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1 author:

Kponyo Jerry
Kwame Nkrumah University Of Science and Technology

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Analysis of Packets Reception Rate for One-Hop Broadcast in 2-D VANETs

Enzhan Zhang, Yujun Kuang, Jerry John Kponyo

MobileLink LAB, University of Electronic and Science Technology of China / Chendu, 611731 / zhangenzhan@126.com, kyj@uestc.edu.cn, jjkponyo@ieee.org

* Corresponding Author: Enzhan Zhang

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Abstract: Reliability is an important issue for safety-critical and traffic situation broadcast services in Vehicular Ad-hoc Networks (VANETs). The Packet Reception Rate (PRR) is a key metric to evaluate broadcast reliability. Most researches of broadcasting in VANETs focus on multi-hop routing and connection establishing, taking all one-hop links for granted. A few have focused on the reliability of one-hop in 1-D VANETs. In this paper, we evaluate the PRR for one-hop broadcast in 2-D VANETs at an intersection analytically and by simulation. Expressions of the PRR are derived with consideration of the hidden terminal problem and collisions caused by concurrent transmissions. The impact of transmission, carrier sensing and interference ranges; the distances of receivers to the senders and the density of nodes on the roads are investigated and discussed. At last, some important observations to the broadcast at an intersection in VANETs are provided.

Keywords: VANETs, broadcast, reliability, packet reception rate

Introduction

Vehicular Ad Hoc Networks (VANETs) are emerging intelligent transportation networks intended for safe and comfortable transportation. Prospective applications include traffic data harvesting, incident notification, and proximity-based advertising. Most of the applications require data to be disseminated to their destinations on time and with a high level of reliability. A common transmission method is broadcasting in VANETs in order to disseminate safety

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messages and traffic information. This is used especially to deliver potential safety applications including collision avoidance warning, lane-changing warning, intersection coordination, traffic accident broadcasting, etc. They usually demand a direct one-hop broadcast due to the highly dynamic topology of vehicular networks. Securing the reliable delivery of messages to all surrounding vehicles in a timely manner in the VANETs is very important. Most investigations into broadcasting in VANETs have focusd on multi-hop connectivity, taking all one-hop links for granted. Yet, the apparent reliability of one-hop broadcast is unwarranted because of the many hurdles in VANETs such as the hidden terminal problem, the collisions caused by concurrent transmissions, and the high node mobility.

As mentioned in paper [1], reliability is defined as the network's ability to ensure that all intended mobile vehicle nodes receive the broadcast messages within a specified timetable. The authors introduced four reliability metrics in this paper [1] that characterize the behaviors of the one-hop real-time broadcast services in 1-D VANETs. However, calculating reliability in a 2-D scenario in the broadcast ad-hoc networks is still an open problem [1-3]. None of the research has focused on the reliability of broadcasting in 2-D VANETs at an intersection. In this paper, we try to evaluate one of the reliability metrics-the Packets Reception Rate (PRR) of a one-hop broadcast in 2-D VANETs at an intersection by analysis and by simulation. We extend the 1-D model in [1] to a 2-D model: Two vertical roads with the tagged node broadcasting at the intersection. The scenario is shown in Figure 1. A closed-form expression of PRR is derived. The impact of transmission, carrier sensing, and interference ranges; the distances of receivers to the senders and the density of nodes on the roads are investigated and discussed.

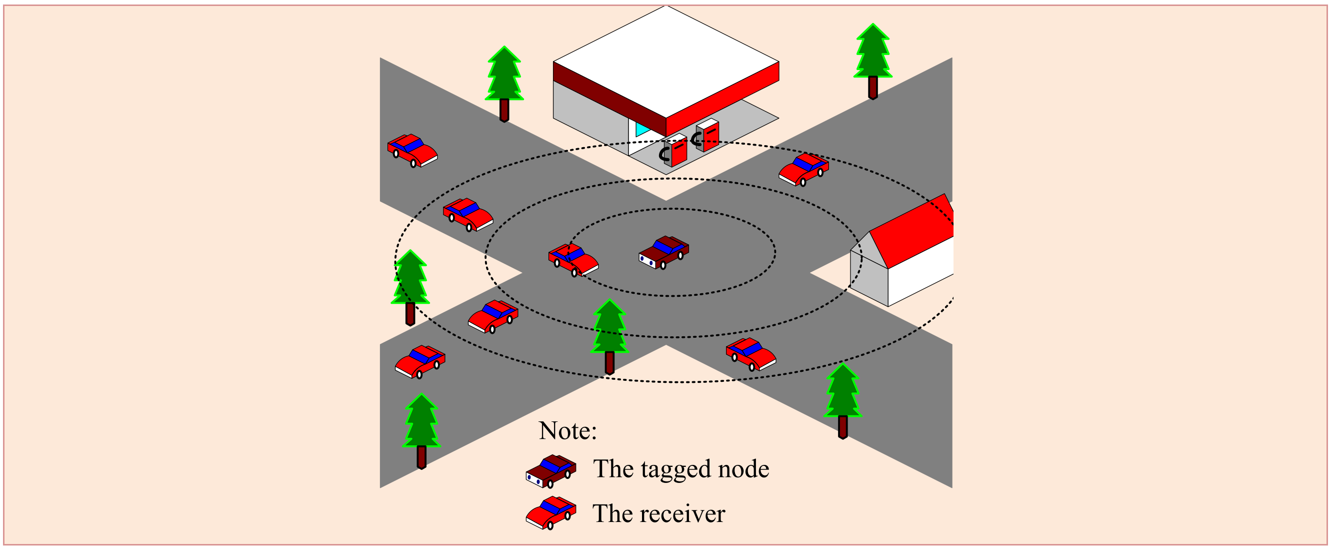

Figure 1. A real scenario of a tagged vehicle node broadcasting at an intersection

The rest of this paper is organized as follows: Section 2 briefly describes any related work. Section 3 presents an analytical model for developing the closed form PRR expression in the 2-D VANETs at an intersection. Section 4 demonstrates and discusses numerical results obtained from the analytic model and simulation, followed by the conclusion in section 5.

Related Work

Most broadcast protocols used in VANETs are IEEE-802.11-variant protocols. In order to improve the reliability of broadcasting in VANETs, existing techniques usually rely on handshaking (RTS/CTS), acknowledgement, rebroadcast, etc. The mechanisms, which rely upon existing broadcast techniques, are summarized in [1][4] as follows:

- Acknowledgement: the source node collects acknowledgements from the receivers;
- Continuous push: the source node repeatedly transmits the data until complete coverage is deduced; and
- Continuous pull: receivers keep requesting data from the source node until all of the data is received.

In fact, most of the investigations have focused on reducing message flooding, reducing the total number of traveling hops for multi-hop relays based on inter-node distance and node mobility direction, increasing connectivity, etc. for broadcast in VANETs [5]. Paper [6] proposed a vehicle-density-based emergency broadcast (VDEB) scheme to solve the problem of high overhead in VANETs. Paper [7] presented an efficient road-based directional broadcast protocol (ERD) to disseminate data to other vehicles efficiently in VANETs. Paper [8] introduced a selective reliable broadcast protocol (SRB) to reduce the effect of the broadcast storm problem in VANETs. In paper [9], several characteristics of directional-store-carry-forward (DSCF) broadcast protocol were revealed in a two-dimensional road model through simulation. In summary, the protocols in [6-9] aimed at improving transmission performance in VANETs. Paper [10] analyzed the delay performance on ad-hoc delay tolerant broadcast networks. In order to evaluate the performance of safety message dissemination in VANETs, paper [11] presented an analytical model for the performance evaluation of safety message dissemination in VANETs with two priority classes. The authors derived the joint distribution of the numbers of low-priority periodic messages through considering the IEEE 802.11 broadcast protocol and by using 2-D Markov modeling. Since IEEE 802.11p has been adopted as VANETs main technology, paper [12] evaluated the performance of the broadcast scheme of IEEE 802.11p standard analytically and verified the model by simulation. Not much work has been done on a thorough investigation analytically and by simulation on reliability, although this is an important issue for safety-critical and traffic situation broadcast services in VANETs.

In order to evaluate the reliability of broadcast for safety-related applications, the PRR was defined and introduced as one of the reliability metrics. However, most of the analyses and observations on PRR were mainly based on simulations. Therefore, paper [1] presented an analytical model and provided four reliability metrics to characterize the behaviors of one-hop real-time broadcast service in 1-D VANETs. The PRR, which is called Reachability (RE) in [13], was also analyzed and developed in 1-D VANETs with Poisson vehicle distribution. Paper [2], analyzed the PRR in 2-D mobile ad-hoc networks (MANETs), which is the extension of 1-D MANETs. However, in this scenario, the authors only considered a MANETs consisting of two straight parallel lines. On the other hand, as pointed out in [1], the assumption that the transmission range, the carrier-sensing range, and the interference range are identical are unreal. As a matter of fact, they are not identical in the real VANETs environment, but the relationships among them are: the carrier-sensing range is greater than and equal to the interference range and the transmission range is less than and equal to the interference range.

Compared with the model in paper [1], the main features of the proposed analytic model in this paper are as follows:

- We only focus on the PRR for one-hop broadcast at an intersection in 2-D VANETs.
- The proposed model accounts for the impact of the transmission range, the carrier sensing range, the interference range, the hidden terminal problem, the distances of receivers to the sender, the vehicle density, and the collisions caused by concurrent transmission.
- The average PRR and the PRR, which is a function of the receivers' distances to the sender, are both presented in this paper.

Packet Reception Rate Analysis

PRR

The PRR is defined as the percentage of vehicle nodes that successfully receive a broadcast packet from the tagged vehicle node among the receivers being investigated at the moment that the packet is sent out. This is a receiver centric reliability index evaluating how a broadcast packet from a sender is received by all intended receivers. In this paper, the tagged vehicle node is at the intersection. The form of PRR is shown as follows:

$$PRR = \frac{\begin{array}{c}No.\,of\;\; nodes\; in\; the\; transmission\; range\; of\;\; the\; tagged\; node\\ receiving\;\; a\;\; packet\;\; from\; the\; tagged\; node\end{array}}{Total\;\; no.\,of\;\; nodes\; in\; the\; transmission\; range\; of\;\; the\; tagged\; node} \tag{1}$$

Parameters

The main parameters used in our analytical model are given in Table1.

Assumptions for one-hop broadcast in 2-D VANETs

In order to simplify the analytical model, we make the following assumptions:

a) A 2-D one-hop broadcast VANETs consisting of statistically identical vehicle nodes randomly distributed on roads (as shown in Figure 2) is considered. The width of the road is negligible compared with the transmission range (greater than 300 meters) of nodes.

b) All nodes have the same transmission range R, an equal carrier-sensing range L_{cs}, and an equal interference range L_{int}. The relationships among them can be described as $R \le L_{\text{int}} \le L_{cs} \le 2R$.

c) Vehicle nodes are placed on roads according to a Poisson point process with density ρ. Thus, the probability of finding *i* nodes in a length of *l* can be described like this:

d)

$$P(i,l) = \frac{(\rho l)^i e^{-\rho l}}{i!} \tag{2}$$

e) This paper does not consider vehicle mobility. As pointed out in [14], the high mobility of vehicles (up to 120mph) has a very minor impact on the performance of the one-hop direct message broadcast network with high data rates (e.g., 12Mb/s) and short safety message lengths (e.g., 200B). For example, vehicles with 80km/h only move around 0.00296 meters during a packet transmission period with a packet size of 200bytes and data rate 12Mb/s.

f) We only concentrate on the impacts of hidden terminals and concurrent transmissions without channel shadowing and fading.

The IEEE802.11 broadcast scheme was used in this model:

Table 1. Parameters

R	Transmission or receiving range;
L_{cs}	Carrier-sensing range;
L_{int}	Interference range;
ρ	Density of vehicles on the roads (vehicles/meter);
ε	Probability that a vehicle node transmits in a generic slot time;
p_0	Probability that there are no packets ready to transmit in a vehicle node;
$P(i,l)$	The probability of finding *i* nodes in a length of *l*;
$DIFS$	Duration of a DCF inter-frame space in IEEE 802.11;
L_H	Size of packet head including the physical-layer head and the MAC-layer head;
W_0	Back-off window size of the back-off counter in each broadcast station;
$E[P]$	Average transmitting packet size;
σ	Back-off slot time duration;
R_d	System transmission data rate;
T	Average time that the channel is sensed busy because of a successful transmission;
τ	Channel propagation delay;
p_b	Probability that the channel is sensed busy by a tagged node;
q_i	Steady-state probability that a packet service time is *i* times the slot time;
$T_{vu\ln}$	The vulnerable period during which the tagged node's transmission is vulnerable to the hidden terminal problem;
λ	Packet arrival rate in each vehicle node;
μ	Packet service rate of the broadcast channel;
NF_H	Expected number of the failed receiving nodes due to the hidden terminal problem;
NF_C	Expected number of the failed receiving nodes due to concurrent transmissions;
PRR	Average packet reception rate;
$PRR(d)$	Average PRR among the receiving nodes whose distances to the tagged node are less than *d*;

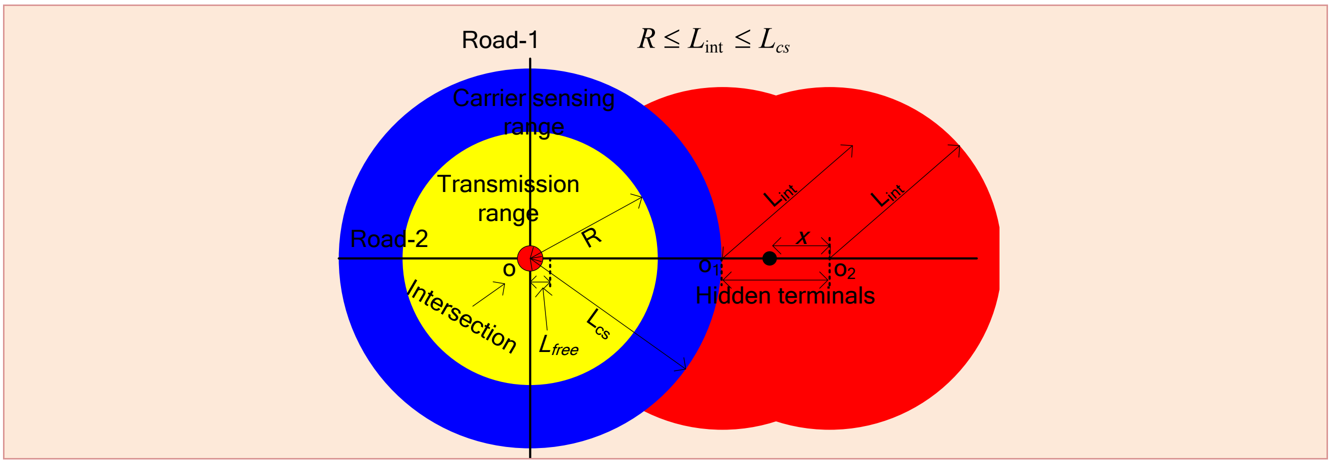

Figure 2. Two-dimensional VANETs model of an intersection

Analysis of PRR

Before analyzing the PRR, we introduce some parameters that will be used later. The impact of hidden terminal and concurrent transmission collisions will be presented separately.

In the back-off process, we denote as the packet broadcast probability of a vehicle in a generic slot. Following a similar procedure in [1][3][14], we can obtain.

$$\varepsilon = \frac{2\left(1-p_0\right)}{w_0+1} \tag{3}$$

Where w_0 is the back-off window size. p_0 is the probability of no packets being ready to transmit at the MAC layer in each node. This depends on the packet arrival rate λ in each vehicle node and the packet service rate μ in a broadcasting channel. Given the average packet length and header (including the physical-layer header and the MAC-layer header), the propagation delay τ and the inter frame space DIFS, a node detects an ongoing transmission. The back-off timer is assigned a time period T.

$$T = \frac{L_H + E[P]}{R_d} + DIFS + \tau \tag{4}$$

The other period is called the vulnerable period, where the tagged node's transmission becomes vulnerable to the hidden terminal problem. The calculation of the vulnerable period is described as

$$T_{vu\ln} = \frac{2\left(E\left[P\right]+L_H\right)}{R_d} \tag{5}$$

As mentioned in Table 1, p_b is the probability that the channel sensed by the tagged node is busy. When the channel is busy, there is at least one node transmitting in the carrier-sensing range of the tagged node. With the exponential distribution of the vehicles on the road, p_b is described as

$$p_b = 1-\sum_{i=0}^{\infty}\left(1-\varepsilon\right)^i \frac{\left(2\rho L_{cs}\right)^i}{i!} e^{-2\rho L_{cs}} = 1-e^{-2\rho L_{cs}\varepsilon} \tag{6}$$

The impact of the hidden terminals

From Figure 2, we can find that the hidden terminals of the tagged node on road-1 and road-2 only have an impact on receivers located on the same side as them. For example, the hidden terminals on the right side of the tagged node only impact the receivers located on the right side of the tagged node on road-2. The number of receivers affected by the hidden terminals only depends on the position of the hidden node. In this section, we focus only on the impact of the hidden terminals on the right side of the tagged node. The impact of the hidden terminals on the other three sides is the same as those to the right.

Let X be a random variable that represents the distance from the hidden crucial node to the outer boundary o_2 as shown in Figure 2. Let L_{no} be the range in the potential hidden terminal area where no node transmits, such that,

$$L_{no} = \left[L_{cs,}\ R + L_{\text{int}} - x\right] \tag{7}$$

The cumulative distribution function of X is then

$$\begin{aligned} P\left(X \le x\right) &= \sum_{k=0}^{\infty}\left[P\left(none\ of\ k\ nodes\ in\ L_{no}\ transmits\ for\ T_{vu\ln}\right)\right] \\ &= \left\{\sum_{k=0}^{\infty}\left(1-\varepsilon\right)^k \frac{\left[\left(R + L_{\text{int}} - L_{cs} - x\right)\right]^k}{k!} \times e^{-\rho\left(R + L_{\text{int}} - L_{cs} - x\right)}\right\}^{\frac{T_{vu\ln}}{(1-p_b)\sigma + p_b T}} \\ &= e^{\frac{-\rho T_{vu\ln}\left(R + L_{\text{int}} - L_{cs} - x\right)\varepsilon}{(1-p_b)\sigma + p_b T}} \end{aligned} \tag{8}$$

As shown in Figure 2, all receivers in $L_{free} = \left\{x \mid x \in \left[0, L_{cs} - L_{\text{int}}\right]\right\}$ are free from the hidden terminal problem. Thus, the expected number of the failed nodes in range $\left[0, R\right]$ is equal to the number of nodes in range $\left[L_{cs} - L_{\text{int}}, R\right]$ due to the hidden terminal problem. The expected number of the failed nodes can be expressed as

$$\begin{aligned} E\left[NF_H\right] &= \int_0^{R + L_{\text{int}} - L_{cs}} \rho x P\left(x \le X \le x + dx\right) \\ &= \int_0^{R + L_{\text{int}} - L_{cs}} \frac{\rho^2 T_{vu\ln}\varepsilon x}{\left(1 - p_b\right)\sigma + p_b T} e^{-\frac{\rho T_{vu\ln}\left(R + L_{\text{int}} - L_{cs} - x\right)\varepsilon}{(1-p_b)\sigma + p_b T}} dx \\ &= \rho\left(R + L_{\text{int}} - L_{cs} - \frac{\left(1 - p_b\right)\sigma + p_b T}{\rho T_{vu\ln}\varepsilon}\right) + \frac{\left(1 - p_b\right)\sigma + p_b T}{T_{vu\ln}\varepsilon} e^{-\left(R + L_{\text{int}} - L_{cs}\right)\frac{\rho T_{vu\ln}\varepsilon}{(1-p_b)\sigma + p_b T}} \end{aligned} \tag{9}$$

Therefore, the percentage of the receivers in range $\left[0, R\right]$ on the right side of the tagged node on road-2 that are free from collisions caused by the hidden terminal problem can be evaluated as

$$\begin{aligned} PRR_{H-right} &= 1 - \frac{E\left[NF_H\right]}{\rho R} \\ &= \frac{L_{cs} - L_{\text{int}}}{R} + \frac{\left(1 - p_b\right)\sigma + p_b T}{\rho R T_{vu\ln}\varepsilon} - \frac{\left(1 - p_b\right)\sigma + p_b T}{\rho R T_{vu\ln}\varepsilon} e^{-\left(R + L_{\text{int}} - L_{cs}\right)\frac{\rho T_{vu\ln}\varepsilon}{(1-p_b)\sigma + p_b T}} \end{aligned} \tag{10}$$

The impact of concurrent transmissions collisions

Nodes within L_{cs} from the tagged node transmit at the time when it may cause collisions. That means when the tagged node transmits in a slot time, collisions will take place in the overlap range of the tagged node and the other transmitting node if any node transmits in the same slot, resulting in a failure to receive nodes in the overlap range.

The concurrent transmitting nodes on the right side of the tagged node: As shown in Figure 3, the concurrent transmitting nodes are in the range $oo_2 = \left[0, L_{cs}\right]$. oo_2 can be divided into two parts, i.e., $oo_2 = oo_1 \cup$, where $oo_1 = \left[0, L_{\text{int}}\right]$, $o_1 o_2 = \left[L_{\text{int}}, L_{cs}\right]$. Any transmission of nodes in oo_1 will result in a failure of all receivers in $\left[0, R\right]$ receiving the broadcast packet from the tagged node in the same time slot. Only when the nodes in oo_1 are silent are the receivers free from collisions. Thus the PRR in the range $\left[0, R\right]$ that are free from collisions caused by concurrent transmissions in oo_1 can be expressed as

$$PRR_{oo_1} = \sum_{i-0}^{\infty}(1-\varepsilon)^i \frac{(\rho L_{\text{int}}-1)^i}{i!} e^{-(\rho L_{\text{int}}-1)} = e^{-(\rho L_{\text{int}}-1)\varepsilon} \tag{11}$$

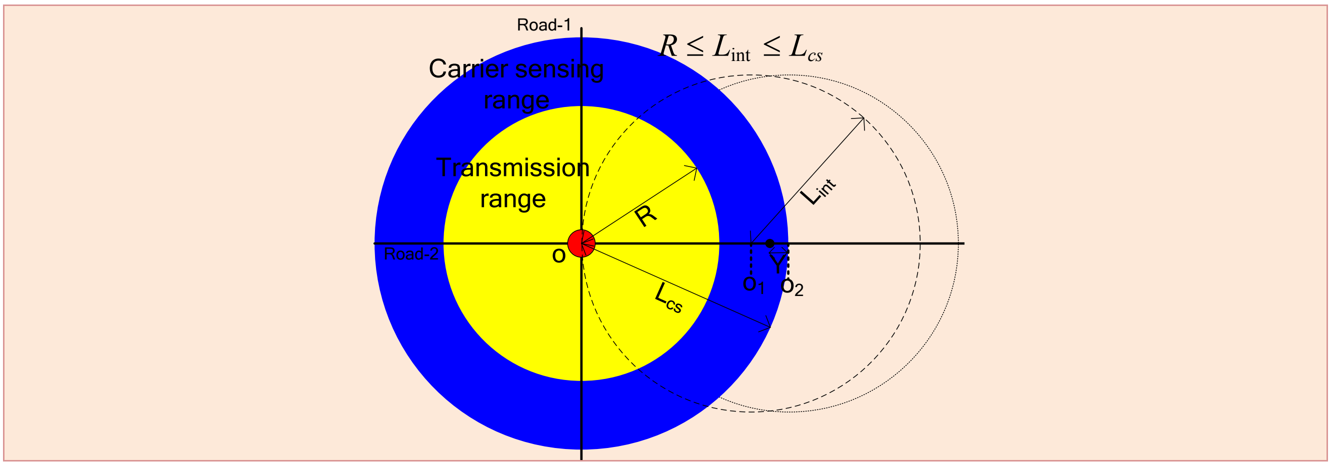

Figure 3. Impact of concurrent transmissions (right side of the tagged node)

The impact of concurrent transmissions in o_1o_2 depends on the position of the closest concurrent transmitting node in o_1o_2 to the tagged node. Let Y be a random variable that represents the distance from the closest transmitting node in o_1o_2 to the outer boundary o_2 as shown in Figure 3. Therefore, no node transmits in the range $[L_{\text{int}}, L_{cs}-Y]$. Similar to equation (8), the CDF of Y is

$$\begin{aligned} P(Y \le y) &= \sum_{k=0}^{\infty}\left[P\left(\textit{none of } k \textit{ nodes in range } [L_{\text{int}}, L_{cs}-Y] \textit{ transmits in a slot}\right)\right] \\ &= \sum_{k=0}^{\infty}(1-\varepsilon)^k \frac{\left[\rho\left(L_{cs}-y-L_{\text{int}}\right)\right]^k}{k!} e^{-\rho(L_{cs}-y-L_{\text{int}})} \\ &= e^{-\rho(L_{cs}-y-L_{\text{int}})\varepsilon} \end{aligned} \tag{12}$$

Thus, the expected number of failed nodes in range $[0, R]$ is equal to the number of nodes in range $[L_{cs}-L_{\text{int}}-Y, R]$. The expected number of failed nodes can be expressed as

$$\begin{aligned} E\left[NF_{c-o_1o_2}\right] &= \int_0^{L_{cs}-L_{\text{int}}} \rho\left(R+L_{\text{int}}+y-L_{cs}\right)P\left(y \le Y \le y+dy\right) \\ &= \int_0^{L_{cs}-L_{\text{int}}} \rho^2\varepsilon\left(R+L_{\text{int}}+y-L_{cs}\right)e^{-\rho\varepsilon(L_{cs}-L_{\text{int}}-y)}dy \\ &= \rho R - \frac{1}{\varepsilon} + \left[\frac{1}{\varepsilon} - \rho\left(R+L_{\text{int}}-L_{cs}\right)\right]e^{-\rho\varepsilon(L_{cs}-L_{\text{int}})} \end{aligned} \tag{13}$$

Thus the percentage of receivers in the range $[0, R]$ that are free from collision caused by concurrent transmissions in o_1o_2 can be expressed as

$$PRR_{o_1o_2} = \frac{\rho R - \left[NF_{c-o_1o_2}\right]}{\rho R} \tag{14}$$

Combining equation (11) with (14), the PRR caused by concurrent transmissions of any node in the right side of the tagged node is given by

$$PRR_{right} = PRR_{oo_1} \times PRR_{o_1o_2} \qquad 15)$$

The concurrent transmitting nodes on the left side of the tagged node: In this part, we will analyze the impact on the receivers located on the right side of the tagged node in range $[0, R]$ caused by the concurrent transmitting nodes located on the left side of the tagged node as shown in Figure 4. These nodes are in range $oo_5 = [0, L_{cs}]$, where the positive and the negative of the range are neglected. Similar to part A, the range oo_5 can be divided into three parts, i.e., $oo_5 = oo_3 \cup \quad \cup \quad$, where $oo_3 = [0, L_{\text{int}} - R]$, $o_3o_4 = [L_{\text{int}} - R, L_{\text{int}}]$, $o_4o_5 = [L_{\text{int}}, L_{cs}]$. Any transmission of nodes in oo_3 will result in a failure of all receivers in $[0, R]$ receiving the broadcast packet from the tagged node in the same time slot. The receivers are freen from collisions only when the nodes in oo_3 are silent. Thus, the PRR in the range $[0, R]$ caused by concurrent transmissions of any node in oo_3 can be expressed as

$$\begin{aligned} PRR_{oo_3} &= \sum_{i-0}^{\infty} (1-\varepsilon)^i \frac{\left[\rho\left(L_{\text{int}} - R\right) - 1\right]^i}{i!} e^{-\left[\rho\left(L_{\text{int}} - R\right) - 1\right]} \\ &= e^{-\left[\rho\left(L_{\text{int}} - R\right) - 1\right]\varepsilon} \end{aligned} \tag{16}$$

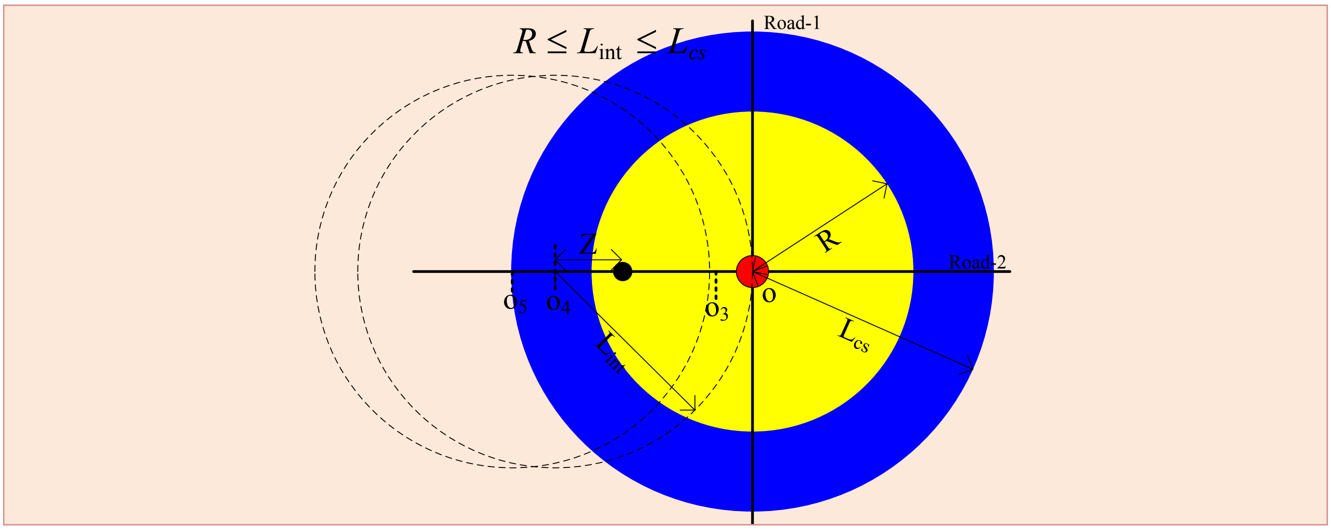

Figure 4. Impact of concurrent transmissions (left side of the tagged node)

The impact of concurrent transmissions in o_3o_4 depends on the position of the closest concurrent transmitting node in o_3o_4 to the tagged node. Let Z be a random variable that represents the distance from the closest transmitting node in o_3o_4 to the outer boundary o_4 as shown in Figure 4. Therefore, no node transmits in range $[L_{\text{int}} - R, L_{\text{int}} - Z]$. Similar to equation (8), the CDF of Z is

$$\begin{aligned} P(Z \le z) &= \sum_{k=0}^{\infty} \left[P\left(none\ of\ k\ nodes\ in \left[L_{\text{int}} - R, L_{\text{int}} - Z\right] transmits\ in\ a\ slot \right) \right] \\ &= \sum_{k=0}^{\infty} (1-\varepsilon)^k \frac{\left[\rho(R-z)\right]^k}{k!} e^{-\rho(R-z)} \\ &= e^{-\rho(R-z)\varepsilon} \end{aligned} \tag{17}$$

Thus, given z, the expected number of the failed nodes in range $[0, R]$ on the right side of the tagged node is equal to the number of nodes in range $[0, z]$ on the right side of the tagged node. The expected number of the failed nodes can be expressed as

$$\begin{aligned} E\left[NF_{c-o_3o_4}\right] &= \int_0^R \rho z P\left(z \le Z \le z + dz\right) = \int_0^R \rho^2 \varepsilon z e^{-\rho(R-z)\varepsilon} dz \\ &= \frac{1}{\varepsilon}\left[\left(\rho\varepsilon R - 1\right) + e^{-\rho\varepsilon R}\right] \end{aligned} \tag{18}$$

Therefore, the PRR in the range $\left[0, R\right]$ on the right of the tagged node caused by concurrent transmissions in o_3o_4 can be expressed as

$$PRR_{o_3o_4} = \frac{\rho R - \left[NF_{c-o_3o_4}\right]}{\rho R} \tag{19}$$

The nodes in the range $\left[0, R\right]$ on the right side of the tagged node are out of the interference of the concurrent transmissions from range o_4o_5. The PRR in the range $\left[0, R\right]$ on the right side of the tagged node caused by concurrent transmissions in o_4o_5 is $PRR_{o_4o_5} = 1$.

The total impact caused by the concurrent transmissions of any node on the left side of the tagged node is expressed as

$$PRR_{left} = PRR_{oo_3} \times PRR_{o_3o_4} \times PRR_{o_4o_5} \tag{20}$$

The impact of the concurrent transmitting nodes above the tagged node: Much like parts A and B, we will analyze the PRR of receivers in the range $\left[0, R\right]$ on the right side of the tagged node on road-2, which is caused by the concurrent transmissions of any node in the above range oo_8 of the tagged node as shown in Figure 5. In the same analyzing way, the range oo_8 can also be divided into three parts, i.e., $oo_8 = oo_6 \cup \quad \cup \quad$, where $oo_6 = \left[0, \sqrt{L_{\text{int}}^2 - R^2}\right]$, $o_6o_7 = \left[\sqrt{L_{\text{int}}^2 - R^2}, L_{\text{int}}\right]$, $o_7o_8 = \left[L_{\text{int}}, L_{cs}\right]$. Any transmission of nodes in oo_6 will result in failure of all receivers in $\left[0, R\right]$ receiving the broadcast packet from the tagged node in the same time slot. Only when the nodes in oo_6 are silent can the receivers be free from collisions. The PRR in the range $\left[0, R\right]$ that are free from collision caused by concurrent transmissions in oo_6 can be expressed as

$$\begin{aligned} PRR_{oo_6} &= \sum_{i-0}^{\infty}\left(1-\varepsilon\right)^i \frac{\left[\rho\sqrt{L_{\text{int}}^2 - R^2} - 1\right]^i}{i!} e^{-\left(\rho\sqrt{L_{\text{int}}^2 - R^2} - 1\right)} \\ &= e^{-\left(\rho\sqrt{L_{\text{int}}^2 - R^2} - 1\right)\varepsilon} \end{aligned} \tag{21}$$

The impact of concurrent transmissions in o_6o_7 depends on the position of the closest concurrent transmitting node in o_6o_7 to the tagged node. Let W be a random variable that represents the distance from the closest transmitting node in o_6o_7 to the outer boundary o_7 as shown in Figure 5. Therefore, no node transmits in the range $\left[\sqrt{L_{\text{int}}^2 - R^2}, L_{\text{int}} - w\right]$. Similar to equation (8), the CDF of W is

$$\begin{aligned} P\left(W \le w\right) &= \sum_{k=0}^{\infty}\left[P\left(\text{none of } k \text{ nodes in} \left[\sqrt{L_{\text{int}}^2 - R^2}, L_{\text{int}} - w\right] \text{transmits in a slot}\right)\right] \\ &= \sum_{k=0}^{\infty}\left(1-\varepsilon\right)^k \frac{\left[\rho\left(L_{\text{int}} - w - \sqrt{L_{\text{int}}^2 - R^2}\right)\right]^k}{k!} e^{-\rho\left(L_{\text{int}} - w - \sqrt{L_{\text{int}}^2 - R^2}\right)} \\ &= e^{-\rho\left(L_{\text{int}} - w - \sqrt{L_{\text{int}}^2 - R^2}\right)\varepsilon} \end{aligned} \tag{22}$$

Given w, the expected number of the failed nodes in range $\left[0, R\right]$ on the right side of the tagged node can be expressed as

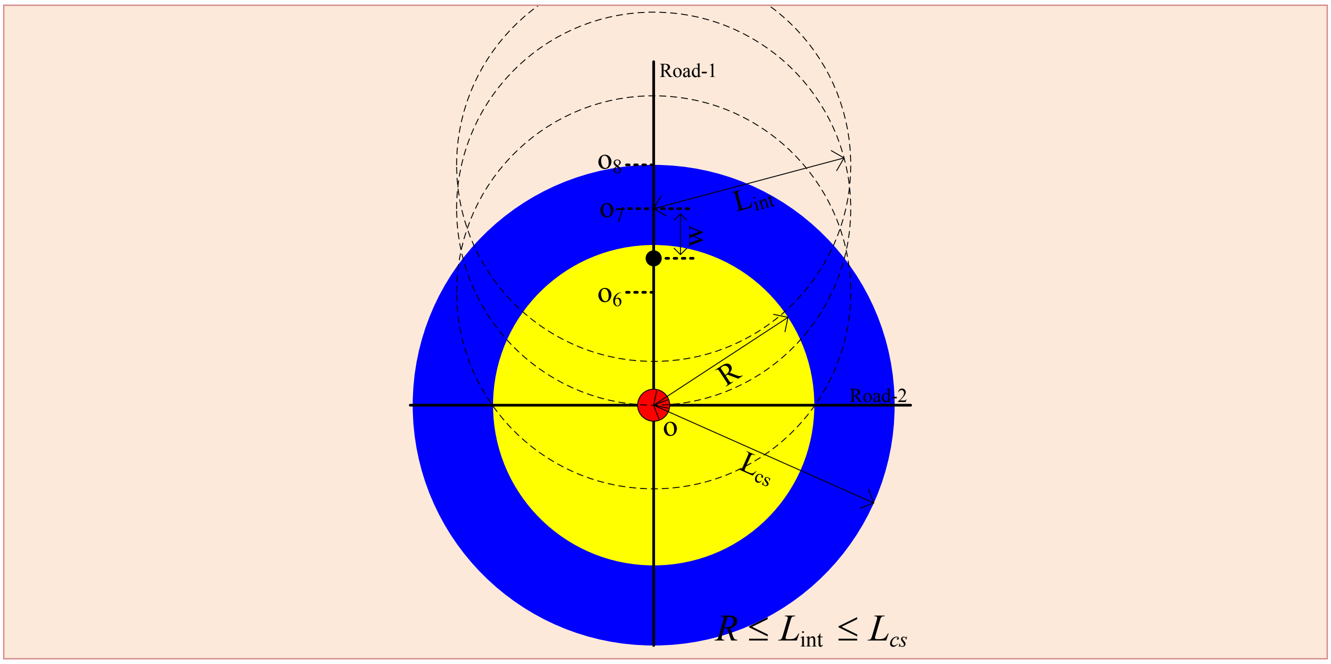

Figure 5. Impact of concurrent transmissions (above of the tagged node)

$$\begin{aligned} E\left[NF_{c-o_6o_7}\right] &= \int_0^{L_{int}-\sqrt{L_{int}^2-R^2}} \rho\sqrt{L_{int}^2-(L_{int}-w)^2}\,P\left(w \le W \le w+dw\right) \\ &= \int_0^{L_{int}-\sqrt{L_{int}^2-R^2}} \rho^2\varepsilon\sqrt{L_{int}^2-(L_{int}-w)^2}\,e^{-\rho\left(L_{int}-w-\sqrt{L_{int}^2-R^2}\right)\varepsilon}dw \end{aligned} \tag{23}$$

Thus, the PRR of the receivers in the range $\left[0, R\right]$ caused by the concurrent transmission of any node in the above range o_6o_7 is expressed by

$$PRR_{o_6o_7} = \frac{\rho R - \left[NF_{c-o_6o_7}\right]}{\rho R} \tag{24}$$

The nodes in the range $\left[0, R\right]$ on the right side of the tagged node are out of the interference of the concurrent transmissions from range o_7o_8. Thus, the PRR in the range $\left[0, R\right]$ caused by concurrent transmissions of any node in o_7o_8 is that $PRR_{o_7o_8} = 1$.

Therefore, the total impact caused by the concurrent transmissions of any node on the above of the tagged node can be expressed as

$$PRR_{up} = PRR_{oo_6} \times PRR_{o_6o_7} \times PRR_{o_7o_8} \tag{25}$$

The impact of the concurrent transmitting nodes on the downside of the tagged node: Based on the geometric symmetrical relationship between the above and the downside of the tagged node, we can obtain the same PRR result

$$PRR_{up} = PRR_{down} \tag{26}$$

The PRR on the other three sides of the tagged node is the same as that of the right side. The PRR of the receivers in the tagged node's transmitting range at the intersection is equal to the PRR of the receivers in the right side range of the tagged node.

In conclusion, taking the impact of the hidden terminal problem and concurrent transmissions into account, we derive

PRR for a single packet transmission as

$$PRR = PRR_H \times PRR_{right} \times PRR_{left} \times PRR_{up} \times PRR_{down} \tag{27}$$

PRR within distance *d* from the tagged node

Some applications are concerned more with how reliably the vehicles that are close to the tagged node receive the warning message when an emergency situation takes place. In this section, we give a deeper insight of the PRR as the range changes. As shown in Figure 6, $0 \le d \le R$.

$$PRR(d) = \frac{No.\ of\ nodes\ within\ distance\ d\ receiving\ a\ packet\ from\ the\ tagged\ node}{Total\ no.\ of\ nodes\ within\ distance\ d\ from\ the\ tagged\ node} \tag{28}$$

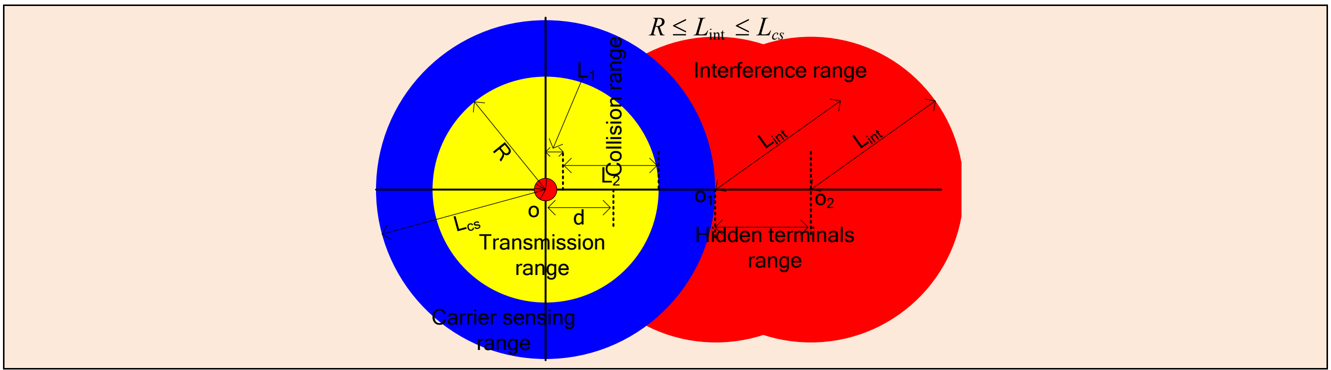

Figure 6. Scenario of PRR within distance d from the tagged node (Hidden terminals in the right side)

The impact of the hidden terminals

The impact of the hidden terminals in the right side range of the tagged node, which affects the $\mathrm{PRR}(\mathrm{d})$ of the receivers in range $[0, d]$, can be obtained as shown in paper [1] and can be expressed as,

$$PRR_H(d) = \begin{cases} 1, & 0 < d \le L_{cs} - L_{\mathrm{int}} \\ \dfrac{\rho d - NF_h(d)}{\rho d}, & L_{cs} - L_{\mathrm{int}} < d \le R \end{cases} \tag{29}$$

Where the $NF_H(d)$ is given by,

$$NF_h(d) = \rho\left(d + L_{\mathrm{int}} - L_{cs} - \frac{(1-p_b)\sigma + p_b T}{\rho T_{vu\ln}\varepsilon}\right) e^{-\frac{\rho T_{vu\ln}\varepsilon(R-d)}{(1-p_b)\sigma + p_b T}} + \frac{(1-p_b)\sigma + p_b T}{T_{vu\ln}\varepsilon} e^{-\frac{\rho T_{vu\ln}\varepsilon(R+L_{\mathrm{int}}-L_{cs})}{(1-p_b)\sigma + p_b T}} \tag{30}$$

The impact of concurrent transmission collisions

The $\mathrm{PRR}(\mathrm{d})$ within distance *d* from the tagged node caused by the concurrent transmissions is similar to previous sections, which is omitted in this part. The difference is that the length *d* is unfixed which results in different forms of $\mathrm{PRR}(\mathrm{d})$. We only give the equations of $\mathrm{PRR}(\mathrm{d})$ here.

The concurrent transmitting nodes on the right side of the tagged node: On the right side, the road is divided into two parts according to transmission and receiving range of nodes

$$PRR_{oo_1^{'}}(d) = e^{-(\rho L_{\mathrm{int}} - 1)\varepsilon} \tag{31}$$

$$PRR_{o_1'o_2'}(d)=\begin{cases}1-\dfrac{1}{\rho d\varepsilon}e^{-\rho(L_{cs}-L_{\text{int}}-d)\varepsilon}+\left(1+\dfrac{1}{\rho d\varepsilon}\right)e^{-\rho(L_{cs}-L_{\text{int}})\varepsilon}, & 0<d\le L_{cs}-L_{\text{int}}\\ \dfrac{1}{\rho d\varepsilon}+\left(1-\dfrac{L_{cs}-L_{\text{int}}}{d}-\dfrac{1}{\rho d\varepsilon}\right)e^{-\rho(L_{cs}-L_{\text{int}})\varepsilon}, & L_{cs}-L_{\text{int}}<d\le R\end{cases} \tag{32}$$

$$PRR_{right}(d)=PRR_{oo_1'}(d)\times PRR_{o_1'o_2'}(d) \tag{33}$$

The concurrent transmitting nodes on the left side of the tagged node:

$$PRR_{oo_3'}(d)=e^{-\rho(L_{\text{int}}-R)\varepsilon} \tag{34}$$

$$PRR_{o_3'o_4'}(d)=1-e^{-\rho\varepsilon R}\left[\left(1-\frac{1}{\rho d\varepsilon}\right)e^{\rho\varepsilon d}+\frac{1}{\rho d\varepsilon}\right] \tag{35}$$

$$PRR_{o_4'o_5'}(d)=1 \tag{36}$$

$$PRR_{left}=PRR_{oo_3'}(d)\times PRR_{o_3'o_4'}(d)\times PRR_{o_4'o_5'}(d) \tag{37}$$

The concurrent transmitting nodes above the tagged node:

$$PRR_{oo_6'}(d)=e^{-\left(\rho\sqrt{L_{\text{int}}^2-d^2}-1\right)\varepsilon} \tag{38}$$

$$\begin{aligned}PRR_{o_6'o_7'}(d)&=1-\frac{NF_{failed-o_6'o_7'}(d)}{\rho d}\\&=1-\int_0^{L_{\text{int}}-\sqrt{L_{\text{int}}^2-d^2}}\frac{\rho\varepsilon}{d}\sqrt{L_{\text{int}}^2-(L_{\text{int}}-w)^2}\,e^{-\rho\left(L_{\text{int}}-w-\sqrt{L_{\text{int}}^2-d^2}\right)\varepsilon}dw\end{aligned} \tag{39}$$

$$PRR_{o_7'o_8'}(d)=1 \tag{40}$$

$$PRR_{up}=PRR_{oo_6'}(d)\times PRR_{o_6'o_7'}(d)\times PRR_{o_7'o_8'}(d) \tag{41}$$

The concurrent transmitting nodes on the downside of the tagged node:

$$PRR_{down}(d)=PRR_{up}(d) \tag{42}$$

Therefore, the $\text{PRR}(\text{d})$ is given by the following equation based on the above equations.

$$PRR(d)=PRR_H(d)\times PRR_{right}(d)\times PRR_{left}(d)\times PRR_{up}(d)\times PRR_{down}(d) \tag{43}$$

Numerical Results

In this section, the comparisons of PRR between the analytical results and the simulation results are used to evaluate the performance of one-hop broadcast in 2-D VANETs at an intersection. The parameters are given in Table2.

Table 2. Parameters

Parameter	Specification
Model Simulator	NS2
Simulation Time	30.0s
Road length (total)	1000m+1000m
Number of Vehicles	40-400
MAC protocol	IEEE802.11MAC
Data rate	12Mbps
DIFS	64 μs
SIFS	32 μs
Slot time	16 μs
Propagation delay	1 μs
CW	15 and 31
Average packet length	200Bytes
p_0	99%

■ PRR

Figure 7 and Figure 8 are the theoretic results. In Figure 7, the distance from the sender in paper [1] is 250m, which is equal to the transmission range and the interference range in this paper. From this figure, we can find that the difference between theoretic results is mainly due to the number of branches. The highway scenario in paper [1] is one road. In this paper, there are two roads crossing at the intersection. The hidden terminals and the concurrent transmissions in the 2-D scenario at an intersection are greater than in the 1-D scenario in paper [1] with the same vehicle density. Therefore, the PRRs in the 2-D scenario are less than in 1-D for different densities. The PRRs are decreasing as the vehicle density increases, meaning that the higher the vehicle density, the more that transmission collisions will occur. We also realized that increasing the carrier sensing range can improve the PRR, because the bigger the carrier sensing range the less the number of hidden terminals. As can be seen in Figure 8, bigger back-off window sizes and shorter message lengths can help increase the PRR. This is because increasing the back-off window sizes and shortening the message length are effective to reduce concurrent collisions.

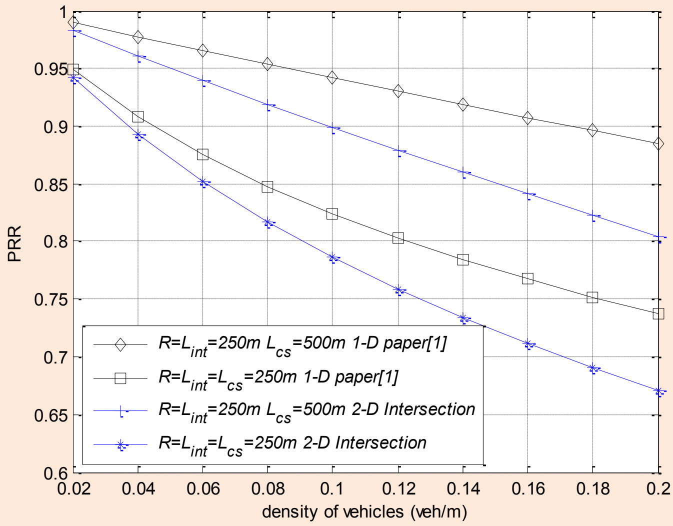

Figure 7. The comparison of PRR between 1-D scenario in paper [1] with d=250m and 2-D scenario at an intersection in this paper

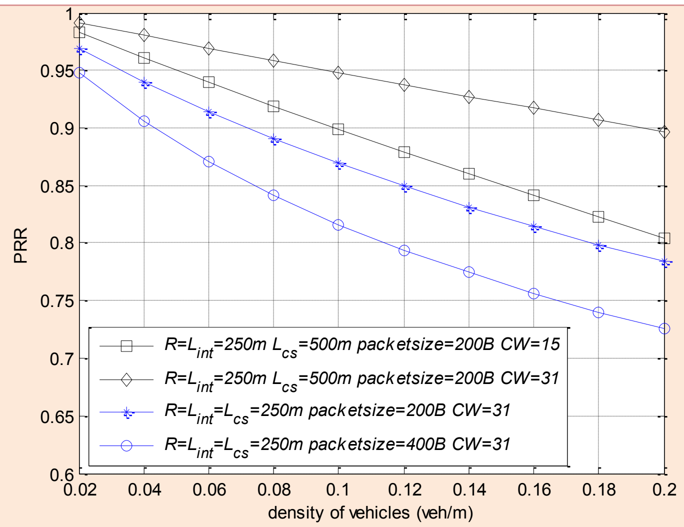

Figure 8. The comparison of PRR with different carrier sensing distance, packet size, and CW

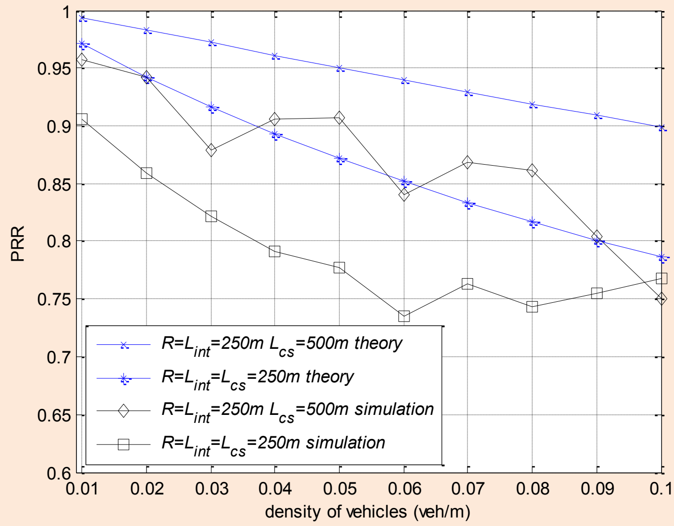

Figure 9. Comparison of theoretical results and simulation results for 2-D scenario at an intersection

Figure 9 shows the comparison of theoretic result with simulation results for the same scenario. We found that the PRRs decrease with increase in the density of vehicles. The fluctuations in the simulation occur because of the random distribution of vehicle positions. Therefore, the density is not uniform in the simulation scenario, which is different from the density in the theoretical analysis process.

■ PRR within distance d from the tagged node

The PRR(d) is a function of the distance from the sender. Figure10-Figure12 shows a comparison of the theoretical and simulated values of PRR(d). In Figure 10, the PRR(d)s increase as the carrier sensing range increases, and decreases as the vehicle density and distance from the sender increases. In order to show the comparison clearly, we present the simulation results separately in Figure 11 and Figure 12 for $\rho = 0.02veh/m$ and $\rho = 0.1veh/m$. The theoretic analysis and simulation results show that PRR(d) decreases as the sender's distance increases. However, in Figure 11, the simulation results of PRR(d) keep fluctuating with $R = L_{\text{int}} = L_{cs} = 250m$, which is a result of few receivers being in the sender's transmission range. The receivers are not uniformly distributed and the carrier sensing range is short. Similarly, the distribution of hidden terminals is not uniform and their number does not increase linearly as the distance does.

From the above we can conclude that the PRR(d) is greater than 90% with $R = L_{\text{int}} = 250m$ $L_{cs} = 500m$ in 100m range and it is enough for emergency traffic information broadcasting at an intersection.

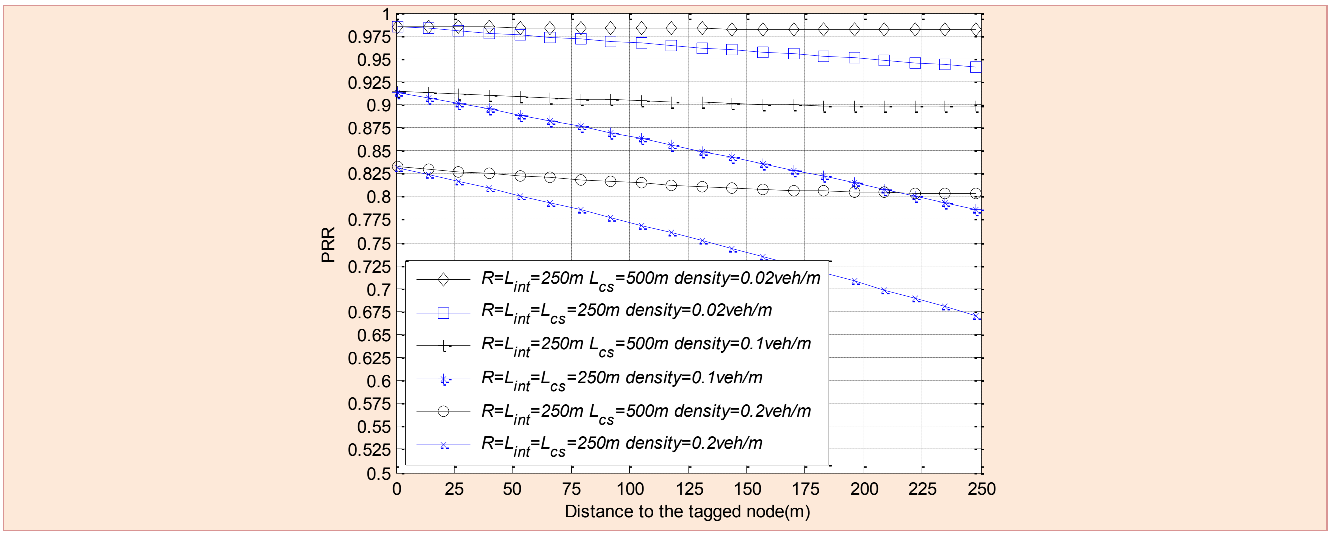

Figure 10. The PRR in 2-D scenario at an intersection in this paper

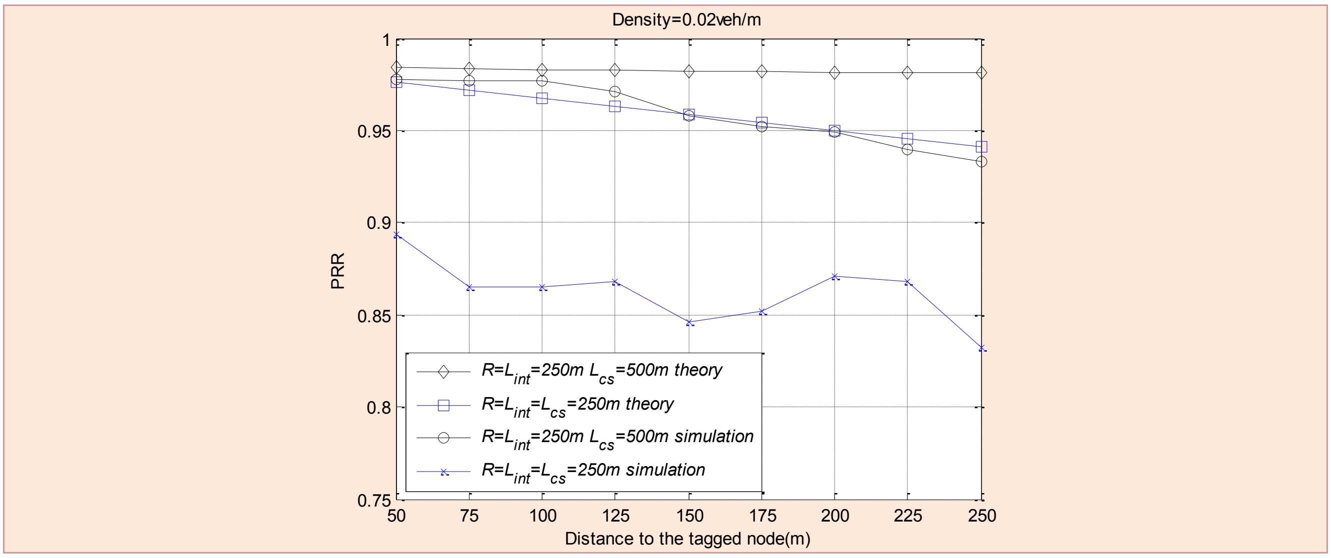

Figure 11. PRR(d) of one hop broadcast at an intersection with density is 0.02veh/m

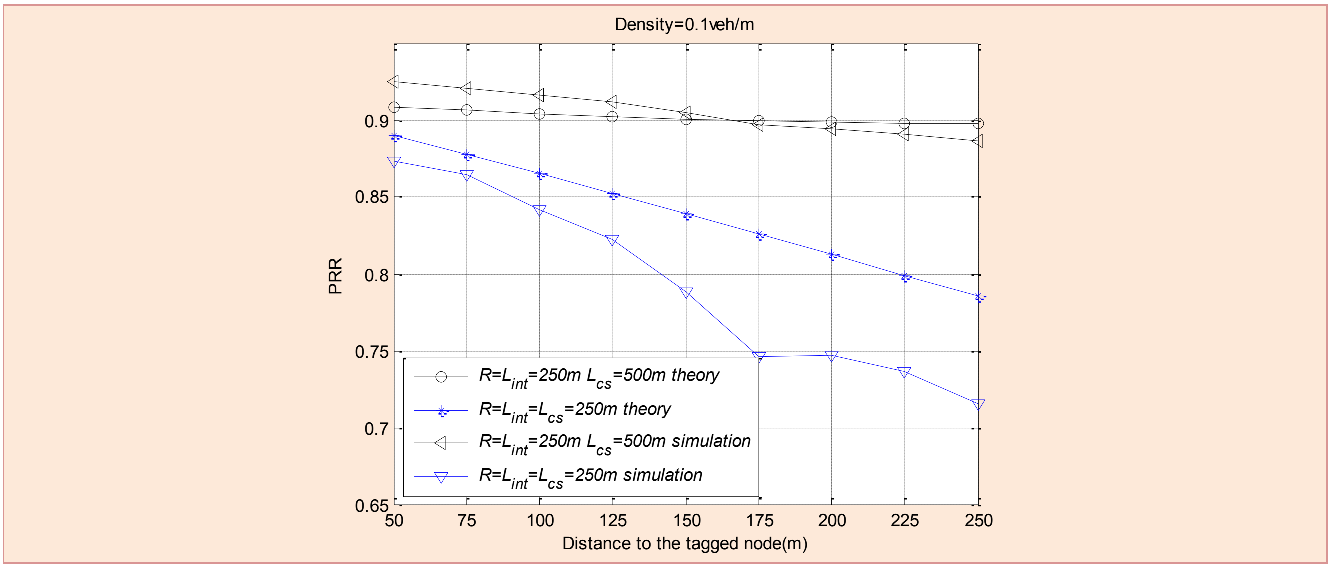

Figure 12. PRR(d)of one hop broadcast at an intersection with density is 0.1veh/m

Conclusion

In this paper, we have derived the expressions of the PRRs for one-hop broadcast of the tagged node at an intersection. The numerical analysis and simulation results offer the following conclusions can be drawn: (1) The broadcast reliability worsens when the receivers' distance to the tagged node (the sender which broadcasts at the intersection) increases. (2) Increasing carrier-sensing range and back-off window can enhance the broadcast reliability. And (3) Choosing nodes near the sender to relay information can improve the reliability of routing for multi-hop broadcast.

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Enzhan Zhang is a Ph.D candidate supervised by Dr. Kuang at the School of Communication and Information Engineering, University of Electronic Science and Technology of China (UESTC). His research topics include Vehicle to vehicle communications (V2V) and Vehicle positioning techniques.

Yujun Kuang, IEEE and IEICE member, is a full-time Professor at the School of Communication and Information Engineering, University of Electronic Science and Technology of China (UESTC) and a Researcher at Mobilelink Laboratory. His research topics include Signal processing in wireless communication, Cooperative communications, Mobility management, Vehicle to vehicle communications (V2V), Intelligent traffic control systems, etc.

Jerry John Kponyo is a Ph.D candidate supervised by Dr. Kuang at the School of Communication and Information Engineering, University of Electronic Science and Technology of China (UESTC). His research topics include wireless communications.