Performance Analysis of CSMA/CA Broadcast Relay Network for ITS V2V Communications

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***Abstract*— The reliability of CSMA/CA vehicle-to-vehicle (V2V) communication under actual road environment suffers from fading, shadowing and hidden terminal (HT) problem. In order to improve the communication reliability, a V2V broadcast scheme with relay stations has been proposed and its effectiveness was shown by some simulations. However, the potential of the CSMA/CA broadcast relay network has not been well analyzed and optimized. In this paper, a theoretical model is proposed to analyze the performance of such network in detail. In order to fit the realistic vehicular environment, the model assumes a typical crossroad and takes into account fading, shadowing, hidden terminal problem and capture effect, as well as distances between nodes. The influence of system parameters including RF frequency band and carrier sense threshold on the reliability of the network is also studied through the analysis. The accuracy of the proposed analytical model was validated by simulations. Some suggestions to enhance the reliability of V2V communication are provided based on the results.**

Keywords- ITS; CSMA/CA; Relay network; Hidden terminal; Capture effect.

I. INTRODUCTION

In order to achieve safe and efficient road transportation, Intelligent Transportation Systems (ITS) have been investigated intensively. One of the promising approaches to reach the goal is vehicle safety communications (VSC) [1], which includes vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) communications. They can avoid potential road accident and enhance efficiency of transportation by broadcasting information of each vehicle's mobility and traffic status on the road.

The reliability of communication is very important in VSC. Under actual road environment, severe attenuation of received power due to shadowing and fading, as well as hidden terminal problem make it difficult to achieve the goal. A vehicle-roadside-vehicle broadcast relay network using CSMA/CA (Carrier Sense Multiple Access with Collision Avoidance) has been proposed [2] and shown to be effective in improving the V2V communication performance [3]. In general, relay systems extend the range of V2V communications, especially under non-line-of sight (NLOS) environment on the crossroads.

However, there are many factors that determine the performance of the CSMA/CA relay network. For example, the extension of communication range greatly depends on the position of the relay station. On the other hand, relaying will increase air time occupancy ratio which increases the chance of collision and may degrade the reliability of communication. Therefore detailed analysis and optimization of the system parameters are necessary to maximize performance of the relay network. Theoretical analysis will give more clear views about how parameters affect the performance. However, the theoretical analysis for broadcast V2V network employing relay stations has not covered by any pervious works.

The performance of CSMA/CA broadcast communications without relay has been analyzed in some works. Among simulation studies, M. Torrent-Moreno et al. [4] provided extensive and detailed analysis of the characteristics of broadcast transmission considering different propagation environments. As for theoretical approaches, ref. [5] analyzed the impact of hidden terminal problem and DCF backoff process on packet reception rate. The performance of V2V communications with two safety services of different priorities was evaluated in [6]. The influence of contention window size and number of vehicles was analyzed and discussed in [7].

However, these theoretical works [5]-[7] only assumed either non-fading channel or fading channel with constant bit error rate. Moreover, they considered that collision always leads to failure transmission which is not always true in real wireless environment because of capture effect[1]. In ref. [8], fading environment and capture effect were taken into account which leads to more detailed packet error analysis, although it never considered relay, nor effect of shadowing in cross roads.

In this paper, we extend the theoretical model proposed by ref. [8] to analyze CSMA/CA broadcast reception reliability with a relay station in cross roads. Since the direct and relayed paths from a transmitting vehicle station (T-VS) to a receiving vehicle station (R-VS) are possible, path diversity effect is taken into account. We also study the impact of both RF frequency band and carrier sense threshold on the packet delivery success performance.

II. ANALYSIS

A. System Model

In V2V communication environment, many vehicles on the road are broadcasting packets. However, if we focus on one vehicle that is transmitting a packet as T-VS, the number of interfering vehicle stations (I-VS) at that moment is not so many. Most probable case is only one I-VS in the vicinity of the T-VS [8]. Then we can set a simple model with four nodes distributed around the intersection as illustrated in Fig. 1.

[1]When two packets collide, if the power ratio of one packet to the other packet plus the noise is higher than a required SINR value, the former packet can be successfully received.

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Node 2 is a relay station (RS) at the center of the cross road, where we set the origin of coordinates. Node 1 is a T-VS placed either on the west or south street. An R-VS (node 3) and an I-VS (node 4) are placed on the east street.

B. Assumptions of the model

1) Both node 1 and node 4 are supposed to have packets ready to be broadcast at the beginning of every time interval of periodic broadcast. Every packet has the same payload size and its length is relatively short. Thus the propagation channel condition does not change during a packet is transmitted. The time interval is set large enough to avoid overlapping between the deferred packet following the IEEE 802.11 CSMA/CA mechanism and the packet generated by the other sending node at the beginning of the next time interval.

2) In broadcast communication, the transmitter is unaware of unsuccessful transmission. Hence there is no ARQ retransmission and no exponential increase of the contention window size W.

C. Packet reception rate

The following formulas define probabilities that will be used throughout the whole analysis.

$$p_1 = p\left(C_{12} + N < \Gamma_{CS}\right) \quad p_2 = p\left(C_{21} + N < \Gamma_{CS}\right)$$

$$p_3 = p(C_{14} + N < \Gamma_{CS}) \quad p_4 = p(C_{41} + N < \Gamma_{CS})$$

$$p_5 = p\left(C_{24} + N < \Gamma_{CS}\right) \quad p_6 = p\left(C_{42} + N < \Gamma_{CS}\right)$$

$$p_7 = p(\frac{C_{12}}{C_{42} + N} \geq \Gamma_{SINR}) \quad p_8 = p(\frac{C_{23}}{C_{43} + N} \geq \Gamma_{SINR})$$

$$p_9 = p(\frac{C_{13}}{C_{43} + N} \geq \Gamma_{SINR}) \quad p_{10} = p(\frac{C_{13}}{C_{23} + N} \geq \Gamma_{SINR})$$

$$p_{11} = p(\frac{C_{12}}{N} \geq \Gamma_{SINR}) \quad p_{12} = p(\frac{C_{23}}{N} \geq \Gamma_{SINR}) \quad p_{13} = p(\frac{C_{13}}{N} \geq \Gamma_{SINR})$$

where N is the thermal noise power, Γ_{CS} is the carrier sense threshold power, and Γ_{SINR} is the required SINR threshold. C_{ij} is the received signal power at node j from node i after experiencing path loss and Rayleigh fading fluctuation. The p.d.f. of C_{ij} is given by,

$$f(c) = \frac{1}{\sigma^2}\exp(\frac{c_{ij}}{\sigma^2}) \tag{1}$$

where σ^2 is the averaged received power determined by path loss model.

Then the probabilities above can be calculated by p.d.f. of C_{ij}. Take p_1 as an example, it can be calculated by the following formula,

$$p_1 = \int_0^{\Gamma_{CS}-N} \frac{1}{\sigma^2}\exp(\frac{c_{12}}{\sigma^2})dc \cdot \tag{2}$$

Situation 1: Node 1 has a packet ready to transmit slightly earlier than node 4. This probability is 0.5.

Situation 1.1: As shown in Fig. 2, if node 4 fails to sense the ongoing transmission of node 1, the two packets will collide at node 2 and node 3. However, the packet can be still received successfully because of capture effect. Under this situation, if node 2 can receive the packet from node 1 successfully, it will forward the packet after decoding it on the premise that the channel is sensed idle for DIFS time interval.

Then node 3 will receive it without interference. The packet

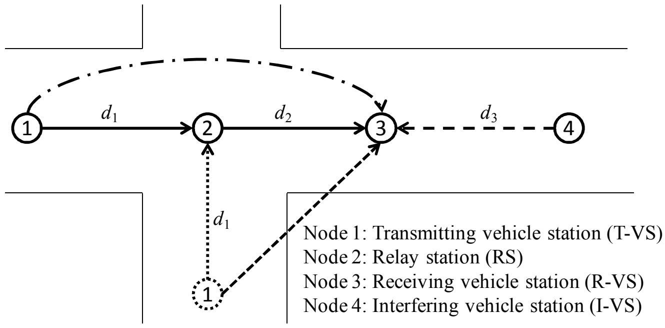
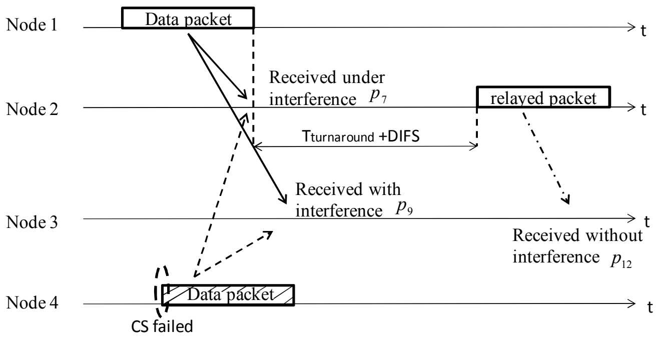


Figure 1. Nodes layout model for analysis



$T_{turnaround}$ = RX/TX turn around time which includes all delays between an transceiver receives a RF signal and the time it finishes transmitting the corresponding response.

Figure 2. Packet transmission in situation 1.1

reception rate at R-VS from T-VS in this case is expressed as

$$p_{1.1} = \frac{1}{2}p_3\left(p_9 + \left(1 - p_9\right)p_7 p_{12}\right) \ , \tag{3}$$

where p_3 is the probability of node 4 fails to sense node 1's transmission, p_7 and p_9 are the probabilities of successful reception at node 2 and node 3 under interference from node 4, respectively. p_{12} is the probability of successful relay transmission without interference. The second term in the bracket on the right side of Equ. (3), $(1\text{-}p_9)p_7p_{12}$, expresses the diversity gain in packet reception rate obtained from relayed path.

Situation 1.2: If node 4 senses the channel is busy, it will postpone its transmission acording to the backoff mechanism defined by IEEE 802.11p. According to the mechanism, node 4 first sets the backoff timer T_b, which can be expressed as:

$$T_b = n_b \times \delta \ , \tag{4}$$

where n_b is a random integer number selected within the backoff range $[0, W-1]$ and δ is the unit slot time.

When the channel becomes idle and stays idle during a DIFS interval, the backoff timer will starts to decrement. Node 4 will transmit when the backoff timer reaches to zero. Therefore, node 1's packet will be received by node 2 and node 3 without interference. However, there is a chance that node 4's deferred transmission will overlap with the relay transmission from node 2.

Situation 1.2.1: If the packet from node 4 collides with the relayed packet, the relayed packet will be received by node 3 under interference. According to the setting of node 4's backoff timer, node 4 can transmit earlier or later than the relay transmission.

As shown in Fig.3, there are two cases for the order of transmissions. The case 1 is that node 4 starts transmission earlier than node 2. The duration of each packet is T_p. If node 2 fails to sense the ongoing transmission of node 4, the two packets will collide. The probability of collision in this case is given by,

$$p_{c1} = (n_1 / W) \times p_6 \, , \tag{5}$$

where n_1 is the integer that satisfies $n_1\delta < T_{turnaround}$, and p_6 is the probability that node 2 fails to sense the transmission of node 4. $n_1\delta$ is shown as T_{b1} in the figure.

Similarly, in the case 2 when node 4 transmit the packet later than node 2, if overlapping happens and node 4 fails to sense the busy channel and stops its decrement of backoff timer, the two packets will collide. This probability can be expressed as:

$$p_{c2} = (n_2 / W) \times p_5 \, , \tag{6}$$

where n_2 is the integer that satisfies $T_{turnaround} < n_2\delta < T_{turnaround} + T_p$ and p_5 is the probability that node 4 fails to sense the transmission of node 2. $n_2\delta$ is shown as T_{b2} in the figure.

Then the packet reception rate under this situation is:

$$p_{1.2.1} = \frac{1}{2}(1-p_3)(p_{c1}+p_{c2})\left(p_{13}+(1-p_{13})p_{11}p_8\right) \tag{7}$$

where p_{11} and p_{13} are the probabilities of successful reception at node 2 and 3 under the interference from node 4, respectively. p_8 is the probability of successful relay transmission under interference.

Situation 1.2.2: If the duration of node 4's transmission does not overlap with relay transmission, or node 2 or node 4 successes to sense the busy channel, the relayed packet will be received without collision. The packet reception rate is expressed as:

$$p_{1.2.2} = \frac{1}{2}(1-p_3)\left(1-(p_{c1}+p_{c2})\right)\left(p_{13}+(1-p_{13})p_{11}p_{12}\right) \tag{8}$$

<**Dedicated frequency band case**> When different frequency bands are assigned for direct V2V communication and relay transmission, collision between node 4's transmission and relay transmission can be avoided. The packet reception rate under situation 1.2 is given by

$$p'_{1.2} = \frac{1}{2}(1-p_3)\left(p_{13}+(1-p_{13})p_{11}p_{12}\right) \tag{9}$$

Situation 2: Node 1 generate a packet slightly later than node 4. This probability is also 0.5.

Situation 2.1: Similar to situation 1.1, if node 1 fails to sense node 4's transmission, the node 1's packet and the node 4's packet will collide at node 2 and node 3. The relay transmission will complete without interference if node 2 receives packet from node 1 successfully. The packet delivery rate from node 1 to node 3 in this case is

$$p_{2.1} = \frac{1}{2}p_4\left(p_9+(1-p_9)p_7p_{12}\right) \tag{10}$$

where p_4 is the carrier sense failure probability in this case.

Situation 2.2: If node 1 senses the channel is busy, it will postpone its transmission according to backoff mechanism. Similar to situation 1.2, node 1's defered transmission might overlap with the relayed transmission from node 2.

Situation 2.2.1: If node 1's transmission overlaps with node 2's transmission, because one node cannot transmit and receive packets at the same time, node 2 cannot receive the packet transmitted from node 1, and therefore cannot relay it.

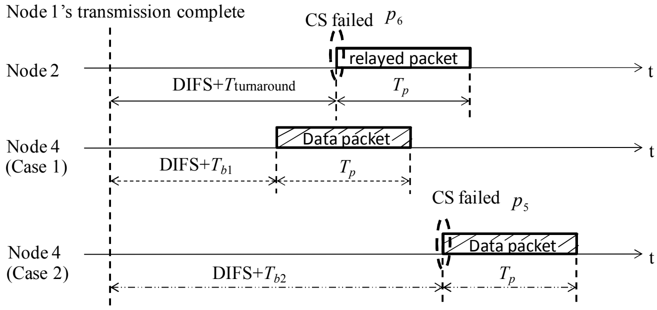


Figure 3. Collision timing of transmissions from node 4 and node 2 when node 4 transmits eariler

Similar to situation 1.2.1, the probability of collision is given by:

$$p_{c3} = (n_1 / W) \times p_1 + (n_2 / W) \times p_2 \tag{11}$$

where p_1 and p_2 are the probability that node 2 fails to sense node 1's transmission and the probability that node 1 fails to carrier sense node 2' transmission, respectively.

Under this situation, the packet delivery rate from the T-VS to the R-VS is given by

$$p_{2.2.1} = \frac{1}{2}(1-p_4)\,p_{c3}p_{10} \tag{12}$$

where p_{10} is the probability of successful transmission from node 1 to node 3 under the interference of node 2.

Situation 2.2.2: Similar to situation 1.2.2, if node 1's packet does not collide with the relayed packet, the probability of successful reception is expressed as:

$$p_{2.2.2} = \frac{1}{2}(1-p_4)(1-p_{c3})\left(p_{13}+(1-p_{13})p_{11}p_{12}\right) \tag{13}$$

<**Dedicated frequency band case**> Direct V2V transmission and relay transmission are free of interference. The packet reception rate from T-VS to R-VS under situation 2.2 is:

$$p'_{2.2} = \frac{1}{2}(1-p_4)\left(p_{13}+(1-p_{13})p_{11}p_{12}\right) \tag{14}$$

Finally, the packet reception rate from T-VS to R-VS is the sum of the successful transmission probabilities corresponding to the above situations, which is expressed as:

$$p = p_{1.1} + p_{1.2.1} + p_{1.2.2} + p_{2.1} + p_{2.2.1} + p_{2.2.2} \tag{15}$$

The packet reception rate when different frequency bands are assigned for direct V2V communication and relay transmission is given by

$$p' = p_{1.1} + p'_{1.2} + p_{2.1} + p'_{2.2} \tag{16}$$

III. NUMERICAL RESULTS

We obtained packet delivery rates of the IEEE 802.11p CSMA/CA broadcast relay network by both mathematical analysis and simulation using QualNet 4.5. Then the results are compared to validate the analytical model.

The configurations and parameters are shown in table I and table II. Given the conditions shown in table I and table II, the duration of each packet T_p is 192 μs, $n_1/W = 0.031$ and $n_2/W =$

TABLE I. PHYSICAL AND MAC PARAMETERS FOR THEORETICAL MODEL AND SIMULATION

RF frequency	5.9 GHz, 700MHz
Transmission Power	18 dBm
VS antenna height	1.5 m
RS antenna height	6 m
Street Width	16 m
Pathloss model	ITU-R P.1411-5
Fading model	Rayleigh
Maximum Doppler frequency	196.7 Hz/5.9 GHz, 23.3 Hz/700MHz
Data rate/Modulation	9 Mbps/QPSK
Contention window size W	32
Slot time	13 µs
DIFS	58 µs
$T_{turnaround}$	2 µs
Carrier sense threshold	-85 dBm, -88 dBm
SINR threshold	10
Noise factor	10

TABLE II. TRAFIC CONDITION AND CONFIGURATIONS OF SIMULATION

Packet type	UDP broadcast
Packet payload size	100 byte
Packet generation interval	100 ms
Simulater	QualNet 4.5
Duration of simulation	1000 s

0.438. The propagation environment is characterized by ITU-R P.1411-5 path loss model [9] which shows both line-of-sight (LOS) and NLOS propagation loss considering influence of shadowing caused by buildings around intersection.

A. LOS Environment

The T-VS is located on the west street, as shown in Fig. 1. The values of d_2 and d_3 are assigned with independent values from 10 m to 310 m with 20 m step, whereas d_1 is fixed as 50 m. Carrier sense threshold Γ_{CS} is set as -85 dBm or -88 dBm.

Fig. 4 and Fig. 5 depict the packet reception rates for 5.9 GHz obtained by theoretical calculation and simulation, respectively. Comparing these two figures, it is found that the theoretical calculation well described the characteristics of the packet reception ratio with various values of d_2, d_3 and carrier sense threshold. The average difference of values between simulation results and numerical results (which is calculated by $mean(|value_{sim} - value_{num}|)$) are 0.33% for Γ_{CS} = -85 dBm and 0.36% for Γ_{CS} = -88 dBm, respectively. Therefore it is concluded that the results obtained by the analytical model can well express the packet error rate performance.

It also can be observed that when carrier sense threshold decreases, the packet reception ratio is improved (about 4% in average) for all ranges of d_2 and d_3. It is because higher carrier sensitivity alleviates the impact of hidden terminal problem.

Fig. 6 shows packet reception rates for 5.9 GHz with different d_1 values for the Γ_{CS} of -85 dBm. Increasing d_1 makes the performance deteriorate in all ranges of d_2 and d_3. It results from the fact that the averaged received power at R-VS decreases as d_1 increases, as well as the averaged received power at RS, which reduce the packet reception rates of direct V2V transmission and relay transmission. It is concluded that the location of the relay station has significant influence on the packet reception rate.

It can be easily observed that when d_1 = 100 m and d_2 = 10 m, the packet reception rate first decreases then increases with

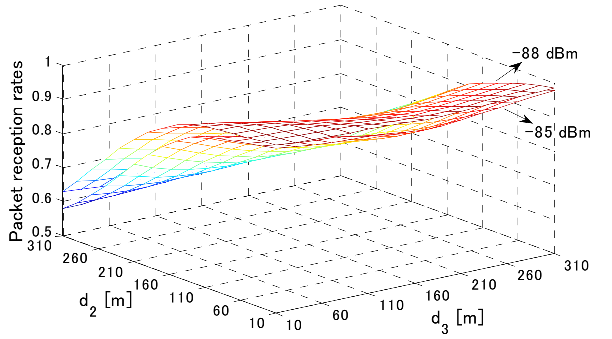


Figure 4. LOS packet reception rates obtained by theoretical calculation

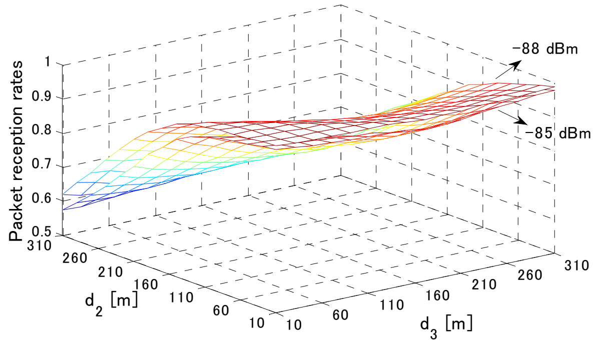


Figure 5. LOS packet reception rates obtained by simulation

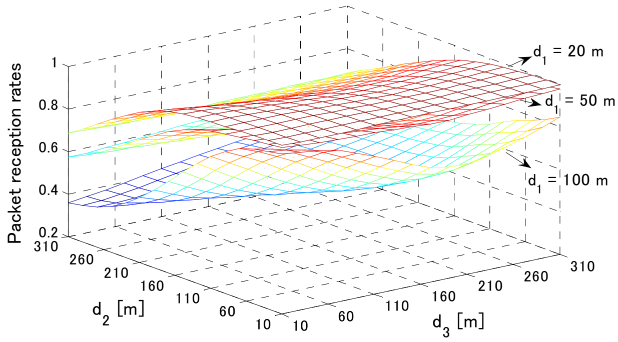


Figure 6. LOS packet reception rates with different d1

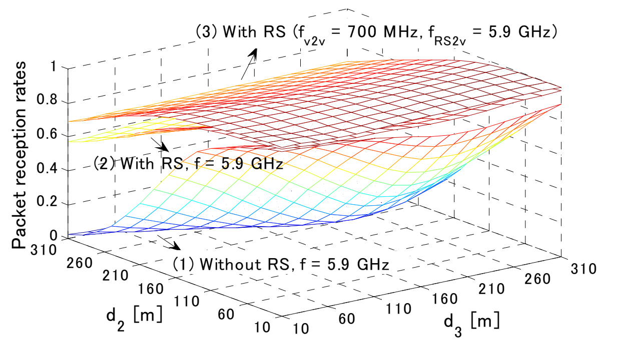


Figure 7. LOS packet reception rates for different schemes: (1) direct V2V communication without relay station, (2) relayed communication with single frequency band, and (3) relayed communication with two frequency bands

increasing d_3. This is because when I-VS is far from T-VS and RS, the probability of collision increases since physical carrier sense cannot work well (p_3 and p_4 increase by 89.1%, and p_5, p_6 increase by 23.7%). However, the average received power at R-VS from the I-VS will also decrease. When it becomes sufficiently small, it cannot block the reception at R-VS.

Fig. 7 shows the improvement in packet reception rate when the relay station is used for Γ_{CS} = -85 dBm. In the assistance of relay station to obtain path diversity effect, maximum improvement is up to 71.3% with single 5.9 GHz frequency band at d_2 of 210 m and d_3 of 230 m. Further improvement (81.6%) is observed when the frequency combination of 700 MHz for direct V2V communication and 5.9 GHz for relay transmission is applied. The latter scheme avoids collision between direct V2V communication and relay transmission. It also improves the packet reception rate and extends carrier sense range in direct V2V communication by using 700 MHz band which has lower propagation loss than 5.9 GHz band.

B. NLOS Environment

In the following analysis, T-VS (node 1) is located on the south street, as shown in Fig 1. The buildings on the corner block the LOS path between T-VS and R-VS. The values of d_2 and d_3 varies as LOS case with d_1 = 50 m and carrier sense threshold Γ_{CS} = -85 dBm.

Fig. 8 shows packet reception rates in NLOS environment with 5.9 GHz frequency band. It is found that direct V2V communication with 5.9 GHz suffers from severe propagation loss, and it is impossible to transmit packet from T-VS to R-VS unless they are very close to each other. With the assistance of relay station, the performance is improved significantly for longer d_2 and d_3. However, when (d_2 + d_3) are short, interference from I-VS is strong, which makes RS difficult to receive the packet from T-VS, and degrades the packet reception ratio.

Fig. 9 depicts packet reception rates in NLOS environment when 700 MHz frequency band is applied. Since 700 MHz has lower diffraction loss and propagation loss than 5.9 GHz band [10], it shows wider communication range both with and without the relay station, compared with Fig. 8. Especially for applying the relay station case, the packet reception rates are above 91% for all ranges of d_2 and d_3.

IV. CONCLUSION

In this paper, an analytical model is proposed to evaluate the packet reception rate performance of a CSMA/CA based broadcast relay network suffering from fading and shadowing. The model considers the impact of distance between nodes, carrier sense failure probability and capture effect. The network simulation results validated the accuracy of the proposed model. From the results, it is concluded that the performance of V2V communication can be improved by the following approaches: 1) increase carrier sensitivity to mitigate the hidden terminal problem; 2) apply relay stations to obtain path diversity gain and locate them close to T-VSs; 3) use different frequency bands to avoid collision between direct V2V transmission and relay transmission; 4) use UHF frequency band to reduce propagation and diffraction losses.

ACKNOWLEDGMENT

This work was supported by KAKENHI (20246066).

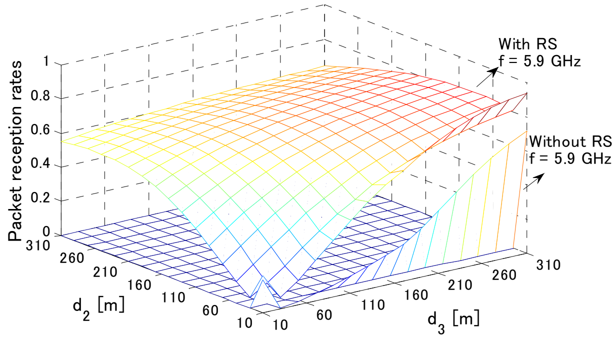


Figure 8. NLOS packet reception rates of direct V2V communication and broadcast relay communication for 5.9 GHz band.

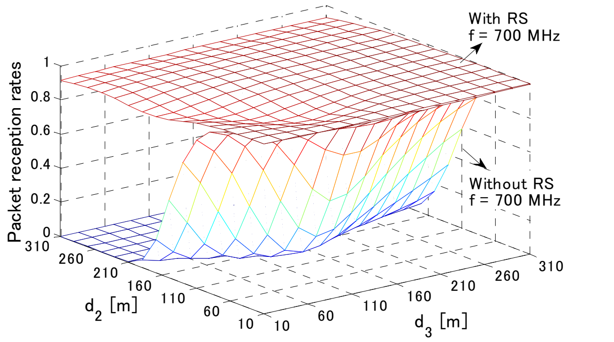


Figure 9. NLOS packet reception rates of direct V2V communication and broadcast relay communication for 700 MHz band

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