Toward an Effective Risk-Conscious and Collaborative Vehicular Collision Avoidance System

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***Abstract*—In this paper, we introduce a cooperative collision-avoidance (CCA) scheme for intelligent transport systems. Unlike contemporary strategies, the envisioned scheme avoids flooding the considered vehicular network with high volumes of emergency messages upon accidental events. We present a cluster-based organization of the target vehicles. The cluster is based upon several criteria, which define the movement of the vehicles, namely, the directional bearing and relative velocity of each vehicle, as well as the intervehicular distance. We also design a risk-aware medium-access control (MAC) protocol to increase the responsiveness of the proposed CCA scheme. According to the order of each vehicle in its corresponding cluster, an emergency level is associated with the vehicle that signifies the risk of encountering a potential emergency scenario. To swiftly circulate the emergency notifications to collocated vehicles to mitigate the risk of chain collisions, the medium-access delay of each vehicle is set as a function of its emergency level. Due to its twofold contributions, i.e., the cluster-based and risk-conscious approaches, our adopted strategy is referred to as the cluster-based risk-aware CCA (C-RACCA) scheme. The performance of the C-RACCA system is verified through mathematical analyses and computer simulations, whose results clearly verify its effectiveness in mitigating collision risks of the vehicles arising from accidental hazards.**

***Index Terms*—Cooperative collision avoidance (CCA), intervehicle communication (IVC), vehicular ad-hoc network (VANET).**

I. Introduction

ALONG with the ongoing advances in dedicated short-range communication (DSRC) and wireless technologies, intervehicular communication (IVC) and road–vehicle communication (RVC) have become possible, giving birth to a new network-type called vehicular ad-hoc network (VANET). The key role that VANETs can play in the realization of intelligent transport systems has attracted the attention of major car manufacturers (e.g., Toyota, BMW, and Daimler-Chrysler). A number of important projects have been subsequently launched. Crash Avoidance Metrics Partnership (CAMP), Chauffeur in Europe Union, CarTALK2000, FleetNet, and DEMO 2000 by the Japan Automobile Research Institute (JSK) are a few notable examples.

VANETs can be used for a plethora of applications, ranging from comfort and infotainment applications to onboard active safety applications. The latter are the most attractive and promising ones. Such applications assist drivers in avoiding collisions. They coordinate among vehicles at critical points such as intersections and highway entries.[1] Via an intelligent dissemination of road information (e.g., real-time traffic congestion, high-speed tolling, or surface condition) to vehicles in the vicinity of the subjected sites, collisions among vehicles can be prevented, and on-road vehicular safety can be accordingly enhanced.

To facilitate safety applications in VANETs, intraplatoon cooperative collision-avoidance (CCA) techniques have significantly evolved recently. With CCA systems, the number of car accidents and the associated damage can be significantly reduced. The prime reason for deploying CCA systems in VANETs is the substantially long reaction time (i.e., 0.75–1.5 s [2]) of any human driver to apply the brake following an emergency scenario. The potential damage inflicted by such a long reaction time of an individual driver is, indeed, remarkably high in case of a close formation of vehicles, which travel at high speeds. Instead of having drivers to traditionally react to the brake lights of vehicles immediately ahead, CCA systems enable vehicles to promptly react in emergency situations via a fast dissemination of warning messages to the vehicles in the platoon. However, the effectiveness of a given CCA system depends not only on the reliability of the circulated warning messages but on the specific nature of the emergency situation at hand as well. To this end, the underlying medium-access control (MAC) protocols of the concerned VANET need to make sure that the medium-access delay associated with each vehicle, under an emergency event, remains as short as possible. Driven by this need, we envision an effective CCA scheme, which takes into account a risk-aware MAC protocol, which we have specifically tailored for VANET environments. Furthermore, we envision clusters of vehicles based on their movement traits, including directional headings and relative velocities, and on the intervehicular distances as well. In a given cluster, each vehicle is assigned an emergency level, which reflects the risk associated with that particular vehicle to fall into an accidental hazard, e.g., collision with the other cars in the platoon. This cluster-based approach also permits us to set the medium-access delay of an individual vehicle as a function of its emergency level. By so doing, the envisioned strategy attempts to provide the drivers of the vehicles with warning messages pertaining to the emergency scenario with

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[1] An abridged version of this work has appeared in [1].

the shortest delivery latencies possible. This feature should prevent chain collisions or reduce the associated damage. Our adopted strategy is referred to as the cluster-based risk-aware CCA (C-RACCA) scheme due to its twofold contributions, namely, the formation of clusters and the adoption of the risk-conscious medium-access protocol.

The remainder of this paper is organized as follows. Relevant research on MAC protocols in VANET environments is presented in Section II. The operations of the envisioned C-RACCA system comprising its clustering mechanism and the risk-aware MAC protocol are delineated in detail in Section III. The performance of the C-RACCA system is evaluated in Section IV, which justifies the simulation setup and provides an in-depth analysis of the simulation results. Concluding remarks follow in Section V.

II. Related Work

VANETs are well characterized for their rapidly and dynamically changing topologies due to the fast motion of vehicles. Unlike traditional mobile ad hoc networks (MANETs), the nodes' mobility in VANETs is constrained by predefined roads and restricted speed limits. Additionally, nodes in VANETs can be equipped with devices with potentially longer transmission ranges, rechargeable source of energy, and extensive on-board storage capacities. Processing power and storage efficiency are, thus, not the issue in VANETs that they are in MANETs.

The work by Little and Agarwal [3] serves as an inspiring one for utilizing clusters of vehicles in VANETs without the use of fixed infrastructures (e.g., access points, satellites, and so forth). The hypothesis of this work states that the vehicles, which travel along the same directed pathway, can form interconnected blocks of vehicles. Thus, the notion of cluster of vehicles is adopted whereby a header and a trailer identify a particular cluster that is on the move. Little and Agarwal used multihop routing in these blocks or clusters of vehicles to obtain an optimum propagation rate to disseminate information pertaining to traffic and road conditions. For this purpose, they characterized the bounds of information propagation under different traffic patterns. In addition, by combining delay-tolerant networking and MANET techniques, they also implemented the safety information dissemination algorithm as a routing protocol.

To inform all the vehicles in a risk area (along a highway) regarding an emergency scenario (e.g., an accident or an impediment on the road) via alarm broadcasts, a novel communications technique called the intervehicles geocast (IVG) protocol was proposed [4]. IVG considers a vehicle to be in the risk area if the accident/obstacle is in front of that vehicle. Based on the temporal and dynamic attributes of the locations, speeds (i.e., highway), and driving directions of the vehicles in the risk zone, IVG defines multicast groups of these vehicles. Since IVG does not maintain neighboring cars' list at each vehicle, the overall signaling overhead is reduced, which saves precious bandwidth to disseminate the actual warning messages according to a defer time algorithm. In addition, relays are deployed dynamically in a distributed manner (in each driving direction) that rebroadcasts the warning messages to ensure their delivery to the vehicles in the risk area.

The broadcast storm problem, in which there is a high level of contention and collisions at the MAC level due to an excessive number of broadcast packets, is presented in the VANET context in [5]. The serious nature of the broadcast storm problem is illustrated in a case study of four-lane highway scenario. This work proposes three lightweight broadcast techniques to mitigate the broadcast storms by reducing redundant broadcasts and packet loss ratio on a well-connected vehicular network. This work, however, does not consider addressing the broadcast storm issue at the MAC layer (i.e., the real source of the problem), which may be able to mitigate the problem more effectively.

To prevent accidents that may occur due to late detection of distant/roadway obstacles, Gallagher *et al.* [6] emphasized the need for longer range vehicular safety systems that are capable of real-time emergency detection. To this end, they investigated the applicability of DSRC resources to improve the efficiency and reliability of vehicle safety communications. This work specifically partitions crucial safety messages and the nonsafety ones. The former is termed as "safety-of-life" messages, which are assigned the highest priority and transmitted on a dedicated safety channel. The underlying MAC and physical (PHY) layers, guided by the higher layers, enable the awareness and separation of safety and nonsafety messages.

In the survey conducted by Hartenstein and Laberteaux [7], the parameters that may influence the probability of packet reception in VANETs have been pointed out, including vehicular traffic density, radio channel conditions, transmission power, transmission rate, contention window sizes, and the prioritization of packets. This work also mentions that for packets prioritization in particular, the enhanced distributed channel access (EDCA), which is also part of 802.11-2007 specifications, can be used. Four distinct access categories, each with its own channel access queue, are provided in this scheme, whereby the interframe space and the contention window size can be tailored to the specific needs of the target VANET. Indeed, Torrent-Moreno [8] demonstrates that, in contrast with the simple carrier sense multiple access (CSMA) scheme, the channel access time and probability of packets reception improve to an extent under EDCA scheme, even in the case of a saturated channel.

Sichitiu and Kihl [9] survey IVC systems and focus on public safety applications toward avoiding accidents and loss of lives of the passengers. Their study points out that safety applications are inherently delay sensitive, e.g., vehicular warning systems to avoid side crashes of cars and trains at crossroads, deploying safety equipments such as inflating air bags and tightening seat belts, and so forth. The system penetration of such applications is, however, subject to determining the zone of relevance as accurately as possible. For instance, when an accident in the right lane of a highway occurs, it is considered in the covered studies to only affect vehicles approaching the accident from behind. The survey also describes the available communication technologies, focusing on their PHY and MAC layers, that may facilitate vehicular communications to disseminate emergency messages. The studied protocols that are considered to be suited for intervehicle emergency communications systems include IEEE 802.11 and its DSRC standard, Bluetooth (standardized within IEEE 802.15.1), and cellular models such as the global system for mobile communications/general packet radio service and third-generation (3G) systems like the universal mobile telecommunications system (UMTS), the UMTS terrestrial radio access network, and so on.

Toor *et al.* [10] suggest that three difficulties arise in the PHY/MAC layer in VANETs. The first problem involves sharing the radio medium to effect robust transmission among the vehicles. The second problem consists of traffic jams or postaccidental scenarios whereby the target VANET exhibits a rather high density of vehicular nodes. The third and most significant problem identified in this work is the support of adequate emergency applications to guarantee quality of service (QoS) in wireless environments. The study elucidates that there exist two main approaches for sharing the medium that may be used for vehicular communications, namely 1) the CSMA-like random scheme and 2) the time-division multiple-access (TDMA)-like controlled scheme. A prime example of the former approach is IEEE 802.11, which is stated to be the most dominant MAC protocol for developing safety applications for vehicular networks. As examples of the latter, the study refers to a number of other technologies derived from 3G telecommunications systems based upon variations of the pure ALOHA protocol [11] such as the slotted ALOHA [12] and reliable reservation ALOHA (RR-ALOHA) [13] access schemes. Recent works such as [14] have also considered QoS issues in VANETs.

As stated earlier, a class of unique applications has been devised for VANETs. For each application, different techniques have been proposed. From the observation that routing protocols originally designed for MANET networks may be suitable only for delay-tolerant content-delivery applications (e.g., in-vehicle Internet) [15], the work in [17] proposed a set of context-aware broadcast-oriented forwarding protocols for delay-sensitive safety applications in VANETs (e.g., CCA systems). The packet-forwarding operation can be selective and based on the geographical locations and the moving directions of the source and the destination vehicles and the packet's information content. Furthermore, mobility-oriented schemes such as "Mobility-centric approach for Data Dissemination in Vehicular networks" (MDDV) [23], which attempts to address the data delivery problem in a partitioned and highly mobile VANET topology, integrates the following three data-forwarding techniques: 1) the opportunistic-based scheme; 2) the trajectory-based scheme; and 3) the geographical forwarding scheme. The former refers to the fact that vehicle movements create the opportunity to pass messages and determine which vehicle to transmit/buffer/drop a message and when. The trajectory forwarding implies that the information is being propagated from the source to the destination. The geographical forwarding, on the other hand, means that the message is conveyed geographically closer to the destination along the source-to-destination trajectory. Localized algorithms specifically designed for vehicles are developed to exploit these data-forwarding schemes. By allowing multiple vehicles to actively propagate a given message, MDDV improves message-delivery reliability. While the aforementioned packet-forwarding protocols can reduce the number of signaling messages in a VANET, ensuring prompt delivery of critical warning messages is also crucial for CCA systems. For this purpose, there is a need to develop adequate MAC protocols.

Many of the MAC protocols that have evolved over the years are, however, not applicable to VANET environments. Among the contemporary MAC protocols, the IEEE 802.11 MAC specification is considered to be the leading choice among VANET designers as a means to provide safety applications [25]. The MAC protocol of IEEE 802.11 consists of a number of sophisticated mechanisms that rely on soft handshaking involving a number of signaling messages (e.g., request-to-send and clear-to-send messages) exchanged between the sender and the receiver. These mechanisms include the following: 1) CSMA with collision avoidance (CSMA/CA); 2) multiple access with collision avoidance (MACA); and 3) MACA for wireless with distributed coordinated function mode. More tailored MAC protocols for VANET environments are also evolving, as shown in the study conducted by Adachi *et al.* [16]. In addition, the following two techniques have evolved into safety-critical application domains such as CCA: 1) data prioritization [17], [26] and 2) vehicle prioritization. We focus on the latter in this paper whereby the emergency level associated with each vehicle in the considered VANET is taken into account to prioritize the vehicle. Intuitively, vehicles with high emergency levels should be always granted prompt access to the medium.

Provisioning security for protecting the vehicular positions in a VANET is also emerging as an active area of research. For example, Yan *et al.* [28] presented a novel approach that employs an on-board radar at each vehicle to detect neighboring vehicles and to confirm their announced coordinates. This notion of local security (i.e., specific to individual vehicles) is extended to achieve global security by using the following two techniques: 1) a preset position-based groups to form a communication network and 2) a dynamic challenging scheme to confirm the coordinate information sent by remote vehicles. Although the scope of our work in this paper does not cover these security aspects, we feel the importance to incorporate such safeguards to securely disseminate safety information/warning messages in VANETs in the future.

III. Cluster-Based Risk-Aware Cooperative Collision-Avoidance System

In this section, we initially provide a brief overview of the functionality of the traditional CCA system proposed by Biswas *et al.* [17] and point out its shortcomings. We then propose our C-RACCA system, which consists of adequate solutions to address these issues, namely, a dynamic clustering procedure to formulate clusters of vehicles, followed by a uniquely designed risk-aware MAC protocol.

A. Shortcomings of the Traditional CCA Systems

In traditional CCA systems [17], upon an emergency situation, a vehicle in the considered platoon dispatches warning messages to all other vehicles behind it. A recipient takes into account the direction of the warning message arrival with respect to its directional bearing and decides whether to pass the message to other vehicles or not. Indeed, the message will be ignored if it comes from behind. To ensure a platoon-wide coverage, the message is transmitted over multiple hops. However, this approach leads to the following two problems: 1) generation of a large number of messages, which literally flood the VANET, and 2) generation of redundant messages (originated from different vehicles) pertaining to the same emergency event. Consequently, message collisions are more likely to occur in the access medium with the increasing number of vehicles in the platoon. In addition, this naive approach of relaying the emergency message contributes to cumulative communication latencies, which, in turn, lead to a substantially high delay in delivering the warning message from the platoon front to the vehicles located at the rear of the platoon formation. To make matters even worse, in the case of multiple failed message retransmissions owing to excessive MAC collisions, this message-delivery latency increases further. To overcome these shortcomings of the existing CCA systems, we offer a novel approach that dynamically forms clusters of the vehicles in a platoon.

B. Dynamic Clustering of Vehicles

Prior to a detailed description of the envisioned clustering mechanism, it is essential to point out a number of assumptions regarding the considered VANET environment, as listed in the following.

1) To accurately estimate the current geographical location, each vehicle in the platoon consists of global positioning systems (GPSs) or similar tracking modules. It should be noted that the knowledge pertaining to the real-time coordinates of the vehicular nodes is an assumption made by most protocols and applications. Indeed, this is a reasonable enough assumption pointed out by Boukerche *et al.* [18] because the GPS receivers can easily be deployed on vehicles. However, as VANETs are evolving into more critical areas and becoming more reliant on localization systems, there may be certain undesired problems in the availability of GPS in certain scenarios (e.g., when the vehicles enter zones where GPS signals may not be detected, such as inside tunnels, underground parking, and so forth). Indeed, there exist several localization techniques, such as dead reckoning [19], cellular localization [21], and image/video localization [22], that may be used in VANETs so that this GPS limitation may be overcome. In addition, GEOCAST [20], which is one of our earlier developed protocols, may be used so that it is still possible to support some vehicles, which have lost GPS signals, or do not have GPS on board, to learn from the other vehicles and position themselves.
2) To facilitate communications, two distinct wireless channels are considered to exchange signaling messages to formulate vehicles' clusters and to issue/forward warning messages, respectively.
3) Each vehicle is assumed to be capable of estimating its relative velocity with respect to neighboring vehicles. In addition, it is also considered to be able to compute, via adequately deployed sensors, intervehicular distances.
4) When a vehicle receives a warning message, it can estimate the direction of the message arrival, i.e., whether the received warning originated from a vehicle from the front or the rear.
5) Each vehicle is considered to have knowledge on its maximum wireless transmission range, which is denoted by T_r. A vehicle constantly uses this parameter to update its current transmission range R in the following manner:

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

where ϵ refers to the wireless channel fading conditions at the current position. Equation (1) is used for simple estimation of the practically possible transmission range from the given surrounding conditions that affect the maximum transmission range of the vehicle. To compute this, a simple parameter ϵ is used, which reflects the surrounding conditions. If the vehicle is currently moving in the downtown, then its transmission range will be lower than the maximum possible one. Because, there will be many obstacles (e.g., high-rise buildings, industries, and other installations), which will interfere with the vehicle's wireless signal. To reflect this situation, ϵ in (1) is set to a high value in a downtown scenario. On the other hand, when a car is moving in the suburbs, there are fewer obstacles affecting the vehicle's transmitted signals. Therefore, in such a scenario, low values of ϵ are used to illustrate that the vehicle may use a transmission range that is closer to the maximum possible one. GPS or other positioning systems (e.g., Galileo) are used to obtain the terrain information so that the appropriate values of ϵ in a given location can be appropriately estimated.

Additionally, we consider, for clustering purposes, a platoon of vehicles, which travel along the same road toward the same direction. Consistent with previous work in this domain [15], the envisioned grouping of vehicles is, thus, based upon their movement directions. Directional-antenna-based MAC protocols [27] may be utilized to group the vehicles more accurately, whereby the transmission range of vehicles is split into M transmission angles of equal degrees $(360/M)$. By assigning each transmission angle to a unique vehicle group, M groups can thus be formulated.

Similar in spirit with the assumptions in [15] and [27], our approach considers, in forming a cluster, only the vehicles that belong to the same group in terms of moving on the same road toward the same direction. Fig. 1 portrays an example of three such clusters. As depicted in this figure, a vehicle may act as a special node, i.e., as a cluster head (CH) or a subcluster head (SCH), or may merely drive as an ordinary vehicle (OV). In case of forming a CH, the vehicles are voluntarily required to consistently advertise for the cluster while maintaining and updating their respective cluster tables. On the other hand, the first SCH node is selected as the last vehicle that is reachable by the CH. Indeed, the SCH node may be used to define a subsequent SCH entity (i.e., the last vehicle reachable from this SCH node), and so forth. SCH nodes are in charge of relaying packets (e.g., emergency warning messages) from either a CH or from SCHs in front to other vehicles within the same cluster that lie outside

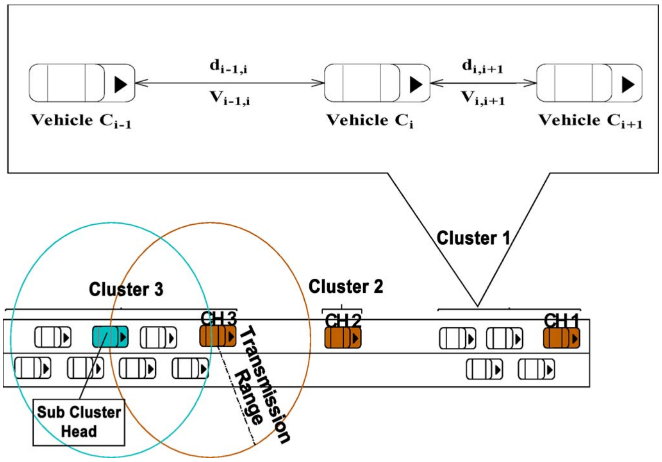

Fig. 1. Example of three clusters.

the CH's (or the front SCH's) transmission range. In addition, a SCH also aggregates information from OVs within its reach and relays them to the CHs/SCHs in front. It should be noted that it is a rare case to have a cluster containing a large number of SCHs. In such case, the cluster size will be significantly large, and vehicles will be more likely moving at very low speeds. Thus, chain collisions will not happen in such case. Finally, OVs comprise the ordinary members in the cluster that perform no specific task.

As demonstrated in the example in Fig. 1, C_i refers to the identification (ID) of vehicle i. For simplicity, we denote C_{i-1} and C_{i+1} as the vehicles ahead of and immediately behind C_i, respectively. The transmission range of the former (provided that it exists) reaches C_i. On the other hand, the latter is reachable by C_i. The distance between a pair of vehicles C_j and C_k is denoted by $d_{j,k}$. V_j and $V_{j,k}$ refer to vehicle C_j's actual velocity and the relative velocity with respect to vehicle C_k, respectively. Therefore, the magnitude of $V_{j,k}$ is assumed to be the same as that of $V_{k,j}$. Additional notations, which are used in the clustering operation, are listed as follows:

1) τ_j^a: time required for a vehicle C_j to reach vehicle C_{j-1} immediately ahead of it (i.e., $\tau_j^a = d_{j-1,j}/V_{j-1,j}$);
2) τ_j^b: time required for a vehicle C_j to be reached by vehicle C_{j+1} right behind it (i.e., $\tau_j^b = d_{j,j+1}/V_{j,j+1}$);
3) ϕ_j: set of CHs or SCHs in front of vehicle C_j; this set also belongs to C_j's group;
4) ϕ_j^{CH}: the closest CH or SCH ($\in \phi_j$) in front of vehicle C_j;
5) ψ_j: set of CHs or SCHs behind vehicle C_j; this set also belongs to C_j's group;
6) ψ_j^{CH}: the closest CH or SCH ($\in \psi_j$) behind vehicle C_j;
7) a_e and a_r: emergency deceleration and regular deceleration, respectively, which indicate the occurrence of an emergency event to trigger the transmission of critical warning messages;
8) δ: the average reaction time of individual drivers ($0.75 \leq \delta \leq 1.5$ s).

For each vehicle C_i and its immediately following vehicle C_{i+1}, we consider that no collision will occur between these two vehicles, and therefore, they are safe, provided that their distance $d_{i,i+1}$ satisfies the following condition for $\Gamma_{i,i+1}$ (i.e., $\overline{\Gamma_{i,i+1}}$ denotes the negation of the condition):

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

where α represents a tolerance factor. In addition, $d_{\max}$ denotes a safety distance in which if two vehicles are distant, no collision will occur between the two vehicles, regardless of the vehicles' velocities (e.g., in case of a maximum velocity $V_{\max} = 180$ km/h, $d_{\max} = V_{\max} \cdot 1.5$ s $= 75$ m). It should be noted that the direction of the vehicles is not included in (2) since we consider the vehicles to be traveling along the same direction in the same lane.

Using the above notations, for any vehicle C_i, we have the following lemma:

$$\exists\, C_{i-1} \Leftrightarrow \phi_i \neq \emptyset \tag{3}$$

$$\exists\, C_{i+1} \Leftrightarrow \psi_i \neq \emptyset. \tag{4}$$

The proof of the lemma is trivial.

Three specific scenarios pertaining to a vehicle may exist in the envisioned clustering operation. A vehicle may be in one of the following three states.

1) It starts its engine and gets on a road.
2) It decides to travel in a different direction. Consequently, it leaves its old group G_o and joins a new group of vehicles, which is denoted by G_n.
3) It continues to travel on the same road without changing its direction. However, it increases or decreases its traveling speed.

In the remainder of this subsection, we describe the clustering mechanism in detail by focusing on each of the above scenarios.

1) Joining a Group for the First Time: A vehicle C_i, after it gets on a road, initially broadcasts a CH solicitation message to the neighboring vehicles, which are assumed to belong to group G_n. The CH solicitation message queries the other vehicles regarding the CH of G_n. Meanwhile, C_i also initiates a timer θ. The following two cases exist: 1) C_i receives no response, or 2) C_i receives at least one affirmative response to its initial query prior to expiration of θ. In the former case, where ($\phi_i = \psi_i = \emptyset$), C_i decides to assume the role of CH in G_n and starts constructing its own cluster. In the latter case, C_i needs to take into consideration the responses from other CH(s). At first, C_i verifies if any CH ahead of it has also transmitted a CH advertisement message. Otherwise, if ($\phi_i = \emptyset$), from the fact that $\psi_i \neq \emptyset$, C_i checks whether it maintains long enough distance ($d_{i,i+1}$) with C_{i+1}, which immediately follows it from behind. This verification is required to ascertain the safety condition ($\Gamma_{i,i+1}$) described earlier. If ($\Gamma_{i,i+1}$) holds, C_i constructs its own cluster and declares itself as the CH of this newly formed cluster. Otherwise (i.e., if $\overline{\Gamma_{i,i+1}}$), C_i takes over, from ψ_i^{CH}, the CH behind it by designating itself as the new CH (i.e., $C_i = \phi_{i+1}^{CH}$).

On the other hand, if C_i obtains a CH advertisement message from at least one CH ahead of it (i.e., $\phi_i \neq \emptyset$), it verifies whether

TABLE I
ALL POSSIBLE CASES FOR A VEHICLE C_i JOINING FOR THE FIRST TIME A GIVEN GROUP

<table>
<tr><td colspan="3">$\phi_i = \emptyset$</td><td colspan="4">$\phi_i \neq \emptyset$</td></tr>
<tr><td>$\psi_i = \emptyset$</td><td colspan="2">$\psi_i \neq \emptyset$</td><td colspan="3">$\Gamma_{i,i-1}$</td><td>$\overline{\Gamma_{i,i-1}}$</td></tr>
<tr><td rowspan="3">Form own cluster</td><td>$\Gamma_{i,i+1}$</td><td>$\overline{\Gamma_{i,i+1}}$</td><td>$\psi_i = \emptyset$</td><td colspan="2">$\psi_i \neq \emptyset$</td><td rowspan="3">Join ϕ_i^{CH}</td></tr>
<tr><td rowspan="2">Form own cluster</td><td rowspan="2">Take authority of ψ_i^{CH}</td><td rowspan="2">Form own cluster</td><td>$\Gamma_{i,i+1}$</td><td>$\overline{\Gamma_{i,i+1}}$</td></tr>
<tr><td>Form own cluster</td><td>Take authority of ψ_i^{CH}</td></tr>
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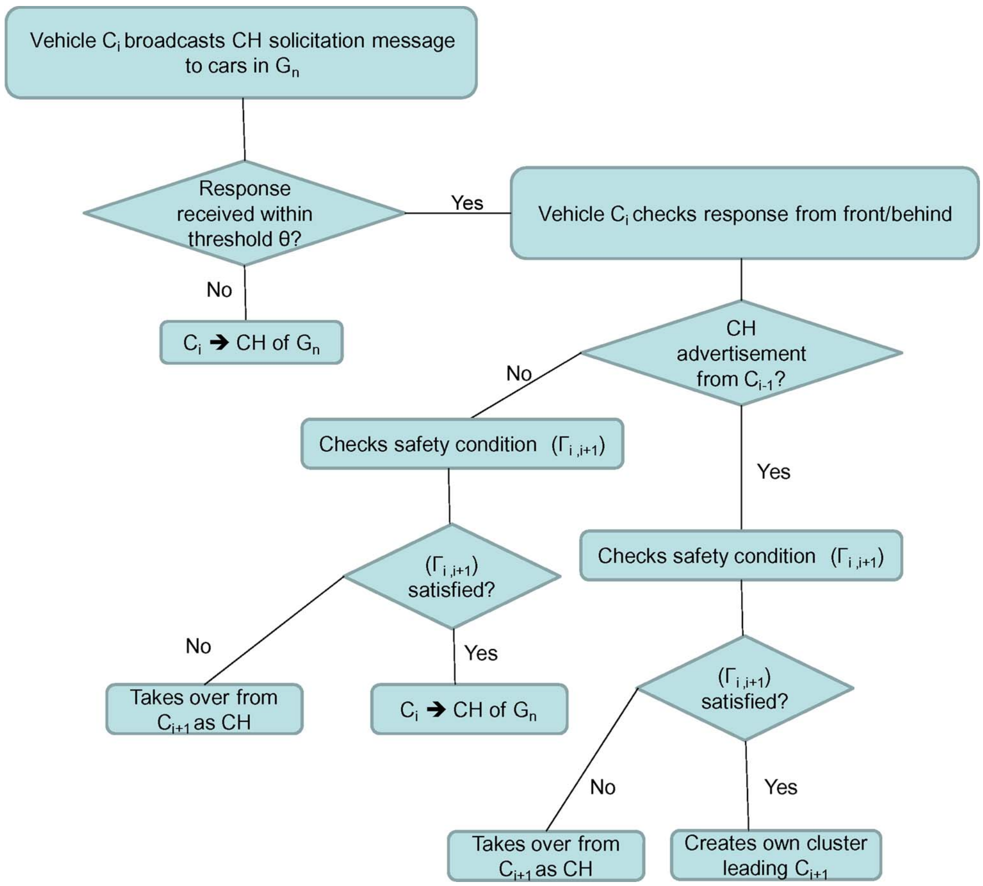

Fig. 2. Steps required for a vehicle to join a group for the first time.

the distance to the vehicle immediately ahead of it (C_{i-1}) and belonging to the cluster CH is sufficiently large to avoid collision with C_{i-1}. C_i constructs its own cluster by designating itself as the CH, provided that 1) the condition $\Gamma_{i,i-1}$ holds and 2) that no vehicle follows it from behind $(\psi_i = \emptyset)$. 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 $(\phi_i = \emptyset, \psi_i \neq \emptyset)$. On the other hand, if the condition $\overline{\Gamma_{i,i-1}}$ persists, C_i is required to join the cluster formed by ϕ_i^{CH}. Table I summarizes all the aforementioned cases. The whole process of joining a group for the first time is illustrated in Fig. 2.

A vehicle C_i, which desires to join a given cluster, issues a self notification (SN) message that contains the vehicle's ID, current location, and transmission range to the concerned CH. Upon receiving the SN, the CH treats it as a solicitation request from C_i to join the cluster. The CH then adds C_i into its cluster table and informs the rest of the cluster members via an updated cluster advertisement (CA) message, which contains the IDs of all the involved entities including the cluster, the CH, the SCH(s), and the OVs. In the case that a new vehicle emerges as a new CH in the considered cluster, the previous CH needs to transfer the most recently updated cluster table to the new CH, which, in turn, broadcasts an updated CA packet to the cluster members to inform them regarding the changes.

2) Departure From a Group and Joining a New One: As mentioned earlier, the second scenario consists of a moving vehicle C_i that changes its direction, which results in its departure from its old group G_o to a new group G_n. C_i, at first, informs G_n about the departure event. Upon joining G_n, C_i either forms its own cluster or joins a preexisting one following the previously described steps in Section III-A1. AQ1

The departure of C_i from G_o may yield three distinct cases, namely, whether C_i was the CH, a SCH, or merely an OV in G_o. These three cases are depicted in Fig. 3 and are delineated as follows.

1) *If C_i is an OV in G_o:* In this case, departure operation of C_i from G_o is trivial since it only requires notifying either the CH (denoted by CH_{G_o}) directly or the corresponding

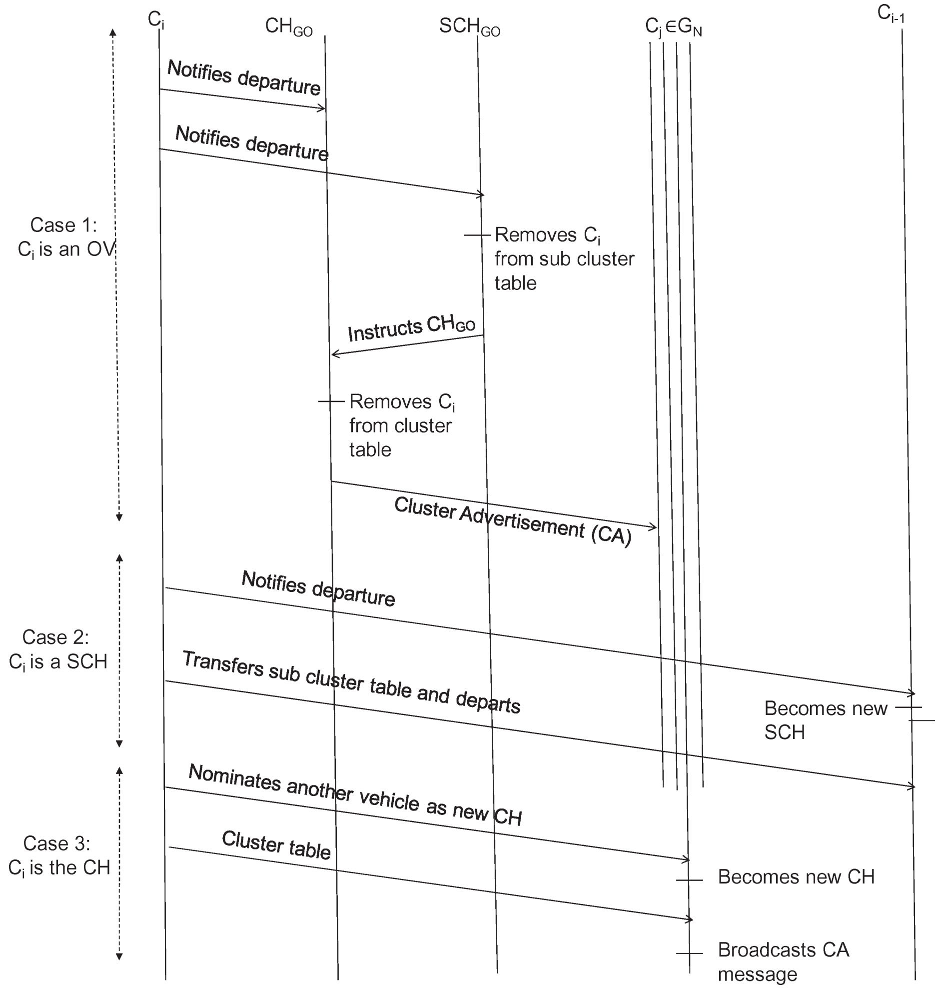

Fig. 3. Timeline diagram illustrating the departure event of a vehicle from a group.

SCH (i.e., SCH_{G_o}) similarly. In latter case, SCH_{G_o} first removes C_i from its subcluster table and instructs CH_{G_o} about the event that prompts CH_{G_o}, in its own turn, to delete C_i's entry from its cluster table. Finally, CH_{G_o} issues an updated CA message to inform the rest of the members that C_i is no longer with G_o.

2) *If C_i is a SCH in G_o:* C_i, in this scenario, will assign C_{i-1} in G_o to assume the responsibility of the new SCH. In addition, C_i also transfers the subcluster table to C_{i-1} before departing G_o.

3) *If C_i is a CH in G_o:* This scenario requires C_i to assign the role of the new CH to another cluster member, which it deems most appropriate. In addition, C_i also transfers the cluster table to the new CH prior to its departure from G_o. The new CH notifies the rest of the cluster members regarding the change via an updated CA message.

Fig. 4 depicts a scenario whereby a vehicle A, with a transmission range T_A and speeding at a velocity V_A, turns onto a new street inclined by an angle α, while vehicle C, which is immediately ahead of it, and vehicle B, which is immediately behind it, continue moving straight along the same road at velocities V_C and V_B, respectively. Fig. 5 demonstrates the results obtained from numerical analysis that there is largely sufficient time for vehicle A to communicate with both vehicles C and B in the case of the following two different scenarios: 1) a highway scenario where vehicles B and C speed at 120 km/h, and vehicle A reduces its speed to 60 km/h upon turning onto the new road and 2) an urban scenario where vehicles B and C move at 60 km/h, and vehicle A turns at a speed equal to 30 km/h. The transmission range of vehicle A is set to 300 and 150 m in the highway and urban scenarios, respectively. Fig. 6 (derived from analytical computations) shows the time required to join a cluster in an urban and a highway scenario for different transmission ranges of vehicles. The figure clearly indicates that the time required for a vehicle to join a cluster is short in both scenarios and can be easily accommodated by the connectivity time shown in Fig. 5.

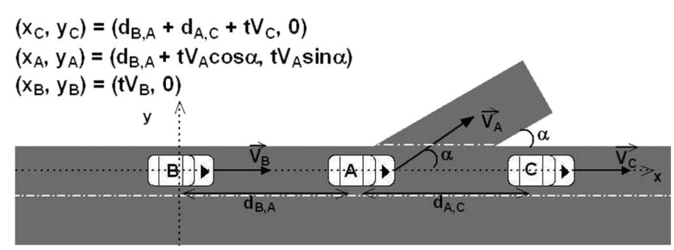

Fig. 4. Scenario showing a vehicle A turning onto a new street inclined by an angle α, while vehicles B and C continue moving straight on the same road.

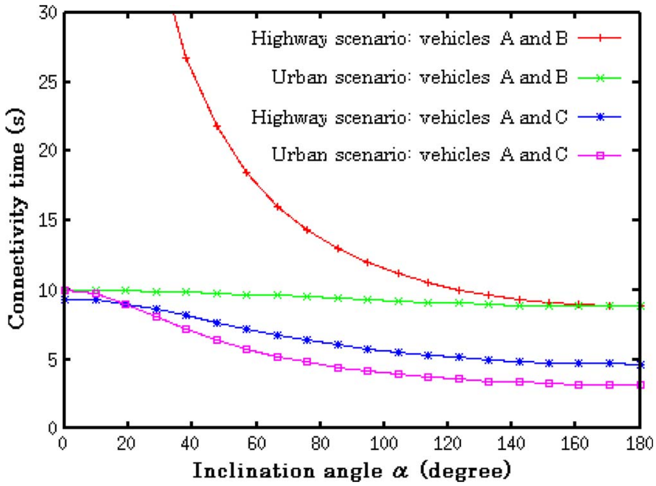

Fig. 5. Connectivity time for a vehicle, turning onto a new street inclined by an angle α, with vehicles right behind it and immediately ahead of it ($d_{\mathrm{B,A}} = d_{\mathrm{A,C}} = 15$ m).

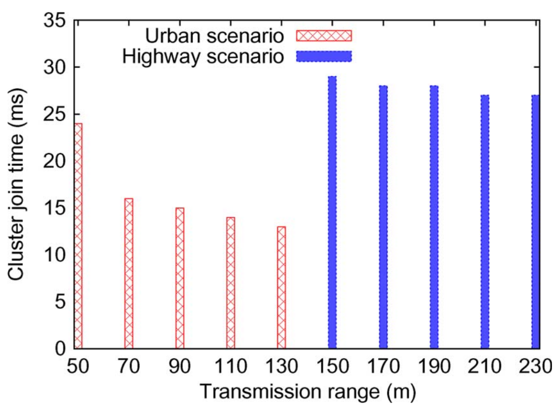

Fig. 6. Time required to join a cluster in an urban and a highway scenario, respectively.

3) Intercluster Interactions Within a Particular Group: In a given group, the envisioned approach permits flexibility in forming and interacting among clusters belonging to the same group. For instance, a cluster may be split into two parts under certain conditions. The reverse may also be possible, whereby two clusters may merge into a single new cluster.

A particular cluster may be divided into two different clusters, provided that each of the two adjacent vehicles, which are denoted by C_i and C_{i+1} (both the vehicles are members of the same cluster) continues to travel at a relative speed $V_{i,i+1}$ until the intervehicular space $d_{i,i+1}$ satisfies the condition $\Gamma_{i,i+1}$. When this condition persists, C_{i+1} becomes the CH in one part of the former clusters containing the vehicles following C_{i+1} from behind. On the other hand, C_i joins another part of the previous cluster (consisting in vehicles C_i and beyond) as an OV.

Two existing clusters may be allowed to merge and evolve as a single one, provided that the distance between the CH of one of the two clusters (denoted by C_l) and the last vehicle C_k in the other cluster becomes so short that the condition $\overline{\Gamma_{k,l}}$ arises and holds. In this new cluster, C_l will handle the cluster table of the former cluster (i.e., to which C_k previously belonged). C_l then broadcasts an updated CA message to all the members to inform them regarding this change.

Conducting the aforementioned dynamic clustering operations, each group of vehicles moving along the same road and in the same direction will be organized into a number of clusters of different sizes and with independent cluster heads (see Fig. 1). The distance between two adjacent clusters is always long enough to avoid collisions between vehicles from both clusters. On the other hand, the intervehicle distance between two adjacent vehicles in a given cluster is always shorter than the "safety distance." Therefore, if a vehicle in a cluster detects an emergency event and applies brakes, collisions among vehicles are likely to happen if drivers do not react promptly. As stated earlier, the exchange of signaling messages for the formation of clusters is performed on a channel different than the one used to transmit warning or emergency messages. MAC collisions due to the transmission of such signals, thus, should not impact the responsiveness of our proposed C-RACCA system.

C. Risk-Aware MAC Protocol

In this section, we describe the envisioned risk-aware MAC protocol. To lay the basis of this work, we consider studying the original MAC protocol in the IEEE 802.11 specifications, owing to its enormous popularity among VANET designers and researchers. For simplicity, the case of a single cluster is considered, whereby the vehicles are indexed based upon their order within the cluster with respect to their movement directions. In other words, without any loss of generality, C_1 refers to the cluster head, C_2 refers to the car immediately behind it, and so forth. In addition, we consider highway platoons for studying the envisaged risk-aware MAC protocol due to the fact that the likelihood of chain vehicle collisions is substantially high in a highway.

The 802.11 standard currently defines a single MAC that interacts with the following three PHY layers: 1) frequency-hopping spread spectrum with a slot time $\xi = 50$ μs; 2) direct sequence spread spectrum with a slot time equal to $\xi = 20$ μs; and 3) infrared with a slot time equal to $\xi = 8$ μs. The general concept behind the MAC protocol in IEEE 802.11 is that when a mobile node desires to transmit, it first listens to the desired channel. If the channel is idle (no active transmitters), the node is allowed to transmit. If the medium is busy, the node will defer its transmission to a later time and then to a further contention period. To resolve contention issues among different stations that are willing to access the same medium, an exponential back-off mechanism is executed in the IEEE 802.11 MAC protocol prior to the calculation of the contention period. This, however, significantly increases the data delivery latency. Consequently, in the case of delay-sensitive safety-critical CCA applications, the effectiveness of the original 802.11 MAC protocol decreases substantially. Indeed, high latency in the dissemination of a warning message will lead to scenarios where some vehicles will not have enough time to react, and vehicle collisions become inevitable. To cope with this shortcoming, we envision that the IEEE 802.11 back-off procedure should be substituted by a more suitable mechanism, which takes into account, in the contention window of a given

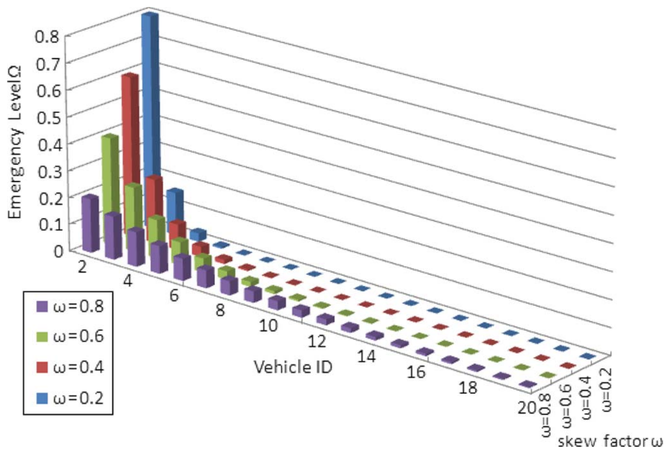

Fig. 7. Emergency level distribution of 20 vehicles for different values of the skew factor.

vehicle, its probability to encounter an emergency scenario. To this end, an emergency level for every vehicle (denoted by C_i without any loss of generality) in a particular cluster is defined according to the distribution in

$$\Omega_i = \frac{(1-\omega)\omega^i}{\omega(1-\omega^S)}, \qquad 1 \le i \le S \tag{5}$$

where S and ω refer to the cluster size and skew factor, respectively. Fig. 7 demonstrates that setting ω to larger values yields a uniform distribution of the emergency level of vehicles, while assigning ω values close to zero results in a highly skewed distribution.

In our envisioned risk-aware MAC protocol, the contention window of a given vehicle C_i is computed based on the following equation (rather than employing the traditional exponential back-off procedure):

$$CW_i = \sum_{j=1}^{k} (1-\Omega_i)^j \cdot cw \cdot \xi \tag{6}$$

where k, ξ, and cw denote the number of transmission attempts, the slot time of the used PHY layer, and the window size, respectively. The reason behind computing the vehicles' contention windows in this manner is to ascertain that the vehicles with high probability of meeting an emergency situation may enjoy short contention windows. Indeed, in case of multiple failures to transmit the warning message ($k \gg 1$), the contention window CW_i will converge to a value equal to ξ/Ω_i. This should ensure smaller latency (after each failed attempt) in the delivery of warning messages for vehicles with high emergency levels Ω_i. Vehicles behind the car that detected the event will then be able to avoid collisions.

Equation (6) ensures the system consistency to some extent while adjusting the contention window of all the vehicles belonging to a given cluster. However, there is a further need to ascertain that the contention window is short enough so that the maximum number of imminent collisions among vehicles may be circumvented. To achieve this, the maximum delay, within which a particular vehicle needs to be informed, is computed. In the following, we consider the example of Fig. 1 and assume that upon an emergency situation, vehicles C_i and C_{i+1} slow down their velocities at rates denoted by a_e and a_r, respectively. The next task is to calculate the maximum latency δ_i since the detection of the emergency event, before which, C_i may be able to notify C_{i+1} (i.e., the vehicle following C_i from behind) of the event to avoid collision.

Vehicle C_i will be moving for a time period $\Delta_i = (V_i/a_e)$ before it eventually stops. The distances traveled by vehicles C_i and C_{i+1} over Δ_i are denoted by l_i and l_{i+1}, respectively. Equation (7) is used to compute l_i, and (8), shown below, is employed to derive l_{i+1} as follows:

$$l_i = \frac{V_i^2}{2 \cdot a_e} \tag{7}$$

$$l_{i+1} = V_{i+1} \cdot \frac{V_i}{a_e} - \frac{a_r}{2}\left(\frac{V_i}{a_e} - \delta_i\right)^2. \tag{8}$$

To avoid collision between C_i and C_{i+1}, the following inequality should be satisfied by taking into consideration l_i and l_{i+1}, i.e.,

$$l_{i+1} > l_i + d_{i+1,i} + L_v \tag{9}$$

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

$$\delta_i^{max} = Max\left(\frac{V_i}{a_e} - \sqrt{\frac{2}{a_r}\cdot\left(\frac{V_i}{a_e}\left(V_{i+1} - \frac{V_i}{2}\right)\right) - d_{i+1,i} - L_v}, 0\right). \tag{10}$$

The collision between C_i and C_{i+1}, however, becomes unavoidable when ($\delta_i^{\max} = 0$), which compels C_i to continue broadcasting warning messages to all vehicles within its transmission range. This provision is required to mitigate further damage inflicted on the platoon by preventing vehicles that are far behind from colliding with one another. Consequently, CW_i (i.e., the contention window for vehicle C_i) is set as follows:

$$CW_i = \begin{cases} \sum_{j=0}^{k}(1-\Omega_i)^j \cdot cw \cdot \xi, & \text{if } \delta_i^{max} = 0 \\ Min\left(\sum_{j=0}^{k}(1-\Omega_i)^j \cdot cw \cdot \xi, \delta_i^{max}\right), & \text{otherwise.} \end{cases} \tag{11}$$

Unless otherwise specified, we set a_e, a_r, and L_v to 8 m/s^2, 4.9 m/s^2, and 4 m, respectively. It should be noted that the values of a_e and a_r can be used by the system as an indication for an emergency event (e.g., a_e for cluster head, a_r or above for other cluster members) to trigger the transmission of warning messages.

On detecting an emergency event, a vehicle issues a warning message to every member of its cluster (including SCHs) that its transmission range currently covers. An SCH entity forwards this message to each of its subcluster members. It should be noted that a vehicle can safely discard messages originating from vehicles following it from the back. Otherwise (i.e., if the warning message arrives from the front), the recipient vehicle, at once, reacts to it based on the event type included in the warning message. If the recipient vehicle encounters redundant warning messages, it takes action based on the first one only and discards the rest of the duplicate copies.

IV. Performance Evaluation

A. Collision Model

Before delving into details of the considered collision model in our simulation, we list a number of important parameters. Let S and L_v denote the size of the considered cluster (where the collisions are simulated) and the average vehicle length, respectively. As mentioned earlier, we are more keen on focusing on highway platoon scenarios, whereby the likelihood of collisions among the cluster members is much higher in contrast with urban scenarios. In our simulated highway platoon environment, we consider the most frequent scenario, whereby the CH (i.e., the vehicle in front of the platoon) identifies an emergency event. When the CH detects an emergency situation at time t_0, it slows down at an emergency deceleration a_e. The rest of the vehicles are considered to slow down at a regular deceleration a_r. For the sake of simplicity and without any loss of generality, we further assume that when a vehicle C_i collides with a vehicle C_{i-1} ahead of it, C_i immediately stops. On the other hand, C_{i-1} keeps on traveling without deceleration. Although this particular assumption does not conform to realistic scenarios, it does not change any of the rudimentary observations made so far on the envisioned C-RACCA framework.

Let Δt_i represent the latency since the detection of the emergency event until vehicle C_i stops or collides with its preceding vehicle C_{i-1}. The velocities of C_i at the time of the event detection and after Δt_i time are denoted by V_i^o and V_i^s, respectively. The delay incurred in delivering the warning message to C_i is referred to as δ_i. It is worth noting that all vehicles in the cluster (or subcluster) ought to experience similar δ_i, provided that the broadcast of warning messages by the CH/SCHs and their deliveries at the recipients are successful. As previously evaluated in (7), l_i defines the distance traveled by C_i since the event detection time until the vehicle completely stops or collides with C_{i-1}. The following equations pertain to the CH, i.e., C_1:

$$\Delta t_1 = \frac{V_1^o}{a_e} \tag{12}$$

$$l_1 = V_1^o \Delta t_1 - \frac{1}{2} a_e \cdot \Delta t_1^2 \tag{13}$$

$$V_1^s = 0. \tag{14}$$

For other vehicles, except for the considered CH (i.e., C_i, $1 < i \leq S$), the conditions for two adjacent vehicles C_i and C_{i-1} not to collide can be obtained in terms of the following equations:

$$\Delta t_i = \frac{V_i^o}{a_r} + \delta_i \tag{15}$$

$$l_i = V_i^o \Delta t_i - \frac{1}{2} a_r \cdot (\Delta t_i - \delta_i)^2 \tag{16}$$

$$V_i^s = 0. \tag{17}$$

TABLE II
Simulation Parameters

Factor	Range of values
Propagation model	TwoRayGround
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	0.8
Average vehicle length, L_v	4 m
Slot time, ξ	50 μs
Tolerance factor, α	3

On the other hand, in the case that C_i and C_{i-1} collide, the following two distinct cases may be envisaged.

Case 1) C_i collides while C_{i-1} is still moving.

Case 2) C_{i-1} stops, and then, C_i hits C_{i-1}.

The following inequality should hold in case 2):

$$l_{i-1} + d_{i,i-1} + L_v \leq l_i. \tag{18}$$

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

$$\Delta t_i = \Delta t_{i-1} \tag{19}$$

$$l_i = l_{i-1} + d_{i,i-1} + L_v \tag{20}$$

$$V_i^s = V_i^o - a_r \cdot (\Delta t_{i-1} - \delta_i). \tag{21}$$

For case 1, a time instant t_m should exist when

$$\exists\, t_m \quad V_i^o(t_m - t_0) - \frac{1}{2} a_r \cdot (t_m - t_0 - \delta_i)^2 = V_{i-1}^o(t_m - t_0) - \frac{1}{2}\eta \cdot (t_m - t_0 - \delta_{i-1})^2 + L_v \tag{22}$$

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

$$\Delta t_i = t_m - t_0 \tag{23}$$

$$l_i = V_i^o(t_m - t_0) - \frac{1}{2} a_e \cdot (t_m - t_0 - \delta_i)^2 \tag{24}$$

$$V_i^s = V_i^o - a_r \cdot (t_m - t_0 - \delta_i). \tag{25}$$

B. Simulation Results

The simulations are conducted using the network simulator (NS-2) [29] based on the collision model delineated in Section IV-A. The simulation parameters are listed in Table II. The transmission ranges of the vehicles and the minimum intervehicular distance are set to 150 and 10 m, respectively. The reason behind these choices is to have at least one SCH in a simulated cluster. As comparison terms, we adopt 1) a CCA system, which is based upon the IEEE MAC protocol that uses the exponential back-off algorithm for calculating contention windows of the vehicles [17] and 2) the absence of a CCA system, whereby the traditional reaction of drivers is considered to be the key factor in avoiding collisions.

We simulate two scenarios. In the first scenario, all vehicles move at a steady speed, and the intervehicle distance is chosen

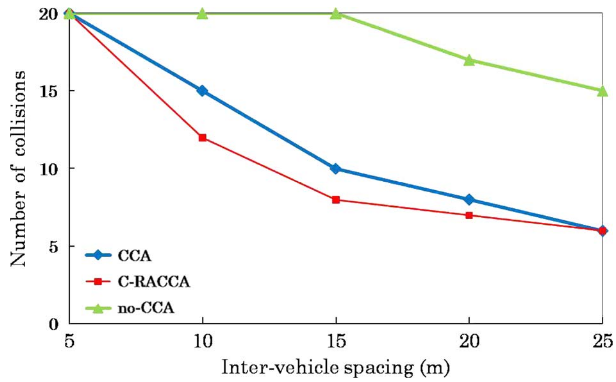

Fig. 8. Number of collided vehicles for different intervehicle distances (scenario 1, vehicle speed = 32 m/s).

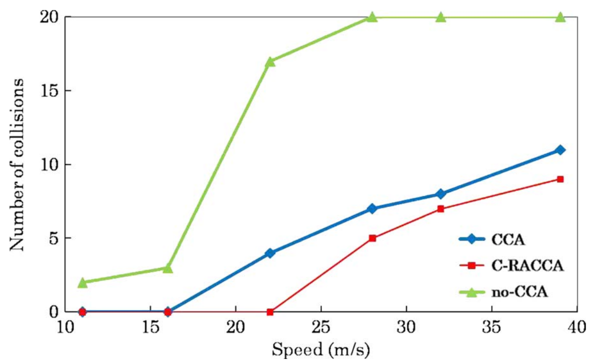

Fig. 9. Number of collided vehicles for different velocities of the cluster head (scenario 2).

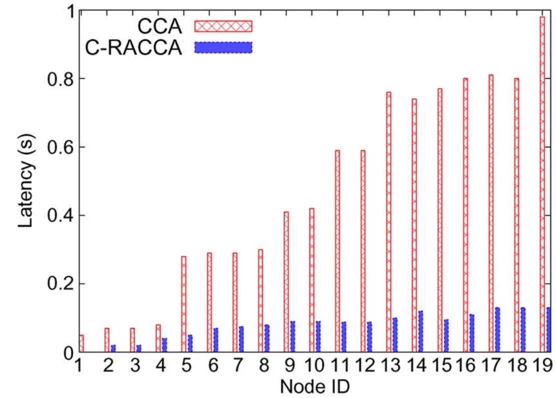

Fig. 10. Warning message delivery latency δ_i for each vehicle C_i (scenario 1, intervehicle distance = 15 m, vehicle speed = 32 m/s).

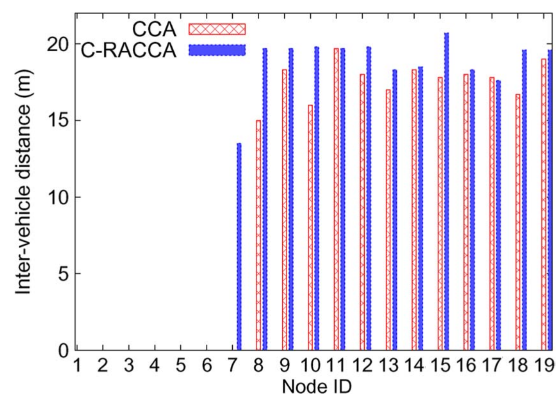

Fig. 11. Relative intervehicle distance $d_{i,i-1}$ after stop (scenario 1, intervehicle distance = 15 m, vehicle speed = 32 m/s).

from within the interval [10 m, 30 m]. On the other hand, in the second scenario, the intervehicle distance is arbitrarily selected from within the range [10 m, 30 m] for each pair of collocated vehicles. Each vehicle travels at varying speeds. The CH, which travels at the front of the cluster, moves at a speed that is selected from an interval [22 m/s, 42 m/s]. The velocities of the rest of the cars are carefully chosen not to cause collisions among them. An emergency situation is simulated by having the CH collide with a fixed object that compels the CH to slow down rapidly. Consequently, a number of warning messages are broadcast. The simulation results that we provide here are an average of multiple simulation runs.

The number of collisions for various intervehicle distances in the case of the proposed C-RACCA, CCA, and no-CCA systems are plotted in Fig. 8. It can be deduced from this figure that the number of collisions decreases as the intervehicle distance increases significantly. The results demonstrate that the C-RACCA scheme helps save many vehicles from colliding into others. Fig. 9 exhibits a similar performance in the case of scenario 2. As shown in this figure, the reduced number of vehicle collisions achieved by the C-RACCA approach, even when the CH travels at a reasonably high speed, in contrast with CCA and no-CCA systems, is attributable to its ability to swiftly inform the cluster members regarding the emergency situation. Fig. 10 sheds more light on this issue by indicating the fact that vehicles experience significantly high delays in delivering/receiving the warning messages in case of the traditional CCA system. It is worth stressing that these latencies also include the delay in receiving the first warning message. Indeed, in the proposed system, not all vehicles reforward the warning message. In fact, only the CH and SCHs do so. Fig. 10 also demonstrates that in the case of the CCA system, the ten last vehicles at the rear of the cluster experience a relatively longer time to disseminate the warning messages. The reason behind this is the occurrence of multiple MAC collisions owing to the concurrent delivery of warning messages by the first ten cars. On the contrary, the envisioned C-RACCA system ascertains that only the vehicle which encountered the emergency situation (e.g., the CH in our simulation scenarios) and/or SCHs are in charge of delivering the warning messages. This provision assists C-RACCA in avoiding message collisions. Consequently, a large number of vehicles receive the warning message in a relatively short latency. Indeed, this enables the vehicles to respond to the emergency situation in a swift manner.

The superior performance of the proposed C-RACCA scheme is further evident from Figs. 11 and 12. Fig. 11 exhibits that the relative intervehicle distances (after the vehicles have stopped) are longer in the case of the proposed C-RACCA scheme compared with the other naive approaches. It should be noted that in most cases, a significantly long relative distance between two adjacent vehicles C_i and C_{i+1} suggests that C_{i+1} responded rapidly to the emergency situation to achieve a sufficiently long distance from the vehicle ahead, i.e., C_i. This distance is of high importance in our evaluation due to the

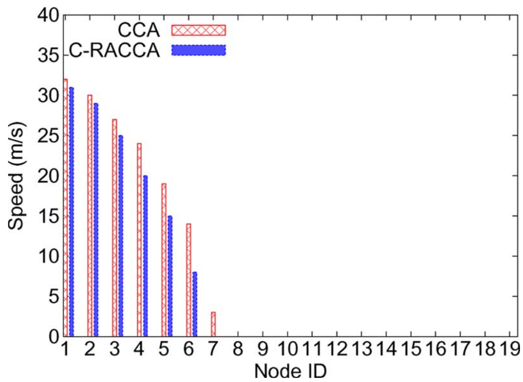

Fig. 12. Relative speed $V_{i,i-1}$ at the time of collision. In the absence of collision, $V_{i,i-1} = 0$ (scenario 1, intervehicle distance = 15 m, vehicle speed = 32 m/s).

fact that C_i may explode at the time of collision (e.g., due to fuel leakage and so forth). Additionally, Fig. 12 demonstrates another important feature of the C-RACCA system in terms of the smaller magnitude of the relative velocity of each vehicle at the time of collision. This mitigates the severity and impact of any collision.

V. Conclusion

In this paper, we have proposed an effective collision-avoidance strategy for vehicular networks that we refer to as the C-RACCA system. As it can be inferred from its name, the C-RACCA forms clusters of vehicles that belong to the same group. A number of features pertaining to the movements of the vehicles are taken into account to construct effective clusters. We envisioned a set of mechanisms to enable vehicles to join or depart from a specific cluster. Indeed, the clustering mechanisms lead to various heterogeneous clusters, i.e., multiple clusters with different sizes, independent cluster heads, and different numbers of subcluster heads.

The other contribution of the C-RACCA system lies in the fact that it enhances existing MAC protocols to ascertain relatively short latencies in disseminating warning messages after an emergency situation is detected. For each vehicle, an emergency level is defined based upon its order in the cluster with respect to the moving direction of the cluster. In the C-RACCA system, the warning message latency is calculated in such a manner that it is inversely proportional to the emergency level of the considered vehicle. This reflects the probability of the vehicle to encounter an emergency event in the cluster. The second rational lies in the fact that the latency estimation takes into consideration the velocities and intervehicle distances of adjacent vehicles and, thereby, manages to avoid colliding with each other.

Various simulations have been conducted in two unique scenarios to verify and compare the performance of the proposed C-RACCA system with those of the naive CCA and no-CCA approaches. The simulation results clearly exhibit the applicability of the C-RACCA approach in VANET environments since it reduces both the number of collisions and the impacts of collisions when they inevitably occur.

Admittedly, our work has considered a distribution with a predetermined skew factor (i.e., ω) to estimate the emergency levels of the vehicles that are used to compute the warning message delivery latency. However, in the future, further investigation regarding any possible correlation between the skew factor and the attributes of a specific cluster (in terms of its average intervehicle distance, average velocity, size, and so forth) is required. The relationship between the transmission ranges of the vehicles in a given cluster and the size of that cluster also needs further investigation. In addition, the impact of channel conditions on the delivery of warning messages and their overall impact on the C-RACCA's performance also deserve further studies. Furthermore, the management of intercluster communications may also open up interesting research scopes. These form some of our future research into this particular area of research.

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Toward an Effective Risk-Conscious and Collaborative Vehicular Collision Avoidance System

Tarik Taleb, *Member, IEEE*, Abderrahim Benslimane, *Senior Member, IEEE*, and Khaled Ben Letaief, *Fellow, IEEE*

***Abstract*—In this paper, we introduce a cooperative collision-avoidance (CCA) scheme for intelligent transport systems. Unlike contemporary strategies, the envisioned scheme avoids flooding the considered vehicular network with high volumes of emergency messages upon accidental events. We present a cluster-based organization of the target vehicles. The cluster is based upon several criteria, which define the movement of the vehicles, namely, the directional bearing and relative velocity of each vehicle, as well as the intervehicular distance. We also design a risk-aware medium-access control (MAC) protocol to increase the responsiveness of the proposed CCA scheme. According to the order of each vehicle in its corresponding cluster, an emergency level is associated with the vehicle that signifies the risk of encountering a potential emergency scenario. To swiftly circulate the emergency notifications to collocated vehicles to mitigate the risk of chain collisions, the medium-access delay of each vehicle is set as a function of its emergency level. Due to its twofold contributions, i.e., the cluster-based and risk-conscious approaches, our adopted strategy is referred to as the cluster-based risk-aware CCA (C-RACCA) scheme. The performance of the C-RACCA system is verified through mathematical analyses and computer simulations, whose results clearly verify its effectiveness in mitigating collision risks of the vehicles arising from accidental hazards.**

***Index Terms*—Cooperative collision avoidance (CCA), intervehicle communication (IVC), vehicular ad-hoc network (VANET).**

I. Introduction

ALONG with the ongoing advances in dedicated short-range communication (DSRC) and wireless technologies, intervehicular communication (IVC) and road–vehicle communication (RVC) have become possible, giving birth to a new network-type called vehicular ad-hoc network (VANET). The key role that VANETs can play in the realization of intelligent transport systems has attracted the attention of major car manufacturers (e.g., Toyota, BMW, and Daimler-Chrysler). A number of important projects have been subsequently launched. Crash Avoidance Metrics Partnership (CAMP), Chauffeur in Europe Union, CarTALK2000, FleetNet, and DEMO 2000 by the Japan Automobile Research Institute (JSK) are a few notable examples.

VANETs can be used for a plethora of applications, ranging from comfort and infotainment applications to onboard active safety applications. The latter are the most attractive and promising ones. Such applications assist drivers in avoiding collisions. They coordinate among vehicles at critical points such as intersections and highway entries.[1] Via an intelligent dissemination of road information (e.g., real-time traffic congestion, high-speed tolling, or surface condition) to vehicles in the vicinity of the subjected sites, collisions among vehicles can be prevented, and on-road vehicular safety can be accordingly enhanced.

To facilitate safety applications in VANETs, intraplatoon cooperative collision-avoidance (CCA) techniques have significantly evolved recently. With CCA systems, the number of car accidents and the associated damage can be significantly reduced. The prime reason for deploying CCA systems in VANETs is the substantially long reaction time (i.e., 0.75–1.5 s [2]) of any human driver to apply the brake following an emergency scenario. The potential damage inflicted by such a long reaction time of an individual driver is, indeed, remarkably high in case of a close formation of vehicles, which travel at high speeds. Instead of having drivers to traditionally react to the brake lights of vehicles immediately ahead, CCA systems enable vehicles to promptly react in emergency situations via a fast dissemination of warning messages to the vehicles in the platoon. However, the effectiveness of a given CCA system depends not only on the reliability of the circulated warning messages but on the specific nature of the emergency situation at hand as well. To this end, the underlying medium-access control (MAC) protocols of the concerned VANET need to make sure that the medium-access delay associated with each vehicle, under an emergency event, remains as short as possible. Driven by this need, we envision an effective CCA scheme, which takes into account a risk-aware MAC protocol, which we have specifically tailored for VANET environments. Furthermore, we envision clusters of vehicles based on their movement traits, including directional headings and relative velocities, and on the intervehicular distances as well. In a given cluster, each vehicle is assigned an emergency level, which reflects the risk associated with that particular vehicle to fall into an accidental hazard, e.g., collision with the other cars in the platoon. This cluster-based approach also permits us to set the medium-access delay of an individual vehicle as a function of its emergency level. By so doing, the envisioned strategy attempts to provide the drivers of the vehicles with warning messages pertaining to the emergency scenario with

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[1] An abridged version of this work has appeared in [1].

the shortest delivery latencies possible. This feature should prevent chain collisions or reduce the associated damage. Our adopted strategy is referred to as the cluster-based risk-aware CCA (C-RACCA) scheme due to its twofold contributions, namely, the formation of clusters and the adoption of the risk-conscious medium-access protocol.

The remainder of this paper is organized as follows. Relevant research on MAC protocols in VANET environments is presented in Section II. The operations of the envisioned C-RACCA system comprising its clustering mechanism and the risk-aware MAC protocol are delineated in detail in Section III. The performance of the C-RACCA system is evaluated in Section IV, which justifies the simulation setup and provides an in-depth analysis of the simulation results. Concluding remarks follow in Section V.

II. Related Work

VANETs are well characterized for their rapidly and dynamically changing topologies due to the fast motion of vehicles. Unlike traditional mobile ad hoc networks (MANETs), the nodes' mobility in VANETs is constrained by predefined roads and restricted speed limits. Additionally, nodes in VANETs can be equipped with devices with potentially longer transmission ranges, rechargeable source of energy, and extensive on-board storage capacities. Processing power and storage efficiency are, thus, not the issue in VANETs that they are in MANETs.

The work by Little and Agarwal [3] serves as an inspiring one for utilizing clusters of vehicles in VANETs without the use of fixed infrastructures (e.g., access points, satellites, and so forth). The hypothesis of this work states that the vehicles, which travel along the same directed pathway, can form interconnected blocks of vehicles. Thus, the notion of cluster of vehicles is adopted whereby a header and a trailer identify a particular cluster that is on the move. Little and Agarwal used multihop routing in these blocks or clusters of vehicles to obtain an optimum propagation rate to disseminate information pertaining to traffic and road conditions. For this purpose, they characterized the bounds of information propagation under different traffic patterns. In addition, by combining delay-tolerant networking and MANET techniques, they also implemented the safety information dissemination algorithm as a routing protocol.

To inform all the vehicles in a risk area (along a highway) regarding an emergency scenario (e.g., an accident or an impediment on the road) via alarm broadcasts, a novel communications technique called the intervehicles geocast (IVG) protocol was proposed [4]. IVG considers a vehicle to be in the risk area if the accident/obstacle is in front of that vehicle. Based on the temporal and dynamic attributes of the locations, speeds (i.e., highway), and driving directions of the vehicles in the risk zone, IVG defines multicast groups of these vehicles. Since IVG does not maintain neighboring cars' list at each vehicle, the overall signaling overhead is reduced, which saves precious bandwidth to disseminate the actual warning messages according to a defer time algorithm. In addition, relays are deployed dynamically in a distributed manner (in each driving direction) that rebroadcasts the warning messages to ensure their delivery to the vehicles in the risk area.

The broadcast storm problem, in which there is a high level of contention and collisions at the MAC level due to an excessive number of broadcast packets, is presented in the VANET context in [5]. The serious nature of the broadcast storm problem is illustrated in a case study of four-lane highway scenario. This work proposes three lightweight broadcast techniques to mitigate the broadcast storms by reducing redundant broadcasts and packet loss ratio on a well-connected vehicular network. This work, however, does not consider addressing the broadcast storm issue at the MAC layer (i.e., the real source of the problem), which may be able to mitigate the problem more effectively.

To prevent accidents that may occur due to late detection of distant/roadway obstacles, Gallagher *et al.* [6] emphasized the need for longer range vehicular safety systems that are capable of real-time emergency detection. To this end, they investigated the applicability of DSRC resources to improve the efficiency and reliability of vehicle safety communications. This work specifically partitions crucial safety messages and the nonsafety ones. The former is termed as "safety-of-life" messages, which are assigned the highest priority and transmitted on a dedicated safety channel. The underlying MAC and physical (PHY) layers, guided by the higher layers, enable the awareness and separation of safety and nonsafety messages.

In the survey conducted by Hartenstein and Laberteaux [7], the parameters that may influence the probability of packet reception in VANETs have been pointed out, including vehicular traffic density, radio channel conditions, transmission power, transmission rate, contention window sizes, and the prioritization of packets. This work also mentions that for packets prioritization in particular, the enhanced distributed channel access (EDCA), which is also part of 802.11-2007 specifications, can be used. Four distinct access categories, each with its own channel access queue, are provided in this scheme, whereby the interframe space and the contention window size can be tailored to the specific needs of the target VANET. Indeed, Torrent-Moreno [8] demonstrates that, in contrast with the simple carrier sense multiple access (CSMA) scheme, the channel access time and probability of packets reception improve to an extent under EDCA scheme, even in the case of a saturated channel.

Sichitiu and Kihl [9] survey IVC systems and focus on public safety applications toward avoiding accidents and loss of lives of the passengers. Their study points out that safety applications are inherently delay sensitive, e.g., vehicular warning systems to avoid side crashes of cars and trains at crossroads, deploying safety equipments such as inflating air bags and tightening seat belts, and so forth. The system penetration of such applications is, however, subject to determining the zone of relevance as accurately as possible. For instance, when an accident in the right lane of a highway occurs, it is considered in the covered studies to only affect vehicles approaching the accident from behind. The survey also describes the available communication technologies, focusing on their PHY and MAC layers, that may facilitate vehicular communications to disseminate emergency messages. The studied protocols that are considered to be suited for intervehicle emergency communications systems include IEEE 802.11 and its DSRC standard, Bluetooth (standardized within IEEE 802.15.1), and cellular models such as the global system for mobile communications/general packet radio service and third-generation (3G) systems like the universal mobile telecommunications system (UMTS), the UMTS terrestrial radio access network, and so on.

Toor *et al.* [10] suggest that three difficulties arise in the PHY/MAC layer in VANETs. The first problem involves sharing the radio medium to effect robust transmission among the vehicles. The second problem consists of traffic jams or postaccidental scenarios whereby the target VANET exhibits a rather high density of vehicular nodes. The third and most significant problem identified in this work is the support of adequate emergency applications to guarantee quality of service (QoS) in wireless environments. The study elucidates that there exist two main approaches for sharing the medium that may be used for vehicular communications, namely 1) the CSMA-like random scheme and 2) the time-division multiple-access (TDMA)-like controlled scheme. A prime example of the former approach is IEEE 802.11, which is stated to be the most dominant MAC protocol for developing safety applications for vehicular networks. As examples of the latter, the study refers to a number of other technologies derived from 3G telecommunications systems based upon variations of the pure ALOHA protocol [11] such as the slotted ALOHA [12] and reliable reservation ALOHA (RR-ALOHA) [13] access schemes. Recent works such as [14] have also considered QoS issues in VANETs.

As stated earlier, a class of unique applications has been devised for VANETs. For each application, different techniques have been proposed. From the observation that routing protocols originally designed for MANET networks may be suitable only for delay-tolerant content-delivery applications (e.g., in-vehicle Internet) [15], the work in [17] proposed a set of context-aware broadcast-oriented forwarding protocols for delay-sensitive safety applications in VANETs (e.g., CCA systems). The packet-forwarding operation can be selective and based on the geographical locations and the moving directions of the source and the destination vehicles and the packet's information content. Furthermore, mobility-oriented schemes such as "Mobility-centric approach for Data Dissemination in Vehicular networks" (MDDV) [23], which attempts to address the data delivery problem in a partitioned and highly mobile VANET topology, integrates the following three data-forwarding techniques: 1) the opportunistic-based scheme; 2) the trajectory-based scheme; and 3) the geographical forwarding scheme. The former refers to the fact that vehicle movements create the opportunity to pass messages and determine which vehicle to transmit/buffer/drop a message and when. The trajectory forwarding implies that the information is being propagated from the source to the destination. The geographical forwarding, on the other hand, means that the message is conveyed geographically closer to the destination along the source-to-destination trajectory. Localized algorithms specifically designed for vehicles are developed to exploit these data-forwarding schemes. By allowing multiple vehicles to actively propagate a given message, MDDV improves message-delivery reliability. While the aforementioned packet-forwarding protocols can reduce the number of signaling messages in a VANET, ensuring prompt delivery of critical warning messages is also crucial for CCA systems. For this purpose, there is a need to develop adequate MAC protocols.

Many of the MAC protocols that have evolved over the years are, however, not applicable to VANET environments. Among the contemporary MAC protocols, the IEEE 802.11 MAC specification is considered to be the leading choice among VANET designers as a means to provide safety applications [25]. The MAC protocol of IEEE 802.11 consists of a number of sophisticated mechanisms that rely on soft handshaking involving a number of signaling messages (e.g., request-to-send and clear-to-send messages) exchanged between the sender and the receiver. These mechanisms include the following: 1) CSMA with collision avoidance (CSMA/CA); 2) multiple access with collision avoidance (MACA); and 3) MACA for wireless with distributed coordinated function mode. More tailored MAC protocols for VANET environments are also evolving, as shown in the study conducted by Adachi *et al.* [16]. In addition, the following two techniques have evolved into safety-critical application domains such as CCA: 1) data prioritization [17], [26] and 2) vehicle prioritization. We focus on the latter in this paper whereby the emergency level associated with each vehicle in the considered VANET is taken into account to prioritize the vehicle. Intuitively, vehicles with high emergency levels should be always granted prompt access to the medium.

Provisioning security for protecting the vehicular positions in a VANET is also emerging as an active area of research. For example, Yan *et al.* [28] presented a novel approach that employs an on-board radar at each vehicle to detect neighboring vehicles and to confirm their announced coordinates. This notion of local security (i.e., specific to individual vehicles) is extended to achieve global security by using the following two techniques: 1) a preset position-based groups to form a communication network and 2) a dynamic challenging scheme to confirm the coordinate information sent by remote vehicles. Although the scope of our work in this paper does not cover these security aspects, we feel the importance to incorporate such safeguards to securely disseminate safety information/warning messages in VANETs in the future.

III. Cluster-Based Risk-Aware Cooperative Collision-Avoidance System

In this section, we initially provide a brief overview of the functionality of the traditional CCA system proposed by Biswas *et al.* [17] and point out its shortcomings. We then propose our C-RACCA system, which consists of adequate solutions to address these issues, namely, a dynamic clustering procedure to formulate clusters of vehicles, followed by a uniquely designed risk-aware MAC protocol.

A. Shortcomings of the Traditional CCA Systems

In traditional CCA systems [17], upon an emergency situation, a vehicle in the considered platoon dispatches warning messages to all other vehicles behind it. A recipient takes into account the direction of the warning message arrival with respect to its directional bearing and decides whether to pass the message to other vehicles or not. Indeed, the message will be ignored if it comes from behind. To ensure a platoon-wide coverage, the message is transmitted over multiple hops. However, this approach leads to the following two problems: 1) generation of a large number of messages, which literally flood the VANET, and 2) generation of redundant messages (originated from different vehicles) pertaining to the same emergency event. Consequently, message collisions are more likely to occur in the access medium with the increasing number of vehicles in the platoon. In addition, this naive approach of relaying the emergency message contributes to cumulative communication latencies, which, in turn, lead to a substantially high delay in delivering the warning message from the platoon front to the vehicles located at the rear of the platoon formation. To make matters even worse, in the case of multiple failed message retransmissions owing to excessive MAC collisions, this message-delivery latency increases further. To overcome these shortcomings of the existing CCA systems, we offer a novel approach that dynamically forms clusters of the vehicles in a platoon.

B. Dynamic Clustering of Vehicles

Prior to a detailed description of the envisioned clustering mechanism, it is essential to point out a number of assumptions regarding the considered VANET environment, as listed in the following.

1) To accurately estimate the current geographical location, each vehicle in the platoon consists of global positioning systems (GPSs) or similar tracking modules. It should be noted that the knowledge pertaining to the real-time coordinates of the vehicular nodes is an assumption made by most protocols and applications. Indeed, this is a reasonable enough assumption pointed out by Boukerche *et al.* [18] because the GPS receivers can easily be deployed on vehicles. However, as VANETs are evolving into more critical areas and becoming more reliant on localization systems, there may be certain undesired problems in the availability of GPS in certain scenarios (e.g., when the vehicles enter zones where GPS signals may not be detected, such as inside tunnels, underground parking, and so forth). Indeed, there exist several localization techniques, such as dead reckoning [19], cellular localization [21], and image/video localization [22], that may be used in VANETs so that this GPS limitation may be overcome. In addition, GEOCAST [20], which is one of our earlier developed protocols, may be used so that it is still possible to support some vehicles, which have lost GPS signals, or do not have GPS on board, to learn from the other vehicles and position themselves.
2) To facilitate communications, two distinct wireless channels are considered to exchange signaling messages to formulate vehicles' clusters and to issue/forward warning messages, respectively.
3) Each vehicle is assumed to be capable of estimating its relative velocity with respect to neighboring vehicles. In addition, it is also considered to be able to compute, via adequately deployed sensors, intervehicular distances.
4) When a vehicle receives a warning message, it can estimate the direction of the message arrival, i.e., whether the received warning originated from a vehicle from the front or the rear.
5) Each vehicle is considered to have knowledge on its maximum wireless transmission range, which is denoted by T_r. A vehicle constantly uses this parameter to update its current transmission range R in the following manner:

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

where ϵ refers to the wireless channel fading conditions at the current position. Equation (1) is used for simple estimation of the practically possible transmission range from the given surrounding conditions that affect the maximum transmission range of the vehicle. To compute this, a simple parameter ϵ is used, which reflects the surrounding conditions. If the vehicle is currently moving in the downtown, then its transmission range will be lower than the maximum possible one. Because, there will be many obstacles (e.g., high-rise buildings, industries, and other installations), which will interfere with the vehicle's wireless signal. To reflect this situation, ϵ in (1) is set to a high value in a downtown scenario. On the other hand, when a car is moving in the suburbs, there are fewer obstacles affecting the vehicle's transmitted signals. Therefore, in such a scenario, low values of ϵ are used to illustrate that the vehicle may use a transmission range that is closer to the maximum possible one. GPS or other positioning systems (e.g., Galileo) are used to obtain the terrain information so that the appropriate values of ϵ in a given location can be appropriately estimated.

Additionally, we consider, for clustering purposes, a platoon of vehicles, which travel along the same road toward the same direction. Consistent with previous work in this domain [15], the envisioned grouping of vehicles is, thus, based upon their movement directions. Directional-antenna-based MAC protocols [27] may be utilized to group the vehicles more accurately, whereby the transmission range of vehicles is split into M transmission angles of equal degrees $(360/M)$. By assigning each transmission angle to a unique vehicle group, M groups can thus be formulated.

Similar in spirit with the assumptions in [15] and [27], our approach considers, in forming a cluster, only the vehicles that belong to the same group in terms of moving on the same road toward the same direction. Fig. 1 portrays an example of three such clusters. As depicted in this figure, a vehicle may act as a special node, i.e., as a cluster head (CH) or a subcluster head (SCH), or may merely drive as an ordinary vehicle (OV). In case of forming a CH, the vehicles are voluntarily required to consistently advertise for the cluster while maintaining and updating their respective cluster tables. On the other hand, the first SCH node is selected as the last vehicle that is reachable by the CH. Indeed, the SCH node may be used to define a subsequent SCH entity (i.e., the last vehicle reachable from this SCH node), and so forth. SCH nodes are in charge of relaying packets (e.g., emergency warning messages) from either a CH or from SCHs in front to other vehicles within the same cluster that lie outside

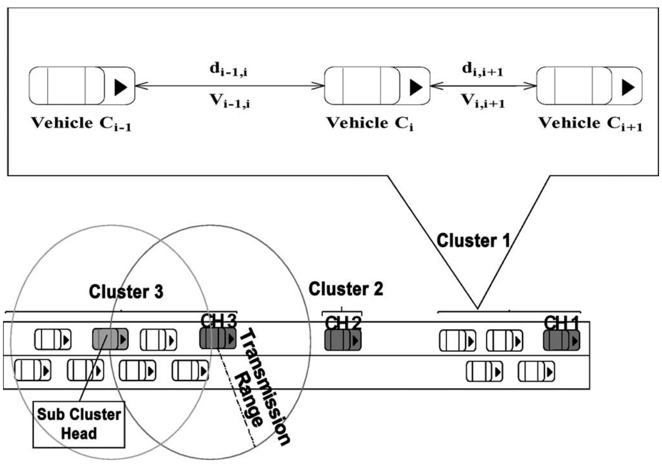

Fig. 1. Example of three clusters.

the CH's (or the front SCH's) transmission range. In addition, a SCH also aggregates information from OVs within its reach and relays them to the CHs/SCHs in front. It should be noted that it is a rare case to have a cluster containing a large number of SCHs. In such case, the cluster size will be significantly large, and vehicles will be more likely moving at very low speeds. Thus, chain collisions will not happen in such case. Finally, OVs comprise the ordinary members in the cluster that perform no specific task.

As demonstrated in the example in Fig. 1, C_i refers to the identification (ID) of vehicle i. For simplicity, we denote C_{i-1} and C_{i+1} as the vehicles ahead of and immediately behind C_i, respectively. The transmission range of the former (provided that it exists) reaches C_i. On the other hand, the latter is reachable by C_i. The distance between a pair of vehicles C_j and C_k is denoted by $d_{j,k}$. V_j and $V_{j,k}$ refer to vehicle C_j's actual velocity and the relative velocity with respect to vehicle C_k, respectively. Therefore, the magnitude of $V_{j,k}$ is assumed to be the same as that of $V_{k,j}$. Additional notations, which are used in the clustering operation, are listed as follows:

1) τ_j^a: time required for a vehicle C_j to reach vehicle C_{j-1} immediately ahead of it (i.e., $\tau_j^a = d_{j-1,j}/V_{j-1,j}$);
2) τ_j^b: time required for a vehicle C_j to be reached by vehicle C_{j+1} right behind it (i.e., $\tau_j^b = d_{j,j+1}/V_{j,j+1}$);
3) ϕ_j: set of CHs or SCHs in front of vehicle C_j; this set also belongs to C_j's group;
4) ϕ_j^{CH}: the closest CH or SCH $(\in \phi_j)$ in front of vehicle C_j;
5) ψ_j: set of CHs or SCHs behind vehicle C_j; this set also belongs to C_j's group;
6) ψ_j^{CH}: the closest CH or SCH $(\in \psi_j)$ behind vehicle C_j;
7) a_e and a_r: emergency deceleration and regular deceleration, respectively, which indicate the occurrence of an emergency event to trigger the transmission of critical warning messages;
8) δ: the average reaction time of individual drivers $(0.75 \leq \delta \leq 1.5$ s).

For each vehicle C_i and its immediately following vehicle C_{i+1}, we consider that no collision will occur between these two vehicles, and therefore, they are safe, provided that their distance $d_{i,i+1}$ satisfies the following condition for $\Gamma_{i,i+1}$ (i.e., $\overline{\Gamma_{i,i+1}}$ denotes the negation of the condition):

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

where α represents a tolerance factor. In addition, $d_{\max}$ denotes a safety distance in which if two vehicles are distant, no collision will occur between the two vehicles, regardless of the vehicles' velocities (e.g., in case of a maximum velocity $V_{\max} = 180$ km/h, $d_{\max} = V_{\max} \cdot 1.5$ s $= 75$ m). It should be noted that the direction of the vehicles is not included in (2) since we consider the vehicles to be traveling along the same direction in the same lane.

Using the above notations, for any vehicle C_i, we have the following lemma:

$$\exists\, C_{i-1} \Leftrightarrow \phi_i \neq \emptyset \tag{3}$$

$$\exists\, C_{i+1} \Leftrightarrow \psi_i \neq \emptyset. \tag{4}$$

The proof of the lemma is trivial.

Three specific scenarios pertaining to a vehicle may exist in the envisioned clustering operation. A vehicle may be in one of the following three states.

1) It starts its engine and gets on a road.
2) It decides to travel in a different direction. Consequently, it leaves its old group G_o and joins a new group of vehicles, which is denoted by G_n.
3) It continues to travel on the same road without changing its direction. However, it increases or decreases its traveling speed.

In the remainder of this subsection, we describe the clustering mechanism in detail by focusing on each of the above scenarios.

1) Joining a Group for the First Time: A vehicle C_i, after it gets on a road, initially broadcasts a CH solicitation message to the neighboring vehicles, which are assumed to belong to group G_n. The CH solicitation message queries the other vehicles regarding the CH of G_n. Meanwhile, C_i also initiates a timer θ. The following two cases exist: 1) C_i receives no response, or 2) C_i receives at least one affirmative response to its initial query prior to expiration of θ. In the former case, where $(\phi_i = \psi_i = \emptyset)$, C_i decides to assume the role of CH in G_n and starts constructing its own cluster. In the latter case, C_i needs to take into consideration the responses from other CH(s). At first, C_i verifies if any CH ahead of it has also transmitted a CH advertisement message. Otherwise, if $(\phi_i = \emptyset)$, from the fact that $\psi_i \neq \emptyset$, C_i checks whether it maintains long enough distance $(d_{i,i+1})$ with C_{i+1}, which immediately follows it from behind. This verification is required to ascertain the safety condition $(\Gamma_{i,i+1})$ described earlier. If $(\Gamma_{i,i+1})$ holds, C_i constructs its own cluster and declares itself as the CH of this newly formed cluster. Otherwise (i.e., if $\overline{\Gamma_{i,i+1}}$), C_i takes over, from ψ_i^{CH}, the CH behind it by designating itself as the new CH (i.e., $C_i = \phi_{i+1}^{CH}$).

On the other hand, if C_i obtains a CH advertisement message from at least one CH ahead of it (i.e., $\phi_i \neq \emptyset$), it verifies whether

TABLE I
ALL POSSIBLE CASES FOR A VEHICLE C_i JOINING FOR THE FIRST TIME A GIVEN GROUP

$\phi_i = \emptyset$			$\phi_i \neq \emptyset$			
$\psi_i = \emptyset$	$\psi_i \neq \emptyset$		$\Gamma_{i,i-1}$			$\overline{\Gamma_{i,i-1}}$
	$\Gamma_{i,i+1}$	$\overline{\Gamma_{i,i+1}}$	$\psi_i = \emptyset$	$\psi_i \neq \emptyset$		
				$\Gamma_{i,i+1}$	$\overline{\Gamma_{i,i+1}}$	
Form own cluster	Form own cluster	Take authority of ψ_i^{CH}	Form own cluster	Form own cluster	Take authority of ψ_i^{CH}	Join ϕ_i^{CH}

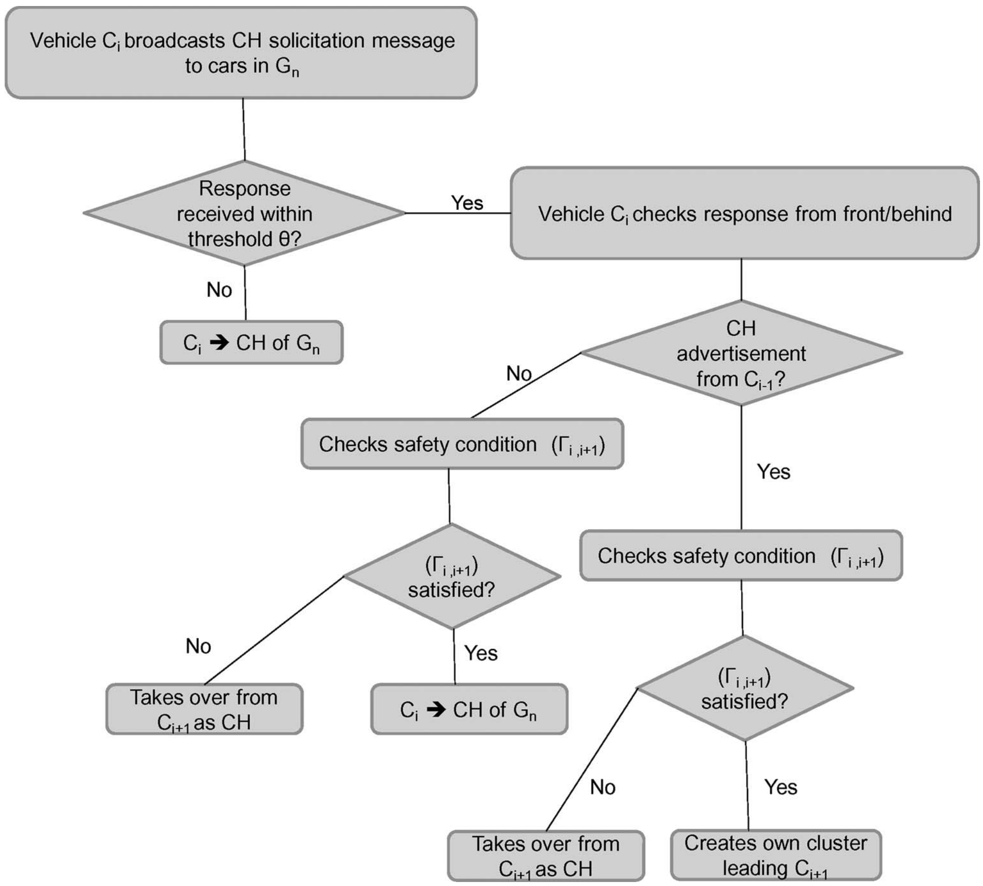

Fig. 2. Steps required for a vehicle to join a group for the first time.

the distance to the vehicle immediately ahead of it (C_{i-1}) and belonging to the cluster CH is sufficiently large to avoid collision with C_{i-1}. C_i constructs its own cluster by designating itself as the CH, provided that 1) the condition $\Gamma_{i,i-1}$ holds and 2) that no vehicle follows it from behind $(\psi_i = \emptyset)$. 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 $(\phi_i = \emptyset, \psi_i \neq \emptyset)$. On the other hand, if the condition $\overline{\Gamma_{i,i-1}}$ persists, C_i is required to join the cluster formed by ϕ_i^{CH}. Table I summarizes all the aforementioned cases. The whole process of joining a group for the first time is illustrated in Fig. 2.

A vehicle C_i, which desires to join a given cluster, issues a self notification (SN) message that contains the vehicle's ID, current location, and transmission range to the concerned CH. Upon receiving the SN, the CH treats it as a solicitation request from C_i to join the cluster. The CH then adds C_i into its cluster table and informs the rest of the cluster members via an updated cluster advertisement (CA) message, which contains the IDs of all the involved entities including the cluster, the CH, the SCH(s), and the OVs. In the case that a new vehicle emerges as a new CH in the considered cluster, the previous CH needs to transfer the most recently updated cluster table to the new CH, which, in turn, broadcasts an updated CA packet to the cluster members to inform them regarding the changes.

2) Departure From a Group and Joining a New One: As mentioned earlier, the second scenario consists of a moving vehicle C_i that changes its direction, which results in its departure from its old group G_o to a new group G_n. C_i, at first, informs G_n about the departure event. Upon joining G_n, C_i either forms its own cluster or joins a preexisting one following the previously described steps in Section III-A1. AQ1

The departure of C_i from G_o may yield three distinct cases, namely, whether C_i was the CH, a SCH, or merely an OV in G_o. These three cases are depicted in Fig. 3 and are delineated as follows.

1) *If C_i is an OV in G_o:* In this case, departure operation of C_i from G_o is trivial since it only requires notifying either the CH (denoted by CH_{G_o}) directly or the corresponding

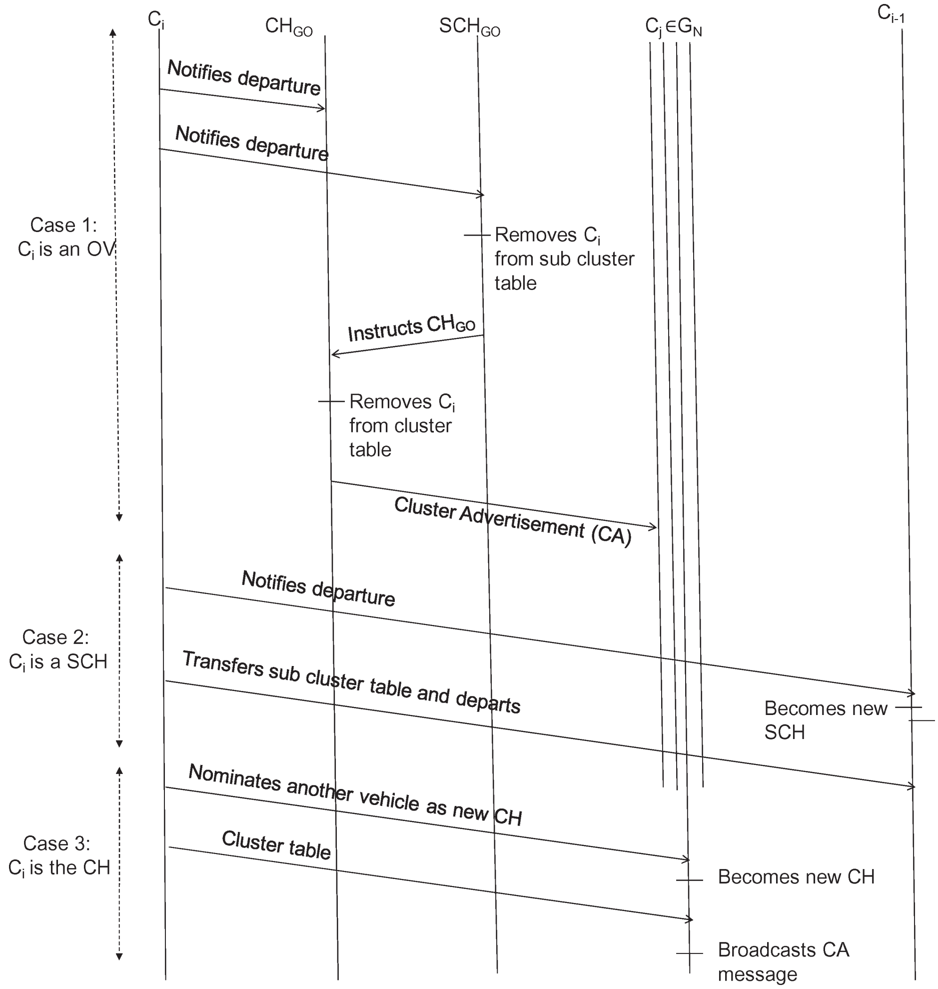

Fig. 3. Timeline diagram illustrating the departure event of a vehicle from a group.

SCH (i.e., SCH_{G_o}) similarly. In latter case, SCH_{G_o} first removes C_i from its subcluster table and instructs CH_{G_o} about the event that prompts CH_{G_o}, in its own turn, to delete C_i's entry from its cluster table. Finally, CH_{G_o} issues an updated CA message to inform the rest of the members that C_i is no longer with G_o.

2) *If C_i is a SCH in G_o:* C_i, in this scenario, will assign C_{i-1} in G_o to assume the responsibility of the new SCH. In addition, C_i also transfers the subcluster table to C_{i-1} before departing G_o.

3) *If C_i is a CH in G_o:* This scenario requires C_i to assign the role of the new CH to another cluster member, which it deems most appropriate. In addition, C_i also transfers the cluster table to the new CH prior to its departure from G_o. The new CH notifies the rest of the cluster members regarding the change via an updated CA message.

Fig. 4 depicts a scenario whereby a vehicle A, with a transmission range T_{A} and speeding at a velocity V_{A}, turns onto a new street inclined by an angle α, while vehicle C, which is immediately ahead of it, and vehicle B, which is immediately behind it, continue moving straight along the same road at velocities V_{C} and V_{B}, respectively. Fig. 5 demonstrates the results obtained from numerical analysis that there is largely sufficient time for vehicle A to communicate with both vehicles C and B in the case of the following two different scenarios: 1) a highway scenario where vehicles B and C speed at 120 km/h, and vehicle A reduces its speed to 60 km/h upon turning onto the new road and 2) an urban scenario where vehicles B and C move at 60 km/h, and vehicle A turns at a speed equal to 30 km/h. The transmission range of vehicle A is set to 300 and 150 m in the highway and urban scenarios, respectively. Fig. 6 (derived from analytical computations) shows the time required to join a cluster in an urban and a highway scenario for different transmission ranges of vehicles. The figure clearly indicates that the time required for a vehicle to join a cluster is short in both scenarios and can be easily accommodated by the connectivity time shown in Fig. 5.

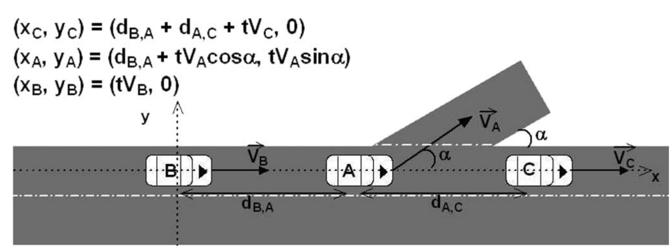

Fig. 4. Scenario showing a vehicle A turning onto a new street inclined by an angle α, while vehicles B and C continue moving straight on the same road.

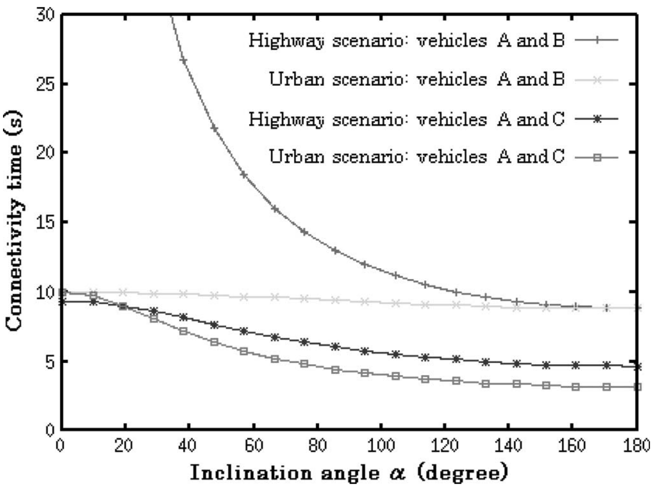

Fig. 5. Connectivity time for a vehicle, turning onto a new street inclined by an angle α, with vehicles right behind it and immediately ahead of it ($d_{\mathrm{B,A}} = d_{\mathrm{A,C}} = 15$ m).

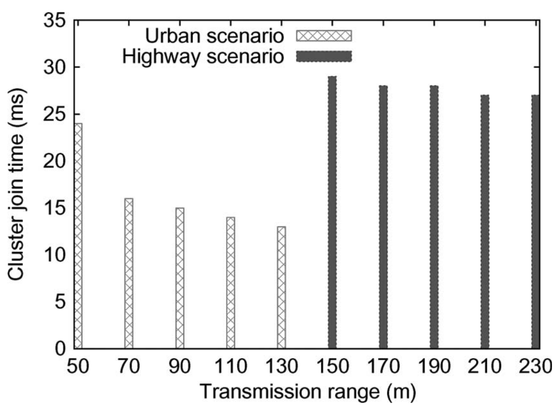

Fig. 6. Time required to join a cluster in an urban and a highway scenario, respectively.

3) Intercluster Interactions Within a Particular Group: In a given group, the envisioned approach permits flexibility in forming and interacting among clusters belonging to the same group. For instance, a cluster may be split into two parts under certain conditions. The reverse may also be possible, whereby two clusters may merge into a single new cluster.

A particular cluster may be divided into two different clusters, provided that each of the two adjacent vehicles, which are denoted by C_i and C_{i+1} (both the vehicles are members of the same cluster) continues to travel at a relative speed $V_{i,i+1}$ until the intervehicular space $d_{i,i+1}$ satisfies the condition $\Gamma_{i,i+1}$. When this condition persists, C_{i+1} becomes the CH in one part of the former clusters containing the vehicles following C_{i+1} from behind. On the other hand, C_i joins another part of the previous cluster (consisting in vehicles C_i and beyond) as an OV.

Two existing clusters may be allowed to merge and evolve as a single one, provided that the distance between the CH of one of the two clusters (denoted by C_l) and the last vehicle C_k in the other cluster becomes so short that the condition $\overline{\Gamma_{k,l}}$ arises and holds. In this new cluster, C_l will handle the cluster table of the former cluster (i.e., to which C_k previously belonged). C_l then broadcasts an updated CA message to all the members to inform them regarding this change.

Conducting the aforementioned dynamic clustering operations, each group of vehicles moving along the same road and in the same direction will be organized into a number of clusters of different sizes and with independent cluster heads (see Fig. 1). The distance between two adjacent clusters is always long enough to avoid collisions between vehicles from both clusters. On the other hand, the intervehicle distance between two adjacent vehicles in a given cluster is always shorter than the "safety distance." Therefore, if a vehicle in a cluster detects an emergency event and applies brakes, collisions among vehicles are likely to happen if drivers do not react promptly. As stated earlier, the exchange of signaling messages for the formation of clusters is performed on a channel different than the one used to transmit warning or emergency messages. MAC collisions due to the transmission of such signals, thus, should not impact the responsiveness of our proposed C-RACCA system.

C. Risk-Aware MAC Protocol

In this section, we describe the envisioned risk-aware MAC protocol. To lay the basis of this work, we consider studying the original MAC protocol in the IEEE 802.11 specifications, owing to its enormous popularity among VANET designers and researchers. For simplicity, the case of a single cluster is considered, whereby the vehicles are indexed based upon their order within the cluster with respect to their movement directions. In other words, without any loss of generality, C_1 refers to the cluster head, C_2 refers to the car immediately behind it, and so forth. In addition, we consider highway platoons for studying the envisaged risk-aware MAC protocol due to the fact that the likelihood of chain vehicle collisions is substantially high in a highway.

The 802.11 standard currently defines a single MAC that interacts with the following three PHY layers: 1) frequency-hopping spread spectrum with a slot time $\xi = 50$ μs; 2) direct sequence spread spectrum with a slot time equal to $\xi = 20$ μs; and 3) infrared with a slot time equal to $\xi = 8$ μs. The general concept behind the MAC protocol in IEEE 802.11 is that when a mobile node desires to transmit, it first listens to the desired channel. If the channel is idle (no active transmitters), the node is allowed to transmit. If the medium is busy, the node will defer its transmission to a later time and then to a further contention period. To resolve contention issues among different stations that are willing to access the same medium, an exponential back-off mechanism is executed in the IEEE 802.11 MAC protocol prior to the calculation of the contention period. This, however, significantly increases the data delivery latency. Consequently, in the case of delay-sensitive safety-critical CCA applications, the effectiveness of the original 802.11 MAC protocol decreases substantially. Indeed, high latency in the dissemination of a warning message will lead to scenarios where some vehicles will not have enough time to react, and vehicle collisions become inevitable. To cope with this shortcoming, we envision that the IEEE 802.11 back-off procedure should be substituted by a more suitable mechanism, which takes into account, in the contention window of a given

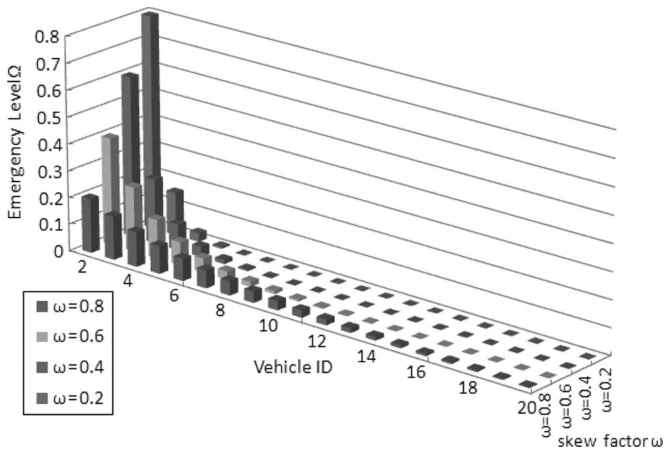

Fig. 7. Emergency level distribution of 20 vehicles for different values of the skew factor.

vehicle, its probability to encounter an emergency scenario. To this end, an emergency level for every vehicle (denoted by C_i without any loss of generality) in a particular cluster is defined according to the distribution in

$$\Omega_i = \frac{(1-\omega)\omega^i}{\omega(1-\omega^S)}, \qquad 1 \le i \le S \tag{5}$$

where S and ω refer to the cluster size and skew factor, respectively. Fig. 7 demonstrates that setting ω to larger values yields a uniform distribution of the emergency level of vehicles, while assigning ω values close to zero results in a highly skewed distribution.

In our envisioned risk-aware MAC protocol, the contention window of a given vehicle C_i is computed based on the following equation (rather than employing the traditional exponential back-off procedure):

$$CW_i = \sum_{j=1}^{k} (1-\Omega_i)^j \cdot cw \cdot \xi \tag{6}$$

where k, ξ, and cw denote the number of transmission attempts, the slot time of the used PHY layer, and the window size, respectively. The reason behind computing the vehicles' contention windows in this manner is to ascertain that the vehicles with high probability of meeting an emergency situation may enjoy short contention windows. Indeed, in case of multiple failures to transmit the warning message ($k \gg 1$), the contention window CW_i will converge to a value equal to ξ/Ω_i. This should ensure smaller latency (after each failed attempt) in the delivery of warning messages for vehicles with high emergency levels Ω_i. Vehicles behind the car that detected the event will then be able to avoid collisions.

Equation (6) ensures the system consistency to some extent while adjusting the contention window of all the vehicles belonging to a given cluster. However, there is a further need to ascertain that the contention window is short enough so that the maximum number of imminent collisions among vehicles may be circumvented. To achieve this, the maximum delay, within which a particular vehicle needs to be informed, is computed. In the following, we consider the example of Fig. 1 and assume that upon an emergency situation, vehicles C_i and C_{i+1} slow down their velocities at rates denoted by a_e and a_r, respectively. The next task is to calculate the maximum latency δ_i since the detection of the emergency event, before which, C_i may be able to notify C_{i+1} (i.e., the vehicle following C_i from behind) of the event to avoid collision.

Vehicle C_i will be moving for a time period $\Delta_i = (V_i/a_e)$ before it eventually stops. The distances traveled by vehicles C_i and C_{i+1} over Δ_i are denoted by l_i and l_{i+1}, respectively. Equation (7) is used to compute l_i, and (8), shown below, is employed to derive l_{i+1} as follows:

$$l_i = \frac{V_i^2}{2 \cdot a_e} \tag{7}$$

$$l_{i+1} = V_{i+1} \cdot \frac{V_i}{a_e} - \frac{a_r}{2}\left(\frac{V_i}{a_e} - \delta_i\right)^2. \tag{8}$$

To avoid collision between C_i and C_{i+1}, the following inequality should be satisfied by taking into consideration l_i and l_{i+1}, i.e.,

$$l_{i+1} > l_i + d_{i+1,i} + L_v \tag{9}$$

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

$$\delta_i^{max} = Max\left(\frac{V_i}{a_e} - \sqrt{\frac{2}{a_r}\cdot\left(\frac{V_i}{a_e}(V_{i+1} - \frac{V_i}{2}\right) - d_{i+1,i} - L_v}, 0\right). \tag{10}$$

The collision between C_i and C_{i+1}, however, becomes unavoidable when $(\delta_i^{\max} = 0)$, which compels C_i to continue broadcasting warning messages to all vehicles within its transmission range. This provision is required to mitigate further damage inflicted on the platoon by preventing vehicles that are far behind from colliding with one another. Consequently, CW_i (i.e., the contention window for vehicle C_i) is set as follows:

$$CW_i = \begin{cases} \sum_{j=0}^{k}(1-\Omega_i)^j \cdot cw \cdot \xi, & \text{if } \delta_i^{max} = 0 \\ Min\left(\sum_{j=0}^{k}(1-\Omega_i)^j \cdot cw \cdot \xi, \delta_i^{max}\right), & \text{otherwise.} \end{cases} \tag{11}$$

Unless otherwise specified, we set a_e, a_r, and L_v to 8 m/s^2, 4.9 m/s^2, and 4 m, respectively. It should be noted that the values of a_e and a_r can be used by the system as an indication for an emergency event (e.g., a_e for cluster head, a_r or above for other cluster members) to trigger the transmission of warning messages.

On detecting an emergency event, a vehicle issues a warning message to every member of its cluster (including SCHs) that its transmission range currently covers. An SCH entity forwards this message to each of its subcluster members. It should be noted that a vehicle can safely discard messages originating from vehicles following it from the back. Otherwise (i.e., if the warning message arrives from the front), the recipient vehicle, at once, reacts to it based on the event type included in the warning message. If the recipient vehicle encounters redundant warning messages, it takes action based on the first one only and discards the rest of the duplicate copies.

IV. Performance Evaluation

A. Collision Model

Before delving into details of the considered collision model in our simulation, we list a number of important parameters. Let S and L_v denote the size of the considered cluster (where the collisions are simulated) and the average vehicle length, respectively. As mentioned earlier, we are more keen on focusing on highway platoon scenarios, whereby the likelihood of collisions among the cluster members is much higher in contrast with urban scenarios. In our simulated highway platoon environment, we consider the most frequent scenario, whereby the CH (i.e., the vehicle in front of the platoon) identifies an emergency event. When the CH detects an emergency situation at time t_0, it slows down at an emergency deceleration a_e. The rest of the vehicles are considered to slow down at a regular deceleration a_r. For the sake of simplicity and without any loss of generality, we further assume that when a vehicle C_i collides with a vehicle C_{i-1} ahead of it, C_i immediately stops. On the other hand, C_{i-1} keeps on traveling without deceleration. Although this particular assumption does not conform to realistic scenarios, it does not change any of the rudimentary observations made so far on the envisioned C-RACCA framework.

Let Δt_i represent the latency since the detection of the emergency event until vehicle C_i stops or collides with its preceding vehicle C_{i-1}. The velocities of C_i at the time of the event detection and after Δt_i time are denoted by V_i^o and V_i^s, respectively. The delay incurred in delivering the warning message to C_i is referred to as δ_i. It is worth noting that all vehicles in the cluster (or subcluster) ought to experience similar δ_i, provided that the broadcast of warning messages by the CH/SCHs and their deliveries at the recipients are successful. As previously evaluated in (7), l_i defines the distance traveled by C_i since the event detection time until the vehicle completely stops or collides with C_{i-1}. The following equations pertain to the CH, i.e., C_1:

$$\Delta t_1 = \frac{V_1^o}{a_e} \tag{12}$$

$$l_1 = V_1^o \Delta t_1 - \frac{1}{2} a_e \cdot \Delta t_1^2 \tag{13}$$

$$V_1^s = 0. \tag{14}$$

For other vehicles, except for the considered CH (i.e., C_i, $1 < i \leq S$), the conditions for two adjacent vehicles C_i and C_{i-1} not to collide can be obtained in terms of the following equations:

$$\Delta t_i = \frac{V_i^o}{a_r} + \delta_i \tag{15}$$

$$l_i = V_i^o \Delta t_i - \frac{1}{2} a_r \cdot (\Delta t_i - \delta_i)^2 \tag{16}$$

$$V_i^s = 0. \tag{17}$$

TABLE II
Simulation Parameters

Factor	Range of values
Propagation model	TwoRayGround
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	0.8
Average vehicle length, L_v	4 m
Slot time, ξ	50 μs
Tolerance factor, α	3

On the other hand, in the case that C_i and C_{i-1} collide, the following two distinct cases may be envisaged.

Case 1) C_i collides while C_{i-1} is still moving.

Case 2) C_{i-1} stops, and then, C_i hits C_{i-1}.

The following inequality should hold in case 2):

$$l_{i-1} + d_{i,i-1} + L_v \leq l_i. \tag{18}$$

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

$$\Delta t_i = \Delta t_{i-1} \tag{19}$$

$$l_i = l_{i-1} + d_{i,i-1} + L_v \tag{20}$$

$$V_i^s = V_i^o - a_r \cdot (\Delta t_{i-1} - \delta_i). \tag{21}$$

For case 1, a time instant t_m should exist when

$$\exists\, t_m \quad V_i^o(t_m - t_0) - \frac{1}{2} a_r \cdot (t_m - t_0 - \delta_i)^2 = V_{i-1}^o(t_m - t_0) - \frac{1}{2}\eta \cdot (t_m - t_0 - \delta_{i-1})^2 + L_v \tag{22}$$

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

$$\Delta t_i = t_m - t_0 \tag{23}$$

$$l_i = V_i^o(t_m - t_0) - \frac{1}{2} a_e \cdot (t_m - t_0 - \delta_i)^2 \tag{24}$$

$$V_i^s = V_i^o - a_r \cdot (t_m - t_0 - \delta_i). \tag{25}$$

B. Simulation Results

The simulations are conducted using the network simulator (NS-2) [29] based on the collision model delineated in Section IV-A. The simulation parameters are listed in Table II. The transmission ranges of the vehicles and the minimum intervehicular distance are set to 150 and 10 m, respectively. The reason behind these choices is to have at least one SCH in a simulated cluster. As comparison terms, we adopt 1) a CCA system, which is based upon the IEEE MAC protocol that uses the exponential back-off algorithm for calculating contention windows of the vehicles [17] and 2) the absence of a CCA system, whereby the traditional reaction of drivers is considered to be the key factor in avoiding collisions.

We simulate two scenarios. In the first scenario, all vehicles move at a steady speed, and the intervehicle distance is chosen

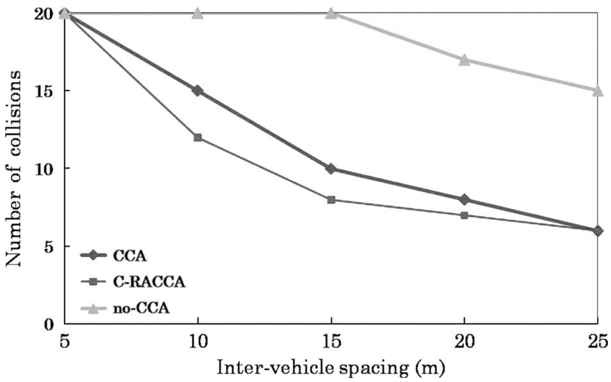

Fig. 8. Number of collided vehicles for different intervehicle distances (scenario 1, vehicle speed = 32 m/s).

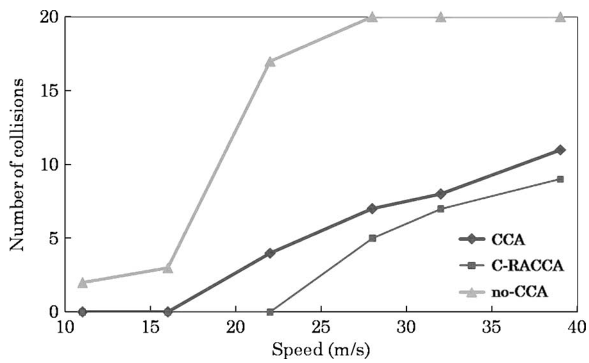

Fig. 9. Number of collided vehicles for different velocities of the cluster head (scenario 2).

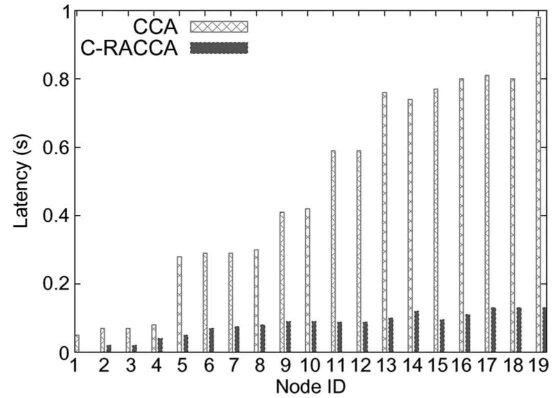

Fig. 10. Warning message delivery latency δ_i for each vehicle C_i (scenario 1, intervehicle distance = 15 m, vehicle speed = 32 m/s).

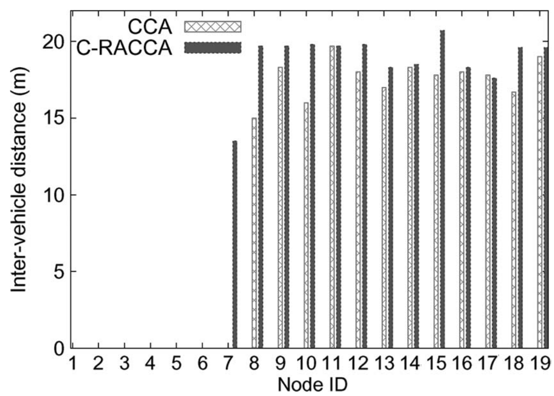

Fig. 11. Relative intervehicle distance $d_{i,i-1}$ after stop (scenario 1, intervehicle distance = 15 m, vehicle speed = 32 m/s).

from within the interval [10 m, 30 m]. On the other hand, in the second scenario, the intervehicle distance is arbitrarily selected from within the range [10 m, 30 m] for each pair of collocated vehicles. Each vehicle travels at varying speeds. The CH, which travels at the front of the cluster, moves at a speed that is selected from an interval [22 m/s, 42 m/s]. The velocities of the rest of the cars are carefully chosen not to cause collisions among them. An emergency situation is simulated by having the CH collide with a fixed object that compels the CH to slow down rapidly. Consequently, a number of warning messages are broadcast. The simulation results that we provide here are an average of multiple simulation runs.

The number of collisions for various intervehicle distances in the case of the proposed C-RACCA, CCA, and no-CCA systems are plotted in Fig. 8. It can be deduced from this figure that the number of collisions decreases as the intervehicle distance increases significantly. The results demonstrate that the C-RACCA scheme helps save many vehicles from colliding into others. Fig. 9 exhibits a similar performance in the case of scenario 2. As shown in this figure, the reduced number of vehicle collisions achieved by the C-RACCA approach, even when the CH travels at a reasonably high speed, in contrast with CCA and no-CCA systems, is attributable to its ability to swiftly inform the cluster members regarding the emergency situation. Fig. 10 sheds more light on this issue by indicating the fact that vehicles experience significantly high delays in delivering/receiving the warning messages in case of the traditional CCA system. It is worth stressing that these latencies also include the delay in receiving the first warning message. Indeed, in the proposed system, not all vehicles reforward the warning message. In fact, only the CH and SCHs do so. Fig. 10 also demonstrates that in the case of the CCA system, the ten last vehicles at the rear of the cluster experience a relatively longer time to disseminate the warning messages. The reason behind this is the occurrence of multiple MAC collisions owing to the concurrent delivery of warning messages by the first ten cars. On the contrary, the envisioned C-RACCA system ascertains that only the vehicle which encountered the emergency situation (e.g., the CH in our simulation scenarios) and/or SCHs are in charge of delivering the warning messages. This provision assists C-RACCA in avoiding message collisions. Consequently, a large number of vehicles receive the warning message in a relatively short latency. Indeed, this enables the vehicles to respond to the emergency situation in a swift manner.

The superior performance of the proposed C-RACCA scheme is further evident from Figs. 11 and 12. Fig. 11 exhibits that the relative intervehicle distances (after the vehicles have stopped) are longer in the case of the proposed C-RACCA scheme compared with the other naive approaches. It should be noted that in most cases, a significantly long relative distance between two adjacent vehicles C_i and C_{i+1} suggests that C_{i+1} responded rapidly to the emergency situation to achieve a sufficiently long distance from the vehicle ahead, i.e., C_i. This distance is of high importance in our evaluation due to the

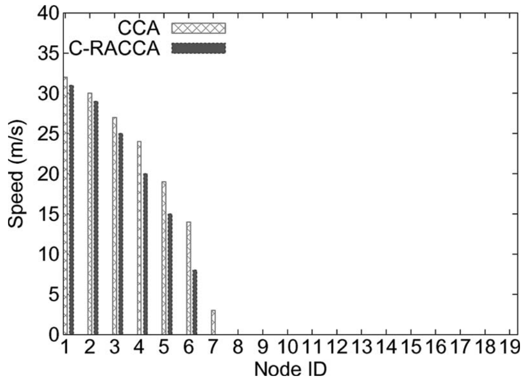

Fig. 12. Relative speed $V_{i,i-1}$ at the time of collision. In the absence of collision, $V_{i,i-1} = 0$ (scenario 1, intervehicle distance = 15 m, vehicle speed = 32 m/s).

fact that C_i may explode at the time of collision (e.g., due to fuel leakage and so forth). Additionally, Fig. 12 demonstrates another important feature of the C-RACCA system in terms of the smaller magnitude of the relative velocity of each vehicle at the time of collision. This mitigates the severity and impact of any collision.

V. Conclusion

In this paper, we have proposed an effective collision-avoidance strategy for vehicular networks that we refer to as the C-RACCA system. As it can be inferred from its name, the C-RACCA forms clusters of vehicles that belong to the same group. A number of features pertaining to the movements of the vehicles are taken into account to construct effective clusters. We envisioned a set of mechanisms to enable vehicles to join or depart from a specific cluster. Indeed, the clustering mechanisms lead to various heterogeneous clusters, i.e., multiple clusters with different sizes, independent cluster heads, and different numbers of subcluster heads.

The other contribution of the C-RACCA system lies in the fact that it enhances existing MAC protocols to ascertain relatively short latencies in disseminating warning messages after an emergency situation is detected. For each vehicle, an emergency level is defined based upon its order in the cluster with respect to the moving direction of the cluster. In the C-RACCA system, the warning message latency is calculated in such a manner that it is inversely proportional to the emergency level of the considered vehicle. This reflects the probability of the vehicle to encounter an emergency event in the cluster. The second rational lies in the fact that the latency estimation takes into consideration the velocities and intervehicle distances of adjacent vehicles and, thereby, manages to avoid colliding with each other.

Various simulations have been conducted in two unique scenarios to verify and compare the performance of the proposed C-RACCA system with those of the naive CCA and no-CCA approaches. The simulation results clearly exhibit the applicability of the C-RACCA approach in VANET environments since it reduces both the number of collisions and the impacts of collisions when they inevitably occur.

Admittedly, our work has considered a distribution with a predetermined skew factor (i.e., ω) to estimate the emergency levels of the vehicles that are used to compute the warning message delivery latency. However, in the future, further investigation regarding any possible correlation between the skew factor and the attributes of a specific cluster (in terms of its average intervehicle distance, average velocity, size, and so forth) is required. The relationship between the transmission ranges of the vehicles in a given cluster and the size of that cluster also needs further investigation. In addition, the impact of channel conditions on the delivery of warning messages and their overall impact on the C-RACCA's performance also deserve further studies. Furthermore, the management of intercluster communications may also open up interesting research scopes. These form some of our future research into this particular area of research.

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