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Safety Driving Support Using CDMA Inter-Vehicle Communications

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Although the near-far effect has been considered to be the major issue preventing CDMA from being used in ad-hoc networks, in this paper, we show that the near-far effect is not a severe issue in inter-vehicle networks for safety driving support, where packet transmissions are generally performed in the broadcast manner. Indeed, the near-far effect provides extremely reliable transmissions between near nodes, regardless of node density, which cannot be achieved by CSMA/CA. However, CDMA cannot be directly applied in realistic traffic accident scenarios, where highly reliable transmissions are required between far nodes as well. This paper proposes to apply packet forwarding and transmission scheduling methods that try to expand the area, where reliable transmissions are achievable. Simulation results show that the proposed scheme significantly excels a CSMA/CA-based scheme in terms of delivery ratio and delay under realistic traffic accident scenarios. Specifically, the proposed scheme achieves approximately 90% of delivery ratio and 4 milliseconds of end-to-end delay in a scenario, where the CSMA/CA scheme achieves 60% of delivery ratio and 80 milliseconds of delay.

1. Introduction

Safety driving applications can be divided into emergency warning support and situation awareness support [1)]. The emergency warning support targets situations such as an unexpected halt of a car due to an engine breakdown, where the broadcasting of an emergency message is triggered to avoid possible car crashes. The situation awareness support is, on the other hand, to provide drivers with an extended range of awareness beyond what drivers can immediately see, playing an important role in avoiding traffic accidents on poor-visibility roads, such as at intersections. In this case, vehicles periodically broadcast state messages that contain the vehicle's current state such as the location and the velocity. Both types of message are transmitted in the broadcast manner, and it is desirable that they are disseminated over a relatively large area [6)]. However, considering the application's task of avoiding car crashes, the messages have especial importance particularly for vehicles located in the vicinity of the message generator.

Due to lack of infrastructures, inter-vehicle communications are required to be performed in a distributed manner. As CSMA/CA (Carrier Sense Multiple Access with Collision Avoidance) [12)] is considered to be the *de-facto* channel access scheme for ad-hoc networks, much research on inter-vehicle networks [1)–11)] has been carried out targeting CSMA/CA. ARIB (Association of Radio Industries and Business) [10)], the ITS Forum under the Ministry of Internal Affairs of Japan, is also considering CSMA/CA as the channel access scheme for inter-vehicle communications. The CSMA/CA based system specified by ARIB targets operating with 10 mW transmission power using $\pi/4$ shift QPSK modulation, over 4.096 MHz spectrum spans in 5.8 GHz frequency band [10)]. However, it is well known that, with the increase of the node density, performances of CSMA/CA-based systems degrade in terms of delivery ratio and delay [5)]. On the other hand, Code Division Multiple Access (CDMA) [13)] provides delay free channel access. However, the use of CDMA for ad-hoc networks is considered to be difficult due to the near-far effect [14)], i.e., the situation, where a node is not able to correctly receive signals from an intended node due to a large interference induced by a nearer node(s). The near-far effect causes the problem especially for unicast packet transmissions that are usually performed between far nodes due to the shortest hop routing strategies. However, as previously noted, in inter-vehicle networks, transmissions are mainly performed in the broadcast manner, and furthermore, the messages have especial importance particularly for nodes in the vicinity of the message generator. This creates a quite different scenario than the one where unicast packet transmissions play the major role. In this paper, by comparing the fundamental characteristics of CSMA/CA and CDMA, we show that the near-far effect is not a severe issue for inter-vehicle communications which target safety driving support. Indeed, the near-far effect can provide extremely reliable transmissions between near nodes, regardless of node density,

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which is difficult to achieve with CSMA/CA. This feature motivates our research and development activities on a CDMA-based inter-vehicle system, called Multi-carrier Multi-code Spread Aloha (MM-SA) [15)–16)], which has the following attributes.

- MM-SA operates on several frequency channels so that vehicles receive packets over one channel while transmitting over the other.
- Each node is equipped with as many matched filters as the number of spreading codes for each frequency channel. With this capability, nodes can concurrently decode packets spread with different codes.

Although, providing reliable transmissions between near vehicles is an extremely attractive feature for inter-vehicle communications, MM-SA by itself cannot be directly applied in realistic traffic accident scenarios, where highly reliable transmissions are required between far nodes as well. In this paper, we propose packet forwarding and transmission scheduling methods that target expanding the area where reliable transmissions are achievable. Performance of the proposed scheme is investigated by a network simulator and compared against that of a CSMA/CA scheme. In what follows, we target dissemination of state messages that contain the message generator's ID, the timestamp indicating message generation time, the state information including the position, the moving direction, and the velocity of the message generator.

2. Fundamental Characteristics of MM-SA and CSMA/CA

Fundamental characteristics of CSMA/CA and MM-SA for a single frequency channel (4.096 MHz bandwidth) are compared using the Qualnet network simulator [17)] under the system parameters shown in **Table 1**. Note that the parameters of the CSMA/CA scheme are tuned to the ARIB specification. In MM-SA, 7-length Gold codes [18)] are used, and the random code selection procedure, i.e., a code is randomly selected from the whole set of spreading codes for a packet transmission, is applied. Following the ARIB specification, Turbo coding is applied to the CSMA/CA scheme. The sensitivity levels of the MM-SA and CSMA/CA schemes are set to −94.5 and −94.41 dBm, respectively, by taking account of the spreading gain for MM-SA and turbo coding gain for CSMA/CA. Performance comparison targets the topology illustrated in **Fig. 1**, where, vehicles are uniformly distributed on a 2-lane per direction intersection. In the simulation, each vehicle, except the one in the center of the intersection (Rx node), periodically generates state message of 140 bytes. The message generation period is set to 100 [ms] [11)]. At Rx node, the average delay and the delivery performances of the message transmissions from the remaining nodes (Tx nodes) are measured. **Table 2** compares the average delay for the different number of Tx nodes. The results show that, in the CSMA/CA scheme, average delay increases with the increase of the node density. On the other hand, due to its delay free channel access nature, MM-SA shows significantly short transmission delay, regardless of the node density.

Table 1 System parameters.

Parameters	MM-SA scheme	CSMA/CA scheme
Message length	140 bytes	
Frequency band	5.8 GHz	
Bandwidth (per channel)	4.096 MHz	
Transmit power	10 mW	
Antenna height	1.5 m	
Modulation type	$\pi/4$ shift QPSK	
Processing gain	7 (Gold code)	-
FEC	-	Turbo code 1/3
Contention window	-	[1,256]
Bit rate	585 Kbps	1,365 Kbps
Receive sensitivity level	−94.5 dBm	−94.41 dBm

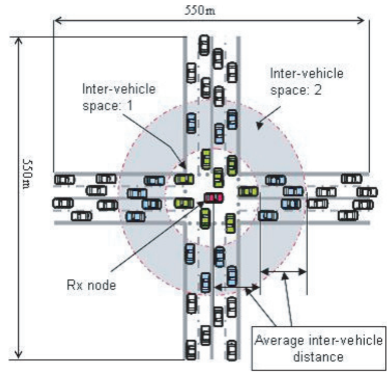


Fig. 1 Simulation topology used for performance comparison.

Figure 2 shows average delivery ratio vs. inter-vehicle space. Specifically, inter-vehicle space between a given Tx node and the Rx node is the rounded value of the distance between the Tx node and the Rx node normalized by the average inter-vehicle distance (see Fig. 1). Therefore, inter-vehicle space is the relative distance between the Tx node and the Rx node, indicating how far the Tx node is from the Rx node compared to the other Tx nodes. For instance, a Tx node with the inter-vehicle space of 1 is the closest node to the Rx node, and a Tx node with the inter-vehicle space of 4 has 3 nodes between itself and the Rx node regardless of the node density. The horizontal axis of the figure is expressed with inter-vehicle space, not with the absolute value of the inter-vehicle distance, in order to focus on the impact of the near-far effect. The figure shows that, in the CSMA/CA scheme, delivery ratio decreases with the increase of node density, without depending much on inter-vehicle space. On the other hand, MM-SA achieves almost 100% of delivery ratio when inter-vehicle space is 1, and the smaller delivery ratios for the larger inter-vehicle spaces, without depending on node density. This shows the fact that the near-far effect indeed provides an extremely attractive feature in CDMA systems. Specifically, regardless of how crowded the network is, successful transmission can be achieved between adjacent nodes. On the other hand, as the figure shows, CSMA/CA does not have this feature. However, it should be noted that, in CSMA/CA, if there are several concurrent transmissions, due to the capture effect, the receiver may receive the signal from the closest transmitter. Unfortunately, because the carrier sensing mechanism prevents several transmissions from being concurrently held, the capture effect is not significant. In Section 4 we enhance MM-SA with packet forwarding and transmission scheduling methods that exploit the positive impact of the near-far effect.

Table 2 Comparison of delay performance of each scheme.

The number of Tx nodes	100	200	300	400	500
CSMA/CA [ms]	4.9	72.4	133.6	168.3	193.9
CDMA [ms]	1.9	1.9	1.9	1.9	1.9

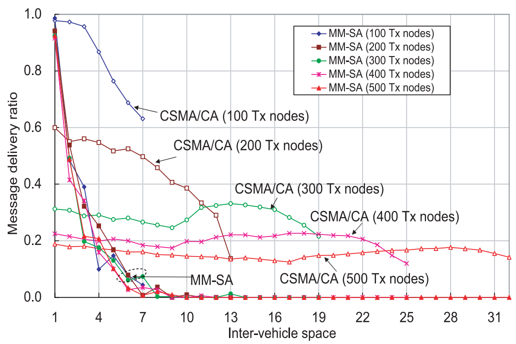


Fig. 2 Comparison of packet delivery performance.

3. Application Requirement of Realistic Traffic Accident Scenario

The Advanced Safety Vehicle (ASV) program [22] assisted by automotive manufacturers and the Ministry of Internal Affairs and Communications Ministry of Land, Infrastructure, Transport and Tourism, has been defining the needs and the requirements for various safety driving scenarios. Among the safety driving scenarios, an especial emphasis has been put on intersection collisions, such as encounter collision and right-turning collision, which cause a large number of fatalities each year. **Figure 3** and **Fig. 4** illustrate traffic accident scenarios where two vehicles, V1 and V2, are subject to encounter and right-turning collisions, respectively. ASV-4 requirement to inter-vehicle technologies for ensuring intersection collision avoidance is that state messages of V2 have to be received at V1

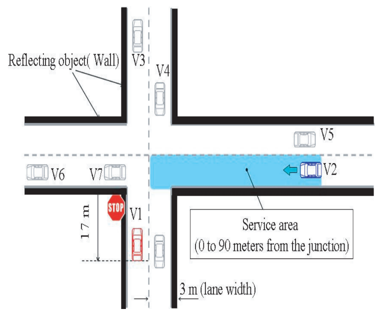


Fig. 3 Encounter collision scenario.

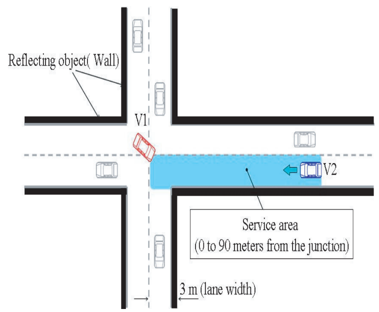


Fig. 4 Right-turning collision scenario.

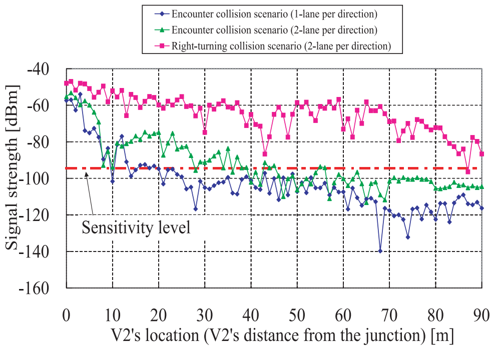


Fig. 5 Received signal strength at V1 from V2.

with larger than 80% of delivery ratio within 100 milliseconds from any location of V2 in the service area illustrated in the Figs. 3 and 4. In what follows, we call the application requirement set by ASV-4 the ASV requirement.

In realistic road environments, reflecting objects tend to degrade the quality of the receiving signal, due to interference induced by multipath signal propagation. Assuming reflecting objects (walls) at each corner of the intersection, the received signal strength at V1 from V2 for encounter collision and right-turning collision scenarios is estimated using the ray-tracing model [13]. Here, antenna height at vehicles is set to 1.5 meters and road lane width is 3 meters. **Figure 5** shows the estimated received signal strength, where the horizontal axis is V2's location in the service area. As the figure shows, for the right-turning collision scenario, because there is a line of sight path between V2 and V1, the receive signal strength at V1 from V2 is above the sensitivity level from any point in the service area, except 87 meters. Note that, as Table 1 shows, the difference in the sensitivity levels of the MM-SA and CSMA/CA systems is very small, therefore, the sensitivity levels for both the schemes are depicted with the same line in the figure. On the other hand, the receive signal strength is quite weak for the encounter collision scenario. Specifically, the received signal strength takes values below the sensitivity level, when V2 is farther than 20 and 40 meters from the junction for the 1- and 2-lane scenarios, respectively. Obviously, neither MM-SA nor CSMA/CA can satisfy the ASV requirement. On the other hand, due to the line of sight paths between V1 and interfering vehicles that are on the same road as V1, the amount of interference is quite large. For example, the signal strength at V1 from V3, which is 90 meters from the junction (see Fig. 3), is −83.8 dBm in the 1-lane scenario. Clearly, the greater the number of interfering vehicles, the larger the interference is, causing MM-SA to have difficulty in satisfying the ASV requirement. On the other hand, in CSMA/CA, V3 and V2 might become hidden terminals due to the shadowing induced by the reflecting objects. The above results motivate us to enhance MM-SA with the following mechanisms.

- Packet forwarding and transmission scheduling: By applying simple packet forwarding and transmission scheduling methods, we enhance MM-SA so that vehicles' state messages can be effectively disseminated over a relatively large area. The methods will be introduced in the next section.
- Topology aware channel assignment: As Fig. 5 shows, reflecting objects largely degrade signal quality. Due to this issue, we apply a simple channel assignment rule that maps vehicles' moving directions to frequency channels, over which the vehicles should transmit their state messages. Specifically, assuming four frequency channels are available, the moving direction in ±45° around the north is mapped to a channel, e.g., f1, and the moving direction ±45° around the west is mapped to a channel, e.g., f2, and so forth. The above rule results in vehicles V1, V2, V4, and V5 in Fig. 3 transmitting their messages over different channels. Although, a vehicle's selected channel fluctuates on a curved road, it does not severely hamper its utility, noting that the fluctuation time scale is relatively large and that our concern is the relative difference in vehicles' moving directions. In what follows, we assume that MM-SA operates under the above channel assignment rule.

4. MM-SA Packet Forwarding and Transmission Scheduling

In order to enable message dissemination over a relatively large area, we propose to enhance MM-SA with packet forwarding and transmission scheduling methods.

4.1 Packet Forwarding

Because a simple flooding scheme suffers from a so called broadcast storm problem, a number of approaches have been proposed to enhance its performance in CSMA/CA networks. Those approaches can be grouped as probability based, area based, and neighbor knowledge based approaches [23]. In the probability based approach, nodes rebroadcast packets with some probability, while in the area based approach, each node decides whether or not to rebroadcast packets based on the additional coverage area induced by its transmissions. The neighbor knowledge based approach requires nodes to explicitly specify the next hop forwarders of the packet. The authors of Ref. 23) compared the characteristics of each approach and showed that, in CSMA/CA networks, the neighbor knowledge based approach is sensitive to nodes' mobility, while the probability based and area based approaches are sensitive to node density. Because the impact of nodes' mobility does not depend much on the channel access method, we can expect that the neighbor knowledge based approach is sensitive to nodes' mobility in MM-SA networks as well. On the other hand, Section 2 teaches us that CSMA/CA plays a major role for a system that is sensitive to node density. Hence, we expect different characteristics from the probability based and the area based approaches in MM-SA networks.

We believe that the area based forwarding approach would be more fitting for safety driving applications, because the messages have especial importance for vehicles in a certain area w.r.t the message generator. For example, as can be seen in Fig. 3, a state message has greater importance for vehicles that are in the preceding area of the message generator. On the other hand, an emergency message generated due to an unexpected halt of a car has greater importance for the vehicles behind the message generator [9]. Hence, we apply an area-based forwarding method to MM-SA, where the forwarding area of a message is determined based on the message type and the location of the message generator. For state messages, the forwarding area can be set to X [m] × Y [m], i.e., the area starting from the message generator's location and extending to X meters along its moving direction. When a vehicle receives a state message, it checks the message generator's location and determines if it is in the forwarding area of the current message. Furthermore, in order to suppress the number of forwarding nodes, moving directions of vehicles can also be taken into account. In this case, the message is forwarded by the vehicles that are in the forwarding area and in the same moving direction as the message generator. In order not to induce unnecessary forwarding latency, as soon as the vehicle determines that the

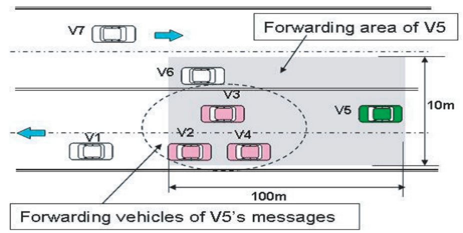


Fig. 6 Illustrating MM-SA forwarding method.

forwarding conditions are met, it rebroadcasts the message over the frequency channel where it received the message. **Figure 6** illustrates an example where the forwarding area is set to 100 [m] × 10 [m]. In the figure, while V2, V3, V4, and V6 are in the forwarding area of V5's message, V5's message is forwarded by V2, V3, and V4, taking vehicles' moving directions into account.

4.2 Transmission Scheduling

In order to effectively exploit CDMA's feature of providing reliable transmissions between near nodes (see Fig. 2), we have to make sure that each node "listens" to its near nodes when they are transmitting. By doing this, and together with the packet forwarding method, we expand the area where reliable transmissions are achievable. The self-interference and the near-far effect can prevent near nodes from listening to each other. Let us say that in Fig. 6, V3 transmits a packet at the same time as V5 transmits its state message. In this case, due to a large amount of self-interference, V3 cannot receive V5's message. Furthermore, due to a large interference induced by V3, V2 and V4 may not be able to receive V5's message, preventing V5's message from being disseminated. This is an example where the near-far effect adversely affects message dissemination. Obviously, the above problems occur when near nodes concurrently transmit different messages. We propose to avoid those problems by a transmission scheduling method. The method controls vehicles' message generation time in such a way that vehicles that concurrently transmit their own messages are located as far as possible from each other. This objective can be achieved by having each vehicle generate its state message $C \times \Delta T$ later than the message generation time at its adjacent vehicle in front. Here, ΔT is the packet transmission time and C is a constant, whose value is larger than 2. Specifically, C = 0 implies that two adjacent vehicles transmit their own messages at the same time causing the self-interference to become a problem. On the other hand, C = 1 implies that, in Fig. 6, at the same time as V5 transmits its own message, V3 forwards V4's message that is broadcast by V4 ΔT ago, causing the near-far effect to become a problem.

Thanks to the on-board GPS system in each vehicle, the transmission scheduling method can be easily realized as follows. The periodical broadcasts of state messages enable each vehicle to determine its adjacent vehicle in front. Furthermore, the timestamp value contained in the message enables the vehicle to adjust its message generation time.

Figure 7 illustrates an example of the timing flow of packet transmission and forwarding operations of state messages generated at V3, V4, and V5 shown in Fig. 6, when C = 3. Here, the numbers in the brackets indicate the message generators' IDs, and the numbers preceding the brackets indicate IDs of the vehicles transmitting the message. The above transmission scheduling method aims to control interference by having vehicles that concurrently transmit their own messages to be located as far as possible. For example, if the message generation period and the transmission time of a packet is 100 and 2 milliseconds, respectively, by setting C to 3, we have approximately 15 vehicles positioned in between the vehicles that concurrently transmit their own state messages. As Fig. 7 shows, forwarding of a message might be concurrently performed by several vehicles that are near to each other. However, it will not cause much problem, because the packets contain the same message, so that it is enough if at least one of the forwarded packets is successfully received at the next hop vehicle. It should be noted that, because each vehicle individually schedules its transmission solely based on information from the adjacent vehicle in front, the transmission scheduling method is performed in a totally distributed manner. Added to this, in MM-SA, at each vehicle, packets arrive in an asynchronous manner. For example, when V4 transmits its state message (see Fig. 6), due to the difference in the propagation delays on the different paths, V3 and V2 do not receive the message at exactly the same time, and therefore, the packet forwarding at V3 and V2 is not performed at exactly the same time. This implies that, in Fig. 7, the packets indicated as 3(4) and 2(4) arrive at a vehicle, e.g., V1, with the time difference that is at least equal to the difference in the propagation delays on the paths V4→V3→V1 and V4→V2→V1. If the difference between the paths is, e.g., 100 meters, the packets arrive at V1 with 100/c = 0.34 μs of inter-arrival time difference (here, c is the speed of light).

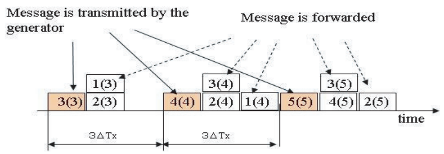


Fig. 7 Illustrating MM-SA transmission scheduling method.

5. Simulation

Using Qualnet network simulator [17], the characteristics of MM-SA schemes, called MM-SA, MM-SA_Fwr, MM-SA_Fwr_TS (see **Table 3**), are compared against the CSMA/CA scheme for encounter and right-turning collision scenarios shown in Figs. 3 and 4. As Table 3 shows, MM-SA refers to the basic MM-SA scheme without being enhanced by the packet forwarding and the transmission scheduling methods. On the other hand, MM-SA_Fwr is the MM-SA scheme with the area based packet forwarding method, and MM-SA_Fwr_TS is the MM-SA scheme with the area based packet forwarding and the transmission scheduling methods. The system parameters in Table 1 are used for each scheme. For fair comparisons, the area based packet forwarding is also applied to the CSMA/CA scheme. Furthermore, the topology aware channel assignment rule is applied to each scheme, assuming four frequency channels are available. In the area based packet forwarding, the forwarding condition is the same as shown in Fig. 6, where the forwarding area is 100 [m] × 10 [m], and vehicles' moving directions are taken into account. The parameter C for the transmission scheduling is set to 3.

Table 3 Attributes of individual schemes.

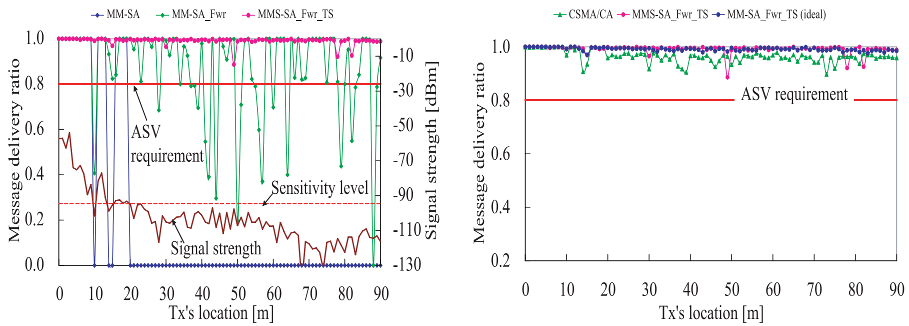
	MM-SA	MM-SA_Fwr	MM-SA_Fwr_TS	CSMA/CA
Channel access	CDMA			CSMA/CA
Packet forwarding	-	Section 4.1		
Scheduling	-	-	Section 4.2	-

In the simulations, vehicles are uniformly distributed along each lane of the road. The average antenna-to-antenna distance between two adjacent vehicles on the same lane is calculated using the method introduced in Ref. 22), where the average velocity of vehicles is taken into account. The minimum antenna-to-antenna distance between two adjacent vehicles on the same lane is 7 meters, which is the sum of 5 meters of a vehicle length and 2 meters of inter-vehicle distance. Furthermore, the message generation interval at each vehicle is set by using the table introduced in Ref. 10), where a vehicle's velocity is converted to the message generation interval at the vehicle. Assuming reflecting objects (walls) to be at each corner of the intersection, signal propagation is estimated using the ray-tracing model. In the simulations, the average delivery ratio, the average number of hops, and the average end-to-end delay for packet transmissions from the subject vehicle V2 are measured at V1 (see Figs. 3 and 4). Throughout the rest of the paper, we describe V2 as Tx and V1 as Rx. For each location of Tx in the service area, the results over 5 runs of 30 seconds simulations are averaged, where at each run, locations of all the vehicles, other than Tx and Rx, are determined randomly.

In the simulations, GPS positioning and synchronization errors are taken into account as follows. At t coordinated universal time (UCT), a vehicle's clock shows $t+\Delta t$ and its location is $[x+\Delta x,\ y+\Delta y]$, where $[x,\ y]$ is the correct location of the vehicle, Δt is a random value taken from the range $[-1,\ 1]$ microseconds [19], and Δx and Δy are random values taken from the range $[-3,\ 3]$ meters [20]. Because the packet forwarding method uses location information, and the transmission scheduling method uses location and timing information, GPS positioning and synchronization errors are applied to MM-SA_Fwr and MM-SA_Fwr_TS. Furthermore, to see the impact of GPS errors, MM-SA_Fwr_TS scheme is also evaluated for the case, where positioning and synchronization errors are assumed to be negligible, i.e., $\Delta t = 0$ and $\Delta x = \Delta y = 0$ (Let MM-SA_Fwr_TS (ideal) represent this version of MM-SA_Fwr_TS).

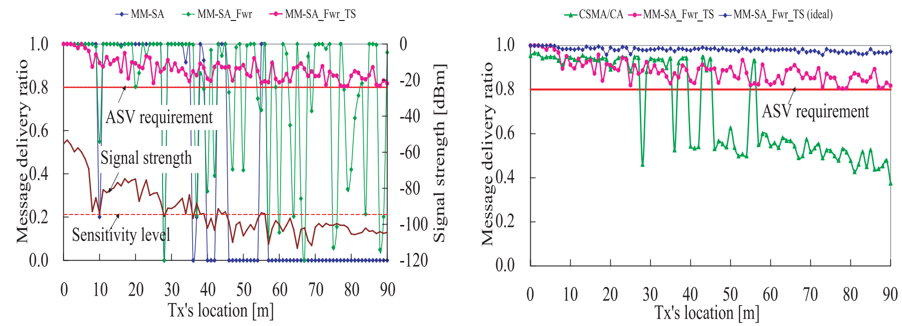
5.1 Simulations for Encounter Collision Scenario

Assuming that the vehicles on the prioritized road (see Fig. 3) run at approximately 70 km/h, the average antenna-to-antenna distance between two adjacent vehicles on the same lane is 19.4 meters, and the message generation interval at vehicles is 100 milliseconds. The number of lanes per-direction is set to 1 and 2, where the total number of vehicles is 88 and 176, respectively. According to ASV [22], inter-vehicle communications systems are required to provide sufficient delivery performance (see Section 3), when the number of vehicles is at least 88.



a) MM-SA, MM-SA_Fwr, and MM-SA_Fwr_TS
b) CSMA/CA, MM-SA_Fwr_TS, and ideal MM-SA_Fwr_TS

Fig. 8 Comparing delivery performances for encounter collision scenario (88 vehicles).



a) MM-SA, MM-SA_Fwr, and MM-SA_Fwr_TS
b) CSMA/CA, MM-SA_Fwr_TS, and ideal MM-SA_Fwr_TS

Fig. 9 Comparing delivery performances for encounter collision scenario (176 vehicles).

Figures 8 and **9** compare the delivery ratios of individual schemes for encounter collusion scenarios with 88 and 176 vehicles, respectively. Each figure consists of two subfigures, a) and b). Subfigures a) compare the performances of the basic MM-SA, MMSA_Fwr, and MM-SA_Fwr_TS and, the performances of MM-SA_Fwr_TS, MM-SA_Fwr_TS (ideal), and CSMA/CA are compared in subfigures b)). As a reference, the receive signal strength at Rx from Tx and the sensitivity level are also shown in the figures. As can be seen in Figs. 8 a) and 9 a), the delivery ratio of the basic MM-SA takes on zero, when Tx is at the locations, where the signal strength is below the sensitivity level, showing the importance of the packet forwarding in realistic road environments. The results of MMSA_Fwr (see subfigures a)) and CSMA/CA (see subfigures b)) show the impacts of packet forwarding when the underlying channel access method is CDMA and CSMA/CA, respectively. Although MM-SA_Fwr shows better performance than that of the basic MM-SA, it fails to satisfy the application requirement for both the scenarios. Conceivably, this is due to the negative effect of the self-interference and the near-far effect (refer to Section 4.2). On the other hand, while the CSMA/CA scheme provides a satisfying performance for the 88-vehicle scenario (see Fig. 8 b)), for the 176-vehicle scenario, the delivery ratio falls down to 60%, failing to meet the application requirement (see Fig. 9 b)). As we saw in Section 2, this is due to the fundamental characteristics of CSMA/CA, i.e., CSMA/CA suffers from performance degradation with the increase of the number of nodes.

Now let us compare the delivery performances of MM-SA_Fwr_TS and MM-SA_Fwr_TS (ideal). Before getting into the details, it should be noted that in the simulations, we could not see a noticeable impact from the GPS synchronization error. In fact, because the synchronization error provides at most 2 microseconds of time difference at two vehicles, the transmission scheduling error is at most 2 microseconds. However, because $C \times \Delta T$ in the transmission scheduling method is 6 milliseconds, which is much larger compared to 2 microseconds of error, there is no noticeable impact. On the other hand, as the simulation results show, performances of the proposed scheme can be degraded due to the positioning error. As Fig. 8 b) shows, the delivery ratio of MM-SA_Fwr_TS is as high as that of MM-SA_Fwr_TS (ideal) for the 88-vehicle scenario. However, for the 176-vehicle scenario (see Fig. 9 b)), MM-SA_Fwr_TS (ideal) shows at most 20% higher delivery ratio than that of MM-SA_Fwr_TS. The reason behind this is as follows. The transmission scheduling method is sensitive to positioning error, because each vehicle regards its adjacent vehicle in front as a reference vehicle, and schedules its transmission based on the message generation time at the reference vehicle. The

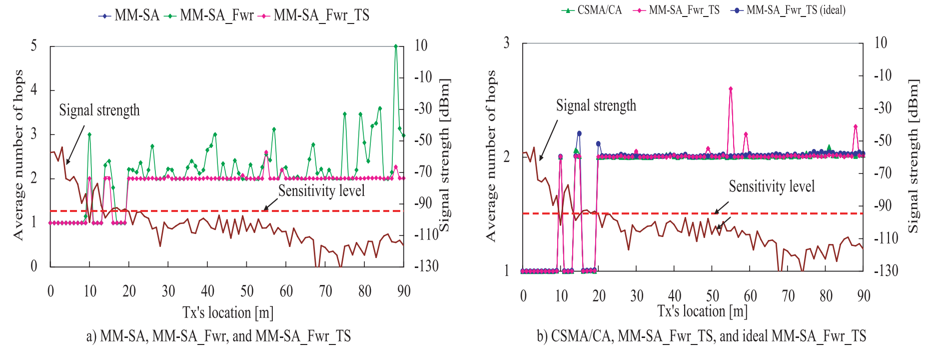
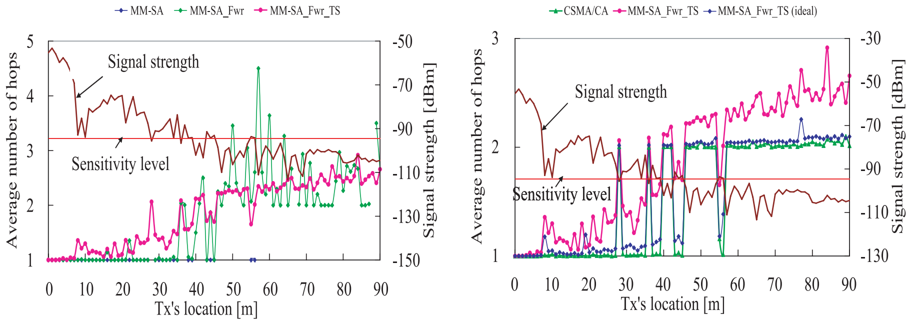


Fig. 10 Comparing average number of hops for encounter collision scenario (88 vehicles).

situation becomes problematic, if due to the positioning error, locations of two adjacent vehicles are "swapped" in their moving direction, causing the reference vehicle to frequently change. In this case, vehicles unnecessarily and frequently re-schedule their transmissions, preventing the transmission scheduling method from showing its optimal performance. However, with at most ±3 meters of positioning error, the locations of two adjacent vehicles will not be swapped if their antenna-to-antenna distance in their moving direction is larger than 6 meters. This explains why the 88-vehicle scenario is not affected much by the positioning error, because it has a 1-lane per direction road where the minimum antenna-to-antenna distance is 7 meters. On the other hand, in the 176-vehicle scenario, because it has 2-lane per direction, the minimum antenna-to-antenna distance can be 0 meters (two vehicles are exactly next to each other) in their moving direction, so that the performance is affected by the error. However, Fig. 9 b) shows that even with positioning error, MM-SA_Fwr_TS achieves the best performance among the schemes, showing the effectiveness of the combined operation of the transmission scheduling and the packet forwarding methods.

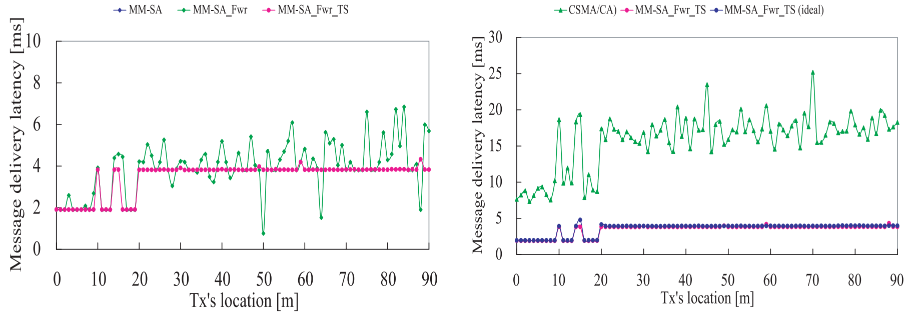
Figures 10 and **11** compare the average number of hops of individual schemes. Note that the number of hops is 1 if Rx receives the message directly from Tx. Because packet forwarding is not performed in the basic MM-SA, the average number of hops is 1 at the points where the receive signal strength is above the sensitivity level, otherwise, it is invalid. The figures show that CSMA/CA and



a) MM-SA, MM-SA_Fwr, and MM-SA_Fwr_TS

b) CSMA/CA, MM-SA_Fwr_TS, and ideal MM-SA_Fwr_TS

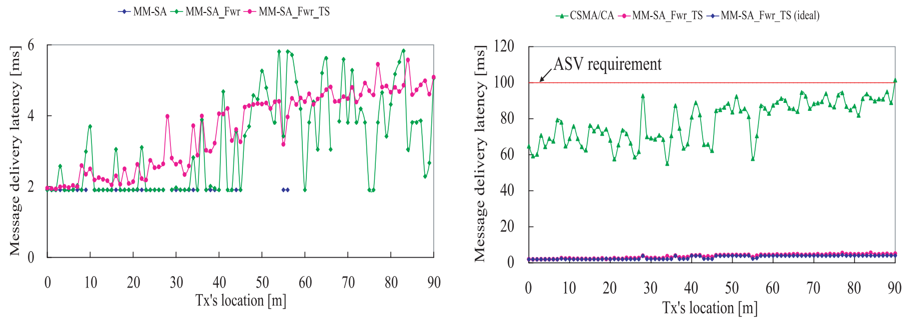
Fig. 11 Comparing average number of hops for encounter collision scenario (176 vehicles).



a) MM-SA, MM-SA_Fwr, and MM-SA_Fwr_TS

b) CSMA/CA, MM-SA_Fwr_TS, and ideal MM-SA_Fwr_TS

Fig. 12 Comparing delay performances for encounter collision scenario (88 vehicles).



a) MM-SA, MM-SA_Fwr, and MM-SA_Fwr_TS

b) CSMA/CA, MM-SA_Fwr_TS, and ideal MM-SA_Fwr_TS

Fig. 13 Comparing delay performances for encounter collision scenario (176 vehicles).

MM-SA_Fwr_TS (ideal) show a quite identical number of hops for both scenarios. Specifically, the number of hops is 1, i.e., Rx could receive messages directly from Tx, at the points where the receive signal strength is above the sensitivity level. On the other hand, if the receive signal strength is below the sensitivity level, the number of hops is 2, regardless of the Tx's location in the service area. This is because, Tx has a line of sight paths with vehicles that are near the junction so that can reach Rx with 1 hop. Therefore, from any location of Tx in the service area, its messages could reach Rx with 2 hops, by being forwarded once at those vehicles. Compared to MM-SA_Fwr_TS, MM-SA_Fwr shows a larger number of hops. This is due to uncontrolled self-interference and near-far effect, preventing Tx from being able to directly communicate with the vehicles that can reach Rx with 1 hop. Finally, Fig. 11 b) shows that MM-SA_Fwr_TS shows larger number of hops than that of MM-SA_Fwr_TS (ideal) for the 176-vehicle scenario. Similarly, this is because the transmission scheduling could not be performed in the optimal way (due to the positioning error), preventing Tx from being able to directly communicate with vehicles that can reach Rx with 1 hop.

Figures 12 and **13** compare the delay performances of individual schemes for 88- and 176-vehicle scenarios, respectively. The figures show that compared to CSMA/CA, MM-SA schemes show significantly shorter end-to-end delay. In MM-SA schemes, the vehicles can access the channel and transmit messages at any time they need to do so. Therefore, the major component of end-to-end delay is the time for the message to be transmitted over the channel. This results in, for example, 4 milliseconds of end-to-end delay for 2 hops of transmission. On the other hand, in CSMA/CA, the end-to-end delay is quite large taking on at most 20 and 100 milliseconds for 88- and 176-vehicle scenarios, respectively. This is because, in CSMA/CA, vehicles have to access the channel in turn, causing messages to be kept long in the outgoing queues of the vehicles.

5.2 Simulations for Right-Turning Collision Scenario

The simulation model for the right-turning collision scenario is depicted in **Fig. 14**. Without much loss of generality, we assumed that the average velocity of

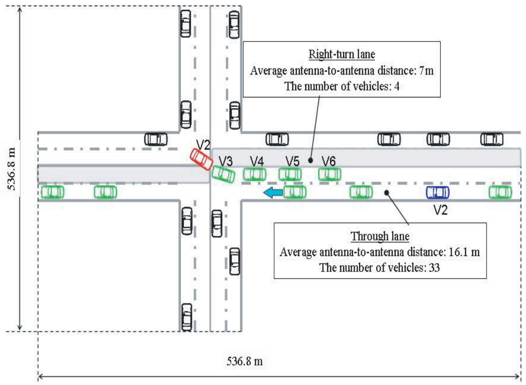
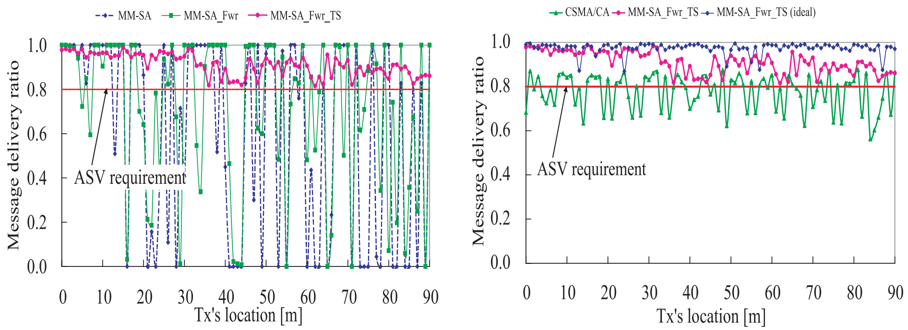


Fig. 14 Simulation topology for right-turning collision scenario.

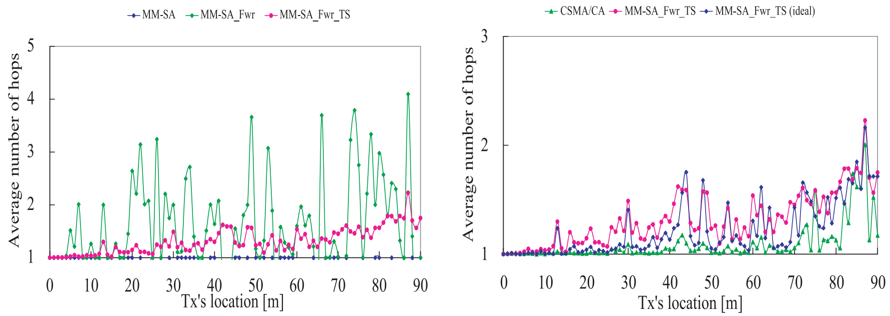


a) MM-SA, MM-SA_Fwr, and MM-SA_Fwr_TS b) CSMA/CA, MM-SA_Fwr_TS, and ideal MM-SA_Fwr_TS

Fig. 15 Comparing delivery performances for right-turning collision scenario.

straight-through vehicles, such as V2, is approximately 40 km/h, and the velocity of the right-turning vehicles, such as V3, is approximately 0 km/h. Considering the vehicles' speed, the average antenna-to-antenna distance and the message generation interval are set to 16.1 meters and 200 milliseconds for the straight-through vehicles, and 2 meters and 1.2 seconds for the right-turning vehicles, respectively.

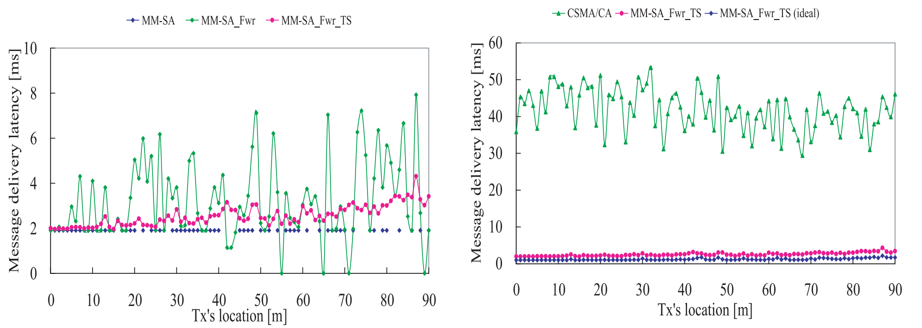
Figure 15 compares the delivery ratio of individual schemes. As the figure shows, the delivery ratio of the basic MM-SA is quite poor. Furthermore, MM-SA_Fwr does not show a better performance. The reason behind this is as follows. As Fig. 5 shows, the receive signal strength at Rx from Tx for the right-turning collision scenario is above the sensitivity level for any point in the service area except 87 meters. Therefore, basically, packet forwarding is not required much for the right-turning collision scenario, and thus, the forwarding method alone cannot improve the performance of the scheme. In fact, uncontrolled self-interference and the near-far effect is the major reason for the schemes having poor performance. Similar to the results for the encounter collision scenario, due to the GPS positioning error, the delivery ratio of MM-SA_Fwr_TS is at most 20% lower than that of MM-SA_Fwr_TS (ideal) (see Fig. 15 b)). However, because the transmission scheduling method mitigates the negative impacts of self-interference and the near-far effect, MM-SA_Fwr_TS provides sufficient delivery performance. Finally, CSMA/CA shows a better delivery performance than the basic MM-SA and MM-SA_Fwr, but it fails to satisfy the application requirement due to its channel access feature.



a) MM-SA, MM-SA_Fwr, and MM-SA_Fwr_TS b) CSMA/CA, MM-SA_Fwr_TS, and ideal MM-SA_Fwr_TS

Fig. 16 Comparing average number of hops for right-turning collision scenario.

Figure 16 compares the average number of hops of individual schemes. MM-SA_Fwr shows a larger number of hops compared to the remaining schemes. This is because, due to uncontrolled strong interference, the area covered by 1-hop transmission is very small, resulting in many hops to cover the forwarding area. One could expect that, for the right-turning collision scenario, packet forwarding is not required especially, for CSMA/CA. However as the results show, indeed



a) MM-SA, MM-SA_Fwr, and MM-SA_Fwr_TS

b) CSMA/CA, MM-SA_Fwr_TS, and ideal MM-SA_Fwr_TS

Fig. 17 Comparing delay performances for right-turning collision scenario.

more than 1 hop transmission is required when Tx is approximately 70 meters or farther from the junction in CSMA/CA. Conceivably, the reason is the hidden terminal problem that prevents Rx from successfully receiving messages from Tx at these points in the service area. On the other hand, in MM-SA_Fwr_TS, the number of hops is larger than 1 when Tx is approximately 20 meters or farther from the junction, showing packet forwarding was necessary. Finally, Fig. 16 b) shows that due to positioning error, MM-SA_Fwr_TS shows a slightly larger number of hops than that of MM-SA_Fwr_TS (ideal).

Figure 17 compares the delay performances of individual schemes. While, all of the schemes satisfy the application requirement, the figure shows that compared to MM-SA schemes, CSMA/CA is characterized by a much longer delay because of its channel access feature.

6. Related Work

A significant number of activities for safety driving support is underway, including the Intelligent Vehicle Initiative (IVI) [2] project in the United States, the e-Safety [3] project in the European Union, and the ITS Forum in Japan [10]. Furthermore, a large number of research papers have appeared in the literature [1)–9)], assuming CSMA/CA is the underlying medium access control protocol. Reference 4) provides a tutorial review of the DSRC (dedicated short-range communications) standard medium access control protocol for inter-vehicle communications. Reference 1) shows how strongly the hidden terminal problem affects broadcast transmissions in CSMA/CA systems, preventing inter-vehicle communications from being able to satisfy the requirements for safety driving support. Reference 5) presents simulations on inter-vehicle communications system where the underlying MAC is the IEEE 802.11p, the upcoming standard for vehicular communications, and showed that IEEE 802.11p channel access cannot be granted in a manner that is sufficiently predictable to support reliable, low-delay communications between vehicles on a highway.

A number of efforts have been made on message forwarding for CSMA/CA inter-vehicle communications [6)–9)]. Reference 6) introduces two packet forwarding methods, called TRADE (TRAck Detection) and DDT (Distance Differ Transmission). In TRADE, nodes approximate road condition by comparing their neighboring nodes' positions and choose candidate nodes from each road for next-hop forwarding. While it is attractive to take road structure into account, as Section 3 shows, the signal characteristics in realistic road environments can be quite poor, preventing nodes from successfully exchanging their position information. On the other hand, DDT is a probability based approach, where the message forwarding probability at a node is a function of the distance between the node and the previous hop node. Reference 7) proposes a similar approach to DDT, called LCN (Least Common Neighbor). Targeting the cases where GPS position information is not available, in LCN, the destination between the node and the previous hop node is estimated by the number of common nodes they share. Reference 8) proposes a similar approach to DDT and LCN, except that the congestion condition is also taken into account for a forwarding decision. DDT, LCN and Ref. 8) share the same idea that it is always better if the message is forwarded by the farthest node from the previous hop node. However, we argue that it is not the best solution in realistic road environments. For example, let us imagine that the above approach is applied to the encounter collision scenario shown in Fig. 3 and V2's message is received at V6 and V7. Since V6 is the farthest node, it forwards the message and V7 simply drops the message. However, due to the reflecting objects, the received signal strength at V1 from V6 might be too low, preventing V1 from receiving the message.

Reference 9) targets the dissemination of emergency information such as emergency-vehicle-approach, and traffic-accident-avoidance over CSMA/CA inter-vehicle networks. Similar to our forwarding method, the scheme in Ref. 9) broadcasts messages in a particular area where the information is needed. The authors built an experimental system and showed that the system could successfully limit the broadcast area.

In the concept of transmission scheduling, Ref. 24) proposes a scheme, where transmissions at each node on a chain topology are scheduled in such a way that the exposed terminal problem is mitigated in CSMA/CA networks. The scheme is highly elaborated and attractive in that it prevents throughput degradation when the number of hops is increased. Because Ref. 24) targets different types of network and traffic models (i.e., unicast traffic), a number of differences exist between Ref. 24) and our transmission scheduling method. Because, node density has to be taken into account for CSMA/CA networks, in Ref. 24), a centralized transmission scheduling is performed with an excessive control overhead. Specifically, one of the edge nodes controls transmissions at every other node in the network, by transmitting control information over a dedicated control channel. On the other hand, because our transmission scheduling targets the near-far effect that does not depend on node density, it is achieved in a distributed manner without incurring any control overhead.

7. Conclusion

In this paper, we showed that the near-far effect is not a severe issue in inter-vehicle networks for safety driving support, where broadcasting is the major form of transmissions and reliable transmissions between adjacent nodes have a higher priority. In fact, the near-far effect provides extremely reliable transmissions between near nodes, regardless of node density, which cannot be provided by the CSMA/CA scheme. This feature motivates our research and development activities on a CDMA-based inter-vehicle system, called Multi-carrier Multi-code Spread Aloha (MM-SA). However, reliable and low latency transmission between near nodes is not sufficient for realistic traffic accident scenarios, where highly reliable transmissions between far nodes are required as well. To overcome this issue, we proposed to apply packet forwarding and transmission scheduling schemes that target expanding the area where reliable transmissions are achievable. We investigated the performance of the proposed scheme through simulations, where realistic road environments and GPS positioning and synchronization errors are taken into account. The simulation results showed that the proposed scheme significantly excels a CSMA/CA scheme in terms of delivery ratio and delay under realistic traffic accident scenarios. Specifically, in 176-vehicle scenario for encounter collision, MM-SA achieves approximately 90% of delivery ratio and 4 milliseconds of end-to-end delay, while CSMA/CA achieves 60% of delivery ratio and 80 milliseconds of delay. Furthermore, for the right-turning collision scenario, MM-SA achieves approximately 90% of delivery ratio and 4 milliseconds of end-to-end delay, while the CSMA/CA scheme achieves 80% of delivery ratio and 40 milliseconds of delay. Ongoing work seeks to propose a mechanism whose performance is not affected much by GPS positioning error. Furthermore, in our future work, we will make simulations targeting larger than 3 meters of positioning error that may exist due to shadowing and multi-path fading effects.

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