Modeling and Simulation of Packet Delivery Rate in LTE-V Network Based on Markov Chain

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Abstract: As one of the most promising communication technologies for vehicular networks, LTE-V has the advantages of wide coverage and a high transmission rate. 3GPP released the technical specification of LTE-V in March 2017, launching a spate of related research and industrialization. In this paper, we propose a communication model based on Markov process to evaluate the reliability of LTE-V. We derived the Packet Delivery Rate (PDR) of LTE-V based on the model. Moreover, we use Poisson process to model the distribution of vehicles on a highway, then combine the communication model with the vehicles' distribution to derive the PDR under this scenario. To verify the correctness of the proposed model, we established a simulation program on the MATLAB platform. By comparing the simulation results and the mathematical results, we found that simulation results are a very good fit for the model.

Key words: Vehicle-to-everything (V2X); LTE-V; vehicle infrastructure cooperation system; packet delivery rate

1 Introduction

Vehicle-to-everything (V2X) communication covers information exchange between vehicles and the environment, including Vehicle-to-Vehicle (V2V), Vehicle-to-Infrastructure (V2I), and Vehicle-to-Pedestrian (V2P). It is currently drawing an increasing amount of attention from both research institutes and automobile manufacturers. Dedicated Short Range Communications (DSRC) is one of the most popular and promising communication standards dealing with the complex topology and mobility of vehicular environment communication. Although 802.11p/WAVE has many advantages for vehicular environment communication, it also faces some shortcomings, such as limited radio range, unbounded delay under circumstances of congestion, and the present lack of widespread roadside infrastructures that are able to communicate through 802.11p[1]. The above mentioned concerns have motivated an interest in LTE as an alternative communication standard for vehicular environments. LTE is the most pervasively deployed wireless broadband technology that can provide high-speed and low-latency mobile communication. The wide deployment of LTE presents an opportunity to build connected vehicle systems, and thereby implement V2X systems[2]. In order to enable the application of LTE technology to V2X systems, 3GPP
actively promotes the formulation of V2X-related standards for LTE. The series of standards in Release 14 put out by 3GPP in 2017 have basically completed the formulation of technical documents supporting V2X-related services. Because this technology is commonly known as LTE-V in China, we use LTE-V in this paper to refer to the use of LTE technology in the vehicle environment\cite{3-9}.

Even since the technical regulations of LTE-V were finalized in Release 14 in 2017, there have been very few studies on the reliability of LTE-V. LTE D2D is generally regarded as synonymous to LTE-V. Piro et al.\cite{10} studied the physical model of D2D communication, including the modulation and coding scheme and physical layer transmission path attenuation, and briefly described the LTE D2D access process. The impact of, and factors that may arise from, multiple terminal access were not taken into account in Piro’s study. The final model presents the relationship between transmission distance, number of vehicles, and modulation encoding scheme. Chen et al.\cite{4} used a simulation to study the communication performance of LTE-V and compared it with the performance of WAVE. Gallo and Haerri\cite{11} described the allocation scheme of LTE D2D communication resources in the time and frequency domains in Time Division Duplexing (TDD) mode, and carried out simulations for the self-organizing Time Division Multiple Access (TDMA) access mode under the LTE D2D protocol. The simulation process was set as a static scenario, in which LTE communication was simplified relative to a real-world situation.

Hu et al.\cite{12} proposed a new Medium Access Control (MAC) method for LTE D2D communication. Zhang et al.\cite{13} studied resource scheduling algorithms in LTE D2D broadcast communication and proposed two location-based scheduling algorithms. Luoto et al.\cite{14} evaluated the performance of LTE-V2X networks at the system level. Möller and Kürner\cite{15} used the random channel model to evaluate the performance of the LTE Link Layer.

Although LTE-V technology has many advantages, as mentioned above, its capacity to be successfully applied to transportation is still under question. In this paper, we study the Packet Delivery Rate (PDR) of LTE-V based on a Markov chain. By focusing on the PDR, we can gain a more intuitive understanding of the reliability of LTE-V technology.

This paper proceeds as follows. In Section 2, we introduce the LTE-V access layer, including access layer architecture and wireless access process. In Section 3, we propose a communication reliability model. In Section 4, we propose an application-oriented evaluation. The simulation setup and analysis of results are shown in Section 5. Section 6 concludes the paper.

# 2 LTE-V Access Layer

## 2.1 Access layer architecture

In the LTE-V architecture, the wireless resource access process is made up of three layers, labelled Layers 1–3 in Fig. 1. Layer 3 is mainly for wireless resource control. Its primary functions include broadcasting information related to the access layer, Radio Resource Control (RRC) connection management between the User Equipment (UE) and E-UTRAN, key management, point-to-point wireless hosting management, and some mobility management functions. Layer 2 includes the Packet Data Convergence Protocol (PDCP) sub-layer, Radio Link Control (RLC) sub-layer, and MAC sub-layer. The PDCP sub-layer is used for receiving the upper data, message header compression, data encryption, etc. The RLC sub-layer is the data channel between the PDCP sub-layer and MAC sub-layer, used for data connection, segmentation, and reorganization. The main functions of the MAC sub-layer include providing different logical channel access to the RLC sub-layer, providing mapping between logical channels and transmission channels and multi-terminal transmission control. Layer 1 is the physical layer, which provides data transmission services for the upper layer. The upper layer sends data to the physical layer through the transmission channel provided by the MAC sub-

![Fig. 1 LTE-V protocol stack.](image)
layer[16]. The LTE physical layer adopts Orthogonal Frequency Division Multiplexing Access (OFDMA) in the downlink and Single Carrier Frequency Division Multiplexing Access (SC-FDMA) in the uplink.

Physical layer resources of LTE communication are defined in terms of resource blocks. The Physical Resource Block (PRB) is a network block composed of a period of time in the time domain and a range of frequency bands in the frequency domain. Figure 2 shows the resource network structure of the physical layer uplink[17–19], where \( l \) represents \( l \)-th symbol ranges from 0 to \( N_{\text{UL}} \text{ symb} - 1 \) and \( k \) temporarily represents \( k \)-th subcarrier in frequency domain. \( N_{\text{RB}} \times N_{\text{sc}} \) is the number of subcarriers in frequency domain, \( N_{\text{RB}} \) is the bandwidth of Sidelink, and \( N_{\text{sc}} \) is the subcarriers number of subcarriers in each Resource Block (RB). In the time domain, \( N_{\text{UL}} \text{ symb} \) is the number of symbols in each Sidelink slot. A PRB includes a slot in the time domain and bandwidth for several subcarriers in the frequency domain. Each PRB has a bandwidth of 180 kHz in the frequency domain, and the subcarriers have three types of bandwidth: 15 kHz, 7.5 kHz, and 1.25 kHz. Each timeslot contains several SC-FDMA symbols, and each symbol occupies a period of time in the time domain and the entire bandwidth in the frequency domain. Symbols and subcarriers cross to form many small blocks, with these small blocks (including time domain and frequency domain resources) being called resource elements.

2.2 Wireless access process

Figure 3 shows the wireless access process of LTE-V, where \( n \) represents the current time, \( n + d \) represents the chosen timeslot, and \( T_{\text{rru}} \) represents the resource reservation interval. The process of direct communication between UEs in LTE-V mainly includes the RRC layer process, MAC sub-layer process, and physical layer process. This paper pays most attention to the MAC sub-layer access process of LTE-V, in which UEs listen to the environment to determine the time and frequency of resource transmission. It adopts a time division multiple access method instead of the random back-off strategy adopted by WAVE. In the independent wireless resource selection mode, the MAC sub-layer requests the physical layer to send data. After listening for 1000 ms, the resources are selected to communicate in a resource pool reported by the physical layer. The resource selection process is as follows[20]:

- **Step 1**: Set the resource reservation period. The resource reservation period is specified in the RRC layer configuration file. This parameter is an enumerated set of values including 0.2, 0.5, and 1 – 10. The MAC sub-layer multiplies this parameter by 100 to arrive at the resource reservation period in milliseconds.

- **Step 2**: Set \( SL.\text{RESOURCE.RESELECTION.COUNTER} \). This value represents the time interval from the current resource being selected for data transfer to the next moment of decision as to whether to reselect the resource. The range of this value is determined by the resource reservation periods. When the resource

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**Fig. 2** LTE-V physical resource diagram.

**Fig. 3** LTE-V access process.
reservation period exceeds 100 ms, the selection range is [5, 15]; when the resource reservation interval is 50 ms, the selection range is [10, 30]; and when the resource reservation interval is 20 ms, the selection range is [25, 75].

- Step 3: Select the times of HARQ retransmission. HARQ refers to hybrid automatic repeat request, which is mixed with an automatic repeat request. Its possible values are 0, 1, and both.
- Step 4: Select the number of frequency domain resources. The selection range is configured by the RRC layer.
- Step 5: Select the physical layer resource block. A time domain and frequency domain resource are randomly selected from the resources provided by the physical layer. The method of random selection requires that all possible choices are equally chosen.
- Step 6: Determine periodic resources. A series of periodic resources are selected from randomly selected resources to serve as transmission opportunities for the Sidelink Control Information (SCI) and Sidelink Shared Channel (SL-SCH). The cycle of these periodic resources is the resource reservation period set in Step 1.
- Step 7: Select retransmission resources. If the HARQ transmission value is 1, and there are resources available, then a time domain and frequency domain resource are randomly selected from the resources available. According to the selected resources, a series of periodic resources separated by the resource reservation period are then selected for retransmission.
- Step 8: Send data. SCI and SL-SCH are transferred using the currently selected resources.
- Step 9: Replace current resources. When a UE independently selects radio resources to transmit data, two or more UEs might simultaneously transmit data with the same radio resources. This will cause packet collision and affect the reliability of communication. Since UEs communicate in half-duplex mode, which means UEs cannot listen and transit at the same time, when two or more UEs use the same resources simultaneously, they cannot sense the collision. So it is necessary for UEs to actively replace the radio resources to avoid the continuous collision. UEs determine the period of resource reservation according to Steps 1 and 2, and the time interval parameter of resource reselection determines the time of resource replacement.

Whenever the MAC sub-layer completes sending a Protocol Data Unit (PDU), the SL_RESOURCE RESELECTION_COUNTER is reduced by 1. When the SLRESOURCE_RESELECTION_COUNTER is reduced to 0, the MAC sub-layer will activate the process of selecting radio resources from Step 1 with a certain probability. Otherwise, the UE continues to send data using the previous resource, while resetting the SLRESOURCE_RESELECTION_COUNTER in Step 2 above. This probability is specified as an enumerated value in the RRC document, with the possible values being 0, 0.2, 0.4, 0.6, and 0.8.

3 Communication Reliability Modeling

In the previous section, we described the LTE-V access process. In order to further analyze the communication reliability, this paper uses the theory of stochastic process to establish a model of communication reliability for LTE-V in the traffic environment.

3.1 Traffic flow modeling based on poisson process

In this paper, the traffic scenario is a highway with a length of \( L \), and there are \( N_{\text{lane}} \) lanes in the same direction. In the traditional communication performance analysis of V2X systems, the spatial Poisson process is often used to model the distribution of vehicles on the highway. Here, we use the Poisson process to model the process of vehicles entering a single lane, where \( \lambda_t \) is the Poisson process parameter and \( k \) is a temporary variable which represents the times of particular event occurs during \( \tau \):

\[
P[N(t + \tau) - N(t) = k] = \frac{e^{-\lambda_t \tau} (\lambda_t \tau)^k}{k!} \tag{1}
\]

According to the features of the Poisson process, the sum of \( N \) Poisson processes will still obey the Poisson process. Therefore, the vehicle convergence process of the whole road consisting of \( N_{\text{lane}} \) lanes can be modeled by a Poisson process with parameter \( N_{\text{lane}} \times \lambda_t \). In the model presented in this paper, the traffic flow composed of vehicles, the speed of which is within \( v \subseteq [V, V + \text{dv}] \), also obeys the Poisson process, and its parameter is

\[
\lambda^V_t = \lambda_t \times N_{\text{lane}} \times f_V(v)dv \tag{2}
\]

where \( f_V(v)dv \) is the probability density function of velocity. Given a constant speed, the spatial distribution of the vehicles also obeys the Poisson process, and the Poisson process parameter of the vehicles, the speed of which are within the above mentioned range is \( \lambda^V_v \), which can be expressed as follows:

\[
\lambda^V_v = \frac{\lambda^V_t}{v} = \frac{\lambda_t \times N_{\text{lane}} \times f_V(v)dv}{v} \tag{3}
\]
The combination of all traffic flow is still a Poisson process, and the overall parameter is the integral of all parameters at a specific speed. Namely, the spatial distribution parameter of the overall traffic flow is $\lambda_s$, which satisfies Eq. (4), where $E$ represents expectation:

$$
\lambda_s = \int \lambda_s^p = \int \lambda_t \times N_{\text{lane}} \times f(v) dv = \lambda_t \times N_{\text{lane}} \times E \left( \frac{1}{v} \right)
$$

(4)

According to the features of the Poisson process, the spatial distribution of vehicles on a road with a length of $L$ obeys the Poisson distribution of parameter $L\lambda_s$.

### 3.2 Modeling of LTE-V wireless access based on Markov process

According to the description of the LTE-V wireless access process given in Section 2, the wireless access process of UEs mainly goes through three main steps:

- **Step 1:** After sensing for 1000 ms, the operation of selecting resources is triggered at the $N$-th slot. A random free time slot is also selected between $[n + T_1, n + T_2]$, for transmission according to the latency requirement.

- **Step 2:** For example, if the resource reselection interval exceeds 100 ms, the node randomly selects an integer between [5, 15], denoted as $T$. The same time slot is used to access the wireless network in the following $T$ resource reservation periods.

- **Step 3:** After sending $T$ times, the node decides whether to change radio resources with probability $p$. If the result shows that the time slot needs to be replaced, then the process returns to Step 1, otherwise it returns to Step 2.

In fact, since the Bernoulli experiments that the node conducts to decide whether to continue using the same time slot are independent, they could all be conducted at the beginning, such that the total number of times that the current time slot is used for transmission can be determined. Considering this, the access process would be the following:

- **Step 1:** After sensing for 1000 ms, the operation of selecting resources is triggered at the $N$-th slot, and a random free time slot is selected between $[n + T_1, n + T_2]$ for transmission according to the time delay requirement.

- **Step 2:** The node randomly selects an integer $j$ between [5, 15], then $T$ is set equal to $j$.

- **Step 3:** The node performs a Bernoulli experiment with probability parameter $p$. If the result is 0, and integer $j$ is randomly selected between [5, 15], $T$ is updated to equal $T + j$, and the step is repeated; otherwise the process moves on to Step 4.

- **Step 4:** The time slot selected in Step 1 is used to transmit $T$ times, then the process returns to Step 1 to reselect the radio resource.

Let $K$ be the number of Bernoulli experiments conducted in Step 3. According to the above process, the range of $K$ is $[1, +\infty]$. Since the infinite state of the time chain is difficult to model, we assume that the Markov chain is $X_n$. $X_n = m$ indicates that the node will continue to send $m$ times using the current time slot currently at the time $n$, where $m$ and $n$ are both non-negative integers. It is obviously that the distribution of $K$ is a geometric. When the probability of resource reselection is at the maximum (0.8), the probability that $K$ exceeds 30 is about 0.001, which can be ignored. Therefore, in this paper, we assume that Bernoulli experiments can be conducted at most 30 times. Correspondingly, the maximum number of transmissions $T$ using the current time slot is 450.

The state transition diagram of the Markov chain is shown in Fig. 4.

The random process shown in Fig. 4 consists of 450 states. A node in the state $S_m$ represents $X_n = m$. There are only two state transitions in the system:

- $1 \rightarrow m$: When the back-off timer of the sending node decrease to 0, the node will select the wireless resource again, and then select a value between [5, 450] for the following packet transmission process.

- $m \rightarrow m - 1$: The node will keep transmitting in the current time slot until the back-off timer reduces to 0. After transmitting a message, the back-off timer is reduced by 1.

Let $P(X_{n+1} = j|X_n = i) = p_{i,j}$; in this random process, the values of $p_{i,j}$ have the following

![Fig. 4 State transition diagram of Markov chain.](image-url)
shown in Eq. (11):

\[ p_{i,j-1} = 1, \quad i \in [2, 450]; \]
\[ p_{1,j}, \quad j \in [5, 450]; \]
\[ p_{i,j} = 0, \quad \text{other} \]  

(5)

For the second condition in Eq. (5), the required number of Bernoulli experiments satisfies Eq. (6) for any \( j \).

\[
\left[ \frac{j}{15} \right] + 1 \leq K \leq \left[ \frac{j}{5} \right]
\]

(6)

Therefore, we can get the expression of \( p_{i,j} \) shown as Eq. (7):

\[
p_{1,j} = \sum_{k=\left[\frac{j}{15}\right]+1}^{k=\left[\frac{j}{5}\right]} P(X_{n+1} = j | X_n = 1, K = k) \cdot P(K = k | K \leq 30)
\]

(7)

As can be seen from the above, \( K \) obeys a geometric distribution, as shown in Eq. (8):

\[
P(K = k | K \leq 30) = \frac{1 - p}{p^{k+1}} \sum_{k=1}^{30} (1 - p)^{k-1} p
\]

(8)

As for \( P(X_{n+1} = j | X_n = 1, K = k) \), it is equivalent to completing Bernoulli experiments \( k \) times, and the sum of the random numbers selected between 5 and 15 after each experiment is \( j \). Then we have

\[
P(X_{n+1} = j | X_n = 1, K = k) = \frac{1}{11^k} \text{choice}(j, k)
\]

(9)

where \( \text{choice}(j, k) \) means the number of results dividing \( j \) into \( k \) parts, and the sizes of each part are between 5 and 15. The final expression is shown in Eq. (10), where \( C \) represents combinatorial number:

\[
\text{choice}(j, k) = C_{j-4k+1}^{k-1} \left\lfloor \frac{j-5m}{11} \right\rfloor + \sum_{l=1}^{\left\lfloor (j-5m)/11 \right\rfloor} (-1)^l C_{j-15l-4k+3}^l C_k
\]

(10)

Therefore, we can get the expression of \( p_{1,j} \) as shown in Eq. (11):

\[
p_{1,j} = \sum_{k=\left[\frac{j}{15}\right]+1}^{k=\left[\frac{j}{5}\right]} P(X_{n+1} = j | X_n = 1, K = k)
\]

(11)

From Fig. 4, we see that the states in the Markov chain are all positive recurrent and the Markov chain is an irreducible chain. Therefore, the Markov chain has a unique stationary distribution, denoted as \( \{ \pi_i \}_{i=1}^{450} \). We can get the state transfer matrix by combining Eqs. (5) and (11). According to the state transfer matrix, the following equation can be obtained:

\[
\pi_1 = \pi_2;
\]
\[
\ldots
\]
\[
\pi_4 = \pi_5;
\]
\[
\pi_5 = p_{1,5} \pi_1 + \pi_6;
\]
\[
\ldots
\]
\[
\pi_{449} = p_{1,449} \pi_1 + \pi_{450};
\]
\[
\pi_{450} = p_{1,450} \pi_1
\]

(12)

Meanwhile, the probabilities of states in the stationary distribution add up to 1, which is

\[
\sum_{j=1}^{450} \pi_j = 1
\]

(13)

Combining Eqs. (12) and (13), the solution of the equation set can be obtained shown in Eq. (14):

\[
\pi_1 = \frac{1}{1 + \sum_{j=1}^{450}(1 - \sum_{l=1}^{j-1} p_{1,l})};
\]
\[
\pi_j = \frac{1 - \sum_{l=1}^{j-1} p_{1,l}}{1 + \sum_{j=1}^{450}(1 - \sum_{l=2}^{j-1} p_{1,l})}, 2 \leq j \leq 450
\]

(14)

In this subsection, we detailed the LTE-V communication model. In the next subsection, we will model the communication reliability parameters in combination with the traffic flow model.

4 Application-Oriented Evaluation

In Section 3.1, we modeled a multi-lane highway. In this section, we will model the PDR using this multi-lane highway model. We set \( R \) as the communication radius of Vehicle A. We assume that A can listen to all nodes within its communication radius and all nodes within the communication radius of Vehicle A can receive a packet sent by Vehicle A correctly under the condition that no collision occurs. Vehicle A broadcasts messages to all vehicles within its communication range; and Vehicle B is in the communication range of Vehicle A. \( P_{V2V(|L_1-L_2|)} \) is the PDR when the distance between the two vehicles is in the range of \( L_1 \) and \( L_2 \).

As shown in Fig. 5, \( H_A \) represents the communication range of Vehicle A and \( H_B \) represents the communication range of Vehicle B. Vehicle B can
receive the messages sent by Vehicle A only if Vehicle B is within the communication range of Vehicle A and there are no vehicles within the communication range of Vehicle B that are using the same time slot as Vehicle A.

In order to analyze the PDR of Vehicle B, we divided the communication range of Vehicle B \( H_B \) into the following two parts.

\[
S_{in} = H_B \cap H_A \quad (15)
\]

\[
S_{out} = H_B / H_A \quad (16)
\]

\( S_{in} \) is the intersection of the communication range of Vehicles A and B, and \( S_{out} \) is the region inside the communication range of Vehicle B and outside the communication range of Vehicle A (as shown in Fig. 5). Nodes in the above-defined regions that send messages simultaneously with Vehicle A will cause Vehicle B to not receive the packets correctly. But the reasons for the failure are different in each of the two situations. Vehicle A is a specific vehicle and Vehicle B is in the region of \( S_{in} \), so it is within the communication range of Vehicle A and can listen to the time slot used by Vehicle A. Therefore, the same time slot will not be occupied in the normal situation. However, when Vehicle A and Vehicle B, replace the time slot at the same time, the two vehicles may choose the same time slot, and then collisions will occur that mean Vehicle B cannot receive the packets from Vehicle A correctly. Vehicle A and Vehicle B, will change the time slot at the same time if and only if Vehicle A and Vehicle B, are in the same state, the probability of which is \( P_{\pi eq} \) shown as Eq. (17).

\[
P_{\pi eq} = \sum_{i=1}^{450} \pi_i^2 \quad (17)
\]

From the mechanism of selecting the time slot of LTE-V, communication nodes will not choose the time slot being used. For Vehicle A and Vehicle B, the time slot being used by the nodes in \( H_A \cap H_B \) will not be selected at the same time. We set \( d_{in} \) as the distance between Vehicle A and Vehicle B; and the average distance \( d_{in} \) is shown as Eq. (18).

\[
\overline{d_{in}} = \frac{1}{2R - x} \int_{-(R-x)}^{R-x} x \, dx \quad (18)
\]

According to the Poisson distribution model of vehicle flow, the average number of vehicles in \( H_A \cap H_B \) is shown as Eq. (19):

\[
N_{in}^i = \lambda_s (2R - d_{in}) + 1 \quad (19)
\]

Assumed that the vehicles in \( H_A \cap H_B \) do not select the same time slot, \( N_{in}^i \) vehicles occupy \( N_{in}^i \) time slots. The probability that Vehicle B, and Vehicle A choose the same time slot is then shown in Eq. (20):

\[
p_{in} = \frac{100 - [\lambda_s (2R - d_{in}) + 1] - 2}{100 - [\lambda_s (2R - d_{in}) + 1] - 1} \quad (20)
\]

The average number of vehicles in the range of \( S_{in} \) is shown in Eq. (21).

\[
N_{in} = \lambda_s (2R - x) + 1 \quad (21)
\]

Therefore, the probability that there are no vehicles in the range of \( S_{in} \) selecting the same time slot as Vehicle A is shown in Eq. (22). \( P_{\pi eq} \) is the probability that Vehicle A and Vehicle B are not in the same state.

\[
P_{in} = [p_{in} \cdot p_{\pi eq} + p_{\pi eq}]^{N_{in}} = \\
\left[ \frac{100 - [\lambda_s (2R - d_{in}) + 1] - 2}{100 - [\lambda_s (2R - d_{in}) + 1] - 1} \cdot \sum_{i=1}^{450} \pi_i^2 + \left( 1 - \sum_{i=1}^{450} \pi_i^2 \right) \right]^{\lambda_s (2R-x) + 1} \quad (22)
\]

We thus arrive at \( P_{in} \), representing the probability that there is no direct collision when Vehicle A sends packets to Vehicle B.

We can then analyze the probability of a hidden terminal collision. Vehicles within the range of \( S_{out} \) cannot listen to packets sent by Vehicle A, making it impossible for them to actively avoid sending packets in the same time slot with Vehicle A. This leads to the potential occurrence of hidden terminal collisions. We set \( B_j \) as a vehicle in the range of \( S_{out} \), with the average distance between \( B_j \) and Vehicle A is shown in Eq. (23).

\[
\overline{d_{out}} = \frac{1}{x} \int_{x}^{R+x} x \, dx \quad (23)
\]

The average number of vehicles in the range of \( H_A \cap H_B \) is shown in Eq. (24).

\[
N_{out} = \lambda_s (2R - \overline{d_{out}}) \quad (24)
\]

Therefore, the probability that Vehicle \( B_j \) and Vehicle A do not select the same time slot is shown in Eq. (25).

\[
p_{out} = \frac{100 - \lambda_s (2R - \overline{d_{out}}) - 2}{100 - \lambda_s (2R - \overline{d_{out}}) - 1} \quad (25)
\]
The average number of vehicles in the range of $S_{\text{out}}$ is $N_{\text{out}} = \lambda_s x$. Therefore, the probability that no vehicles in the range of $S_{\text{out}}$ select the same time slot as Vehicle $A$ is shown in Eq. (26):

$$P_{\text{out}} = (P_{\text{out}})^{N_{\text{out}}} = \left[ 100 - \lambda_s (2R - d_{\text{out}}) + 1 \right]^{\lambda_s x}$$

The probability that Vehicle $B$ will receive packets sent by Vehicle $A$ correctly with neither a direct collision nor a hidden terminal collision, is $P_{V2V}$ shown in Eq. (27):

$$P_{V2V} = P_{\text{in}} \cdot P_{\text{out}}$$

Further, for the nodes within the range of $[L_1, L_2]$, the average PDR is the mean of $P_{V2V}$. $x$ obeys a uniformly distribution in the range of $[L_1, L_2]$, so $P_{V2V_{[L_1, L_2]}}$ is expressed as Eq. (28):

$$P_{V2V_{[L_1, L_2]}} = \int_{L_1}^{L_2} \frac{1}{L_2 - L_1} P_{V2V} \, dx$$

The average PDR of Vehicle $A$ to all nodes within its communication range is shown in Eq. (29), being the model for PDRs in V2V communication within the communication range of Vehicle $A$:

$$P_{V2V} = \int_0^R \frac{1}{R} P_{V2V} \, dx = \int_0^R \left[ \left( 100 - \frac{\lambda_s (2R - d_{\text{in}}) + 1}{\lambda_s (2R - d_{\text{in}}) + 1} \sum_{i=1}^{450} \pi_i^2 \right) \cdot \left( 1 - \sum_{i=1}^{450} \pi_i^2 \right) \right] \cdot \left[ \frac{100 - \lambda_s (2R - d_{\text{out}}) + 1}{100 - \lambda_s (2R - d_{\text{out}}) + 1} \right] \, dx$$

That is the model of packet delivery rate in V2V communication within the communication range of Vehicle $A$.

### 5 Simulation Establishment and Result Analysis

In order to verify the model proposed in the previous section and conduct further numerical analysis on the influence of various parameters, we built a simulated highway system on the MATLAB platform to simulate the communication process of LTE-V. In this simulation, we primarily sought to analyze the model of the MAC mechanism.

#### 5.1 Simulation parameter setting

The main simulation parameters, as shown in Table 1, were the total time of simulation, traffic flow density, speed, resource reservation period, and time slot length.

In Table 1, $V_H$ represents the average speed of high-speed vehicles; $V_L$ represents the average speed of low-speed vehicles; and $R_{H:L}$ represents the ratio of high-speed vehicles to low-speed vehicles.

#### 5.2 Application layer PDR analysis

Our study looked at the influence on PDR of communication range, traffic density, and the Probability of Resource Reselection (PRR). Figures 6 – 9 show the comparison between the mathematical model and the simulation results of PDR for different PRR parameter values. From these four figures, it is obvious that the mathematical model fits the simulation results well, thus verifying the correctness of the mathematical model.

It can be seen from the four figures that the PDR...
is mainly affected by the communication distance and traffic flow density, both of which will increase the number of nodes in the communication range, thus increasing the probability of direct collision and the probability of hidden terminal collision. Comparing these four figures, the probability of resource reselection has no obvious influence on the PDR, as is more directly shown in Table 2.

Six sets of combined parameters of traffic flow density and communication range are selected in Table 2. The selection principle is to cover all reasonable levels of traffic flow density and communication range. Given that the influence of random factors in the results of the simulation cannot be seen, the influence of PRR on the PDR of LTE-V communication technology can be disregarded.

6 Conclusion

In this paper we first described the architecture of the access layer protocol stack of LTE-V and the specific functions of each layer, and then described the access process of LTE-V in detail. Following this, we established the communication reliability model based on traffic flow and the LTE-V wireless access model. In Section 3, we verified the mathematical model by building a simulation system on the MATLAB platform and analyzing the influences of the model parameters on PDR.

In our analysis, we found that with an increase of traffic density, the number of nodes in the communication range increases, causing the PDR to gradually decrease. Likewise, an increase of communication range shows the same effect on PDR. However, with an increase of the probability of resource reselection, the PDR will decrease only slightly, by less than 1%. The simulation results match the numerical results well, thus verifying the correctness of the mathematical model.

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| Parameter value | $p = 0.2$ | $p = 0.4$ | $p = 0.6$ | $p = 0.8$ |
|------------------|-----------|-----------|-----------|-----------|
|                  | Simulation | Model     | Simulation | Model     | Simulation | Model     | Simulation | Model     |
| $\lambda = 0.25, R = 200$ | 0.9866     | 0.9868    | 0.9855     | 0.9868    | 0.9861     | 0.9867    | 0.9852     | 0.9867    |
| $\lambda = 0.5, R = 400$  | 0.9617     | 0.9637    | 0.9630     | 0.9636    | 0.9614     | 0.9635    | 0.9600     | 0.9633    |
| $\lambda = 0.75, R = 500$ | 0.9250     | 0.9288    | 0.9231     | 0.9287    | 0.9233     | 0.9285    | 0.9230     | 0.9281    |
| $\lambda = 1.5, R = 400$  | 0.8746     | 0.8792    | 0.8731     | 0.8790    | 0.8717     | 0.8786    | 0.8703     | 0.8778    |
| $\lambda = 0.1, R = 800$  | 0.8223     | 0.8294    | 0.8233     | 0.8292    | 0.8203     | 0.8285    | 0.8199     | 0.8274    |
| $\lambda = 1.75, R = 800$ | 0.5699     | 0.5651    | 0.5679     | 0.5637    | 0.5524     | 0.5606    | 0.5562     | 0.5549    |
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