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Broadcast Performance Analysis and Improvements of the LTE-V2V Autonomous Mode at Road Intersection

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***Abstract*—An autonomous V2V communication mode (also known as side-link mode 4), which facilitates V2V communication in out of eNB coverage areas, has recently been introduced into the Long term evolution (LTE) standard. Recent research has studied the performance of this LTE-V2V autonomous mode for a highway use case. However, performance analysis for a highway use case cannot be easily applied to an intersection use case as it may contain non-line-of-sight (NLOS) communication links. In this paper, we analyze and evaluate the safety message broadcasting performance of LTE-V2V autonomous mode in an urban intersection scenario. Considering practical path loss models, we present the impact of NLOS communication link on the overall message dissemination performance. Through the analytical and simulation results, we show that the overall message dissemination performance degrades drastically with increasing vehicle density and increasing distance of the transmitting vehicle from the intersection. To improve the performance, we propose a vehicle-assisted relaying scheme in which the relaying vehicle is selected in an autonomous manner. We also present two resource allocation strategies for the relaying vehicle. For low to medium vehicle density along the street, we observe significant improvement in message dissemination through relaying compared to the scheme without relaying.**

***Index Terms*—LTE-V2V, Side-link mode 4, Autonomous mode, V2V communication, VANET.**

I. Introduction

Vehicle-to-vehicle (V2V) communication is seen as an essential tool for improved road safety and plays an important role in intelligent transport systems (ITS) [1], [2]. In V2V communication, one vehicle communicates with other vehicles through exchanging safety messages to alert them of dangereous conditions or accidents and to help improve traffic condition. The safety messages, e.g. Cooperative Awareness Message (CAM) [3] or Basic Safety Message (BSM) [4], [5], contain a vehicle's instantaneous maneuvering information (such as location, speed, acceleration, heading etc.) as well as other important information such as vehicle type, break conditions, etc. Based on received safety messages from neighbouring vehicles, a suitable audio/visual warning is displayed to the driver for enhanced driver safety and comfort. Thus, reliably receiving safety messages is important in a dense vehicular communication network to avoid accidents and collisions.

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Currently, there are two leading technologies for vehicular communication networks, (i) the IEEE 802.11p standard based DSRC (Dedicated Short Range Communication) [6]–[10], and (ii) the LTE-V2V standard [11], [12]. The latter is developed on the basis of 4G cellular technology and enables a vehicle to communicate with other vehicles or mobile devices both in coverage and out of coverage scenarios. The first scenario is a centralized approach, where the base station, e.g. eNodeB, takes care of the resource management/allocation. In contrast, in the out of coverage scenario, vehicles decide in a decentralized or *autonomous* fashion the allocation of resources as there is no base station coverage available. This paper focuses on Basic Safety Message (BSM) dissemination in the LTE-V2V autonomous mode.

A number of previous studies have addressed the LTE-V2V autonomous mode such as [12]–[23]. Most of these works analyse and evaluate the performance of the autonomous mode for highway scenarios. To the best of our knowledge, no work has addressed the performance of the LTE-V2V autonomous mode for urban intersection scenario yet. V2V communication in urban intersection is different from highways, since the communication links in an urban intersection can be either line-of-sight (LOS) or non-line-of-sight (NLOS) (due to buildings, urban canyons, or other structures), while only LOS communication links are expected in highway scenario. In an urban intersection, the V2V communication performance can be severely affected due to the presence of NLOS communication links. Hence, the previous performance analysis of the LTE-V2V autonomous mode in highway scenario cannot be transferred to an urban intersection use case. On the other hand, numerous works have been done on relaying (both vehicle and RSU assisted) in the context of DSRC based communication to enhance the broadcasting performance. However, not much work has been done on relaying in the context of LTE-V2V autonomous mode.

This has motivated this work, where we study the broadcast performance of the LTE-V2V autonomous mode. The main

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contributions of this work are as follows:

- For the first time, we present the safety message broadcast performance of the LTE-V2V autonomous mode in an urban intersection scenario and present an analytical model of packet delivery ratio (PDR) while considering practical LOS and NLOS path loss models.
- For different transmitting positions and vehicle densities, we evaluate the performance of the BSM broadcast service and show that the presence of NLOS communication links severely degrade the overall broadcast performance.
- To improve the broadcast performance, we propose a vehicle-assisted relaying strategy, where the relaying vehicle is chosen autonomously and the relaying vehicle rebroadcasts the BSMs in a selective manner.
- We propose two resource allocation strategy for the relaying vehicle, namely relaying with fixed resources and relaying with dynamic resources.

The rest of the paper is organized as follows. Section II describes the geometric model of an urban intersection and a brief introduction of the LTE-V2V autonomous mode. Section III demonstrates the communication characteristics of LTE-V2V autonomous mode at an intersection and presents simulation results. In Section IV, we propose a vehicle assisted relaying technique and present resource usage strategies by the relaying vehicle. In this section, we compare the vehicle assisted strategies numerically and show the performance improvement through the proposed technique over a scheme without relaying. Finally, we conclude this paper in Section V.

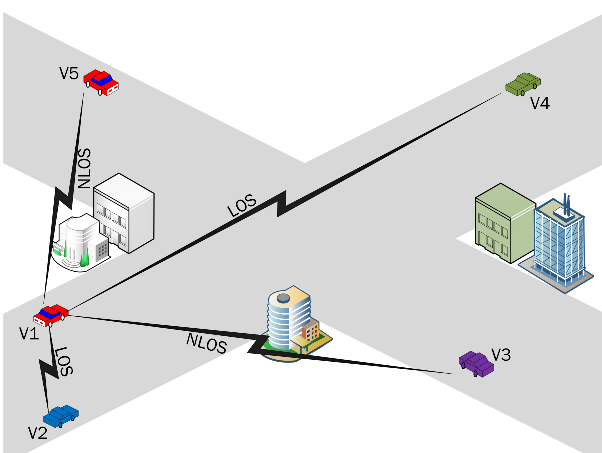

Fig. 1: Communication scenario at an intersection.

II. Preliminaries

A. Intersection Model

In this paper, we consider a four-way urban intersection scenario as depicted in Fig. 1. Typically, when two vehicles are on the same street, one can consider the communication link between them as line-of-sight (LOS). However if the positions of the vehicles are on the perpendicular street, the direct radio path may be blocked by buildings and hence one can consider the communication link between them as non-line-of-sight (NLOS). In Fig. 1, the characteristics of the communication links between vehicle V1 and other vehicles are shown. For instance, the communication link between V1 and V2 (or V4) is LOS, whereas the link between V1 and V3 (or V5) is NLOS.

B. LTE-V2V and Sidelink Mode 4

LTE-V2V communication exploits LTE uplink resources while utilizing single carrier frequency division multiple access (SC-FDMA) at the PHY and MAC layers [21]. According to the LTE specifications, the available bandwidth is subdivided into equally-spaced (spacing of 15 kHz) orthogonal subcarriers. A resource block (RB) in LTE is formed by 12 consecutive subcarriers (i.e., 180 kHz) and one time slot (i.e., 0.5 ms). The number of data bits carried by each resource block depends on the modulation and coding scheme (MCS). Hence, from the adopted MCS and safety message packet size, we can obtain the number of resource blocks required for the transmission of one safety message, and we refer to that group of resource blocks as a safety message resource (SMR). Based on the available bandwidth, the total number of available safety message resources can also be calculated.

To utilize the available safety message resources, the current LTE-V2V communications operate in both network-controlled and autonomous modes. In the first mode (also known as Sidelink Mode 3), it is assumed that the vehicles are fully covered by one or more evolved NodeBs (eNBs), where eNBs dynamically assign the resources being used for V2V communications through control signalling. In the autonomous mode (also known as Sidelink Mode 4), vehicles are assumed to be in areas where no cellular coverage is available and hence, resources are allocated in a distributed manner. A sensing based semi-persistent transmission mechanism is introduced in Sidelink Mode 4 to enable distributed resource allocation. The distributed algorithm is implemented among the vehicles, which optimizes the use of the channel by increasing the resource reuse distance between vehicles that are using the same resources. In this work, we investigate autonomous resource allocation mechanisms (Sidelink Mode 4) with a sensing-based autonomous resource re-selection scheme proposed by Qualcomm Inc. [24]. For the sake of completeness, we show the pseudo-code of the autonomous resource allocation in Algorithm 1. In the pseudo-code, θ is defined by $\theta = M \cdot \min(\text{received power})$, where M is the Hysteresis threshold in linear scale. The entire algorithm is performed at each sensing interval. Vehicles that choose reallocation with probability p, do not transmit for a sensing interval and hence, during the interval time they appear invisible to neighboring vehicles. The design parameters (p, k, *threshold*) of Algorithm 1 can be optimized to achieve lowest packet error rate.

III. Communication at Intersection and LTE-V2V Performance Evaluation

For a transmitter X, a receiver Y and N_i interfering vehicles $I = \{I_1, I_2, \ldots, I_{N_i}\}$, the signal to noise and interference ratio (SINR) at the receiver can be calculated by,

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Algorithm 1: Sensing-based autonomous resource allocation proposed by Qualcomm Inc. [21], [24].

```
for each vehicle do
    toss a coin with probability of SMR reselection p
    if reselection = true then
        stop transmitting on currently selected SMR
        for each SMR do
            measure received power
        sort SMRs by received power
        select the k best SMRs candidates
        if received power on currently selected SMR > θ then
            from the k best SMRs candidates, randomly select one
        else
            keep currently selected SMR for next transmission
    else
        transmit without SMR reselection
```

$$\Gamma = \frac{P_{Tx} N_{RB} \mathbb{G}_r}{PL_{XY}\left(\bar{P}_n N_{RB} + \sum_{j=1}^{N_i} \frac{P_{Tx} N_{RB} \mathbb{G}_r}{PL_{I_j Y}}\right)} \quad (1)$$

where P_{Tx} is the transmission power per RB, N_{RB} is the number of RBs needed for one SMR (i.e., to transmit one beacon), $\mathbb{G}_r$ is the receiver's antenna gain, PL_{uv} is the path-loss when signal propagates from vehicle u to vehicle v and P_n is the noise power per RB. The path-loss in (1) is determined by the nature of communication link between the transmitter and receiver (i.e., LOS or NLOS). For LOS scenario between two vehicles u and v, the path-loss can be modeled as,

$$PL(\text{LOS}) = PL_0 d_{uv}^{\beta} \quad (3)$$

where PL_0 is the path loss at 1m, β is the path-loss exponent, and d_{uv} is the distance between the vehicle v and vehicle u.

For the NLOS scenario, we adopt the measurement-based path loss model reported in [25]. In this model, the path loss depends on the distance of transmitter/receiver from the intersection-center, the carrier frequency, width of the receiver street, and the distance of transmitter to the wall. The NLOS path-loss model is shown in eq. 2 (in dB), where d_t and d_r are the distance of transmitter and receiver respectively from the intersection-center; w_r is the width of the receiver street; d_w is the distance between transmitter and wall; i_s is the environment parameter (1 for suburban environment and 0 for urban), d_b is the the critical distance, λ is the wave length.

A. Theoretical Analysis

We now present an analytical model of packet delivery ratio (PDR) for the intersection scenario. We present the PDR performance as a function of tagged/transmitting vehicle's distance (d_t) from the intersection center. For a given d_t, PDR is defined as,

$$PDR(d_t) = 1 - \Pr(\text{packet loss}|d_t) \quad (4)$$

where $\Pr(\text{packet loss}|d_t)$ is the average packet loss probability in a region of interest conditioning on the transmitter's distance d_t. To derive the analytical $\Pr(\text{packet loss}|d_t)$, we consider the following assumptions: (i) A simplified intersection model as depicted in Fig. 2, where a street is approximated with a line and vehicles as dots, (ii) vehicles that can decode the safety message from the tagged vehicle do not use the same SMR used by the tagged vehicle and hence those vehicles do not interfere, (iii) a single interferer is considered at the receiver, (iv) the impact of vehicles outside the region of interest $ROI \in \{L_{min}, L_{max}\}$ is neglected, and (v) the impact of the vehicles' speed is neglected. With the above assumptions, $\Pr(\text{packet loss}|d_t)$ can be written as

$$\Pr(\text{packet loss}|d_t) = \int_{ROI}\int_{ROI} \Pr(r)\Pr(i)\xi\left(N_{SMR}, N_{pi}\right) \mathbf{1}\left(\Gamma_{d_t,r,i} < \gamma_d\right) dr\, di \quad (5)$$

where r and i are the receiver and interferer distances, respectively from the intersection center; $\Pr(r)$ and $\Pr(i)$ are the probabilities that the receiver and interferer will be at the distances r and i, respectively; $\Gamma_{d_t,r,i}$ can be obtained from (1) with d_t, r, and i; function $\mathbf{1}\left(\Gamma_{d_t,r,i} < \gamma_d\right)$ returns 1 when $\Gamma_{d_t,r,i} < \gamma_d$, otherwise the function returns 0; γ_d is the threshold representing the receiver sensitivity, and $\xi\left(N_{SMR}, N_{pi}\right)$ is the probability that the interferer vehicle will use the same SMR as the tagged vehicle, which is defined as,

$$\xi\left(N_{SMR}, N_{pi}\right) = \left(1 - \left(1 - \frac{1}{N_{SMR}}\right)^{N_{pi}}\right) \quad (6)$$

where N_{SMR} is the number of available SMRs and N_{pi} is the number of vehicles that cannot sense the transmission from tagged vehicle. In (5), for a given d_t, the receiver vehicle is always assumed to be either in the same street or a perpendicular street. Eq. 5 can be simplified to

$$\Pr(\text{packet loss}|d_t) = \sum_{r=L_{min}}^{L_{max}} \sum_{i=L_{min}}^{L_{max}} \Pr(r)\Pr(i)\xi\left(N_{SMR}, N_{pi}\right) \mathbf{1}\left(\Gamma_{d_t,r,i} < \gamma_d\right) \quad (7)$$

We now present the results from the above theoretical PDR analysis. In Fig. 3 and Fig. 4, we present the PDR performance for the same and for perpendicular streets, respectively, with respect to the distance of the transmitter from the intersection center. In the analytical results, we consider $ROI \in \{-150m, 150m\}$ and the parameters shown in Table I. We observe that PDR gradually drops as d_t increases, since increasing d_t increases the chance of having an interfering vehicle in a perpendicular street. We observe a drastic PDR drop for the perpendicular street case due to the limited coverage of the tagged vehicle as d_t increases. As expected, for both cases, the PDR decreases as the vehicle density increases.

B. Simulation Setup and Parameters

The simulation model is based on the system architecture described in Section II. This simulation model is implemented using the LTEV2Vsim simulator presented in [16]. We have extended the LTEV2VSim by adding the intersection topology and incorporating the earlier described path loss models. We have simulated with a 2km $\times$ 2km road network where

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$$PL(\text{NLOS}) = 3.75 + 2.94 i_s + \begin{cases} 10\log_{10}\left(\left(\frac{d_t^{0.957}}{(d_w w_r)^{0.81}}\frac{4\pi d_r}{\lambda}\right)^{\beta}\right), & \text{if} \quad d_r \le d_b \\ 10\log_{10}\left(\left(\frac{d_t^{0.957}}{(d_w w_r)^{0.81}}\frac{4\pi d_r^2}{\lambda d_b}\right)^{\beta}\right), & \text{if} \quad d_r > d_b \end{cases} \tag{2}$$

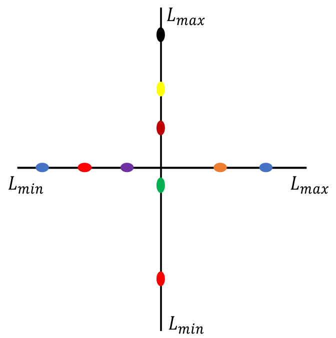

Fig. 2: Simplified representation of an intersection.

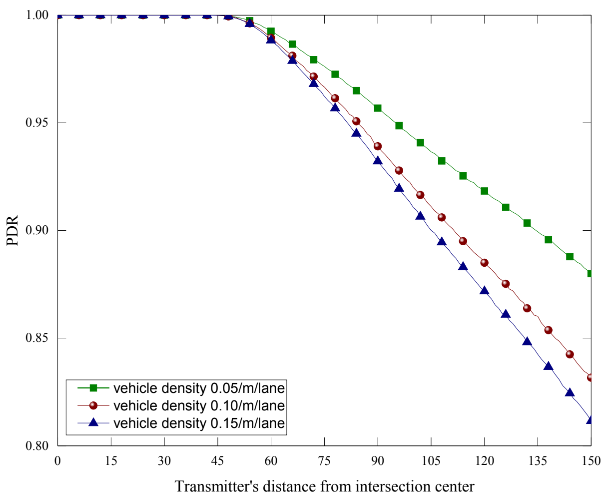

Fig. 3: Analytical packet delivery ratio (PDR) at same street.

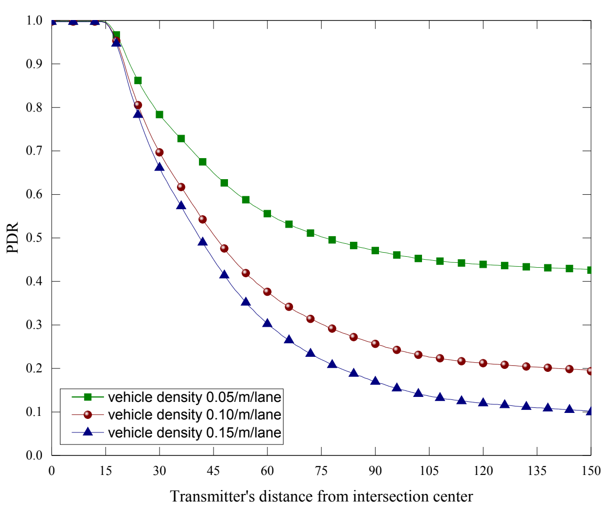

Fig. 4: Analytical packet delivery ratio (PDR) between perpendicular streets.

the intersection-center is assumed at the middle of the road network. We consider three lanes per travel direction with uniformly distributed (generated in random locations) vehicles along the street. We model the vehicular mobility by assigning an average speed of 50.08 km/h and 3.21 km/h as standard deviation. Although a 2km $\times$ 2km road network is considered in the simulation, we limit our region of interest to the 150m $\times$ 150m area around the intersection. In the first instance, the vehicles are generated at random locations along the street, where the total number of vehicles depends on the predefined vehicle density. During the simulation, once a vehicle goes outside of the road network, it appears on the opposite street. This strategy maintains a constant vehicle density along the street. The simulation results are captured when the simulated time has reached 100 seconds. In the simulation, each vehicle transmits safety messages in a conventional half-duplex manner with a rate of 10 Hz. We consider QPSK modulation with code rate 0.407 as the modulation and coding scheme (MCS) with a dedicated bandwidth of 10 MHz. With the above settings, we choose a safety message packet size of 190 Bytes, which makes the available beacon resources equal to 100. The parameters used in the simulation are summarized in Table I with relevant description. The justification for the parameter values can be found in [16].

TABLE I: Simulation Parameters

Parameter	Value
Road network related	
Simulated area	2km $\times$ 2km
Number of lane per street	6
Lane width	3m
Receiver street width	18m
Average distance of Tx to wall	9m
Vehicle density/lane	10-50 per km
Average speed	50.08 km/h
Standard deviation of speed	3.21 km/h
Received power related	
Bandwidth	10MHz
Transmit power per message	23dBm
Antenna gain	3dBm
Carrier Frequency	5.89GHz
Path-loss exponent β_{NLOS}	2.69
Path-loss at 1m (L_0)	47.86dB
Noise power per RB ($\bar{P}_n$)	-110 dBm
Critical distance d_b	100m
Threshold of decoding	4.17dB
Resource allocation related	
Safety message rate	10 Hz
Packet size	190 bytes
Channel bandwidth	10 MHz
Total number of SRM	100
SMR reselection probability (p)	0.1
Number of best SMR candidates (k)	20
Hysteresis threshold (M)	6 dB

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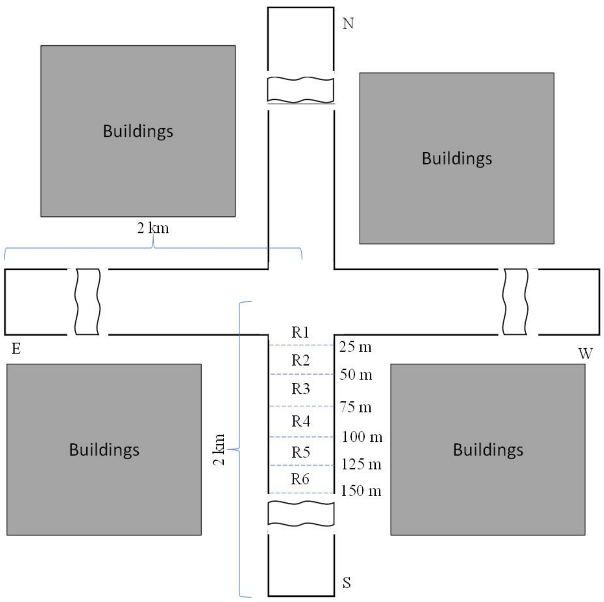

Fig. 5: Intersection scenario considered in the simulation.

C. Performance Evaluation

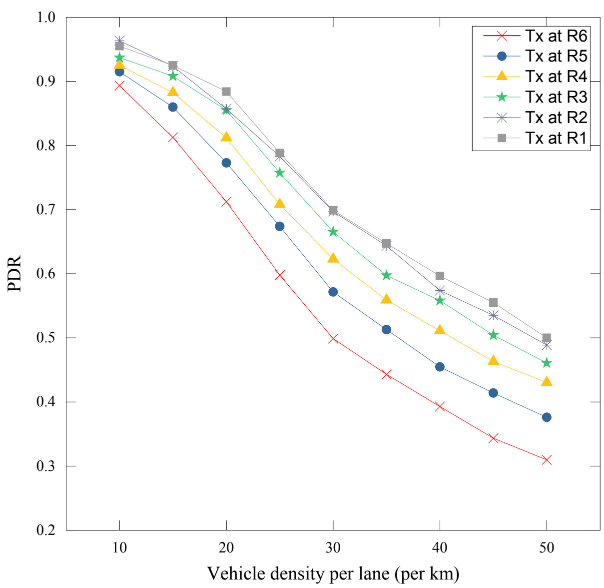

Fig. 6: Packet delivery ratio (PDR) at the same street.

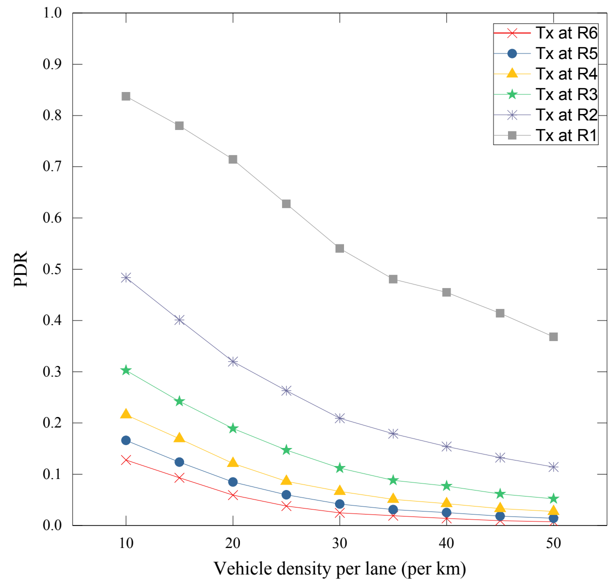

Fig. 7: Packet delivery ratio (PDR) at perpendicular street.

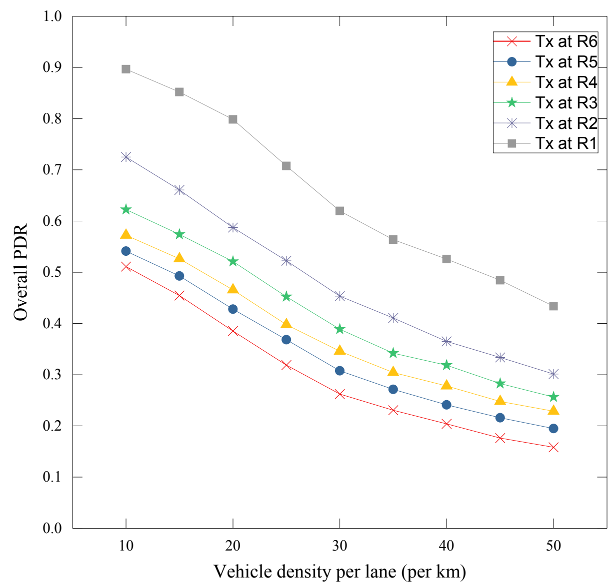

Fig. 8: Overall packet delivery ratio (PDR) at an intersection.

Now we present the simulation results for the LTE-V2V autonomous mode around an urban intersection. In the simulation results, we vary the position of tagged/transmitting vehicle (Tx) and observe the packet delivery ratio (PDR) on different streets. For simplicity, we divide the region of interest into six regions (as depicted in Fig. 5). In Fig. 6, we present the PDR performance on the same street. First of all, as expected, we observe that the PDR decreases as the vehicle density increases. We observe this characteristics due to the following two reasons: (i) when the number of vehicles increases, reuse distance of using same SMR decreases, which may cause more interference at the receiver, (ii) increase of number of hidden nodes from perpendicular street. The latter case occurs for quick drop of signal strength at perpendicular street due to the presence of NLOS links in an urban intersection. Thus, it is highly likely that the vehicles in the perpendicular street will not be able to sense the transmission of tagged vehicle and may end up with choosing same SMR as the tagged. This will cause severe packet collision at the receivers that are very close to the intersection center. From Fig. 6, we also observe that for a given vehicle density, the PDR increases when tagged vehicle's position gets closer to the intersection center. This is because when the tagged vehicle gets closer to the intersection center, the transmission range of the tagged vehicle can cover all the vehicles located in the region of interest (i.e., 150m $\times$ 150m). From the results, we observe similar PDR performance for tagged vehicle at region R1 and region R2, which indicates that the transmission range (within the region of interest) of

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the tagged vehicle remains same when the tagged vehicle is located within 50m from the intersection center.

In Fig. 7, we show the PDR performance between perpendicular streets. Similar to the previous case, the PDR decreases with as the vehicle density increases. However, the PDR for a given vehicle density is much lower than the PDR for the same street case (i.e., Fig. 6). The drastic PDR drop on perpendicular street is due to the NLOS link between the tagged vehicle and the receivers. The impact of the NLOS link decreases when the tagged vehicle moves closer to the intersection center. Hence, we observe an improvement in PDR as the tagged vehicle approaches closer to the intersection center. Note that for a given vehicle density, we observe an opposite PDR behavior compared to the same street case when we vary the tagged vehicle's position. For the perpendicular street, we observe a large variation in PDR for the tagged vehicle in the regions closer to the intersection center (performance curves for region R1, R2 and R3), while a little variation is observed when the tagged vehicle is away from the intersection center (performance curves for region R4, R5 and R6).

The overall PDR within the region of interest is shown Fig. 8. We observe that the overall PDR drops drastically, when the tagged vehicle is away from the intersection center. The communication performance of the tagged vehicle on a perpendicular street plays a vital role in the drop of the overall performance. Compared to the PDR of a tagged vehicle near the intersection center, we observe a 50% PDR drop when the tagged vehicle is 100m away from the intersection center. To improve the PDR performance, in the following section, we propose vehicle assisted relaying.

Algorithm 2: Proposed vehicle assisted relaying.

```
for each vehicle i do
    find its distance D_i from the intersection center
    if position of the vehicle is within 50m from intersection center
      then
        find all the surrounding vehicles' distances from the
          intersection center
        if D_i is the smallest of all the distances then
            vehicle i nominates itself as relaying vehicle and
              performs relaying
Relaying vehicle select the messages M_{R_tag} from region R_tag.
Among M_{R_tag}, N_R messages that belongs to farthest vehicles from
  intersection center, are re-broadcast from the relaying vehicle.
```

IV. Vehicle Assisted Relaying

From the results in the previous section, it is obvious that presence of NLOS links at the urban intersection causes drastic packet drops, since the transmitted signal from one street cannot reach the perpendicular street due to building obstructions. To mitigate this impact, we now propose vehicular assisted relaying for the LTE-V2V autonomous mode at urban intersection. In the following relaying schemes, we refer to the vehicle that will relay/rebroadcast the received messages as the *relaying vehicle*. The relaying vehicle is chosen autonomously by the vehicle itself. We assume that at each time instant, each vehicle computes its surrounding vehicles' distance (including its own distance) from the intersection center. This is a realistic assumption, since each vehicle will have safety messages from the vehicles that are close in distance and each safety message will contain the current position of the corresponding vehicle. Then the vehicle close to the intersection center nominates itself as relaying vehicle. Once a relaying vehicle is nominated it performs the following selective relaying task. Let us assume that PDR performance of a tagged region[1] $R_{tag} \in \{R1, R2, R3, R4, R5, R6\}$ needs to be improved through relaying and a maximum N_R received safety messages from R_{tag} can be re-broadcast by the relaying vehicle. Note that the constraint on maximum number of re-broadcast messages is due to the limitation of safety message resources (SMR). The vehicle chooses from the received safety messages by the relaying vehicle, those messages that came from vehicles in R_{tag} and rebroadcasts N_R messages that belong to vehicles farthest away from the intersection center. The relaying algorithm is summarized in Algorithm 2. In the algorithm, a vehicle that resides outside of the 50m range from the intersection center, excludes itself from nominating itself as relaying vehicle. The rationale behind this choice is that those vehicles (outside of 50m from the intersection center) do not exhibit good broadcast performance on the perpendicular street (as shown in Fig. 7). In terms of resources used by the relaying vehicle, we consider two strategies, namely relaying with fixed/dedicated resources and relaying with dynamic resources, which are described below.

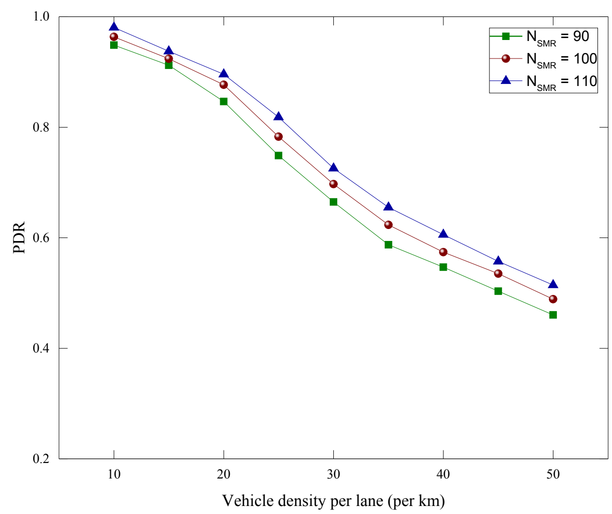

Fig. 9: Impact of available safety message resources (SMRs) on the PDR performance.

A. Relaying with Dedicated Resources

In this strategy, we reserve N_R safety message resources (SMR) for the relaying vehicle. Thus, all the vehicles (including the relaying vehicle) perform the autonomous resource allocation (as described in Algorithm 1) considering $N_{SMR} - N_R$ number of SMR, where N_{SMR} is the total allocated SMRs

[1]We denote the tagged region as a particular area or region of interest around the intersection. In the calculation of packet delivery ratio, only the transmitting messages from the tagged region were considered.

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Algorithm 3: Strategies for vehicle assisted relaying.

Find the relaying vehicle according to Algorithm 2.
if *we set rebroadcasting with dedicated resources* **then**
    the relaying vehicle rebroadcasts the selected messages with dedicated SMRs
else
    for *each SMR* **do**
        measure received power
    sort SMRs by received power
    select first N_R SMRs with lowest received power.
    Rebroadcast the selected messages with the selected SMRs.

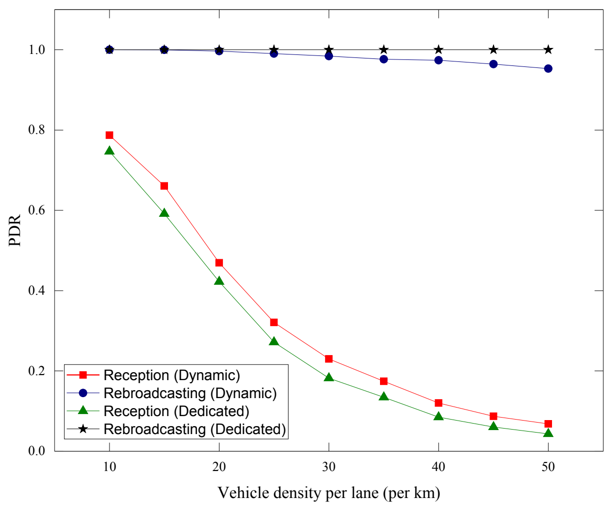

Fig. 10: PDR Performance characteristics of relay vehicle.

for the LTE-V2V autonomous mode. All the vehicles transmit their safety messages without using the reserved safety message resources and the relaying vehicle uses the reserved resources only for the rebroadcast purpose. As the number of available SMRs for regular safety message transmission decreases, the reuse distance of SMR will be reduced and hence the message dissemination performance is expected to drop. For varying number of SMRs, in Fig. 9, we present the ”without relaying” PDR performance when the tagged vehicle is in region R2. Before relaying, we observe that the PDR performance drops as the available SMRs decreases. It is worth mentioning that the re-broadcast messages will not suffer from interference in this strategy.

B. Relaying with Dynamic Resources

In this strategy, we do not reserve resources for re-broadcast of safety messages. Instead, the relaying vehicle finds the candidate resources for relaying. Before re-broadcast, the relaying vehicle observes the received power over each safety message resource (SMR) and then identifies the N_R SMRs with the lowest observed power. Compared to the previous strategy, the re-broadcast messages may suffer from interference from other vehicles. However, regular safety message broadcasting performance will be better than the previous strategy as all the vehicles can use all the available resources.

To illustrate how the above strategies can impact the reception and broadcast performance of the relaying vehicle, we consider a scenario with a relaying vehicle at the center of the intersection. In Fig. 10, we present the reception probability of that relaying vehicle for messages from tagged region R6. We observe that the reception probability of the relaying vehicle is worse for the dedicated scenario due to the lower number of SMRs available for the vehicles than in the dynamic scenario. In Fig. 10, we also present the broadcast performance (within region of interest) of the relaying vehicle positioned at the center of the intersection. Since relaying vehicle use dedicated resources in the fixed strategy, the broadcast PDR is 1 due to the absence of interference. We observe that at low and moderate vehicle density (below 25 vehicles/km/lane), interference does not impact the broadcast performance with dynamic resources i.e., broadcast PDR is 1 (same as the dedicated resources). However, the broadcast performance with dynamic resources drops slightly at high vehicle density. The above relaying strategies is summarized in Algorithm 3.

C. Performance Evaluation with Relaying and Comparison

We now present the performance comparison and improvement through the proposed relaying schemes. Along with the parameters mentioned in Table I, we consider $N_R = 10$ in the simulation. In case of reception of duplicate messages due to re-broadcast, we assume that the receiving vehicle simply discards the replicated messages. In Figs. 11, 12, and 12, we present the packet delivery ratio (PDR) performance comparison between relaying with dedicated and dynamic resources, while considering the tagged vehicle's position at R4, R5, and R6, respectively. For all the scenarios, we observe that the PDR performance with dynamic resources is better than the performance with dedicated resources for the relaying vehicle. This performance characteristics can be explained by dividing the performance curve into two regions: low vehicle density region and high vehicle density region. At low vehicle density, it is expected that most of the messages from the tagged region will be relayed by the relaying vehicle. Hence, in this region, the PDR performance is dominated by the reception and broadcast performance of the relaying vehicle. With dynamic resources, the relaying vehicle has better reception probability than the case where dedicated resources are used, while similar broadcast performance is observed for both cases in the low vehicle density region (as shown in Fig. 10). Above factors result in better performance with the dynamic resource scenario than the dedicated resource scenario. On the other hand, in the high vehicle density region, only few messages can be relayed compared to the number of vehicles present in the tagged region. Hence, rebroadcasting will give insignificant improvement in packet delivery ratio and hence post-relaying PDR performance will be dominated by the ”without relaying” PDR performance. As observed from Fig. 9, the strategy with dedicated resources yields worse ”without relaying” PDR performance than the strategy with dynamic resources, due to the reduction of available resources in the former strategy. Although, the relaying vehicle's broadcast performance is slightly better with the former strategy, this impact does not influence the post-relaying performance due to the limited number of relayed messages. Although the performance of

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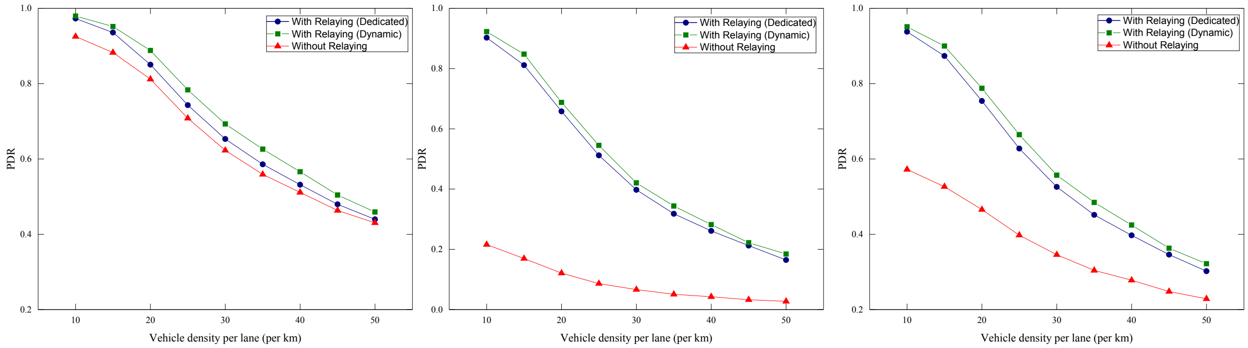
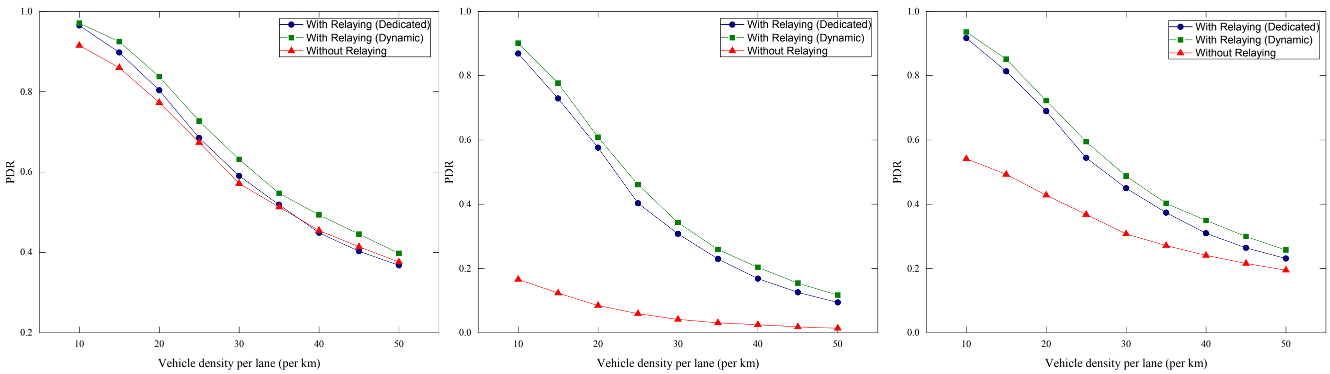


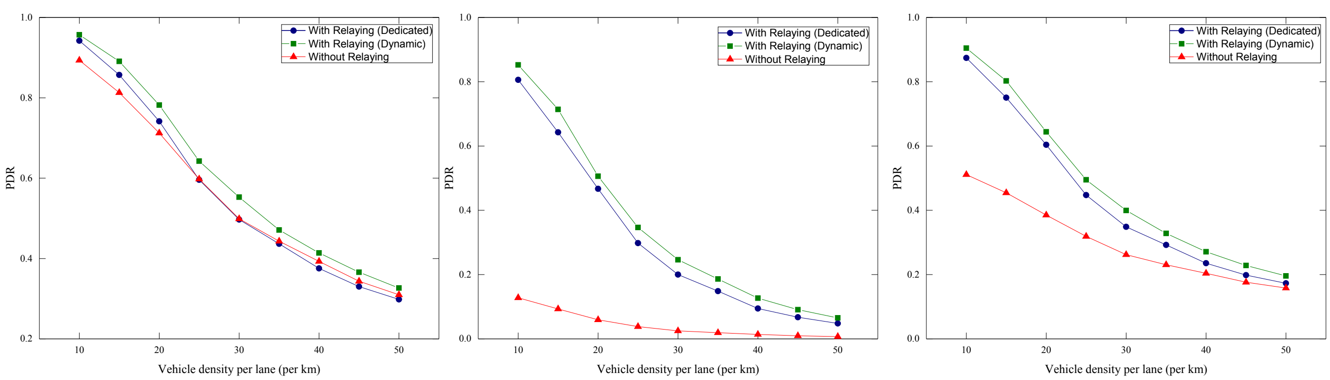
(a) Same street. (b) Perpendicular street. (c) Overall.

Fig. 11: Packet delivery ratio (PDR) performance comparison when tagged vehicle at R4.



(a) Same street. (b) Perpendicular street. (c) Overall.

Fig. 12: Packet delivery ratio (PDR) performance comparison when tagged vehicle at R5.

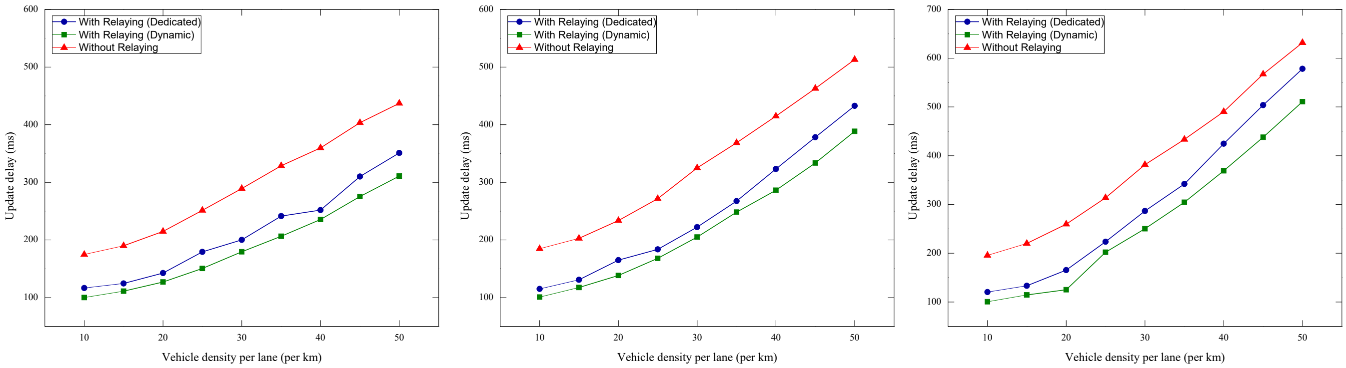


(a) Same street. (b) Perpendicular street. (c) Overall.

Fig. 13: Packet delivery ratio (PDR) performance comparison when tagged vehicle at R6.

relaying with dynamic resources outperforms the performance of relaying with dedicated resources, the former strategy exhibits higher complexity in the resource allocation process. With dynamic resources, the relaying vehicle needs to monitor the channel and then executes a channel selection algorithm based on the observations. On the other hand, these procedures are not required for the relaying with dedicated resources and hence this strategy exhibits lower complexity.

In Figs. 11, 12, and 13, we also present the PDR performance for ”without relaying” as a benchmark. For the same street case, we observe a little improvement through relaying strategies. This is due to the fact that the tagged vehicle can reach most parts of the same street in the region of interest (due to LOS communication link) and hence relaying does not help much to improve the message dissemination performance in the same street. For PDR dissemination in the perpendicular street, we observe a significant improvement through relaying when the vehicle density is low to moderate. This is because the transmission range of the vehicles at the tagged region cannot cover the vehicles in the perpendicular street, while the relaying vehicle helps to disseminate their messages to the out of reach vehicles in the perpendicular street. At high vehicle



(a) Tagged vehicle at R4.
(b) Tagged vehicle at R5.
(c) Tagged vehicle at R6.

Fig. 14: Communication latency comparison.

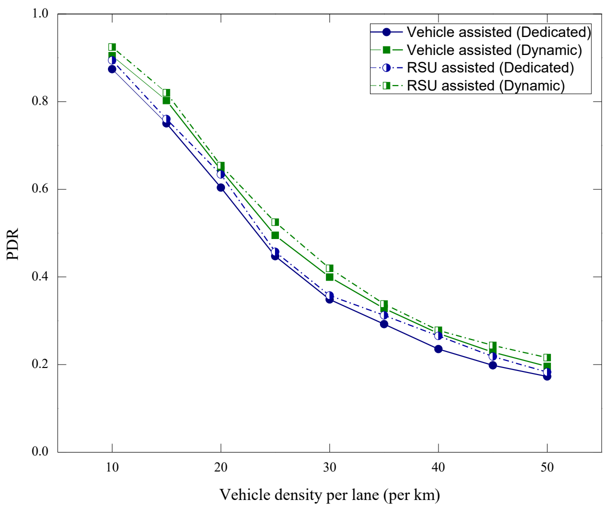


Fig. 15: Comparison between RSU and vehicle assisted relaying.

density, we observe a little performance improvement over the "without relaying" scenario since the number of relayed messages is insignificant compared to the vehicles present in the tagged region. Due to the above factors, we observe more than 50% overall improved PDR performance with relaying strategies compared to the "without relaying" scenario. In Fig. 14, we present the communication latency performance of "with relaying" and "without relaying" schemes in terms of *update delay*. We define update delay as a metric which measures the time difference between two consecutive correctly received messages for each couple of vehicles in the region of interest. Compared to the relaying scenarios, longer update delay is observed for the "without relaying" scenario due to the higher packet loss. Note that it is also possible to relay the safety messages with a road side unit (RSU). In Fig. 15, we show the performance comparison between RSU assisted relaying and the proposed vehicle assisted relaying. In the simulation, we consider the RSU at the center of the intersection. The performance of RSU relaying is similar to the performance of vehicle assisted relaying, as in most cases a relaying vehicle is found close to the center of the intersection.

V. CONCLUSIONS

In this paper, we have presented the safety message broadcast performance of the LTE-V2V autonomous mode (also known as sidelink mode 4) at an urban intersection. In the performance analysis, we consider practical path loss models for V2V communication in LOS and NLOS scenarios. We have developed an intersection-based simulation environment to evaluate the performance of LTE-V2V autonomous mode. From the analytical and simulated results, we observe that the LTE-V2V broadcast performance at the intersection degrades significantly due to the presence of NLOS communication links specially for the case when the transmitting vehicle is away from the intersection center. To improve the performance, we have proposed vehicle-assisted relaying for the LTE-V2V autonomous mode, where relaying vehicles are determined autonomously by other vehicles. We have presented two types of resource usage strategies for the relaying vehicle, namely relaying with dedicated resources and relaying with dynamic resources. Through simulation, we observe that the latter strategy gives slightly better performance than the relaying with dedicated resources. We also observe that the proposed relaying schemes exhibit significant broadcast performance improvement over the scheme without relaying when the vehicle density is low to moderate. In future, it will be interesting to investigate the impact of on-road obstacles (like big vehicles) which may degrade the performance of LOS communication.

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