A Joint Vehicle-Vehicle/Vehicle-Roadside Communication Protocol for Highway Traffic Safety

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Abstract

In this paper, a joint vehicle-vehicle/vehicle-roadside communication protocol is proposed for cooperative collision avoiding in Vehicular Ad Hoc Networks (VANETs). In this protocol, emergency warning messages are simultaneously transmitted via Vehicle-to-Vehicle (V2V) and Vehicle-to-Roadside (V2R) communications in order to achieve multipath diversity routing. In addition, to further improve communication reliability and achieve low-latency, a Multi-Channel (MC) technique based on two non-overlapping channels for Vehicle-Vehicle (V2V) and V2R (or R2V) is proposed. The simulation results demonstrate that the proposed joint V2V/V2R (R2V) communication protocol is capable of improving the message delivery ratio and obtaining low-latency, which are very important merits for highway traffic safety.

Index Terms

Vehicular ad hoc netwroks, broadcast protocols, Vehicle-Vehicle, Vehicle-Roadside, AODV.

I. Introduction

Every year thousands of deathes occur due to traffic accidents, about 60 percent of which could be avoided if drivers were provided with a warning at least one-half second prior to a collision [1]. Because of perception limitations, vehicle drivers cannot react in time to emergency events, hence resulting in a long delay in delivering warning messages and potential automobile crashes (especially multicar chain accidents). As stated in [2], perception limitations are mainly caused by the line-of-sight limitations of brake lights and driver reaction to it, which typically ranges from 0.7 to 1.5 seconds. Aimed at a reduction of vehicular fatalities, Intelligent Transportation Systems (ITS) applications, such as emergency message communication protocols, have been developed to substantially reduce the delay in propagating emergency messages. In July 2003, the Dedicated Short Range Communication (DSRC) standard [3] is adopted by the American Society for Testing and Material (ASTM) standardization committee to support public safety and non-safety applications, where safety messages have higher priority [4]. DSRC is a short to medium range wireless protocol specifically designed for vehicles at typical highway speeds, including V2V and V2R (R2V) communications.

Previous research for V2V communications has focused on two main areas, namely Medium Access Control (MAC) and message forwarding. Although IEEE 802.11 MAC is considered the de facto MAC protocol for DSRC [5], other protocols, such as Time Division Multiple Access (TDMA)-based slotted MAC protocols has also been proposed [6], [7]. The main problem with the latter approach is the difficulties in handling distributed slot synchronization and allocation in multihops networks under the high mobility conditions typical of highway traffic. Therefore, 802.11 MAC with an appropriate optimization has been found more suitable for DSRC applications, although it faces performance limitations, such as hop-unfairness and a lack of MAC protocol stability [5]. The hop-unfairness problem, which is caused by 802.11's self-competition between adjacent nodes in the same flow, can severely limit the effective data throughput of a multi-hop flow over 802.11 [5]. On the other hand, 802.11 routing protocols such as Ad Hoc Distance Vector (AODV) are considered as candidates for DSRC message forwarding applications. However, in AODV an explicit route-discovery process is required before message forwarding, which is not suitable for the low-latency requirement of DSRC safety applications. Furthermore, in some emergency situations, the source vehicle (for example, the accident car) has no prior knowledge about Identities (IDs) of the potential receivers. Obviously, in contrast to AODV, broadcast-oriented routing protocols are more applicable for delivering emergency warning messages. In [8], a multiple-hop broadcast protocol is designed to limit the amount of packets in the network and therefore realize multiple-hop inter-vehicle communication in a non-platoon driving situation. A V2V communication protocol, comprising congestion control policies, service differentiation mechanisms and methods for emergency warning dissemination, is developed in [2] to achieve low latency in propagating emergency messages. Biswas *et al.* present an overview of broadcast forwarding protocols for a DSRC-based cooperative collision avoidance application in [5]. In order to reduce the overhead of the broadcast protocols, broadcast storm mitigation techniques are proposed in [9], [10], where each node forwards a message with some probability. In [11], direction antenna techniques are employed to address the broadcast storm problem by avoiding excessive amounts of redundant traffic, exaggerated contention and collision caused by an excessive number of broadcast messages. Along a different way, a Multi-Channel (MC) wireless communication protocol is designed to support potentially high-bandwidth commercial or infotainment communications between a vehicle and roadside in hotspots over several service channels, while concurrently enabling time-critical vehicle-vehicle communication for safety in a separate channel [12]. Specifically, during the Contention-Free Period (CFP), one of vehicles can transmit its safety messages via roadside units while all others remain silent. During the following Contention Period (CP), vehicles located in the service region of roadside units can receive services by switching to service channels, while the remaining vehicles can send safety messages using an ad-hoc protocol. This means that the safety messages are not simultaneously delivered, even when the vehicles are in the service region of roadside units. In [13], the authors provided an overview of IEEE 802.11p, where a mechanism is designed to reduce long connection establishment delays. In this mechanism, a station operating in WAVE (Wireless Access in Vehicular Environment) mode is capable of immediately communicating with each other using a wildcard BSSID (Basic Service Set Identification) without the involvement of authentication and association processes, dramatically reducing the connection setup overhead and message delivery delay.

Most of the above-mentioned works focused on the design and development of message forwarding protocols either for V2V communication or for V2R (R2V) communication. In this paper, a joint V2V/V2R (R2V) communication protocol is proposed to simultaneously forward emergency warning messages via V2V and V2R (R2V) communications, in order to improve the message delivery ratio and achieve low-latency by exploiting the multi-route diversity. Furthermore, MC techniques are employed to eliminate co-channel interference between V2V and V2R (R2V) communications by assigning a different frequency band to each of them.

The rest of this paper is organized as follows. In Section II, a joint V2V/V2R (R2V) communication protocol is designed and developed for emergency message forwarding. In Section III the attainable performance of the proposed communication protocol is investigated in highway traffic scenarios. Finally, we offer our conclusions in Section IV.

II. Joint V2V/V2R Communication Protocol

In highway traffic scenarios, when a vehicle meets an emergency event or behaves abnormally when confronted by unexpected/improper manoeuvre or major mechanical failure, it generates emergency collision warning messages and broadcasts them to all vehicles within its platoon.

In V2V communication, the collision warning messages are broadcast from vehicle to vehicle across multiple hops without the involvement of a roadside unit. By contrast, the warning messages in V2R (R2V) communications are first sent to a roadside unit, and then broadcast by the roadside unit to all vehicles in range. Vehicles which receive a warning message via V2V communication will then send it to a roadside unit if they did not receive a warning message with same event ID from roadside units. According to the enclosed information in warning messages, such as event ID, accident vehicle (source vehicle) ID, transmitter ID, and location information of the transmitter (obtained through GPS), receivers generate necessary warning instructions to avoid collisions. The enclosed location information of the transmitter can be used by the receiving vehicle to detect whether a message is from a vehicle ”in front” or ”from behind”. Vehicles in V2V communication mode will selectively forward the warning messages to surrounding vehicles.

In general, the faster the warning messages are successfully received by the endangered vehicles, the higher the possibility for vehicle drivers to react. Therefore, it is very important to achieve high delivery ratio and low latency in delivering warning messages. However, due to packet collisions and the unreliability of the wireless channel in highway traffic scenarios, warning messages may not be correctly delivered in time [14]. Specifically, the wireless channel between vehicles is affected by various propagation phenomena, such as shadowing and multipath fading. Multipath fading occurs due to sometimes constructive, sometimes destructive interference between two or more echoes of the transmitted signal, arriving at the receiver at slightly different times. Since the phases of these multipath components are random, the sum of their contributions varies widely. The transmitted signal is diffracted and reflected by the surrounding buildings and other objects between vehicles, resulting in multiple versions of the transmitted signal with different shifts in arrival time, amplitudes, and phases. This will make the received signal (the sum of these multiple received signals) change significantly in amplitude and phase, and hence degrade the reliability of wireless channels under mobility conditions. Furthermore, in conventional broadcast protocols, a large amount of overhead is broadcast within networks, resulting in long contention and excessive packet collisions. In order to overcome the above-mentioned difficulties, a novel joint V2V/V2R (R2V) communication protocol is proposed and described in this section for highway traffic safety. First, V2V and V2R (R2V) communications are incorporated to suppress the impact of the unreliability of the wireless channel by exploiting the multi-route diversity. Second, a mechanism similar to Intelligent Broadcast with Implicit Acknowledgement (I-BIA) in [5] is employed to reduce the redundant warning messages and consequently reduce the packet collisions. Third, MC techniques are employed to eliminate co-channel interference between V2V and V2R (R2V) communications by assigning a different frequency band to each.

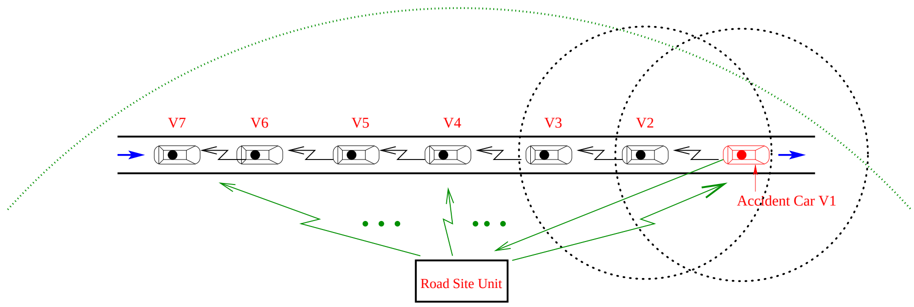


Fig. 1. A single-lane highway traffic scenario: V2V and V2R (R2V) communication protocols are employed to enhance public safety.

For the sake of simplicity a single lane highway traffic scenario as shown in Fig. 1, is employed to assess the proposed joint V2V/V2R (R2V) communication protocol is employed to enhance the road safety. In this paper we assume that two independent transceivers working in different frequency bands are installed on all vehicles; one for V2V communication on channel-1 and the other for V2R (R2V) communication on channel-2. Under these conditions, vehicles are capable of simultaneously communicating in V2V and V2R (R2V) modes, as seen in Fig. 1. Since these transceivers work in different channels, signals for V2V communication and V2R (R2V) communication can be transmitted/received and processed by these transceivers simultaneously, without interfering with each other. More specifically, signals for V2V communication and V2R (R2V) communication are handled separately in the PHY and MAC layer. In the network layer, however, they are processed jointly as shown in Fig. 2. In the proposed joint V2V/V2R (R2V) communication protocol, when a vehicle (for example V1) has a mechanical failure or detects road hazards, it generates an emergency warning message which includes all the related information and keeps one copy in its buffer for possible retransmission. It then broadcasts it to neighboring vehicles as well as sends it to a roadside unit, through two transceivers operating in two different frequency bands (in the case of high way scenarios). In V2R (R2V) communication, the source vehicle will periodically send the warning message to a roadside unit until it receives the message with same event ID from roadside unit. Similarly, the source vehicle will periodically broadcast the warning message in V2V communication mode to neighboring vehicles until it receive the message with same event ID from vehicles behind. Once the roadside unit receives the warning message from the source vehicle, it replaces the transmitter ID with its own ID and immediately forwards it to all vehicles within its range. Note that in IEEE 802.11p, a station with the wildcard BSSID value [13] is capable of immediately communicating with each other without the involvement of authentication and association processes. This aims at substantially reducing overhead and delay.

On the other hand, after receiving the warning message, vehicles will take the following steps according to the enclosed information in the message:

- The warning message has been received by the transceiver working in V2R (R2V) communication mode:
    1) If the receiving vehicle is the source vehicle (checking the source vehicle ID in the warning message), it stops retransmitting the warning message to the roadside unit in order to reduce overhead in networks.
    2) If the receiving vehicle is not the source vehicle and is in front of the source vehicle, it ignores the warning message.
    3) If the receiving vehicle is behind the source vehicle, but has received warning messages with the same event ID from other vehicles in V2V communication, it ignores the warning message.
    4) If the receiving vehicle is behind the source vehicle and warning messages with same event ID have not yet been received, it carries out appropriate manoeuvres to avoid collision. In the mean time it waits for a random duration to receive a warning message

(with same event ID) from vehicles behind.

A. If it receives a warning message with same event ID, it stops rebroadcasting the warning message for same event. Obviously, this behavior helps to reduce overhead.

B. Otherwise, it will periodically broadcast this warning message until it receives a warning message with same event ID from vehicles behind.

- The warning message is received by the transceiver working in V2V communication mode:

1) If the receiving vehicle is in front of the broadcasting vehicle, it will not rebroadcast the warning message with same event ID. Again this is to reduce broadcast messages in networks.
2) If the receiving vehicle is behind the broadcasting vehicle and this message was received before, it will ignore it.
3) If the receiving vehicle is behind the broadcasting vehicle and receives this warning message for the first time, it will carry out appropriate maneuvers to avoid collision. At the same time it checks whether a warning message with same event ID has also been received from its roadside unit. If not, it will periodically transmit this warning message to the roadside unit until it receives a warning message with same event ID from the roadside unit. Meanwhile the receiving vehicle waits for a random duration for warning messages with same event ID from vehicles behind.

A. If it receives such a message, it will stop rebroadcasting it for same event. Similarly, this behavior helps to reduce overhead.

B. Otherwise, it will periodically broadcast this warning message until it receives a warning message with same event ID from vehicles behind.

The flowchart in Fig. 2 illustrates receiving vehicles' behaviors using the proposed joint V2V/V2R (R2V) communication protocol. By contrast, receiving vehicles' behaviors using either V2R (R2V) communication or V2V communication are portrayed in Figs. 3 (a) and (b). In this paper the retransmission number of intermediate vehicles is set to 6, which is big enough

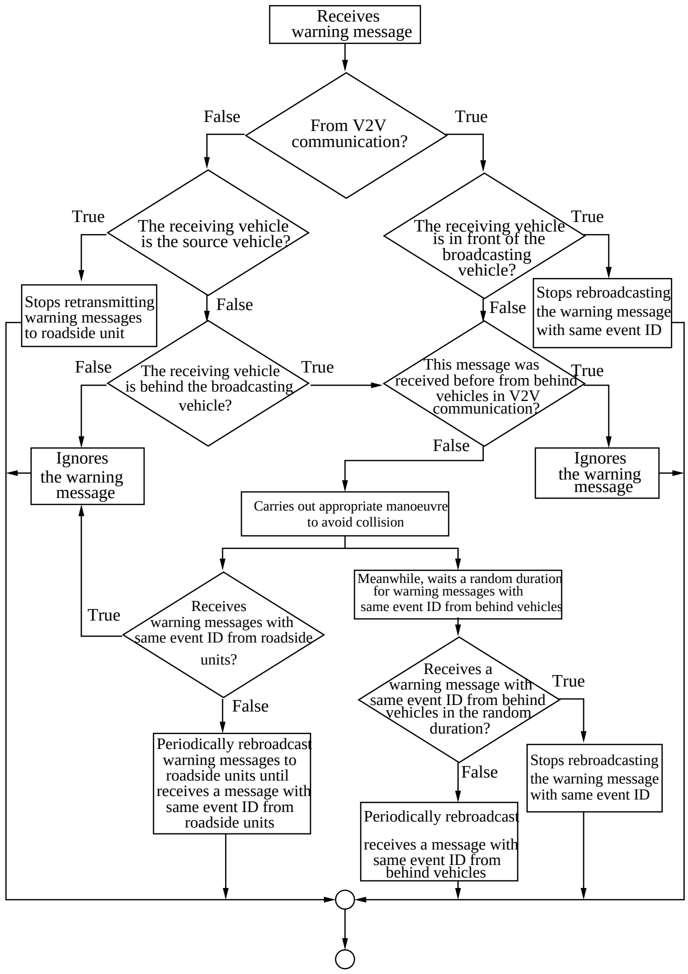
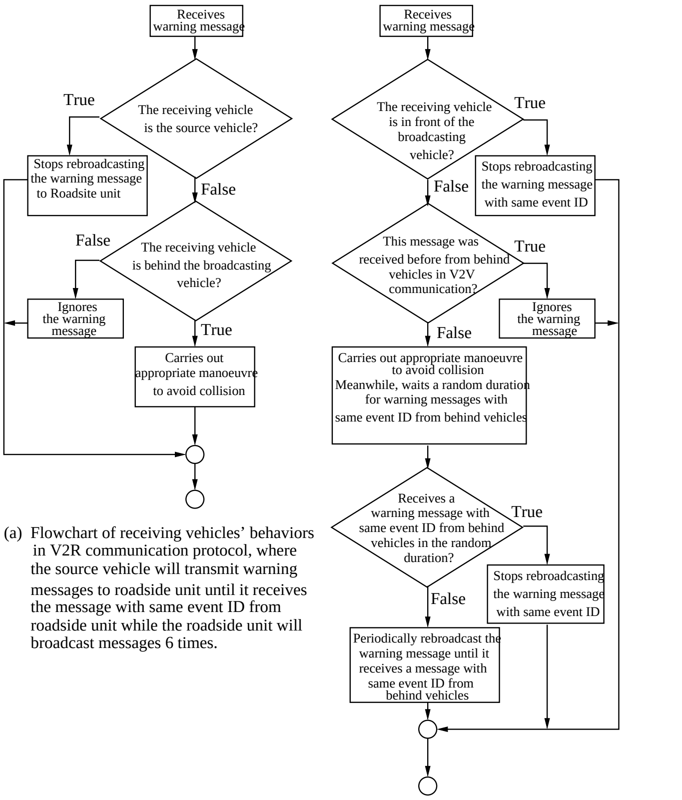


Fig. 2. Flowchart illustrating receiving vehicles' behaviors based on the information enclosed in the received warning message.

to ensure that all vehicles within the platoon will eventually receive the emergency warning message. As shown in Fig. 2, intermediate vehicles will receive warning messages with same event ID from the roadside unit and neighboring vehicles through V2R (R2V) communication and V2V communication, respectively. This mechanism helps to achieve multi-route diversity and overcome the unreliability of wireless channels in high mobility environments, resulting in significant improvement of the message delivery ratio. This advantage is demonstrated by the simulation results in Figs. 5 and 6. It is reasonable to assume that a higher message delivery ratio may lead to lower latency in delivering the message and lower level of overhead in networks. Furthermore, based on our observation in Figs. 7, 8, 9 and 10, the proposed joint protocol achieves the lowest averaged delivery delay for messages. This directly helps to achieve a low



(a) Flowchart of receiving vehicles' behaviors in V2R communication protocol, where the source vehicle will transmit warning messages to roadside unit until it receives the message with same event ID from roadside unit while the roadside unit will broadcast messages 6 times.

(b) Flowchart of receiving vehicles' behaviors in V2V communication protocol, where vehicles will periodically broadcast warning messages to surrounding vehicles until it receives the message with same event ID from behind vehicles.

Fig. 3. Flowchart illustrating receiving vehicles' behaviors using either V2R communication or V2V communication.

latency in delivering messages.

III. Performance Results

In this section the performance of the proposed joint V2V/V2R (R2V) communication protocol is investigated in a single-lane highway traffic and a three-lane highway traffic scenarios using our real-time simulation testbed, where the IEEE 802.11b standard is invoked. In the physical layer, the receiver sensitivity is -93.0 dBm, the IEEE 802.11b data-rate is 2 Mbps and the noise factor is 10.0. In our simulations, the transmit power of vehicles working in V2V communication mode and those operating in V2R (R2V) mode are adjusted separately in order to achieve a similar averaged received power for each vehicle. The transmit power of transmitters working in V2V communication mode is set to 10.5 dBm, while the transmit power of those working in V2R (R2V) communication mode is set to 9.5 dBm. Small-sized omni-directional antennas with 0 dB antenna gain are used on vehicles, while big-sized omni-directional antennas with 20 dB antenna gain are installed on roadside units. The average transmit/receive range for V2V communication is 125 meters. By contrast, the average transmit/receive range for V2R/R2V communication is 1500 meters. This means that the coverage of a roadside unit is 1500 meters. Without loss of generality, Rician fading channels with different K factors are used to comparatively study the proposed joint communication protocol. Rician fading is a stochastic model for radio propagation where the signal arrives at the receiver via two different paths (hence exhibiting multipath interference), and at least one of the paths is changing (lengthening or shortening). Rician fading occurs when one of the paths, typically a line of sight signal, is much stronger than the others. K factor is the ratio between the power in the direct path and the power in the other, scattered, paths.

In the MAC layer, the retransmission limit is 6. The emergency warning message's size is 64 bytes. The periodic time for the source vehicle to retransmit warning messages to the roadside unit is set to 0.01 second, while the periodic time for all vehicles to rebroadcast a warning message to neighboring vehicles is set to 0.005 second. The random duration waiting for warning messages from vehicles behind is between 0 to 0.003 seconds. Furthermore, delays caused by authentication and association processes will not be considered in our simulation model. This is mainly based on the assumption that in V2R (R2V) communication, vehicles will transmit warning messages to the roadside unit without undergoing the association processes as required by other IEEE 802.11 standards.

Two scenarios are considered in this paper, namely the single lane scenario where 15 vehicles are driving at the speed of 30 m/s, and the multiple lane scenario, where 45 vehicles are driving at the speed of 30 m/s while the lane width is 3 meters. The distance between vehicles is around 50 meters while the vehicle length is 4 meters. Since we main focus is to improve the message delivery ratio and average delay by exploiting transmit diversity, braking situations are not specifically considered in this paper. In this paper, we only consider situations where accidents can occur in one direction. Nonetheless, it can be easily extended to cover vehicle accidents in both directions. For example, when accident vehicles' information such as location information is included in the safety messages, the receiving vehicles can detect if the accident car is in front of it in the driving direction. No additional process is required to deal with situations where accidents happen in both directions.

In Fig. 1, the performance of the proposed joint V2V/V2R (R2V) communication protocol is investigated in a single-lane highway traffic scenario. The message delivery ratio of three communication protocols, namely, the protocol using only V2V communication (as described in Fig. 3 (a)), the protocol using only V2R (R2V) communication (as described in Fig. 3 (b)), and the proposed joint V2V/V2R (R2V) protocol, is studied and compared in Fig. 4 where the K factor of the Rician channel is 50, as well as Fig. 5 with the K factor being 20. These two Figures show that the proposed joint V2V/V2R (R2V) protocol significantly improves the message delivery ratio and hence achieves the best performance. This demonstrates that the multi-route diversity achieved by the proposed protocol is capable of overcoming the unreliability of the wireless channel in high mobility environments. Furthermore, by comparing the results in Figs. 4 and 5, we can reasonably conclude that the more reliable the wireless channel, the higher the message delivery ratio. In addition, the latency effect of these protocols is investigated in Figs. 6, 7, 8 and 9, where the message delivery delay is defined as the duration from the time the warning message is generated in the source vehicle to the time an endangered vehicle successfully receives the first corresponding warning message. It can be seen from Figs. 6, 7, 8 and 9 that the proposed joint V2V/V2R (R2V) protocol achieves the best performance, substantially increasing the ratio of ”message delivery delay $\leq$ 6 ms and 10 ms”, especially for vehicles 2 and 3 hops away. This illustrates that the proposed joint protocol is capable of attaining low latency in delivering emergency warning messages.

A multi-lane highway traffic scenario is used to investigate the proposed joint V2V/V2R (R2V) communication protocol, as shown in Fig. 10. The corresponding simulation results in Figs. 11 and 12 demonstrate that the proposed joint V2V/V2R (R2V) communication protocol has the lowest averaged message delivery delay in multi-lane scenario, and hence is capable of achieving low latency in message delivery. In Fig. 13, we investigate the proposed protocol in the multi-lane scenario of Fig. 10, where the source vehicle is unable to communicate with roadside units. As shown in Fig. 13, the proposed protocol is capable of outperforming the V2V

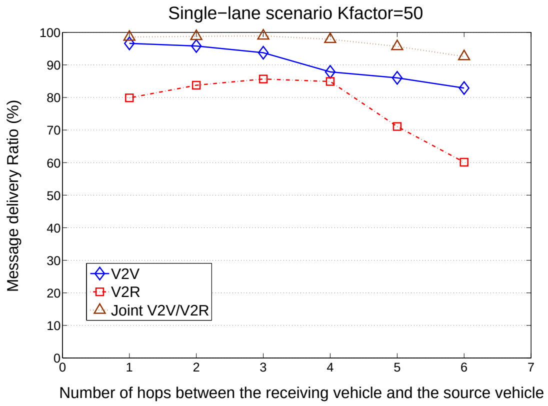


Fig. 4. Single-lane highway traffic scenario, where the message delivery ratio performance of the three communication protocols is investigated in a Rician channel with the K factor being 50.

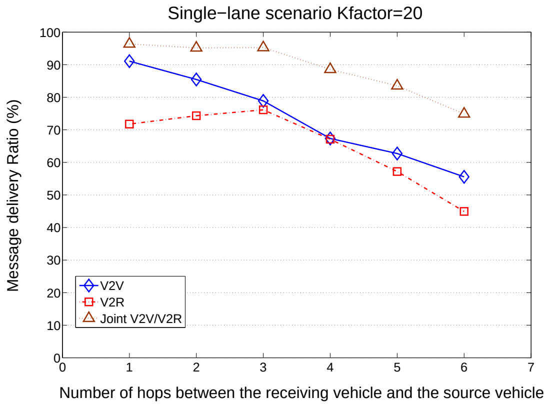


Fig. 5. Single-lane highway traffic scenario, where the message delivery ratio performance of the three communication protocols is investigated in a Rician channel with the K factor being 20.

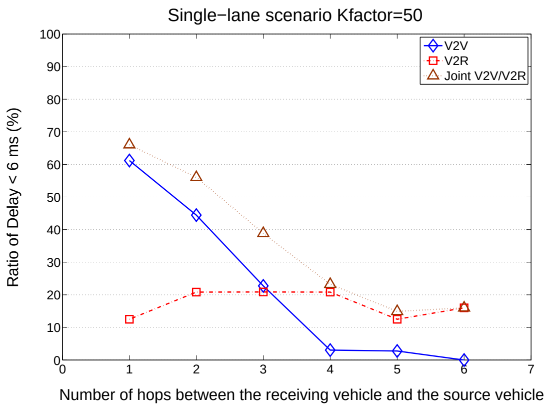


Fig. 6. Single-lane highway traffic scenario, where the ratio of delay < 6 ms performance of the three communication protocols is investigated in a Rician channel with the K factor being 50.

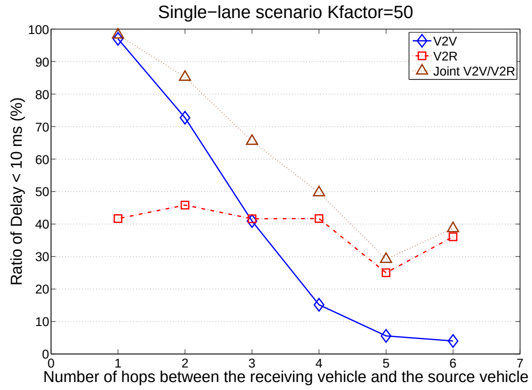


Fig. 7. Single-lane highway traffic scenario, where the ratio of delay $<$ 10 ms performance of the three communication protocols is investigated in a Rician channel with the K factor being 50.

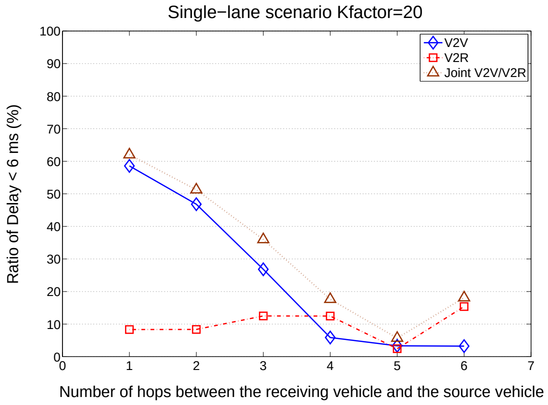


Fig. 8. Single-lane highway traffic scenario, where the ratio of delay $<$ 6 ms performance of the three communication protocols is investigated in a Rician channel with the K factor being 20.

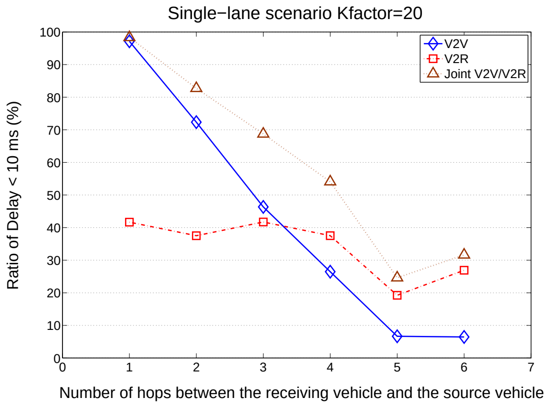


Fig. 9. Single-lane highway traffic scenario, where the ratio of delay $<$ 10 ms performance of the three communication protocols is investigated in a Rician channel with the K factor being 20.

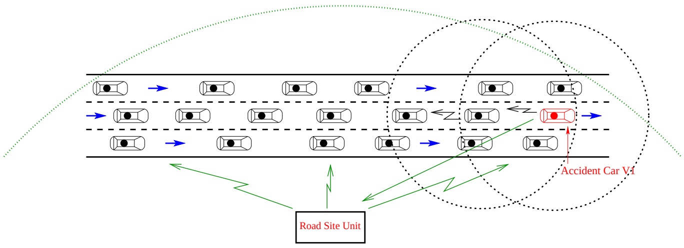


Fig. 10. A Multi-lane highway traffic scenario: V2V and V2R (R2V) communication protocols are employed to enhance public safety.

communication, even when the source vehicle is not able to communicate with roadside units.

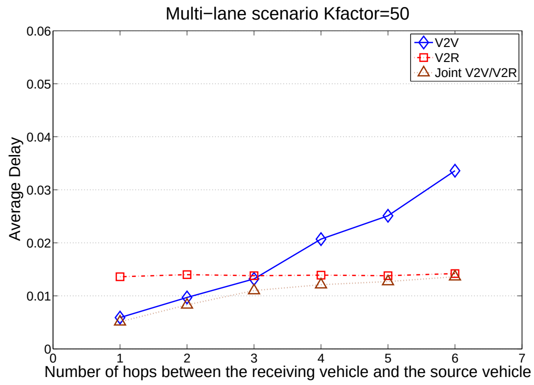


Fig. 11. Multi-lane highway traffic scenario, where the delay performance of the three communication protocol is investigated in a Rician channel with the K factor being 50.

IV. Conclusions

In this paper we have proposed a joint V2V/V2R (R2V) communication protocol for co-operatively collision avoiding, in order to improve the communication reliability and achieve low-latency by exploiting the transmit diversity. By exploiting the multi-route diversity, the proposed joint communication protocol is capable of suppress the impact of the unreliable wireless channel in high mobility environment, leading to significant improvement of the message delivery ratio. Reasonably, higher message delivery ratio may result in lower latency in delivering message and lower level of overhead in networks. Furthermore, the average delay for messages propagated through the V2R (R2V) communication is around 0.012 second despite the distance

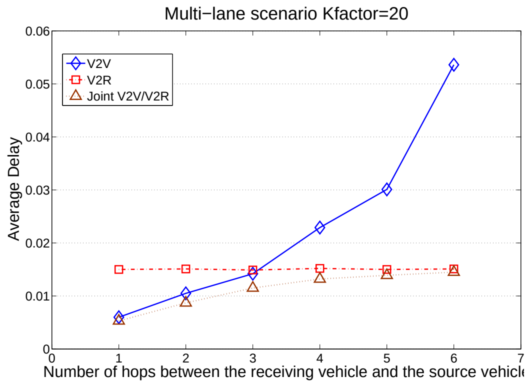


Fig. 12. Multi-lane highway traffic scenario, where the delay performance of the three communication protocol is investigated in a Rician channel with the K factor being 20.

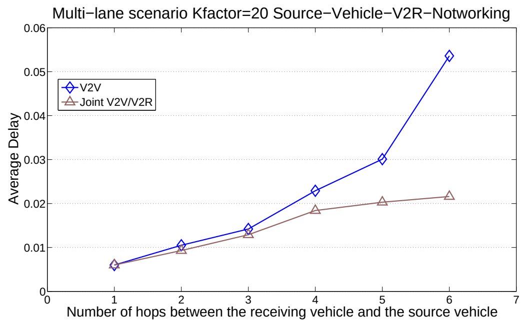


Fig. 13. Multi-lane highway traffic scenario, where the source vehicle is not able to communicate with roadside units.

from receiving vehicles to the source vehicle. This directly helps to reduce the message delivery delay for vehicles 3 hops away.

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