Transmission Capacity Analysis of Distributed Scheduling in LTE-V2V Mode 4 Communication

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Abstract. LTE-V2X sidelink/PC5 communication aimed at supporting device-to-device (D2D) communications in vehicular scenario has been developed as an appropriate technology by 3GPP. Particularly, mode 4 operating without cellular coverage permits vehicles autonomously to select resources and has the potential to achieve an efficient and reliable transmission for vehicle safety applications. However, there is very little research conducted on theoretical understanding of the characteristics and performance of mode 4. In this work, we propose a tractable mathematical analysis to evaluate the performance of LTE-V2V in mode 4. Specifically, we assume that vehicles driving on 1-D abstract lane follow a Poisson Point Process (PPP). By means of probability model, we analyze the event that vehicles randomly select the same resource inducing collision, and investigate the failure probability of transmission. Also, the distance between adjacent vehicles is log-normally distributed and the transmission outage probability under a fixed threshold is given. Furthermore, we derive the expression of transmission capacity. To this end, numerical results verify that the transmission capacity of mode 4 can be improved to a certain extent with the increasing of density of vehicles.

Keywords: LTE-V2V mode 4 communication · Distributed scheduling
Collision · Interference · Transmission capacity

1 Introduction

In recent years, the Intelligent Transportation System (ITS) considered as an effective method can be push forward by the revolution of automotive industry and vehicle wireless communication. Exchanging information acquired by on-board sensors with neighbors including location, direction and speed, plays a crucial role in vehicle safety application. Meanwhile, in order to ensure the reliability of vehicular communication, different standardizations have devoted efforts into normalizing vehicle-to-everything (V2X) wireless technologies. To date, there are two main standards, i.e. IEEE 802.11p

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[1] and 3GPP's LTE-V2X [2]. At the end of 2016, 3GPP developed LTE sidelink/PC5 communication as a potential technology for vehicular applications in the first version of Release14 [2].

In Release 14, the standard concludes two modes for sidelink/PC5 communication, in which vehicles directly communicate with each other. In mode 3, the management or scheduling of resources is controlled by the base station (i.e. eNB), but vehicles autonomously select and utilize resources in a distributed manner in mode 4. Currently, some referable results of reliability of LTE-V2V have been acquired by simulations [3–6] and rarely theoretical studies. Especially, mode 4 has been considered the baseline mode and represents an alternative to IEEE 802.11p. The performance of mode 4 for V2 V communications has increasingly being discussed in last few years. So far, most of these studies focus on simulation analysis of reliability that is considered as the important performance indicator measured by Packet Delivery Ratio, such as [3, 4]. Additionally, the presented model in [7] has characterized an upper performance of vehicular D2D communication relying on LTE-D2D (Release 12) as function of the application traffic pattern, without the effect of interference. In [6], the authors propose 'spatial capacity' defined as the total amount of bits that can be successfully delivered in 1 km and 1 s to assess the performance of LTE-V2 V mode 4 by using the vehicle traffic simulator. As far as we know, the study of capacity on mode 4 is still a blank field.

Since Gupta and Kumar's remarkable study on the capacity of ad hoc network [8], S. Weber and J. G. Andrews proposed the notion that the spatial density of successful transmission is defined as transmission capacity (TC) [9]. After that, some researchers have conducted a series of studies on transmission capacity for Vehicle Ad Hoc Network (VANET) [10–12]. These related studies consider 1-D linear road and discuss the concurrent transmitters and interference on distributed access scheme. For example, they are mostly based on Carrier Sense Multiple Access/Collision Avoidance (CSMA/CA) mechanism that vehicles successfully access the channel after going through the sensing phase and the finite back-off process. Different from this typical distributed scheme, vehicles in mode 4 use the time-frequency resources determined by sensing results and randomly select some resources to transmit immediately. Vehicles may conflict with others when they choose the same resource, leading to the failure of transmission. Thus, the existing models of capacity for distributed scheme in VANET cannot be directly applied to mode 4.

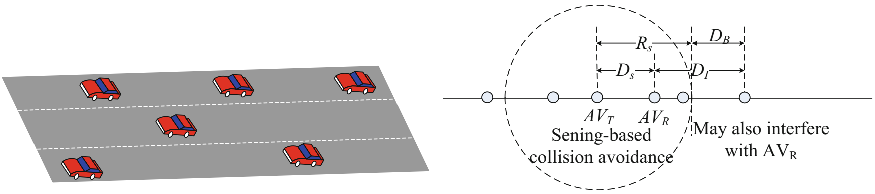
To better understand characterizes of decentralized scheme in mode 4, we undertake to develop a novel transmission capacity analysis model of mode 4 by taking its resource collision avoidance and vehicle scenarios into consideration. In this paper, we firstly analyze the collision probability due to the resource competition between transmitters, further obtain the density of concurrent transmitters. Then, the transmission outage probability is derived, considering interference to receivers under a simplified channel. Our ultimate goal is to extend a theoretical study on the capacity for LTE-V2V mode 4.

The rest of the paper is organized as follows. System model is built in Sect. 2. In Sect. 3, theoretical analysis of collision probability, interference analysis, and transmission capacity is given. Numerical results are presented in Sect. 4. Finally, in Sect. 5, the conclusion is obtained.

2 System Model

2.1 Network Model

As represented in Fig. 1(a), a multi-lane highway scenario constituted from N parallel traffic lanes separated by a fixed distance. Compared with the transmission range of vehicles, the road width is much smaller. Thus the 2-D multiple lanes are always approximated by a 1-D single lane in previous works, such as [10–12].



(a) Multi-lane model (b) Single lane abstraction model

Fig. 1. Highway scenario

In order to simplify the analytical model, we also consider a 1-D straight lane that is shown in Fig. 1(b). From the independent theorem of PPP [13], the set of vehicles Π_λ within the abstract 1-D line follows a one-dimensional PPP of density λ vehicles/km.

Additionally, for vehicle mobility, we utilize the well-known Car-following model [14], which models the mean distance between any two adjacent vehicles as a log-normal distribution with the main parameters μ and σ.

$$D_X(x) = \frac{1}{\sqrt{2\pi}\sigma x} \exp\left(\frac{-(\ln x - \mu)^2}{2\sigma^2}\right). \tag{1}$$

Each vehicle, hereafter Autonomous Vehicle (AV), broadcasts beacons periodically for V2 V safety application by a D2D type of radio link (sidelink).

Channel model: All AVs are assumed to transmit with a fixed power P_t and have the same transmission rate R. The signal power decays with the distance according to the large-scale fading model with a path-loss exponent $\alpha > 1$. Besides path loss attenuation, the signal power experiences with the small-scale Rayleigh fading which follows an exponential distribution with mean equal to 1. Consequently, the power received is $P_t H d^{-\alpha}$, where H represents the channel fading, d represents the transmission distance that is defined the Euclidean distance.

2.2 Distributed Scheduling Scheme in Mode 4

In LTE-V2V mode 4 communication, AVs transmit to each other in direct mode, with resource allocation performed by distributed scheduling. According to the framework in R14 specification, radio resources are selected from a selection window, which is the beacon generation period (here equal to t_p = 100 ms). We assume that all the resources in the selection window are available, which is defined as $L = \{1, 2, \ldots, M\}$. Each AV continuously senses the radio channel to learn about the periodic transmission status of the neighboring AVs. When a packet needs to be transmitted, the last 1000 ms history, referred as the sensing window, is used to make a process of resource exclusion and selection. In detail, the AV decodes the SCI information and measures the energy level of related signals. We define that the maximum distance at which the neighbors are able to decode sidelink control information (SCI) messages is R_s, i.e. sensing distance. Thus, the final candidate resource pool $L_1 = \{1, 2, \ldots, m\}$ is composed of the remaining available resources. The AV randomly chooses one of the in L_1. Once a resource is chosen, AV may keep using that resource for a random time before resource reselection occurs as described above.

2.3 Performance Metric

Transmission capacity (TC): It is defined as the maximum spatial capacity accommodated in the network [9], that is

$$C_T = \lambda P_s (1 - \tau) R, \tag{2}$$

Where λ describes the density of the potential transmitters in the network. P_s represents the probability of transmission. τ is the outage probability of transmission when the signal-to-interference ratio (SIR) is smaller than the threshold β. R represents the transmission rate and equals 1 bps. In this case, we would assess the normalized TC in the final results.

3 Theoretical Analysis

In the context of V2 V mode 4 operation, given these assumptions in Sect. 2.2, the number of vehicles that can be allocated initially in the selection window is equal to $M = \lfloor t_p / t_{sfr} / n_{sfr\_bcn} \rfloor$, where *nsfr_bcn* equals to 1 that means one sub-frame needed to transmit each beacon. Through the resource selection procedure, the size of resource pool available L_1 is denoted as

$$m = E\left[\sum_{i=1}^{M} X_i\right], \tag{3}$$

where X_i is a random variable that determines whether a resource i is selected into the resource L_1, as

$$X_i = \begin{cases} 1, & i \, is \, in \, L_1 \\ 0, & i \, is \, not \, in \, L_1 \end{cases}. \tag{4}$$

Note that for the tagged AV, each resource is selected with different probability. Nevertheless, this issue will not be discussed in this paper that may be investigated in our future work.

3.1 Collision Probability

In this subsection, we present a model to capture the collision probability. The approach of resource reservation in LTE-V2V mode 4 does not completely resolve collisions when trying to reserve an idle slot.

Lemma 1. The target probability of failure probability due to collisions is

$$P_{failure} = 1 - e^{-\bar{n}} \cdot \sum_{k=0}^{m} \frac{\bar{n}^k}{m^k} \cdot C_m^k. \quad (5)$$

Proof. AVs use sensing to determine transmission opportunity, i.e. a suitable resource for transmission. The resource occupancy and energy detection level are two important conditions to conduct resource exclusion. We convert these into spatial constraints and infer the density of the competitive AVs that cause resource collision with the tagged AV.

We arbitrarily choose an AV that constructs a resource utilization map based on the occupancy of resources for each interfering AV indicated by decoding SCI. Based on the sensing-based protocol, the subset of competing AVs can be expressed as

$$\Pi_c = \{AV_1, AV_2, \ldots | AV_j \in \Pi_\lambda, a_j = 0\}. \quad (6)$$

where $a_j = 0$ represents AV_i hasn't occupied resources. Note that the density is $Q \cdot \lambda$, Q represents the probability of competition that AVs need to select resources at the same slot.

Obtaining through the independent thinning from Π_c, the average number of vehicles competing in t_p within the sensing range R_s is $\bar{n} = R_s \cdot Q \cdot \lambda$. A segment l_r of sensing range R_s have k competing vehicles,

$$P_{l_r}(k) = \frac{\bar{n}^k \cdot e^{-\bar{n}}}{k!}. \quad (7)$$

Then, we calculate the collision probability $P_c(k)$ conditioned to having a number of AVs equal to k. Provided that AVs exceed m, AVs have not sufficient resources inducing collision. The number of AVs is smaller than available resources, collisions happen when more than two vehicles randomly select the same reserved slot in the same one-hop set. The detail expression can be given as

$$P_c(k) = \begin{cases} 1 - \frac{m!}{(m-k)!m^k}, & k \leq m \\ 1, & k > m \end{cases}. \quad (8)$$

According to the Total Probability Theorem, the collisions under the given number of AVs from zero to infinity make up a complete event. Thus, the failure probability is derived as follows

$$\begin{aligned} P_{failure} &\underset{=\!=}{(a)} \sum_{k=0}^{\infty} P_{l_r}(k) \cdot P_c(k) \underset{=\!=}{(b)} \sum_{k=0}^{\infty} P_{l_r}(k) \cdot (1 - P_{nc}(k)) \\ &\underset{=\!=}{(c)} 1 - \sum_{k=0}^{m} P_{l_r}(k) \cdot P_{nc}(k) \underset{=\!=}{(d)} 1 - e^{-\bar{n}} \cdot \sum_{k=0}^{m} \frac{\bar{n}^k}{m^k} \cdot C_m^k, \end{aligned} \tag{9}$$

where $P_{nc}(k)$ in (b) and (c) is defined as the condition probability that the k AVs do not collide; (a) comes after applying the Total Probability Theorem; (c) after invoking the property of probability that the sum is 1; and (d) after substituting Eqs. (7) and (8).

3.2 Interference Analysis

In subsection 3.1, we have considered the transmission collision. When the tagged AV successfully selects some suitable resources, other concurrent transmitters out of the sensing range R_s still may cause interference to the receivers in the transmission range D_s. We define the sensing range R_s as exclusive range, hereafter ER.

To simplify the calculation, we consider the closest AV outside of ER as an active node transmit packet using the same resource that is illustrated as Fig. 1(b), D_s represents the distance between transmitter AV_T and receiver AV_R. The notation D_B is used to represent the distance between the right boundary of AV_T's ER and AV_R's interferer AV_I. D_I is the distance between AV_T and AV_R.

Lemma 2. Under Rayleigh fading, we can approximate the Laplace transform of the interference I from AV_I as

$$L_I(s) == \int_0^{\infty} f_{D_B}(d - R_s + D_s) \frac{1}{sx^{-\alpha} + 1} dx, \tag{10}$$

where $f_{D_B}(\cdot)$ represents the Probability Distribution Function (PDF) of ER's boundary location.

Proof Combining channel model and node distribution in subsection 2.1, the interference can be derived as follows

$$\begin{aligned} L_I(s) &= E[\exp(-sI)] = E\left[\exp\left(-sHD_I^{-\alpha}\right)\right] \\ &= \int_0^{\infty} f_{D_I}(x) E_H[\exp(-sHx^{-\alpha})] dx \\ &\underset{=\!=}{(e)} \int_0^{\infty} f_{D_I}(x) \frac{1}{sx^{-\alpha} + 1} dx \underset{=\!=}{(f)} \int_0^{\infty} f_{D_B}(d - R_s + D_s) \frac{1}{sx^{-\alpha} + 1} dx, \end{aligned} \tag{11}$$

where (e) follows by $f_H(x) = \exp(-x)$, and (f) comes after substituting the geometrical relationship (12) into (e).

$$D_I = R_S - D_S + D_B. \tag{12}$$

Since the boundary of ER can locate anywhere between the two neighboring nodes uniformly, the random variable D_B can be treated as $D_B = Y \cdot U$, where Y is a random variable following the log-normal distribution mentioned in Eq. (1), and U is a random variable following a uniform distribution within [0,1]. With omitting the specific derivation process, the PDF of D_B is

$$\begin{aligned} f_{D_B}(z) = \frac{dF_{D_B}(z)}{dz} = \frac{d\ \Pr\{Y \cdot U \le z\}}{dz} = \exp\left(\frac{\sigma^2}{2} - \mu\right) \cdot \Phi\left(\frac{\mu - \sigma^2 - \ln z}{\sigma}\right) \\ - \frac{1}{\sqrt{2\pi}\sigma} \exp\left(\frac{\sigma^2}{2} - \mu - \frac{(\mu - \sigma - \ln z)^2}{2\sigma^2}\right) + \frac{1}{\sqrt{2\pi}\sigma z} \exp\left(-\frac{(\ln z - \mu)^2}{2\sigma^2}\right) \end{aligned}. \tag{13}$$

3.3 Transmission Capacity

Based on the previous analysis, the outage probability τ is calculated as

$$\begin{aligned} \tau &= \Pr(SIR \le \beta) = \Pr\left(\frac{P_t H d_s^{-\alpha}}{P_t I} \le \beta\right) = \Pr\left(H \le \beta D_s^{\alpha} I\right) \\ &= 1 - \mathrm{E}\left[\exp\left(-\beta D_s^{\alpha} I\right)\right] = 1 - L_I\left(\beta D_s^{\alpha}\right). \end{aligned} \tag{14}$$

The success probability is defined as the probability that the tagged transmitter has the access right and the data is received by the tagged receiver without outage. Finally, transmission capacity that is derived as

$$\begin{aligned} C_T &= \lambda P_s (1 - \tau) R = \lambda (1 - P_{failure})(1 - \tau) R \\ &= \lambda \cdot e^{-\bar{n}} \cdot \sum_{k=0}^{m} \frac{\bar{n}^k}{m^k} \cdot C_m^k \cdot L_I\left(\beta D_s^{\alpha}\right) \cdot R, \end{aligned} \tag{15}$$

where R equals to 1 bps that is defined as a normalized value.

4 Numerical Results

We have conducted a series of experiments with MATLAB to verify our previous analytical models. Main parameters in LTE-V2V standard are presented in Table 1.

Figure 2 represents the failure probability caused by collisions varying the density of AVs, for two various sensing range R_s = 300, 400 m. A 6 lane highway with a density of 0 to over 30 vehicles/km/lane is assumed. As expected, the curves are monotonically increasing as the density increases. The failure probability is increased due to the increment of AVs competing for the limited resources. Figure 3 compares the failure probability versus the density of AVs when Q = 0.1, 0.3, 0.5, respectively, and R_s = 300 m. By the analytical results illustrated by Figs. 2 and 3, it is seen that the collision is more likely to occur when the density of concurrent AVs increases.

Table 1. Main parameters

Parameter	Value	Parameter	Value
AV density (λ)	Variable input	Beacon period (t_p)	100 ms
Distance between source and destination (D_s)	Variable input	Beacon packet size	190 bytes
Sensing range (R_s)	Variable input	Equivalent transmission power (P_t)	23 dBm
Bandwidth (W)	10 MHz	Loss exponent (α)	2.75

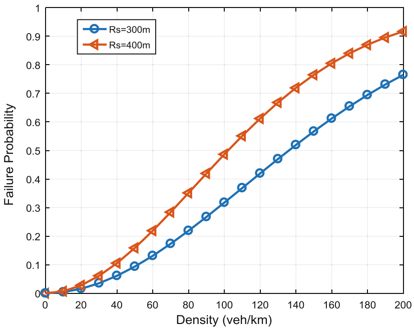


Fig. 2. Failure probability vs. density

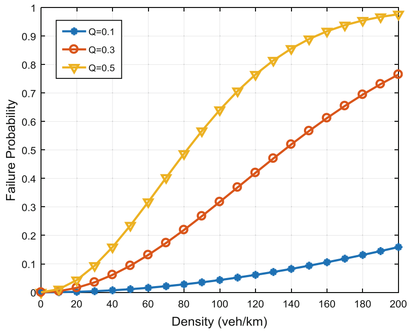


Fig. 3. Failure probability vs. density

Figure 4 represents the outage probability varying with the density of AVs, when D_s = 100 m and R_s = 300, 400 m are assumed. Generally, when the sensing range or ER increases, the probability for the receiver AV_R to have a high SIR is reduced due to the interferer is closer. However, the increase of outage probability is not obvious as the density increases. In Fig. 5, the outage probability versus the distance between the transmitter and the receiver D_s are presented, when λ = 10 veh/km, R_s = 100, 300, 500 m are assumed. As observed, the farther away the receiver is from the transmitter

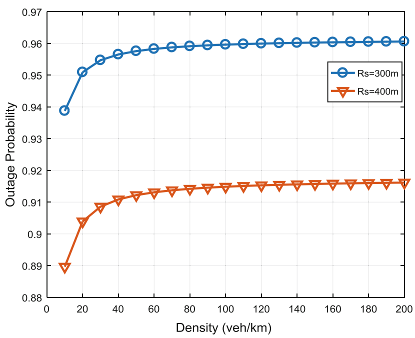


Fig. 4. Outage probability vs. density

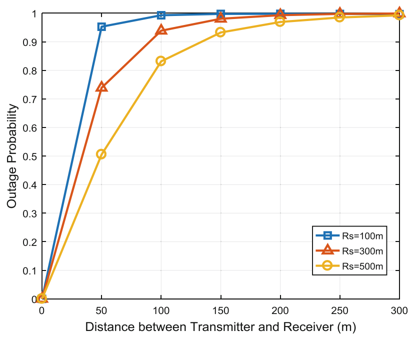


Fig. 5. Outage probability vs. D_s

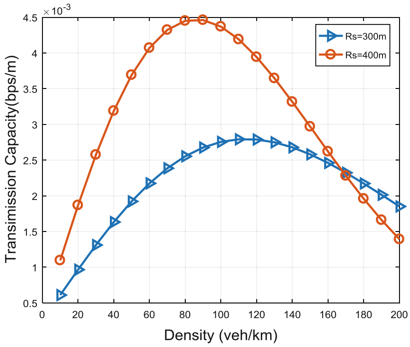


Fig. 6. Transmission capacity vs. density.

AV_T, the lower SIR is. Therefore, under the same condition, the near-destination AVs have better packet reception performance.

Finally, Fig. 6 depicts the transmission capacity over the density with given D_s = 100 m and R_s = 300, 400 m. It can be seen that two curves have the same two tendencies. As the density of AVs increases, the transmission capacity is improved to some extent (e.g., up to 90 and 110 veh/km for R_s = 300, 400 m, respectively), and then is degraded. The reason for the increasing part is that the transmission capacity increases with the number of transmitters; while the decreasing part is that the collision probability and the outage probability all increase that have been illustrated in Figs. 2 and 4, respectively. The peak point for the transmission capacity curve is also moved to the high density of AVs with the decreasing of R_s. In short, the transmission capacity depends on the interaction between AVs' density and sensing capability.

5 Conclusion

In this paper, we analyze the transmission capacity for LTE-V2V sidelink distributed communication (mode 4). When the tagged AV_T acquire available resources to deliver the packet before the deadline, resource collisions would result to fail in delivering. Simultaneously, the transmitting AVs can lead to interference for the tagged AV_R. Based on these analyses, some simple expressions have been obtained for collision probability, outage probability and transmission capacity. Integrating these expressions and simple numerical simulation, we can quickly evaluate the performance of the LTE-V2V mode 4. As a result, vehicle density, road model and resource allocation scheme have a significant impact on the transmission capacity of LTE-V2V mode 4.

On the basis of this paper, the simulation for validating the proposed model should be conducted. In addition, the performance of centralized scheduling (mode 3) in LTE-V2X also needs to be assessed. We will target these topics for further works.

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