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Media Access Process Modeling of LTE-V-Direct Communication Based on Markov Chain

Jiayang Li[1], Mengkai Shi[1], Ji Li[2] and Danya Yao[2], IEEE member

Abstract— **As one of the most promising communication technologies in vehicular networks, LTE V2X related technical specifications are released in Release 14 by 3GPP in 2017. In the newest specifications, the LTE V2X can work with or without eNBs, namely LTE-V-Cell and LTE-V-Direct. In this study, we focus on the media access process of LTE-V-Direct. First, we proposed a model to describe the MAC process of LTE-V-Direct, and based on that model, we derived the Frame Information Loss Rate and Inter-Reception Gap of LTE-V-Direct. Then, we designed a simulation to verify the model. By comparing the simulation result and numerical result of the model, the correctness and precision of the model is verified.**

Key words: LTE-V-Direct, Frame Information Loss Rate, Inter-Reception Gap

I. INTRODUCTION

Vehicular networks are drawing more and more attention in ITS (Intelligent Transportation System). Vehicle to Everything (V2X) technology, an extension of vehicular networks, intends to promote the safety and efficiency of transportation system by sharing information among vehicles, pedestrians and infrastructures. In recent years, governments, institutes and companies have done much research and achieved many developments. For example, V2X test areas have been built in Shanghai, Chongqing, Beijing in China. At the same time, other test areas are also under construction thanks to the great support by government. Demonstrations of V2X are performed in these test areas.

Although demonstrations are performed pervasively, the deployment of V2X in real traffic environment is quite rare. The V2X system could be used in real traffic environment only if it is very reliable. The reliability of V2X system is directly affected by the reliability of communication, which lays the foundation of the entire V2X system. Dedicated Short Range Communication (DSRC) is one of the most pervasively used communication technologies in V2X system. DSRC is modified based on 802.11 protocol, thus it can be easily deployed and used to support ad-hoc network originally. And the modifications makes DSRC device access the network more quickly. But on the other hand, MAC protocol of DSRC is CSMA/CA, which may cause unbounded latency and unguaranteed reliability.

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[1]Jiayang Li and Mengkai Shi are with Beijing Nebula Link Tech. Co. Ltd., Caizhi International Plaza, Haidian District, Beijing, China `jy-li15@mails.tsinghua.edu.cn`, `smk13@mails.tsinghua.edu.cn`

[2]Ji Li and Danya Yao are with the Department of Automation, Tsinghua University, Beijing, China `superliji163@163.com`, `yaody@tsinghua.edu.cn`

To avoid these drawbacks, alternative communication technologies are studied. LTE is one of the most promising communication technologies because of its high reliability and large bandwidth. But, modifications are still needed to be deployed in V2X system[1]. In 2017, 3GPP released the latest technical specifications of LTE V2X. In these specifications, unlike traditional LTE network traffic using uplink and downlink, the physical link of LTE V2X is called Sidelink, and LTE V2X could work at two mode, which are LTE-V-Cell when using eNB and LTE-V-Direct when using Sidelink as physical link[4], [5], [6], [7], [8], [9].

When LTE V2X works at LTE-V-Direct mode, it adopts self-organized TDMA as MAC protocol. The time resource in LTE-V-Direct STDMA is divided into slots. When accessing the channel, the communication nodes need to listen to the channel for a period of time to acquire frame information, then randomly select an idle slot to access the channel. However, collisions cannot be avoid thoroughly due to simultaneous channel selection. And because the LTE-V-Direct devices are communicating half-duplex, the collisions cannot be detected spontaneously. If the devices continue to use the same slot, the collision would continue, too. Thus, in the self-organized TDMA process, the devices would change the slot after sending packets several times[10].

Frame Information Loss Rate, which is the probability that both of the two vehicles within the radio range fail to acquire the frame information of the other, and Inter-Reception Gap, which is the interruption between successful data transmission, are important indications of the reliability of LTE-V-Direct. To achieve a lower Frame Information Loss Rate and a narrower Inter-Reception Gap, the interval between channel reselection should be well scheduled. In this work, we proposed a Markov Chain to model the MAC process of LTE-V-Direct, based on which, we derived the Frame Information Loss Rate and Inter-Reception Gap of LTE-V-Direct. Numerical analysis and simulation result are compared to validate the model.

This paper is arranged as follows, the key features of LTE-V-Direct and its detailed MAC process is described in section II. All the essential parameters described in the technical documentation are introduced, while some other parameters are proposed by us for further modeling. In section III, we proposed the model of media process control and both the Frame Information Loss Rate and Inter-Reception Gap of LTE-V-Direct can be derived based on this model. Then, a highway scenario simulation is run by Python and the validation part is in section IV. Eventually, section V concludes the paper.

II. LTE-V-DIRECT AND KEY FEATURES

A. Key Parameters

According to the latest technical specifications of LTE-V-Direct, there are several key parameters[8], [10]:

- **Resource Reservation Period**. In LTE-V-Direct, time resource is allocated periodically. All of the communication vehicles choose slots in a period, and keep transmitting in that slot of every period. This period is called Resource Reservation Period. In the specifications, Resource Reservation Period is an enumerator, its value includes 0.2, 0.5, 1, 2,...,10 seconds.
- **Resource Reselection Counter**. After a communication vehicle selects a slot to transmit messages, it triggers a counter, which decrements by one after transmitting a message. When the counter decreases to 0, the communication vehicle decides whether to change slots. In the specifications, the Resource Reselection Counter varies with Resource Reservation Period, and when the RRP excess 100ms, the RRC is randomly chosen between 5 and 15.
- **Resource Reselection Probability**. When the RRC counter reaches 0, the vehicle would decide whether to change slot or continue to use current slot randomly. The probability of changing slot is called Resource Reselection Probability, it can be derived from the parameter *probReourceKeep* in specifications. The parameter *probResourceKeep* is an enumerator, its value includes 0, 0,2, 0.4, 0.6, 0.8.

B. Media Access Process

Then the media access procedures of LTE-V-Direct can be summarized as follows[10]:

1) Monitors all the transmitting vehicles within communication range, and records the slots occupied in a Resource Reservation Period.
2) Randomly selects an idle slot between $[n+T_1, n+T_2]$ at slot n, where T_1 and T_2 are set according to latency requirement. Then sets the initial Resource Reselection Counter value.
3) Decides whether to change slot or not when the Resource Reselection Counter decreases to 0. If decides to change slot, turn back to step 1, otherwise turns back to step 2.

C. Cause of Collision

There are two types of message collision: hidden-terminal collision and one-hop collision. Denote Hop_V as the one-hop range of vehicle V. Then for a packet broadcasted by Vehicle A, all vehicles in Hop_A are receivers of this broadcast. For B in Hop_A, it can receive the packet iff no vehicle in H_B occupies the same slot of A. And Hop_B can be divided into two subsets:

- $Area_{in} = Hop_B \cap Hop_A$. Vehicles in this area and A share their frame information together, thus $Area_{in}$ is a collision-free area. However, nodes may change their slots based on frame information at the same time, due to the frame synchronization. Thus, they have the probability to select the same slot, which leads to one-hop collision.
- $Area_{out} = Hop_B \setminus Hop_A$. Vehicles in this area lack the frame information of A, thus the slot occupied by A can be assigned to vehicles in this area, which leads to hidden-terminal collision.

And once either collision condition happens, the collision would last for several Resource Reservation Periods.

D. Resource Reselection Interval

Resource reselection is required for nodes to be adapted to the dynamic topology. Denote the length of the interval between resource reselection as $T_{occupied}$, which is the most important parameter of MAC process. However, there is a trade-off when scheduling $T_{occupied}$:

- On the one hand, $T_{occupied}$ for different vehicles at different time is requested to be sufficient stochastic in order to prevent one-hop collision, i.e. vehicles within the radio range change their slots at the same time thus fail to acquire the latest slot information of each other. To achieve this requirement, a large $Var(T_{occupied})$ is required, which also causing $T_{occupied}$s to be large. In other words, low Frame Information Loss Rate is highly related to large $T_{occupied}$.
- On the other hand, nodes need to change to a new slot based on latest frame information promptly to be adapt environment changing and to terminate hidden-terminal collisions led by the current slot occupation. In order to meet these requirements, $T_{occupied}$s are request to be as small as possible. In other words, narrow Inter-Reception Gap is highly related to small $T_{occupied}$.

To analyze the performance of LTE-V-Direct from these two aspects, two key state parameters are essential:

- **Backward transmission state number** $\{X_n\}$. Let $X_n = m$ denote that the node will use the current slot for m frames (including the current frame) during the n^{th} frame
- **Forward transmission state number** $\{Y_n\}$. Let $Y_n = m$ denote that the node has used the current slot for m frames (including the current frame) during the n^{th} frame.

III. MODELING OF LTE-V-DIRECT

In this section, we interpret the slot assignment procedure of LTE-V-Direct as an analytical mathematical model, to model the stationary probabilities of transmission state number, and then analyze the Frame Information Loss Rate and Inter-Reception Gap based on the transmission state number.

A. Slot Assignment

The MAC protocol, with proper simplification, can be summarized as follow for modeling:

1) *The node checks slot occupied information of the previous frame and randomly selects one from idle slots, recording $Slot = i$ if it is the i^{th} slot.*

2) *The node randomly selects an integer j from 5 to 15, recording $T = j$.*
3) *The node uses the slot recorded in $Slot$ to transmit during the next T frames.*
4) *The node conducts a Bernoulli trial with mean of p: go back to step 1 if the outcome is 1; go back to step 2 otherwise.*

Under this procedure, the backward transmission state number of a node during one frame is determined by both its value during the last frame and whether it will keep on using this slot when T reduces to 0. Thus, it is not a Markov chain. However, it can be seen that it is not necessary to conduct the Bernoulli trial in Step 4 after Step 3. The node can begin Step 4 right after Step 2 and add up T until get a 0 from Bernoulli trial. The procedure can be modified as follow without any difference of actual effect:

1) *The node checks slot occupied information of the previous frame and randomly selects one from idle slots, recording $Slot = i$ if it is the i^{th} slot.*
2) *The node randomly selects an integer j from 5 to 15, recording $T = j$.*
3) *The node conducts a Bernoulli trial with mean of p: go back to Step 4 if the outcome is 1; if the outcome is 0, randomly selects an integer j from 5 to 15 and record $T = T + j$, and go back to step 3 otherwise.*
4) *The node uses the slot recorded in $Slot$ to transmit during the next T frames.*

With this modification, the backward transmission state number of the node is only determined by its value during the last frame. Accordingly, it becomes a Markov chain that can be analyzed.

B. Transmission State Number

We first derive the stationary probability of backward transmission state number based on the modification of the last subsection. It is a stochastic process that takes on all positive integers. Let K denote the number of integer chose from Step 1 to Step 4, then K follows geometric distribution. According to the property of geometric distribution, the probability that K takes a large value can be ignored. Therefore, it can be assumed that $K \leqslant 30$ or $T \leqslant 450$. The probability that $K \leqslant 30$ is

$$P_{sum} = \sum_{k=1}^{30} (1-p)^{k-1} p.$$

Under this assumption, only two kinds of transitions are involved:

$$\begin{cases} P(X_{n+1} = i-1 | X_n = i) & 2 \le i \le 450 \\ P(X_{n+1} = j | X_n = 1) & 5 \le j \le 450 \end{cases}$$

Whenever the process is in state i, there is a fixed probability that it will next be in state j. Thus, we can denote $P(X_{n+1} = j|X_n = i)$ as $P_{i,j}$. Since for $2 \leqslant i \leqslant 450$, $P_{i,i-1} = 1$, we only need to compute $P_{1,j}$. For particular j, we have

$$[\frac{j}{15}] + 1 \leqslant K \leqslant [\frac{j}{5}],$$

thus it can be derived that $P_{1,j}$ equals

$$\sum_{k=[\frac{j}{15}]+1}^{[\frac{j}{5}]} P(X_{n+1} = j|X_n = 1, K = k) P(K = k|K \le 30).$$

Since K obeys a geometric distribution,

$$P(K = k|K \le 30) = \frac{(1-p)^{k-1} p}{P_{sum}}.$$

Meanwhile, it can be obtained that

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

where $choice(j,k)$ is the choice number to divide a queue of j into k sections with length between 5 and 15. There are up to

$$a = [\frac{j-5m}{11}]$$

sections that have at least 16 elements. Thus, $choice(j,k)$ equals the choice number to divide a queue of j into k sections of at least 5, minus 1 section of at least 16 while $k-1$ sections of at least 5, plus 2 sections of at least 16 while $k-2$ sections of at least 5, until minus/plus a sections of at least 16 while $k-a$ sections of at least 5. In conclusion,

$$choice(j,k) = C_{j-4k-1}^{k-1} + \sum_{l=1}^{[\frac{j-5m}{11}]} (-1)^i C_{j-15l-4(k-l)-1}^{k-1} C_k^l.$$

Eventually, we have

$$P_{1,j} = \sum_{k=[\frac{j}{15}]+1}^{[\frac{j}{5}]} \frac{1}{11^k} choice(j,k) \frac{(1-p)^{k-1} p}{P_{sum}}.$$

Denote $\{\pi_i\}_{i=1}^{450}$ as the stationary probabilities of every state, then $\{\pi_i\}$ can be obtained by solving the following equations:

$$\begin{cases} \pi_j = \sum_j \pi_i P_{i,j} \\ \sum_j \pi_j = 1 \end{cases}$$

The solution is:

$$\begin{cases} \pi_1 = \frac{1}{1+(\sum_{l_1=2}^{180} 1-\sum_{l_2=1}^{l_1-1} P_{1,l_2})} \\ \pi_i = \pi_1(1 - \sum_{l=1}^{i-1} p_{1,l}), \ 2 \leqslant i \leqslant 450 \end{cases}$$

where we assume that $p_{1,i} = 0, \ i = 2,3,4$.

The forward transmission state number during one frame is determined by both its value during the last frame and the $T_{occupied}$ it selected during the beginning of this cycle. Thus, $\{Y_n\}$ is still not a Markov chain. However, it can be regarded as the backward chain of $\{X_n\}$. Thus, the stationary probabilities of these chains are equal. We denote $\{\pi_i\}$ as the stationary probabilities of both $\{X_n\}$ and $\{Y_n\}$ in the following sections. And denote the forward and backward transmission state number of vehicle V is $fore_V$ and $back_V$ respectively.

C. Frame Information Loss Rate

For two vehicles within the radio range of each other, the same slot occupying is not avoidable if they both of them fail to acquire the latest frame information of each other. Thus, it is essential to compute the frame information loss rate p_{loss}.

If vehicle A decides to change slot at the i^{th} frame, then A will begin to use the new slot from the $(i+1)^{th}$ frame. However, this slot selection is based on the frame information acquired at the $(i-1)^{th}$ slot, which leading to the loss of frame information.

- If another vehicle B decides to change the slot at the i^{th} frame, i.e. $fore_A = fore_B$, then both A and B fails to select the new slot based on the other's latest frame information.
- If another vehicle B decides to change the slot at the $(i-1)^{th}$ frame, i.e. $fore_B - fore_A = 1$, then the new slot selection of A is based on the frame information of B at the $(i-1)^{th}$ frame, when B has just decided to change the new slot; and the new slot selection of B is based on the frame information of A at the $(i-2)^th$ frame, when A had not decided to change the slot. Thus, both A and B lose the latest frame information of the other.
- By symmetry of A and B, $fore_A - fore_B = 1$ will lead to the same result.
- If $|fore_A - fore_B| \geqslant 2$, then the vehicle with the smaller forward transmission state number can acquire the frame information of the other successfully.

In summary, the frame information loss rate between A and B is equal to the probability that $|fore_A - fore_B| \leqslant 1$. Although the slot occupied by every node is dependent on each other, the backward and forward state number of all nodes are totally independent. Therefore,

$$p_{loss} = \sum_{i=1}^{450} \pi_i(\pi_{i-1} + \pi_i + \pi_{i+1}),$$

where we assume that $\pi_0 = 0$ and $\pi_{451} = 0$.

D. Transmission Interrupted Time

The transmission between two vehicles will be interrupted when one-hop collision or hidden terminal collision happens. The packet loss between A and B will last for a few frames once message transmission fails. Denote T_{fail} as the time of this interruption, which is a measurement of the Inter-Reception Gap.

Consider the transmission from Vehicle A to Vehicle B. Then communication interruption between Vehicle A and Vehicle B happens when one vehicle within Hop_B change to a occupied slot of another vehicle in H_B. The backward state number of the slot changing vehicle is i with probability $P_{1,i}$ while j with probability π_j of the other. Then after $i \wedge j$ frames, one changes the slot again and communication resumes. Therefore,

$$P\{T_{fail} = kT_f\} = P_{1,k}\pi_k + \sum_{i=k+1}^{450} P_{1,i}\pi_k + \sum_{j=k+1}^{450} P_{1,k}\pi_j,$$

where RRP is the value of Resource Reservation Period. And the average of T_{fail} is

$$ET_{fail} = RRP \sum_{i=1}^{450}\sum_{j=1}^{450} P_{1,i}\ \pi_j\ (i \wedge j).$$

E. Transmission Recovery Time

Although T_{fail} is an effective parameter to measure Inter-Reception Gap, other parameter needs to be measured for specific scenarios. If one vehicle needs to transmit a warning message to another vehicle, then it is possible that their communication is experiencing interruption. Under this circumstance, we only need to care how long it will take for the transmission to recovery. Therefore, $T_{recovery}$ is denoted as the time for two vehicles experiencing transmission interruption to resume communication.

If A and B is experiencing communication interruption, the backward state numbers of the two cars occupying the same slot within H_B are i and j with probability π_i and π_j respectively, then the communication resumes after $i \wedge j$ frames when one of them change the slot. Therefore,

$$P\{T_{recovery} = kRRP\} = \pi_k^2 + 2\sum_{i=k+1}^{450} \pi_k\pi_i.$$

And the average of $T_{recovery}$ is

$$ET_{recovery} = RRP \sum_{i=1}^{450}\sum_{j=1}^{450} \pi_i\ \pi_j\ (i \wedge j).$$

IV. NUMERICAL ANALYSIS

To validate the model, we conducted a simulation of LTE-V-Direct based on Python. The scenario is a oneway, multi-lane highway without traffic lights and intersection and the vehicles appear as Poisson process. The speeds of vehicles follow a distribution which is the mixture of two normal distribution of different means to describe the existence of both small vehicles with higher speeds and large vehicles with lower speeds. We assume that high-speed cars can overtaking by lane changing, thus all vehicles keep a constant speed. In the simulation, Resource Reservation Period is 100ms and a slot lasts 1ms. Resource Reselection Probability is set as 0.2, 0.4, 0.6, 0.8, respectively. The simulation runs 2.5 million slots totally, where about 40 thousand Inter-Reception Gaps are detected for each condition.

A. Model Validation

Fig. 1 and Fig. 2 show the PDF (Probability Density Function) of Transmission Interrupted Time and Transmission Recovery Time with different Resource Reselection Probability, respectively. The RRP in labels of axis x represents Resource Reservation Period. It can be seen from the figures that there is almost no difference between the PDF derived from the simulation and the PDF computed by the model. Therefore, the correctness and precision of the model is verified. While Frame Information Loss Rate is a probability, thus it is not easy to be acquired from the simulation. However, both Transmission Interrupted Time and

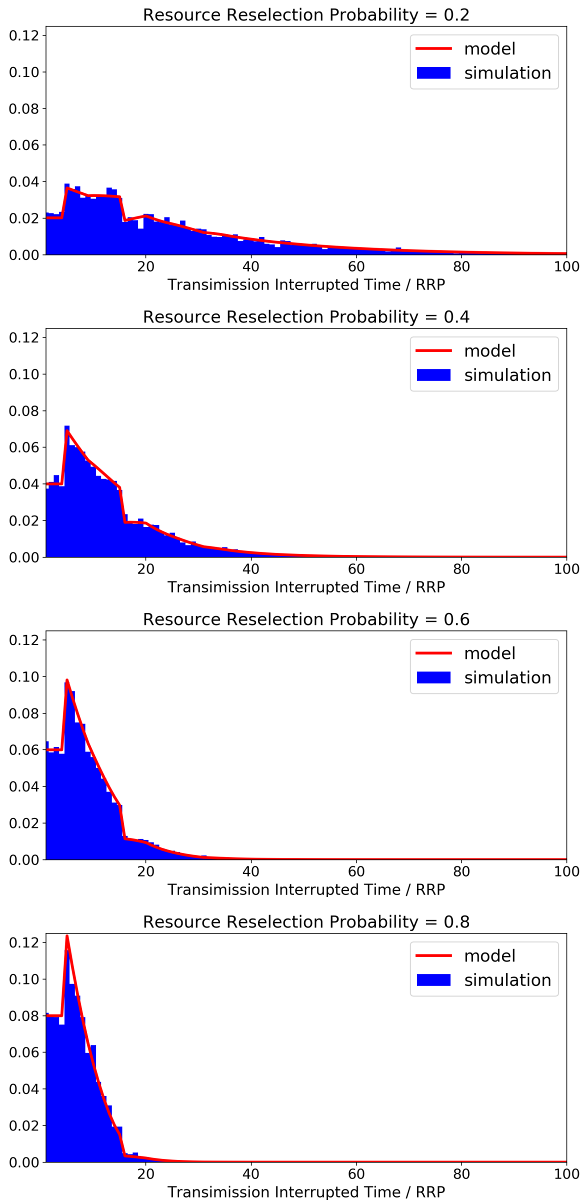

Fig. 1. PDF of Transmission Interrupted Time

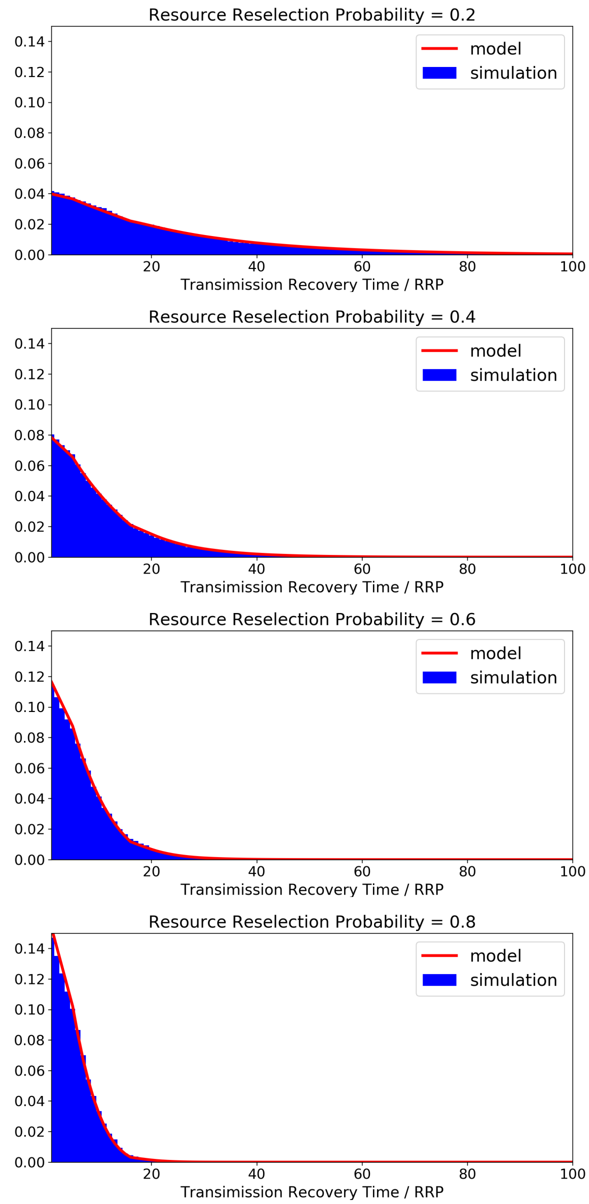

Fig. 2. PDF of Transmission Recovery Time

Transmission Recovery Time are derived from Transmission State Number and we have mentioned that it is the key parameter for modeling. The correctness of Inter-Reception Gap indicates that the modeling of Transmission State Number is sufficient precise. Since Frame Information Loss Rate is directly derived from Transmission State Number, it can be inferred that the modeling of Frame Information Loss Rate is correct.

B. Result Analysis

Based on the model, we can further analysis the Frame Information Loss Rate and Transmission Recovery Time. Fig. 3 incorporate the PDF of Transmission Interrupted Time and Transmission Recovery Time under different Resource Reselection Probability in one subfigure, respectively. It can be obtained that the smaller the Resource Reselection Probability, the narrower the Inter-Reception Gap.

TABLE I shows the mean value of Frame Information Loss Rate, Transmission Interrupted Time and Transmission Recovery Time, where the headers are acronyms. The mean value is presented with Resource Reservation Period. Transmission Interrupted Time and Transmission Recovery Time are measured in seconds.

In real world application of V2V communication, the improper setting of Resource Reselection Probability may cause terrible result. For example, when designing V2V communication protocol for automated braking on highway, there can be no reaction time for the following vehicle if the Inter-Reception Gap continues for more than 1 second, due to the high speed of vehicle on highway. And if a collision

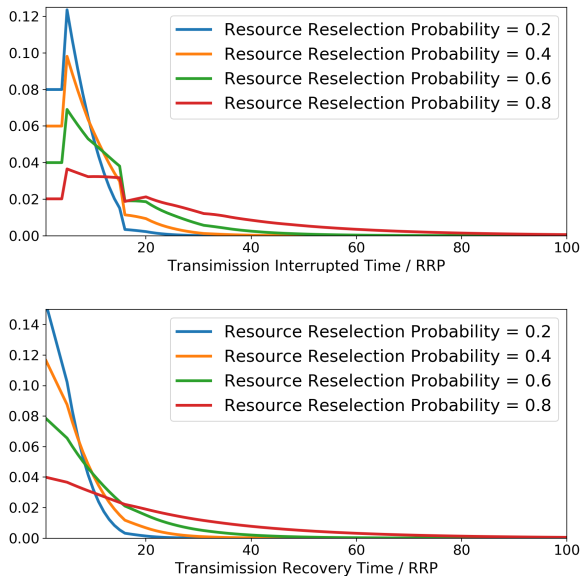

Fig. 3. Comparison of different Resource Reselection Probabilities

TABLE I
MEAN VALUE

RRP	0.2	0.4	0.6	0.8
FILR	3.29%	7.05%	11.55%	16.92%
TIT/s	25.09	12.80	8.66	6.62
TRT/s	23.06	10.96	6.92	5.00

warning protocol is designed for intersection in urban area, then the message collision is almost unavoidable when the Frame Information Loss Rate is larger than 10%, due to the high density at intersection. The numerical analysis shows that the Resource Reselection Probability should be 0.6 or 0.8 to make the Transmission Interrupted Time and Transmission Recovery Time under 1 second. On the other hand, the Resource Reselection Probability should be 0.2 or 0.4 to make the Frame Information Loss Rate under 10%.

V. CONCLUSION

In this paper, we propose a Markov chain to model the MAC process of LTE-V-Direct firstly. Based on solving the steady state of the proposed Markov chain, we derive the Frame Information Loss Rate, Transmission Interrupted Time and Transmission Recovery Time. A simulation is conducted to verify the correctness and precision of the model.

Numerical analysis shows that both Frame Information Loss Rate and Inter-Reception Gap are strongly related to Resource Reselection Probability. Large Resource Reselection Probability leads to narrower Inter-Reception Gap and higher Frame Information Loss Rate. In other words, a trade-off has to be made between the lasting of communication gap and the reliability of recording the channel of neighboring vehicles when we use LTE-V-Direct in real traffic environment.

From the above results, it can be obtained that parameters require cautious design and adjustment is necessary for different circumstances, such as the speed of the vehicle and the vehicle density. Now, we are working toward how to choose the most desirable parameter and how to modify the protocol for different kinds of applications. Further model are built based on this one, especially based on the Frame Information Loss Rate, which lacks sufficient discussion in this paper.

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