An IEEE 802.11p-Assisted LTE-V Scheduling for Reliable Multi-Link V2X Communications

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***Abstract*—V2X deployments using IEEE 802.11p have already been announced, and the 3GPP has published the first Cellular V2X standard based on LTE-V. The limitations of IEEE 802.11p and LTE-V, and the increasing requirements of enhanced V2X applications, raise the question of whether existing V2X standards can provide the reliability levels required to support large scale deployments and the introduction of connected automated driving. Redundancy (two or more V2X links) can increase the reliability, but the gains can be limited if the various links are correlated. IEEE 802.11p and LTE-V utilize sensing-based scheduling schemes, and their MAC errors can hence be correlated since they both suffer packet collisions due to the hidden terminal problem. To address this limitation, this paper proposes the design of multi-link V2X communications where the operation of a link is adjusted with the information received through the other link. This approach is applied in this paper to design an IEEE 802.11p-assisted LTE-V scheduling scheme for multi-link and multi-RAT V2X communications. The proposed scheme is designed to increase the reliability of V2V communications in intersections under NLOS conditions.**

Keywords*—LTE-V, scheduling, multi-link, V2X, V2V, vehicular networks, LTE-V2X, Cellular V2X, C-V2X, multi-RAT, IEEE 802.11p, DSRC, connected automated vehicles, reliability, 5G V2X.

I. INTRODUCTION

V2X (Vehicle to Everything) communications will facilitate the introduction of advanced traffic safety and management applications, and will support the development of connected automated vehicles by extending their awareness range beyond line of sight. Toyota, Volkswagen and GM have already announced V2X deployments using IEEE 802.11p technology and the DSRC (US) and ITS G5 (EU) standards. Significant efforts have also been devoted lately to develop cellular and 5G solutions for V2X communications. For example, the Third Generation Partnership Project (3GPP) published under Release 14 a Cellular V2X (C-V2X) standard based on LTE that is commonly known as LTE-V or LTE-V2X [1]. This standard evolves the LTE PC5 or Sidelink interface, and introduces two modes of operation. The LTE-V mode 4 does not require support from the cellular infrastructure, and vehicles autonomously select their radio resources. In LTE-V mode 3, vehicles directly communicate with each other, but their radio resources are selected and assigned by the cellular network. Release 15 is analyzing improvements to LTE-V, and a study item has been recently created to develop a 5G NR interface for V2X communications [2].

Some studies have shown that the reliability and scalability of IEEE 802.11p can be compromised under large scale and dense deployments [3]. In these scenarios, the sensing-based IEEE 802.11p Medium Access Control (MAC) scheme suffers from significant packet collisions. LTE-V improves the link budget in comparison to IEEE 802.11p [1][4]. However, its scheduling is also sensing-based, and is hence prone to packet collisions due to hidden terminal and half-duplex problems [5]. These constraints, and the increasing requirements to support enhanced V2X applications (eV2X) [6], raise the question of whether existing standards can provide the reliability levels required to support large scale deployments and the introduction of connected automated driving.

An approach for increasing the reliability of V2X communications is redundancy. In fact, Volvo already announced that its self-driving vehicles will have redundancy for everything[1]. It is hence reasonable to consider redundancy for V2X communications since V2X communications will be a fundamental component of connected automated driving. In this context, vehicles will simultaneously transmit packets over two (or more) V2X links, which will augment the probability to correctly receive a packet at the application level. If the various links implement the same radio interface, transmissions can be correlated. Larger gains could be expected if both links are uncorrelated, and transmissions can benefit from diversity and combining. In this context, this paper proposes the design of multi-link V2X communications where the operation of a link is adjusted with the information received through the other link in order to reduce correlations at the MAC level. The proposal is here applied to a multi-RAT V2V scenario where vehicles integrate two radio interfaces, one using IEEE 802.11p and the second one using LTE-V mode 4. Deployments have already been announced for IEEE 802.11p, while LTE-V increases the link budget. So combining the two radio interfaces is an interesting option since it will guarantee the capacity to communicate with vehicles only integrating IEEE 802.11p while improving the link level performance for the additional V2X link. In addition, both technologies have different physical and MAC layers, and hence some level of diversity between the two radio links exists. However, both

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[1] https://spectrum.ieee.org/cars-that-think/transportation/self-driving/volvos-selfdriving-program-will-have-redundancy-for-everything

IEEE 802.11p and LTE-V mode 4 implement MAC schemes that are sensing-based and are hence prone to packet collisions generated by the hidden terminal problem. In this context, the proposed approach is here applied to design an IEEE 802.11p-assisted LTE-V scheduling scheme for multi-link and multi-RAT V2V communications. The proposed scheme is designed to increase the reliability of V2V communications in intersections under NLOS conditions.

II. IEEE 802.11P-ASSISTED LTE-V SCHEDULING

The proposed scheduling scheme is designed to improve V2V communications between vehicles approaching an intersection under Non-Line of Sight (NLOS) conditions. Intersections account for more than 36% of accidents in the US [7]. In urban scenarios, buildings generally obstruct the LOS which significantly reduces the communications range of vehicles approaching an intersection under NLOS [8]. Reducing the communication range significantly degrades the capacity of vehicles to detect a potential risk at the intersection with sufficient time to react [9]. Intersections with NLOS also represent a significant challenge to automated vehicles. Automated vehicles can rely on their cameras, radars and lidars under LOS conditions. However, their sensing capacity significantly degrades in intersections under NLOS, and hence connected and automated vehicles will also significantly benefit from improved V2X communications under NLOS at intersections. To this aim, we consider that vehicles are equipped with IEEE 802.11p and LTE-V interfaces, and they can transmit each packet over both interfaces.

A. LTE-V Mode 4

LTE-V divides its (10 or 20MHz) channels into sub-frames, Resource Blocks (RBs), and sub-channels. Sub-frames are 1ms long, and RBs are 180kHz wide. LTE-V defines sub-channels as a group of RBs in the same sub-frame. The number of RBs per sub-channel can vary. Sub-channels are used to transmit data and control information. The data is transmitted in Transport Blocks (TBs) and the control information in Sidelink Control Information (SCI) messages. A TB contains a full packet to be transmitted (e.g. a beacon), and each TB must be transmitted with its associated SCI. The SCI includes important control information that must be correctly received to be able to decode a transmitted TB. A TB and its associated SCI must always be transmitted in the same sub-frame.

LTE-V mode 4 defines a scheduling mechanism for vehicles to autonomously select their radio resources without any cellular infrastructure support [10]. The algorithm is known as sensing-based Semi-Persistent Scheduling (SPS). With SPS, vehicles sense previous transmissions from other vehicles to select free sub-channels or the sub-channels with lower probability to experience interference. Vehicles reserve the selected resources for a number of transmissions so that other vehicles can accurately estimate interference levels. Readers are referred to [1] for a detailed presentation of LTE-V mode 4 and its SPS scheduling. The authors demonstrated in [1] that LTE-V mode 4 can outperform IEEE 802.11p. However, the performance of LTE-V mode 4 can be affected by the well-known hidden terminal problem (that also affects IEEE 802.11p). LTE-V mode 4 hence suffers from packet collisions and half-duplex errors [5]. The hidden-terminal problem particularly affects vehicles approaching an intersection under NLOS since they might not sense each other, and therefore select sub-channels resulting in packet collisions or half-duplex errors. The objective of this study is then to exploit multi-link V2X communications to design an alternative scheduling scheme for LTE-V (the IEEE 802.11p interface is not modified and operates following the standard). This scheme uses information received over the IEEE 802.11p link to schedule LTE-V transmissions and reduce packet collisions and half-duplex errors. The proposed IEEE 802.11p-assisted LTE-V scheduling is designed to improve the reliability of V2V communications in intersections under NLOS conditions.

B. Proposal

The proposal divides the LTE-V sub-frames within the Selection Window into as many pools as incoming streets to an intersection (four in the example in Fig. 1a). Each pool is reserved for vehicles approaching the intersection through the same incoming street (see Fig. 1b). Consequently, vehicles approaching an intersection through different streets under NLOS conditions will never transmit on the same sub-frame. This eliminates possible packet collisions (resulting from the hidden terminal problem) and half-duplex errors between these vehicles that require reliable V2X communications to avoid possible safety risks at the intersection.

Vehicles within the same incoming street to an intersection sequentially select their transmission sub-frame in their corresponding pool. The selection is based on their increasing position in the queue of vehicles towards the intersection as illustrated in the example in Fig. 1c. Vehicles estimate their position in the queue using the location information of surrounding vehicles transmitted on IEEE 802.11p beacons[2] (generally known as BSMs or CAMs). Vehicles must share sub-frames if there are more vehicles in the queue than available sub-frames in the pool. In this case, the selection of sub-frames is also sequential and position-dependent. For example, the 6th and 7th vehicles in the queue in Fig. 1c select the 1st and 2nd sub-frames respectively since there are only 5 sub-frames in the pool. This approach maximizes the distance between vehicles using the same sub-frame. For each packet transmission, vehicles randomly select a sub-channel within the selected sub-frames. This randomization adds flexibility in the resource selection process when considering packets of different size. In addition, it reduces the probability of packet collisions when several vehicles share the same sub-frame. When a vehicle crosses an intersection and enters a new road segment, it reselects its sub-frame according to its position in the new road segment.

The proposed LTE-V scheduling scheme minimizes the transmission errors between vehicles experiencing the most challenging communication conditions, i.e. vehicles approaching an intersection under NLOS conditions. This is done at the expense of the vehicles driving on the same street. For these vehicles, the proposed scheme exploits IEEE 802.11p

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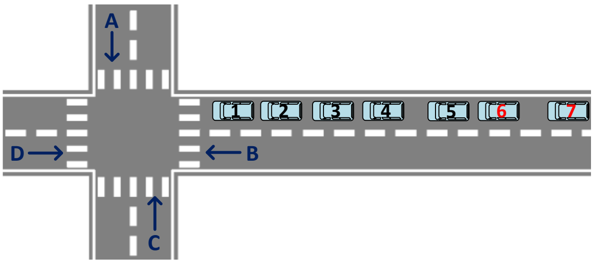
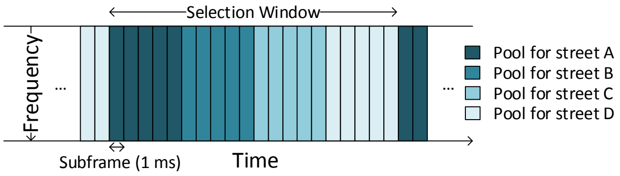
[2] For robustness, the position is estimated considering all beacons received during the last second, and it is updated following the mobility of vehicles.

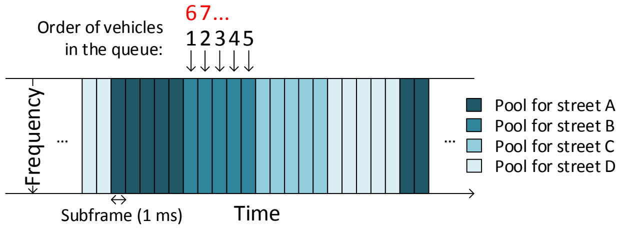
data to reduce possible packet collisions. It should be noted that the IEEE 802.11p radio interface is not modified (and hence does not prioritize NLOS transmissions over LOS ones), and that the performance of IEEE 802.11p is significantly better under LOS than under NLOS conditions [5]. The perception capacity of connected and automated vehicles is also higher under LOS than under NLOS conditions.



(a) Road traffic scenario



(b) Organization of LTE-V sub-frames



(c) Selection of LTE-V sub-frames

Fig 1. IEEE 802.11p-assisted LTE-V scheduling in intersection scenarios.

III. SIMULATION ENVIRONMENT

The proposed solution has been evaluated using Veins, an open source simulator for vehicular networks. Veins integrates OMNeT++ (an event-based network simulator) and SUMO (a road traffic simulator). The current version of Veins includes an IEEE 802.11p interface for V2X communications. We have extended Veins to simulate multi-link and heterogeneous V2X communications, and we have implemented the LTE-V mode 4 interface [1]. The simulator can evaluate the performance achieved with standalone IEEE 802.11p and LTE-V mode 4 interfaces, and with various multi-link V2X configurations.

All the simulated radio interfaces operate at the 5.9GHz band (in 10MHz channels) with a transmission power of 23dBm. The noise figure has been set to 9dB. Following the 3GPP guidelines and recommendations [10], the radio propagation effects are modeled using the WINNER+ B1 model. This model implements a log-distance pathloss that differentiates between LOS and NLOS conditions, and models shadowing using a log-normal distribution with a standard deviation of 3dB for LOS and 4dB for NLOS conditions. The shadowing is spatially correlated with a decorrelation distance of 10m, and takes the same value for both radio interfaces. The link level performance of LTE-V is estimated using the BLER-SINR (Block Error Rate-Signal to Interference and Noise Ratio) curves from [11]. These curves were obtained from link-level simulations using the vehicular channel model in [12]. This study also considers the effect of In-Band Emissions (IBE) following [12]. The link level performance of IEEE 802.11p is taken into account by using the FER (Frame Error Rate) curves from [13].

Vehicles transmit data packets following the 3GPP traffic model for connected and automated vehicles [12]. In particular, vehicles periodically transmit data packets every 50ms or 20ms (20 or 50 packets per second). Vehicles transmit packets of 190 bytes, except one of every five packets that has a size of 300 bytes. The IEEE 802.11p interface is configured with the 18Mbps data rate since this data rate minimizes the channel load and maximizes the PDR [14]. Each TB is transmitted with its SCI (that occupies 2 RBs) in the same sub-frame. LTE-V is configured to transmit packets of 190bytes with the MCS9 modulation and coding scheme, and packets of 300bytes with the MCS7. This configuration results in that packets of 190 and 300 bytes occupy a TB with 10 RBs and 20 RBs respectively. The LTE-V bandwidth in a sub-frame is divided in four sub-channels with 12 RBs each. The adjacent SCI+TB transmission configuration is used [1]. As a result, SCI+TB packets use 1 and 2 sub-channels when the TB has a size of 190 and 300bytes respectively. Each SCI+TB packet can be transmitted once or twice as indicated in 3GPP standards.

This study implements the Urban Case road traffic scenario specified by 3GPP working groups [12]. This scenario simulates a Manhattan grid layout with 433mx250m building blocks. All streets have two lanes in each direction (four in total), and each lane is 3.5m wide. The scenario has 9x7 building blocks, and statistics are collected in the streets and intersections around the center of the scenario to avoid border effects. Vehicles are randomly dropped in the scenario and follow random routes in the Manhattan grid. Simulations have been conducted for an average traffic density of 90 vehicles per kilometer following the 3GPP specifications of the Urban Case scenario [12]. 3GPP studies usually consider a simplified mobility model where vehicles move at constant speed [12]. Our simulations use the Krauss car following model implemented in SUMO. This results in variable speeds depending on the location of vehicles and the traffic context.

IV. RESULTS

Fig. 2 plots the PDR (Packet Delivery Ratio) as a function of the road distance between transmitter and receiver when vehicles are approaching an intersection[3]. All the results depicted in Fig. 2 for LTE-V have been obtained using the sensing-based SPS scheduling included in mode 4. The results confirm that a standalone LTE-V mode 4 interface outperforms a standalone IEEE 802.11p interface due to its better link level performance. Adding a redundant IEEE 802.11p interface (i.e. each vehicle simultaneously transmits each packet over the two IEEE 802.11p interfaces) improves the PDR, but the

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[3] Sufficient simulations have been conducted to ensure a relative error below 5% for all the results presented in this section.

improvement is low due to the high correlation of packet losses between the two radio interfaces. Higher gains are obtained when the second interface is LTE-V. It is important noting that the gains are also constrained by the strong propagation effects under NLOS conditions.

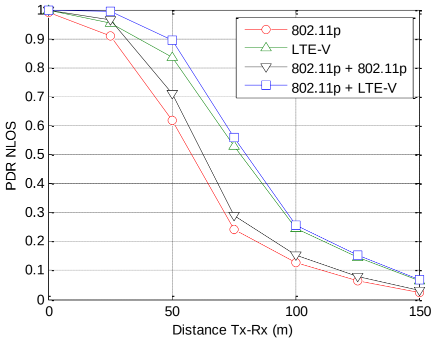
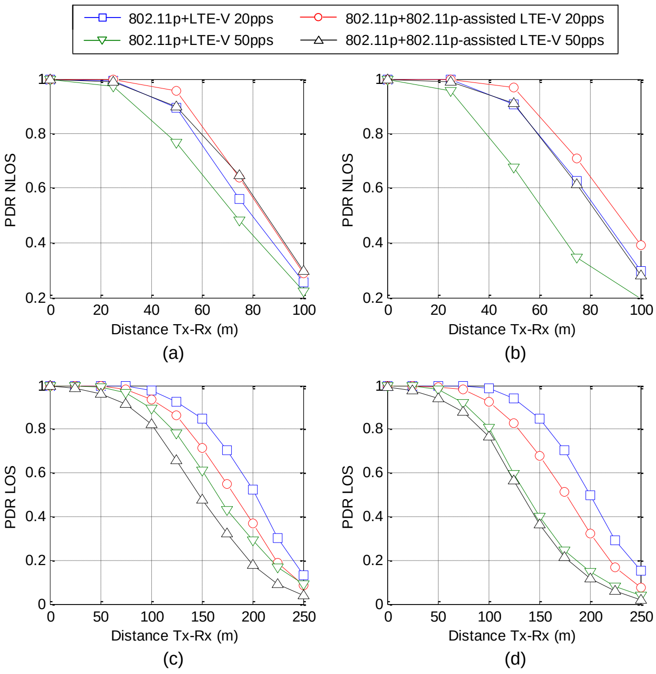


Fig 2. PDR as a function of the road distance between transmitter and receiver. LTE-V transmits one SCI+TB per packet (no retransmission). NLOS. Packet generation interval: 50ms (equivalent to packet rate of 20pps).

The results depicted in Fig. 2 for the 802.11p+LTE-V configuration have been obtained using the MAC defined in the IEEE and 3GPP standards. Both are sensing-based, and are hence similarly affected by the hidden-terminal problem. This limits the performance gain achievable with the addition of a second radio interface since packet loses due to collisions are correlated between both interfaces. Using a second interface that reduces such correlation could yield higher performance gains. This is in fact illustrated in Fig. 3a and Fig. 3b that compares the performance achieved with the proposed scheme (802.11p+802.11p-assisted LTE-V) and the performance obtained using the standard 802.11p+LTE-V configuration (i.e. the configuration achieving the best results in Fig. 2). Fig. 3a and Fig. 3b represent the PDR obtained between vehicles approaching an intersection under NLOS conditions. Fig. 3a corresponds to the case in which every packet is only transmitted once in LTE-V (no retransmission), and Fig. 3b corresponds to the case in which every packet is transmitted twice in LTE-V (with retransmission). The proposed scheme also uses two radio interfaces. The first one is a standard IEEE 802.11p interface, and the second one is an interface that implements the 802.11p-assisted LTE-V scheduling scheme presented in Section II. Fig. 3a and Fig. 3b show that the proposed scheme successfully improves the PDR under NLOS conditions. The largest improvements are obtained when the channel load is higher (i.e. 50pps and/or every packet is transmitted twice over the LTE-V interface), and hence packet collisions and half-duplex errors are more important in LTE-V. This is illustrated in Fig. 4 that represents the percentage of packets lost on the LTE-V interface due to packet collisions and half-duplex errors for vehicles under NLOS conditions. The figure compares the packets lost when LTE-V implements the standard sensing-based SPS scheduling and when it implements the proposed 802.11p-assisted LTE-V scheduling scheme[4]. Fig. 4 shows that when the channel load is high (e.g. when vehicles transmit 50 packets per second), the proposed 802.11p-assisted LTE-V scheduling scheme significantly reduces the percentage of packets lost due to packet collisions compared to the standard LTE-V sensing-based scheme. This is particularly noticeable for distances between 50m and 75m where packet collisions are more frequent. The percentage of errors due to packet collisions decreases for higher distances because packet loses due to propagation effects become dominant [5]. Fig. 4 also shows that the proposed scheduling scheme completely eliminates the half-duplex errors that characterize the sensing-based LTE-V scheduling scheme and that are relevant when the load increases. The proposed 802.11p-assisted LTE-V scheduling scheme also significantly reduces packet collisions and eliminates half-duplex errors when the channel load decreases (i.e. when vehicles transmit 20pps). The improvements on the PDR are smaller than for higher channel loads because the percentage of packet errors due to collisions is smaller, and errors are mostly dominated by the high propagation loses due to the NLOS conditions.

Fig. 3c and Fig. 3d compare the PDR experienced by vehicles communicating under LOS conditions. The proposed scheme prioritizes NLOS transmissions, and hence slightly reduces the performance under LOS compared to the use of a standard 802.11p+LTE-V configuration[5]. However, the proposed scheme achieves a similar performance under LOS to the standard 802.11p+LTE-V configuration in high channel load scenarios (50pps). In addition, it is important noting that the communications range is larger under LOS (independently of the radio interfaces), and that the proposed scheme always



(a) (b)

(c) (d)

Fig 3. PDR as a function of the road distance between transmitter and receiver. (a) NLOS without LTE-V retransmissions, (b) NLOS with LTE-V retransmissions, (c) LOS without LTE-V retransmissions, (b) LOS with LTE-V retransmissions.

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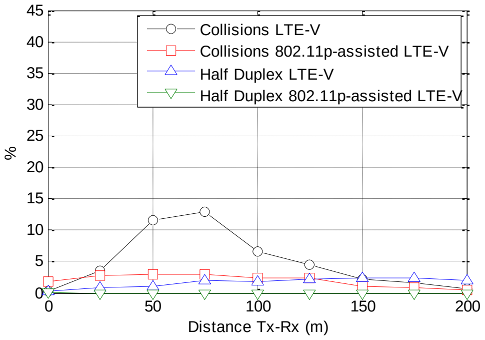
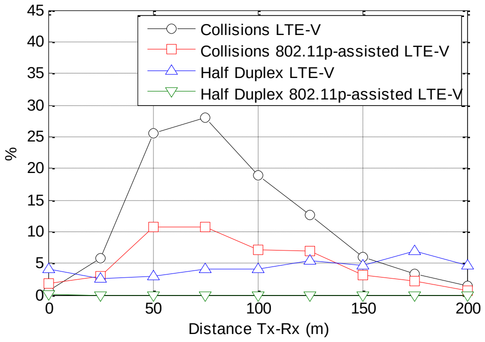
[4] All loses represented in Fig. 4 do not result in packet loses at the application level since packets are also transmitted via the IEEE 802.11p radio interface.

[5] This effect is produced because vehicles in adjacent intersections under LOS conditions can transmit using the same subframe and cause packet collisions if they select the same sub-channel. However, under LOS conditions, the performance of IEEE 802.11p and the available sensors of connected automated vehicles can be sufficient to satisfy the requirements and the redundant interface is not so important.

outperforms the use of single IEEE 802.11p radio interface. Table I summarizes the performance trade-offs observed when comparing the standard 802.11p+LTE-V configuration (Standard in Table I) and the proposed 802.11p+802.11p-assisted LTE-V scheme (Proposal in Table I). The table represents the communications range at which a PDR equal to 0.9 is guaranteed, and the relative variation between both configurations (a positive variation reflects an improvement of the Proposal configuration versus the Standard one). The proposed scheme can increase the communications range under NLOS by up to 70%. These improvements are important to successfully avoid collisions at intersections under NLOS.



(a) 20pps



(b) 50pps

Fig 4. Percentage of packet errors on the LTE-V interface due to half duplex and packet collisions for vehicles under NLOS conditions.

TABLE I. COMMUNICATIONS RANGE (METERS) WITH PDR EQUAL TO 0.9

Packet rate (pps)	LTE-V retransmission	LOS-NLOS	Range - Standard	Range-Proposal	Relative variation
20	No	LOS	133.7	112.2	-16.1%
		NLOS	48.5	54.5	12.4%
	Yes	LOS	138.9	106.5	-23.3%
		NLOS	50.7	56.7	11.8%
50	No	LOS	97.5	79.0	-19.0%
		NLOS	33.7	50.1	48.7%
	Yes	LOS	79.7	66.9	-16.1%
		NLOS	29.9	50.9	70.2%

V. CONCLUSIONS

This paper has proposed the design of multi-link V2X communications where the operation of a link is adjusted with information received through other links. The proposal is applied in this paper to reduce possible correlations at the MAC level between the various links. In particular, the paper presents an IEEE 802.11p-assisted LTE-V scheduling scheme for multi-link V2V communications. The proposed scheme uses information received over an IEEE 802.11p link to design a scheduling scheme for a LTE-V link that reduces packet collisions resulting from the hidden terminal problem and eliminates half-duplex errors. The scheme presented in this paper has been designed to increase the reliability of V2V communications in intersections under NLOS conditions. However, the concept of multi-link V2X communications where the operation of a link is adjusted with information received through other links can be applied to other scenarios and objectives. The motivations for this study also raise the question of whether new V2X radio interfaces with different and complimentary characteristics compared to the existing IEEE 802.11p and LTE-V interfaces (both suffer similar problems e.g. at the MAC) should be created to obtain the benefits that multi-link V2X communications can provide.

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