Section IV portrays the simulation philosophy and discusses the simulation results. The paper concludes in Section V.

II. RELATED WORK

Ensuring prompt delivery of critical warning messages is crucial for CCA systems. For this purpose, there is need to develop adequate MAC protocols. In the recent literature, a large library of MAC protocols has been proposed. Not all of them are suitable for VANET networks. Indeed, VANET-oriented protocols do not need to take power constraints or time synchronization into account. However, they need to assure short medium access delays for vehicles, particularly those in emergency situations in case of CCA systems. An insightful discussion on major MAC protocols and their applicability to VANETs can be found in [4].

The most preferred MAC protocol for safety applications in VANETs is the IEEE 802.11 scheme [5]. The strength of IEEE 802.11 consists in its adoption of mechanisms such as CSMA with Collision Avoidance (CSMA/CA), Multiple Access with Collision Avoidance (MACA), and MACAW (MACA for wireless) in its Distributed Coordinated Function (DCF) mode of operation. These schemes rely on soft handshaking between the sender and the receiver via exchange of signaling messages (e.g., Request-to-Send (RTS) and Clear-to-Send (CTS) messages). Indeed, to access the medium, a vehicle needs to first check the medium state. If it is idle, it sends a RTS packet including its ID and the duration time of the data transmission. In response, the receiver waits for a Short Inter-Frame Spacing (SIFS) and issues a CTS message. All neighboring vehicles hear the RTS and the CTS messages and set their Network Allocation Vector (NAV) to the indicated transmission duration. In case the medium is not idle, the sending vehicle backs off and attempts again after a time chosen within a contention window (CW). Whilst this procedure minimizes the data collisions, it may delay access to the medium for vehicles that are in emergency situation and need to immediately inform their neighboring vehicles of the emerging incident. To cope with this issue in the context of safety-critical applications such as CCA, there is need for either data prioritization [3][6] or vehicle prioritization. In this paper, we consider the prioritization of vehicles using their emergency levels.

III. THE CLUSTER-BASED RISK-AWARE CCA SYSTEM

In [3], a set of mechanisms for packet forwarding schemes is proposed. In all the proposed schemes, when a vehicle meets an emergency situation, it notifies all vehicles behind

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it via warning messages. The recipients decide to forward the message or not based on its direction of arrival with respect to the direction of the vehicles' movements. The message transmission is performed in a multi-hop manner. While this operation ensures a complete coverage within the platoon, it gives rise to two issues. First, it results in the generation of an excessive number of critical signaling messages and the reception of duplicate messages from different vehicles. This may eventually escalate message collisions in the access medium. The second primary limitation pertains to the fact that it results in cumulative delays in communication and in a long message-delivery latency from when the emergency event is detected at the platoon front till when vehicles in the platoon back are notified of the event. This message-delivery latency becomes further increased in case of multiple failed message retransmissions due to high MAC collisions. As a remedy to these issues, we suggest a dynamic clustering of vehicles.

A. *Dynamic Clustering of Vehicles*

Before delving into details about the clustering operation, we first list our assumptions about the envisioned VANET network.

- Vehicles are assumed to be equipped with Global Positioning Systems (GPS) or alike that enable them to accurately detect their geographical locations.
- Two wireless channels are considered for communications. One serves for the exchange of signaling messages to form vehicle clusters and the other is used for the transmission of critical warning messages.
- Vehicles are assumed to have the capacity of estimating relative velocity and distance to vehicles immediately ahead of them and right behind them.
- Upon receiving a message, vehicles are assumed to have the ability to tell whether the received message is sent by a vehicle ahead of them or behind them.
- Vehicles are assumed to have knowledge on their maximum wireless transmission range T_r. Using this parameter, a vehicle constantly updates its current transmission range R as follows:

  $$R = T_r \cdot (1 - \epsilon) \qquad 0 < \epsilon \leq 1 \tag{1}$$

  where ϵ reflects the wireless channel fading conditions in the current location. For instance, ϵ can be set to small values in environments with no major obstacles (e.g., highway) and take high values in urban areas with tall buildings. A mapping function between the geographical locations and the values of ϵ can be provided by the used positioning system (e.g., GPS, Galileo), while taking into account the weather conditions.

In the proposed system, clusters are formed among vehicles belonging to the same group (i.e., moving along the same road and in the same direction) similar to [2] and to some directional-antenna based MAC protocols [7]. Vehicles can play three modes of operations, namely as cluster heads (CHs), sub-cluster heads (SCHs), or as ordinary vehicles (OVs). In the former, vehicles are voluntarily responsible for forming the cluster, constantly advertising for the cluster, and maintaining and updating its table. Sub-cluster heads are responsible for forwarding messages from cluster heads (or SCHs in front) to vehicles that are in the same cluster but are outside the reach of the cluster head (SCHs in front). They are also responsible for aggregating information from ordinary vehicles within their reach and forwarding it the cluster head or SCHs in front. SCHs are chosen as the last vehicle reachable by the cluster head (or SCHs in front). Ordinary vehicles are ordinary members in the cluster with no specific tasks.

Let C_i denote the ID of car i. For the sake of simplicity of notation, we denote the vehicle which is immediately ahead of vehicle C_i (if it exists) and whose transmission range reaches C_i as C_{i-1} and the vehicle right behind C_i (if it exists) and reachable by C_i as C_{i+1}. In the clustering operation, we use the following notations.

- $d_{j,k}$: Distance between vehicles C_j and C_k.
- V_j: Velocity of vehicle C_j.
- $V_{j,k}$: Magnitude of the relative velocity of vehicle C_j with respect to vehicle C_k (i.e., $V_{j,k} = V_{k,j}$).
- ϕ_j: Set of cluster heads or sub-cluster heads ahead of vehicle C_j and belonging to the same group as C_j.
- ϕ_j^{CH}: Closest CH or SCH ahead of vehicle C_j from within the set ϕ_j.
- ψ_j: Set of cluster heads or sub-cluster heads behind vehicle C_j and belonging to the same group as C_j.
- ψ_j^{CH}: Closest CH or SCH behind vehicle C_j from within the set ψ_j.
- a_e and a_r: Emergency deceleration and regular deceleration, respectively. The two values can be used by the system as an indication for an emergency event to trigger the transmission of warning messages.
- δ: Driver's average reaction time ($0.75 \leq \delta \leq 1.5s$)

We also use the following definition. For each two adjacent vehicles C_i and C_{i+1} where C_i is ahead of C_{i+1}, we say the two vehicles are safe (i.e., no collision will occur between them) if their inter-vehicle distance $d_{i,i+1}$ satisfies the following condition $\Gamma_{i,i+1}$ (i.e., $\overline{\Gamma_{i,i+1}}$ denotes the negation of the condition).

$$\Gamma_{i,i+1} \Leftrightarrow d_{i,i+1} > \alpha \cdot \big(V_{i+1} \cdot \delta + \frac{V_{i+1}^2}{2a_r} - \frac{V_i^2}{2a_e}\big) \tag{2}$$

where α is a tolerance factor.

In the clustering operation, three scenarios can be envisioned.

- A vehicle gets on a road (i.e., at the start-up of the engine).
- A vehicle changes its moving direction (i.e., leaves its old group G_o and joins a new group G_n).
- A vehicle continues moving in the same direction and on the same road but alters the magnitude of its velocity.

We discuss the clustering operation for each scenario.

1) Joining a group: Upon getting on a road, a vehicle C_i (belonging to group G_n) first broadcasts a CH solicitation message inquiring if there exists any CH from group G_n in its neighborhood and sets a timer θ. If the timer expires and vehicle receives no response to its query ($\phi_i = \psi_i = \emptyset$), the vehicle shifts its mode to that of a cluster head and starts forming its own cluster.

In case of an affirmative response to its query, the vehicle sorts the list of replying CHs. It first checks whether there is any CH advertisement message from any CH ahead of it. In case of none ($\phi_i = \emptyset$), from the fact that $\psi_i \neq \emptyset$, the vehicle checks if there is enough distance to vehicle C_{i+1} right behind it to assure no collision will occur between the two vehicles. In case $d_{i,i+1}$ is long enough to avoid collision between the two vehicles (i.e., $\Gamma_{i,i+1}$), vehicle C_i forms a cluster on its own and designates itself as its cluster head. Otherwise (i.e., $\overline{\Gamma_{i,i+1}}$), the vehicle takes over the authority of the cluster head behind it, ψ_i^{CH}, and designates itself as the new cluster head (i.e., $C_i = \phi_{i+1}^{CH}$).

In case vehicle C_i receives a CH advertisement message from at least one CH ahead of it ($\phi_i \neq \emptyset$), the vehicle checks if its distance to vehicle C_{i-1} immediately ahead of it is long enough to avoid collision between C_i and C_{i-1}. If not (i.e., $\overline{\Gamma_{i,i-1}}$), the vehicle joins the cluster formed by ϕ_i^{CH}. The vehicle will form its own cluster with itself as the cluster head if the condition $\Gamma_{i,i-1}$ holds and no vehicle is behind it ($\psi_i = \emptyset$). If ($\psi_i \neq \emptyset$), the vehicle will check its distance to the vehicle right behind it and behave in a way similar to the case when ($\phi_i = \emptyset$, $\psi_i \neq \emptyset$).

Whenever a vehicle desires to join a cluster, it transmits a Self Notification (SN) message indicating its ID, its current location and its transmission range to the respective CH. The CH interprets the message as a solicitation from the vehicle to join the cluster and adds the vehicle to the cluster table. An updated Cluster Advertisement (CA) message is then transmitted to all the cluster members. The CA message contains information on the cluster's ID, the CH's ID, the IDs of selected sub-cluster heads, and the IDs of all remaining ordinary members. When a newly entering vehicle is selected as the new CH for a given cluster, the former CH of the cluster handles the cluster table to the new CH and an updated CA message is broadcasted to all the members of the cluster notifying them of the changes.

2) Joining a group and leaving another: In case of the second scenario whereby a vehicle shifts from an old group G_p to a new group G_n upon a change in its moving direction, the vehicle follows the aforementioned steps to join an already-existing cluster or forms a new one on its own. At the same time, the vehicle should notify the old cluster it was joining of its departure. Three cases can be envisioned depending on whether the vehicle was the CH of the old cluster, a SCH, or just an ordinary member. In case of the latter, the leave operation is simple. The vehicle needs to inform the cluster head or its respective SCH of its departure. In response, the SCH removes the vehicle from the sub-cluster table and notifies the CH of the event. The CH removes then the vehicle from the cluster table and notifies all the members of the new structure of the cluster via a cluster advertisement message. If the departing vehicle is a SCH in the cluster, it will designate the vehicle immediately ahead of it as the new SCH and the sub-cluster table will be handled to it. Similarly, if the departing vehicle is the CH of the cluster, it will then designate the most appropriate vehicle from within the cluster members as the new CH of the cluster. The cluster table will be handled to the new CH who will notify the cluster members of the change via a CA message.

3) Interactions within clusters belonging to the same group: A given cluster can be split into two different clusters if two adjacent vehicles C_i and C_{i+1} from within the same cluster keeps moving at a relative speed $V_{i,i+1}$ till their inter-vehicle spacing $d_{i,i+1}$ satisfies the condition $\Gamma_{i,i+1}$. Vehicle C_{i+1} will become thus the cluster head of one portion of the former cluster (the portion formed from vehicles behind C_{i+1}) whereas vehicle C_i will join the other portion of the cluster (consisting of vehicles C_i and beyond) as an ordinary vehicle.

Similarly, two clusters can merge into one single cluster if the distance between the cluster head C_l of one of the two clusters and the last vehicle C_k in the other cluster gets shorter to the point where the negation of condition $\Gamma_{k,l}$ holds. Vehicle C_l will then handle the table of the former cluster it was heading to the cluster head of the cluster where vehicle C_k belongs. An updated CA message will be then broadcasted to all the members of the newly formed cluster.

B. Risk-Aware MAC Protocol

For the sake of simplicity, we consider the case of a single cluster. Without any loss of generality, we index vehicles according to their order in the cluster with respect to their direction of movement (i.e., C_1 denotes the cluster head). Given the fact that serious damage may happen in case of chain vehicle collision in a highway, we focus on highway platoons. Due to its wide use, particularly in the implementation of VANETs, we consider the 802.11 protocol in our studies.

In IEEE 802.11, the contention period is computed following an exponential back-off procedure. Whilst the exponential back-off algorithm aims at resolving contention between different stations willing to access the medium, it results in increased latency in data delivery. This renders the efficiency of the protocol questionable when it is applied to safety-critical CCA applications that are highly sensitive to delay. To cope with such an issue, we suggest substituting the back-off algorithm in IEEE 802.11 by a mechanism that reflects the likelihood of a vehicle to meet an emergency situation in its contention window. For this purpose, we define an emergency level for each vehicle C_i in the cluster based on the following distribution.

$$\Omega_i = \frac{(1-\omega)\omega^i}{\omega(1-\omega^S)} \qquad 1 \leq i \leq S \tag{3}$$

where S denotes the size of the cluster. The parameter ω is referred to as the skew factor.

In the proposed Risk-aware MAC protocol, instead of the exponential back-off operation the contention window of a vehicle C_i with an emergency level Ω_i is computed as follows.

$$CW_i = \sum_{j=0}^{k}(1-\Omega_i)^j \cdot cw \cdot \xi \tag{4}$$

where k denotes the number of transmission attempts. ξ denotes the slot time of the used physical layer. The rational behind the above computation of the contention window is to ensure short contention windows for vehicles with high emergency levels.

While the above equation ensures some system consistency in the setting of the contention window among all vehicles in a particular cluster, there is still need to ensure that the contention window is short enough to prevent the maximum number of imminent collisions between vehicles. For this purpose, we compute the maximum delay within which a vehicle should be notified to avoid collision with the vehicle ahead of it. We assume that in case of an emergency event vehicles C_i and C_{i+1} decelerate at a_e and a_r, respectively. We need to compute the maximum latency δ_i (from the event detection time) before which vehicle C_i should inform C_{i+1} of the emergency event so that C_{i+1} does not collide with C_i. It should be noted that a vehicle also assures its safety by preventing collision with vehicles right behind it.

As will be detailed in the collision model used in the next section, vehicle C_i will be moving for a time $\Delta_i = \frac{V_i}{a_e}$ before it stops. During that time, vehicles C_i and C_{i+1} will move for a distance equal to

$$\begin{aligned} l_i &= \frac{V_i^2}{2 \cdot a_e} && (5) \\ l_{i+1} &= V_{i+1} \cdot \frac{V_i}{a_e} - \frac{a_r}{2}\left(\frac{V_i}{a_e} - \delta_i\right)^2 && (6) \end{aligned}$$

To prevent collision, the following inequality should be satisfied.

$$l_{i+1} > l_i + d_{i+1,i} + L_v \tag{7}$$

where L_v is the average vehicle length. This condition can be satisfied only and only if C_{i+1} is notified at maximum δ_i^{max} time after the event detection time (i.e., the time when C_i starts decelerating).

$$\delta_i^{max} = Max\left(\frac{V_i}{a_e} - \sqrt{\frac{2}{a_r} \cdot \left(\frac{V_i}{a_e}\left(V_{i+1} - \frac{V_i}{2}\right) - d_{i+1,i} - L_v\right.}, 0\right) \tag{8}$$

It should be noted that the collision would be inevitable in case $\delta_i^{max} = 0$. While in such scenario, collision between C_{i+1} and C_i is impossible to avoid, C_i should keep broadcasting warning messages to all vehicles within its transmission range to reduce further damage that may occur by having vehicles far behind colliding. The contention window CW_i for vehicle C_i is thus set as follows.

$$CW_i = \begin{cases} \sum_{j=0}^{k}(1-\Omega_i)^j \cdot cw \cdot \xi & \text{if } \delta_i^{max} = 0 \\ Min(\sum_{j=0}^{k}(1-\Omega_i)^j \cdot cw \cdot \xi, \delta_i^{max}) & \text{otherwise} \end{cases} \tag{9}$$

When an emergency event is detected by a vehicle, the vehicle broadcasts a warning message to the members of the cluster it belongs to and that are within its transmission range, including the sub-cluster heads. The sub-cluster heads, in turn, forward the message to all the members of its sub-clusters. Vehicles ignore messages originating from vehicles behind them. If the message comes from a vehicle ahead, the vehicle immediately reacts to it according to the event type as indicated in the warning message. In case of the reception of duplicate warning messages, the vehicle reacts only to the first one and ignores the others.

IV. PERFORMANCE EVALUATION

A. Collision model

Let S denote the cluster size. In a highway platoon scenario, having the cluster head detect an emergency event represents the most frequent scenario. Upon detection of an emergency event at time t_0, the cluster head decelerates at an emergency deceleration a_e. The other vehicles decelerate at a regular deceleration a_r. Let L_v denote the average length of vehicles.

In the simulated collision model, for the sake of analysis simplicity we assume that when a vehicle C_i collides with a vehicle C_{i-1} ahead of it, vehicle C_i stops immediately while vehicle C_{i-1} continues moving with no changes to its velocity or deceleration. Admittedly, this assumption is not realistic. However, it should be emphasized that it does not change any of the fundamental observations we make about our C-RACCA system.

For each vehicle C_i, let Δt_i denote the time since the event detection time till the vehicle stops or collides with the vehicle in front of it, C_{i-1}. Let V_i^o and V_i^s denote the velocities of vehicle C_i at the event detection time and the time when the vehicle stops or collides with C_{i-1}, respectively. Let δ_i denote the latency from when the event is detected till when the respective warning message reaches vehicle C_i. It should be noted that in case of a successful broadcasting of the warning message by the cluster head (a sub-cluster head) and successful reception of the warning message by all vehicles within the reach of the cluster head (or the sub-cluster head), all the vehicles should experience similar δ_i. Let l_i denote the distance vehicle C_i traveled since the event detection time till the vehicle stops or collides with C_{i-1}. For the cluster head C_1, we have the following equations.

$$\begin{aligned} \Delta t_1 &= \frac{V_1^o}{a_e} && (10) \\ l_1 &= V_1^o \Delta t_1 - \frac{1}{2} a_e \cdot \Delta t_1^2 && (11) \\ V_i^s &= 0 && (12) \end{aligned}$$

For vehicles other than the cluster head $(C_i,\ 1 < i \leq S)$, if no collision occurs between vehicles C_i and C_{i-1}, we have the following equations.

$$\begin{aligned} \Delta t_i &= \frac{V_i^o}{a_r} + \delta_i && (13) \\ l_i &= V_i^o \Delta t_i - \frac{1}{2} a_r \cdot (\Delta t_i - \delta_i)^2 && (14) \\ V_i^s &= 0 && (15) \end{aligned}$$

In case of collision, two cases can be envisioned: $i)$ vehicle C_i hits vehicle C_{i-1} while C_{i-1} is on move, $ii)$ vehicle C_i

TABLE I

SIMULATION PARAMETERS.

Factor	Range of values
Cluster size S	20
Vehicle speed V_i	15 - 45 m/s
Inter-vehicle distance $d_{i,i+1}$	10 - 30 m
Emergency deceleration a_e	8 m/s^2
Regular deceleration a_r	4.9 m/s^2
Driver's reaction time δ	0.75 - 1.5 s
Transmission range T_r	150 m
Skew factor ω	2
Average vehicle length L_v	4 m
Slot time ξ	50 μs
Tolerance factor α	3

collides with vehicle C_{i-1} after C_{i-1} stops. In the latter case, the following inequality should hold.

$$l_{i-1} + d_{i,i-1} + L_v \leq l_i \quad (16)$$

In that time, Δt_i, l_i and V_i^s will be computed as follows.

$$\Delta t_i = \Delta t_{i-1} \quad (17)$$

$$l_i = l_{i-1} + d_{i,i-1} + L_v \quad (18)$$

$$V_i^s = V_i^o - a_r \cdot (\Delta t_{i-1} - \delta_i) \quad (19)$$

In the former case, there should exist a time t_m when

$$\exists t_m \quad V_i^o(t_m - t_0) - \frac{1}{2}a_r \cdot (t_m - t_0 - \delta_i)^2 \quad (20)$$

$$= V_{i-1}^o(t_m - t_0) - \frac{1}{2}\eta \cdot (t_m - t_0 - \delta_{i-1})^2 + L_v$$

where $\eta = a_e$ in case of $i = 2$, or $\eta = a_r$ for $3 \leq i \leq S$. In that time, Δt_i, l_i and V_i^s are computed as follows.

$$\Delta t_i = t_m - t_0 \quad (21)$$

$$l_i = V_i^o(t_m - t_0) - \frac{1}{2}a_e \cdot (t_m - t_0 - \delta_i)^2 \quad (22)$$

$$V_i^s = V_i^o - a_r \cdot (t_m - t_0 - \delta_i) \quad (23)$$

B. Simulation Results

Using the above described collision model, we conduct simulation. In order to have a cluster with at least one sub cluster head, we set the transmission range of vehicles and the minimum inter-vehicle distance to 150m and 10m, respectively. The simulation parameters are as shown in Table I. In the performance evaluation, we compare our C-RACCA system to a CCA system with a MAC protocol using the exponential back-off algorithm for the computation of the contention window. We also compare our proposed system to the case when there is no CCA and collision avoidance is based on only the traditional reaction of drivers.

Two scenarios are simulated. In the first scenario, all vehicles move at a steady speed. The inter-vehicle distance is chosen from within the interval $[10m, 30m]$. In the second scenario, the inter-vehicle distance is randomly chosen from within the interval $[10m, 30m]$ for each couple of adjacent vehicles. The vehicles are moving at varying speeds. The speed of the cluster head (the vehicle in the front) is chosen from a range $[22m/s - 42m/s]$ and the velocity of the other vehicles is carefully chosen not to cause collision between vehicles. In the simulation, an emergency situation is simulated by having the cluster head hit a fixed object. This forces the cluster head to rapidly decelerate. Following this, a number of wireless collision messages is broadcasted. The presented simulation results are an average of multiple simulation runs.

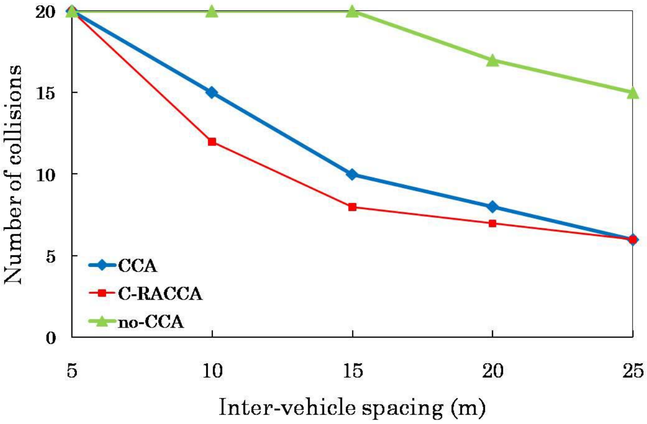

Fig. 1. Number of collided vehicles for different inter-vehicle distances (scenario 1, vehicle speed = 32 m/s).

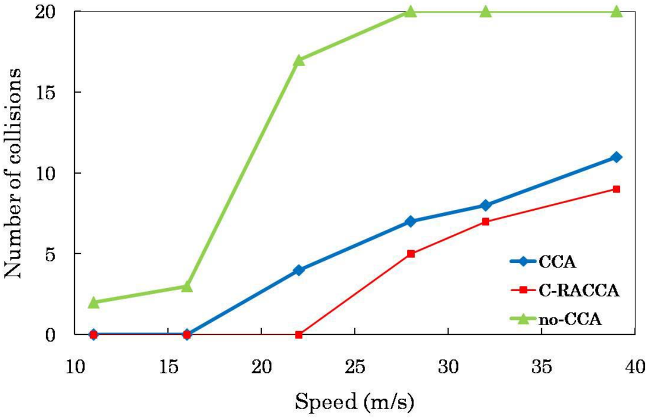

Fig. 2. Number of collided vehicles for different velocities of the cluster head (scenario 2, $\omega = 0.8$).

Fig. 1 plots the number of collided vehicles for different inter-vehicle distances and in the case of the simulated systems. The figure demonstrates that the use of the proposed C-RACCA system saves many vehicles from crashing. A similar performance is achieved in scenario 2 (Fig. 2). This reduced number of vehicle collisions is attributable to the ability of the C-RACCA system in promptly notifying vehicles of the emergency situation. This becomes clear from Fig. 3. Indeed the figure indicates that in case of the former CCA system, vehicles experience high latencies in the delivery of their warning messages. It should be noted that this latency reflects also the latency in the reception of the first warning message by vehicles as vehicles are assumed to re-forward a warning message immediately after receiving it. The figure shows that in case of the former CCA system the ten last vehicles experienced a relatively longer time till they received and delivered the warning message. This is due to the multiple MAC collisions that occurred due to the simultaneous delivery of warning messages by the first ten vehicles. In case of the proposed C-RACCA system, the delivery of warning message

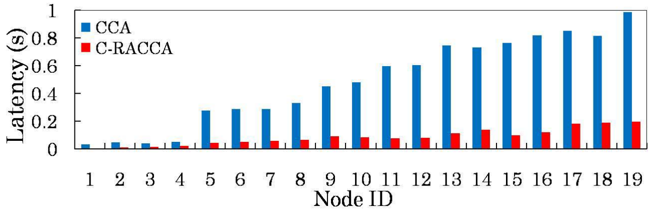

Fig. 3. warning message delivery latency δ_i for each vehicle C_i (scenario 1, inter-vehicle distance = 15m, vehicle speed = 32 m/s, $\omega = 0.8$).

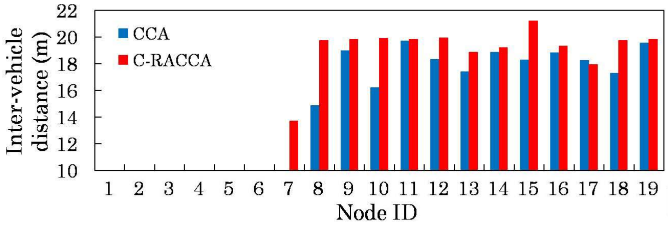

Fig. 4. Relative inter-vehicle distance $d_{i,i-1}$ after stop (scenario 1, inter-vehicle distance = 15m, vehicle speed = 32 m/s, $\omega = 0.8$).

is done by only the vehicle that met the emergency event (the cluster head in this example) and the sub-cluster heads. Message collisions are thus avoided and a large number of vehicles receive the warning message in a short latency in the order of μs. This enables vehicles to promptly react to the emergency situation as can be inferred from Figs. 4 and 5. Indeed, Fig. 4 demonstrates that the relative distances between consecutive vehicles after stop are longer in case of the C-RACCA system than in case of the other naive CCA system. It should be recognized that in most cases a long relative distance between two consecutive vehicles C_i and C_{i+1} indicates that vehicle C_{i+1} reacted promptly to the emergency situation to a point that it could keep a sufficient distance from vehicle C_i. This distance is highly important in case the vehicle ahead explodes at the time of collision (e.g., due to fuel leak). On another hand, the smaller magnitude of the relative velocity, at the time of collision, achieved by the proposed system in Fig. 5, is another important feature of the system as it reduces the severity of the collision and the associated damage.

V. CONCLUDING REMARKS

In this paper, we have proposed an efficient car collision avoidance strategy dubbed as Cluster-based Risk-Aware Cooperative Collision Avoidance (C-RACCA) system. The proposed system first clusters vehicles based on particular features of their movements. A set of mechanisms is proposed to enable vehicles to join or leave a particular cluster. The clustering operation results in a number of clusters of different sizes, with independent cluster heads, and distant from each other by a distance long enough to avoid collisions between vehicles from the clusters.

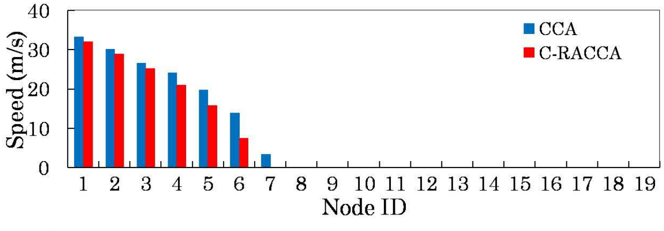

Fig. 5. Relative speed $V_{i,i-1}$ at the time of collision. In the absence of collision, $V_{i,i-1} = 0$ (scenario 1, inter-vehicle distance = 15m, vehicle speed = 32 m/s, $\omega = 0.8$).

From the observation that in an emergency situation vehicles within the same cluster can collide if they are not notified promptly, an enhancement to existing MAC protocols is proposed to ensure short latency in the delivery of warning messages upon the detection of an emergency event. An emergency level is defined for each vehicle based on its order in the cluster with respect to the moving direction of the cluster. The rational behind the computation of the warning message delivery latency of a particular vehicle is two fold. First, it is computed in inverse proportion to the emergency level of the vehicle to reflects its likelihood to meet an emergency situation in the cluster. Second, the latency is computed in a way that prevents collision between the vehicle and the vehicle right behind it while taking into account their velocities and their inter-vehicle distance.

To evaluate the performance of the system, a set of simulations is conducted. The performance of the proposed system is compared to CCA systems with traditional MAC protocols. The simulation results elucidated that the proposed system reduced both the number of collisions and the severity of the collisions when they inevitably occurred. Finally, while in the computation of the warning message delivery latency, the emergency levels of vehicles are computed following a distribution with a predetermined skew factor ω, the authors are currently investigating for any possible correlation between the skew factor and the features of a particular cluster (its average inter-vehicle distance, its average velocity, and its size).

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