

Efficient CSMA/CA Packet Relay-Assisted Scheme with Payload Combining for ITS V2V Communication

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Abstract: CSMA/CA (Carrier Sense Multiple Access with Collision Avoidance) based relay-assisted V2V scheme is effective in compensating shadowing loss and hence improves performance of ITS V2V communications, especially for non-line-of-sight (NLOS) areas such as intersections. However, when the number of vehicle stations becomes large, packet congestion happens frequently at the relay station (RS). It causes interruption of packet relaying transmission and limits the improvement by the scheme. This paper proposes a packet payload combining relay (PCRL) scheme to alleviate the congestion issue at RS by compressing packet overheads of broadcast packets. With adaptive modulation and coding technique at RS, PCRL can further mitigate the packet interruption by reducing the air time of relayed packets. Time division grouping method is also applied to PCRL to mitigate the hidden terminal problem at intersections. Analyzed and simulated results show that the proposed schemes can effectively mitigate packet congestion issue and improve the reliability of the V2V communication.

Keywords: ITS, CSMA/CA, relay, payload combining, 16QAM

1. Introduction

Wireless vehicular communications for Intelligent Transport Systems (ITS) have the potential to enable safety driving and enhance automated driving systems. Vehicle-to-vehicle (V2V) communication, vehicle-to-infrastructure (V2I) communication and vehicle-to-pedestrian (V2P) communication have been regarded as promising solutions to achieve the goals [1].

The IEEE 802.11p is a well-known PHY/MAC standard for ITS V2V communications [2]. The effectiveness of this technology highly depends on the reliability of broadcast communications in vehicular environments. In general, the reliability of wireless communications is severely affected by distance dependent path loss, shadowing, and fast fading caused by multipath propagation, as well as hidden terminal (HT). Especially, packet delivery rate (PDR) of V2V communication severely decreases under non-line-of-sight (NLOS) environments such as intersections. Buildings around corners not only reduce the range of V2V communications but also cause HT problems and make it difficult to achieve high reliability.

A packet relay-assisted V2V scheme using CSMA/CA (Carrier Sense Multiple Access with Collision Avoidance) was proposed [3] as a solution to improve the reliability in NLOS environments. In the scheme, a relay station (RS) that has line-of-sight (LOS) links to two communicating VSs assists the communication. By compensating the large path loss and obtaining the path diversity effect, the PDR improves. Its effectiveness has

been shown in previous works by theoretical analysis and simulations [4], [5].

However, as the number of vehicle stations (VSs) increases, the number of need-to-be transmitted packets at RS also increases. This poses an issue that is not obvious when traffic is low. It takes RS longer time to contend for its transmission under high traffic conditions, hence the number of awaiting packets in the transmit queue at RS increases. Since the queue size is limited and each packet has its delay requirement, the packets may need to be dropped. If the packet drop happens, the relay-assisted scheme cannot improve the PDR. Therefore, the potential improvement brought by RS cannot be fully obtained as investigated in Ref. [5]. Thus, it is necessary to avoid the packet congestion at RS.

There are many studies about the performance of CSMA/CA MAC protocol under high traffic conditions. The authors in Ref. [6] proposed an adaptive contention window mechanism, which dynamically selects the optimal back-off window according to the estimate of the number of contending stations. Another approach is dynamic optimization on range (DOOR) [7] method which was proposed to improve the whole system performance by partitioning the number of stations into many sub-ranges and calculating the optimal parameters for each sub-range. Although the proposals dynamically adjust the parameters of CSMA/CA, they don't intend to decrease the packet drop due to congestion.

For unicast duplex communication, network coding (NC) [8], [9] is considered as a solution to reduce air traffic by relay. The principle of NC is to mix two data at an intermediate network node and multicast it to both senders. The senders receive the encoded packets and extract the messages that were originally intended to be received. Regarding vehicular safety communication (VSC) system, a retransmission scheme using NC was

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proposed [10] to improve the PDR of V2V communication. In the scheme, m native V2V packets are encoded with exclusive-or (XOR) operation and the encoded packet is used for retransmission. However, retransmission increases air traffic and is not effective when the number of VVs is large.

In order to mitigate the packet congestion at RS, the authors have recently proposed a packet payload combining relay (PCRL) scheme [11]. In the proposed scheme, a packet with the payload combined from multiple V2V packet payloads is rebroadcasted once the channel becomes idle. Since multiple V2V packet payloads can be forwarded in one transmission opportunity, the number of awaiting packets in the transmit queue decreases and hence the packet transmission rate at RS increases. In Ref. [11], performance of the proposed PCRL scheme has been elucidated by computer simulations under an intersection environment. However, the potential benefit of the proposed scheme has not been well analyzed yet.

This paper aims to theoretically analyze the packet transmission rate at RS by modeling the backoff process at RS as a Markov chain and using the signal transfer function of the generalized state transition diagram, and proposes an adaptive modulation PCRL scheme to further improve the relaying performance. Moreover, a time division grouping method is introduced to the PCRL scheme for mitigating the HT problem. From analysis and computer simulation results, we confirm that the PCRL scheme can effectively mitigate the packet congestion and remarkably increase the packet transmission rate at RS. As a result, the reliability of V2V communication improves.

The rest of this paper is organized as follows. Section 2 describes the proposed PCRL scheme. Section 3 presents the model for the analysis of packet transmission rate at RS. The performance of the proposed combining scheme is discussed in Section 4. Finally, Section 5 concludes the paper.

2. Packet Combining Relay (PCRL) Scheme

2.1 Packet Relay-Assisted V2V Scheme

Figure 1 shows the model of the relay-assisted V2V scheme considered in this paper. The transmitting VS (T-VS) periodically broadcasts its data packet with a transmission interval T_f following CSMA/CA mechanism. Since the receiving VS (R-VS) can receive the packet via direct and/or relay path, path diversity gain can be obtained. PDR of the relay-assisted V2V scheme PDR_{RA} can be calculated as

$$PDR_{RA} = p_{T,R} + (1 - p_{T,R}) \cdot q_{T,RS} \cdot \xi_{RS} \cdot q_{RS,R}, \quad (1)$$

where $p_{T,R}$ is the PDR from T-VS to R-VS via the direct path. $q_{T,RS}$ and $q_{RS,R}$ are the packet reception rate (PRR) at RS from T-VS and that at R-VS from RS, respectively. ξ_{RS} is the packet transmission rate at RS. Since RS is installed at a high position at intersection enabling LOS propagation to VVs, the propagation loss between RS and T-VS/R-VS is small, then $q_{T,RS}$ and $q_{RS,R}$ are high. If T-VS and R-VS are in the relation of NLOS, the first term of right hand side in Eq. (1) is quite low. In the relay-assisted V2V scheme, the diversity gain increases the PDR. However, packet congestion occurs at the RS under high traffic conditions, resulting in large number of awaiting packets in the transmit queue. A

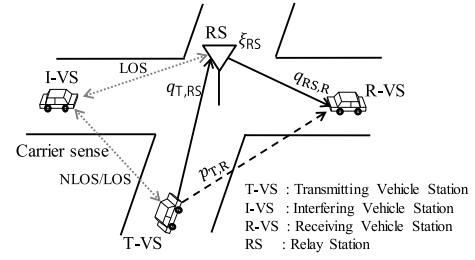


Fig. 1 Packet relay-assisted V2V model.

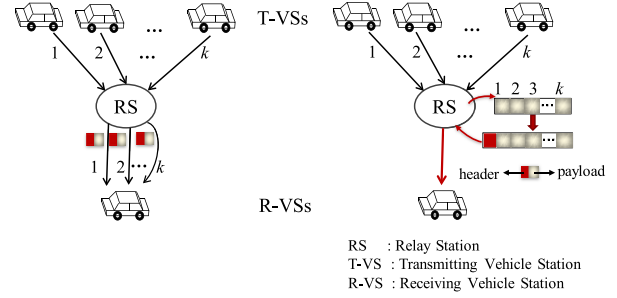


Fig. 2 Packet relay-assisted V2V schemes.

packet older than its predetermined lifetime will be dropped. If packet drop happens, ξ_{RS} decreases and hence the gain of RS cannot be achieved as expected. For example, if $\xi_{RS} \approx 0$, the PDR of relay-assisted scheme is close to that of the direct V2V system, i.e., $PDR_{RA} \approx p_{T,R}$. This means the benefit of introducing RS vanishes. Therefore, it is necessary to increase ξ_{RS} .

2.2 Principle of Packet Payload Combining Relay

Hereafter we assume the IEEE 802.11p based relay-assisted V2V broadcast communication. A V2V packet sent by a T-VS is received by RS as a layer 3 packet and then forwarded to other VVs.

Figure 2 shows the relay-assisted V2V schemes. Normal relay (RL) scheme in Fig. 2 (a) forwards all received V2V packets individually. Once the channel becomes idle, RL scheme forwards one V2V packet. Since RS is not permitted to continuously transmit even if it has a packet in the transmit queue, RS needs to contend for the channel again. The scheme is thus not effective under high traffic conditions which result in the large contention delay. Moreover, the payload size for vehicular safety application is as small as 100 bytes, and the overhead time ratio in each packet is large. For example, the overhead time ratios for 100 bytes payload [12] are 49% and 56% if the IEEE 802.11p physical layer of 6 Mbps QPSK and 12 Mbps 16QAM are employed, respectively. Consequently, the normal relay scheme is not efficient in the sense of air time resource utilization.

The PCRL scheme in Fig. 2 (b) creates a packet with the payload that has been combined from k V2V packet payloads and forwards it once the channel becomes idle. This reduces the number of awaiting packets in the transmit queue, hence increases ξ_{RS} . As a result, the relaying gain is improved.

The number of payload combining k dynamically changes according to the traffic volume on the roads considering the restrictions on packet size and waiting time. When the k counts up to

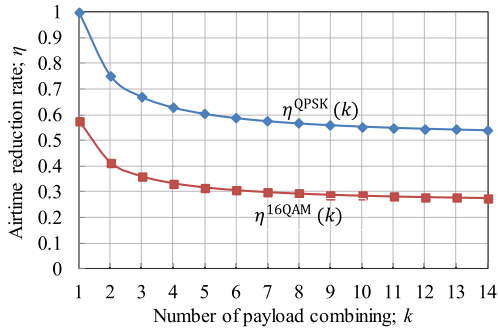


Fig. 3 Relationship between η and k .

a predetermined number K , a new combined packet with K payloads is created and sent immediately. K is called the *maximum number of payload combining*. The number K is limited by the maximum payload size of a V2V packet, which is determined by the IEEE 1609 specification [13]. It specifies that the maximum payload length of an IEEE 802.11p frame is 1,400 bytes. Considering vehicle safety applications, the normal V2V payload size is 100 bytes [12]. Then K is equal to 14. However, when traffic is low, time for waiting K packets may be longer than transmission interval. In V2V communication for safety application, each VS broadcasts its packet every transmission interval T_f of 100 ms [12]. The maximum waiting time for packet combining should not exceed T_f . From this view point, the *maximum allowable waiting time* T_{\max} should be introduced, i.e., $T_{\max} = \varepsilon T_f$ ($\varepsilon \ll 1$). If the predetermined waiting time T_{\max} counts up before the number of V2V packets reaches K , a packet with the payload combined from less than K V2V payloads is rebroadcasted.

2.3 Analysis of Airtime Reduction

Now we analyze the improvement in airtime reduction by replacing RL scheme with PCRL scheme. Let T_{oh} and T_d denote the lengths of overhead and data payload of a normal relayed packet, respectively. By sending k packets individually, the total time for relay transmission is $k(T_{\text{oh}} + T_d)$. In the proposed PCRL scheme, transmission time for the combined packet is reduced to $(T_{\text{oh}} + kT_d)$. Here, we assume that the T_{oh} keeps the same because the overhead parts of broadcast packets do not include any individual addresses of sender VSs. We then define the airtime reduction rate $\eta(k)$ as the following equation

$$\eta(k) = \frac{T_{\text{oh}} + kT_d}{k(T_{\text{oh}} + T_d)} = \frac{T_{\text{oh}}/T_d + k}{k(T_{\text{oh}}/T_d + 1)}. \quad (2)$$

Smaller $\eta(k)$ means larger air traffic reduction.

The value of $\eta(k)$ depends on the ratio of T_{oh} to T_d . T_{oh} and T_d depend on the data transmission rate employed at RS. Figure 3 shows the relationship between $\eta(k)$ and the number of payload combining k . Two cases of modulation/data rate: QPSK/6 Mbps and 16QAM/12 Mbps for PCRL are compared with QPSK/6 Mbps RL. The airtime reduction rate $\eta^{\text{16QAM}}(k)$ for PCRL using 16QAM/12 Mbps is calculated as the following equation

$$\eta^{\text{16QAM}}(k) = \frac{T_{\text{oh}}^{\text{16QAM}} + kT_d^{\text{16QAM}}}{k(T_{\text{oh}} + T_d)}. \quad (3)$$

As shown in the figure, PCRL scheme using 16QAM/12 Mbps

(16QAM-PCRL) for relaying transmission has smaller airtime reduction rate than PCRL scheme using QPSK/6 Mbps (QPSK-PCRL), which means that 16QAM-PCRL scheme is better in the sense of airtime reduction. Since we set the waiting time T_{\max} , the average of k is close to K for high traffic condition and smaller than that for low traffic condition.

2.4 Packet Combining Relay Scheme with Adaptive Modulation and Coding

For V2V communication, QPSK modulation with data rate of 6 Mbps has been employed considering communication range and safety message sizes [14]. In the PCRL relaying transmission, however, higher level modulation such as 16QAM provides smaller airtime reduction rate and results in saving air traffic for relay. This may increase the chance of packet transmission at the RS and further mitigate the packet congestion issue. On the other hand, high level modulation requires higher received power and SINR, which may deteriorate the performance of PCRL.

Thus, there exists a trade-off between the air time reduction and the communication quality. That means it is necessary to automatically select the modulation scheme based on the actual air traffic. Therefore, we propose to introduce an adaptive modulation and coding (AMC) scheme for RS transmission. The AMC is controlled by RS that can monitor the air traffic volume as the number of received packets. By setting a proper threshold for the observed air traffic volume during the transmission interval (100 ms), RS can choose QPSK/6 Mbps for low traffic and 16QAM/12 Mbps for high traffic. This scheme is hereafter called AMC-PCRL, in contrast to the basic scheme, QPSK-PCRL. The airtime reduction rate of QPSK-PCRL scheme is 0.54 for large k , whereas that of AMC-PCRL scheme is 0.28. Under the same traffic condition, the proposed AMC-PCRL can improve the packet transmission rate at RS.

2.5 Time Division Grouping (TDG) Method

In general, contention issue is solved by carrier sense (CS) and the back-off mechanism. However, CS is not always perfect in vehicular environments. The propagation on urban streets is known as multipath environment, which causes fading and unstable received signal power. Also, propagation loss for NLOS communication is very large due to diffraction by corner buildings. Thus, VSs that cannot sense each other will be in the situation of HT. As a result, the PRR at RS $q_{\text{T,RS}}$ may be degraded.

In order to alleviate the HT problem, a time division grouping (TDG) method has been proposed [15]. In the method, the grouping of vehicles is performed based on their locations on the road. This avoids the packet collision among the VSs in HT relationship. There are two kinds of grouping method proposed, namely direction-based linear grouping and radius-based circular grouping. In this paper, we propose to combine PCRL and TDG method with linear grouping. In the employed linear grouping method, all VSs are divided into four groups by the streets as shown in Fig. 4. Each group is assigned to a dedicated transmission time period that doesn't overlap with others. The RS broadcasts grouping information to let VS distinguish its group association from its location. This enables a moving VS to switch

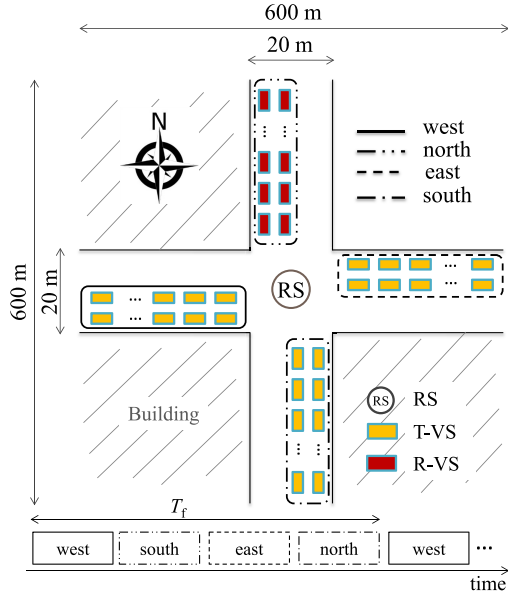


Fig. 4 An example of linear TDG with four groups [15].

from one group to another according to its location obtained by GPS. The TDG method mitigates HT problem then improves the probability $q_{T,RS}$. Combination of PCRL and TDG improves the PRR and the packet transmission rate at RS, increases the gain of relay-assist and thus improves reliability of V2V communication.

3. Analysis Model

In order to analyze the packet transmission rate at RS for the proposed scheme, we first present an approximate probability distribution of MAC layer service time of RS by modeling the back-off process as a Markov chain and using the signal transfer function of the generalized state transition diagram. Then the mean value of MAC layer service time is calculated. After that, the packet transmission rate at RS for the proposed PCRL scheme is derived.

3.1 MAC Layer Service Time of RS

The MAC layer service time (or MAC service time for short) is the time interval from the time instant that a packet becomes the head of the queue and starts to contend for transmission, to the time instant that the packet has been transmitted. The distribution of the MAC service time is a discrete probability distribution because the smallest time unit of the backoff timer is a time slot δ . Let T_s be the non-negative random variable of MAC service time, which has a discrete probability of p_i for T_s being T_i . The probability generating function (PGF) of T_s is given by

$$P_s(z) = \sum_{i=0}^{\infty} p_i z^{T_i}, \quad (4)$$

and completely characterizes the discrete probability distribution of T_s . From Eq. (4), we have two important properties of PGF as follows:

$$\begin{cases} P_s(1) = 1 \\ E[T_s] = P'_s(1) \end{cases}, \quad (5)$$

where $E[x]$ denotes the expectation value of x .

We will apply the generalized state transition diagram to derive

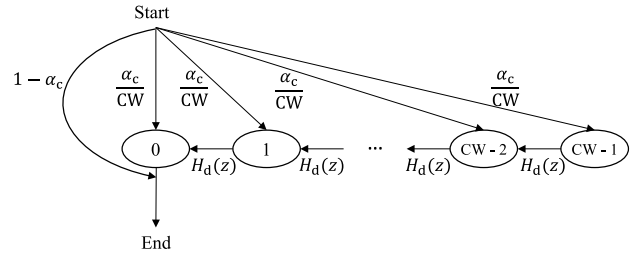


Fig. 5 Generalized state transition diagram for transmission process.

$P_s(z)$. Let α_c be the channel-in-use time ratio at RS, which is the ratio of time that the RS senses the channel as busy due to the transmissions of VSs. The expression of α_c will be derived later. The transmissions include collision-free process that takes time T_p for a V2V packet plus DIFS, and collision process that takes time T_{col} , a random variable representing the period the channel is sensed as busy at the RS when packet collision happens. The RS will start its transmission immediately if the channel is sensed as idle. The probability is $(1 - \alpha_c)$. On the other hand, when the backoff process is evoked due to busy channel, the backoff timer has the probability of $(1 - \alpha_c)$ to decrement by one after a slot time δ , the probability of α_{col} to stay at the current state during T_{col} plus DIFS, and the probability of $(\alpha_c - \alpha_{col})$ to stay at the current state during T_p plus DIFS. The expression of channel-in-use time ratio due to collision process, α_{col} , is derived later. So the decrement process of backoff timer is a Markov process. The signal transfer function of its generalized state transition diagram is expressed as Ref. [16].

$$H_d(z) = \frac{(1 - \alpha_c)z^\delta}{1 - \alpha_{col}z^{\bar{T}_{col}+DIFS} - (\alpha_c - \alpha_{col})z^{T_p+DIFS}}, \quad (6)$$

where \bar{T}_{col} is the mean value of T_{col} . The generalized state transition diagram for transmission process at RS is shown in Fig. 5. From the figure, we can derive the $P_s(z)$ as

$$P_s(z) = (1 - \alpha_c)z^{T_p} + \frac{\alpha_c}{CW} \cdot z^{T_p} \cdot \sum_{i=0}^{CW-1} [H_d(z)]^i, \quad (7)$$

where CW is the contention window size and $T_p = T_{oh} + \bar{k}T_d$ is the length of a relayed packet. Here, \bar{k} is the expected value of k . For RL scheme, \bar{k} is 1. To calculate \bar{k} for PCRL scheme, we model the packet arrival process at RS as a Gaussian process with the mean of μ arrivals during T_f and the variance of σ^2 by using continuity correction [17]. In Section 4, we will confirm the validity of this model by computer simulations.

Given the first packet that has already arrived at the transmit queue, the probability that there are n packets arriving at RS during T_{max} is calculated as

$$p(n) = \int_{n-0.5}^{n+0.5} \frac{1}{\sqrt{2\pi} \frac{T_{max}}{T_f} \sigma} \exp \left\{ -\frac{(x - \frac{T_{max}}{T_f} \mu)^2}{2 \left(\frac{T_{max}}{T_f} \sigma \right)^2} \right\} dx. \quad (8)$$

The \bar{k} for PCRL scheme is calculated as

$$\bar{k} = \sum_{n=0}^{K-2} (n+1) \cdot p(n) + \sum_{n=K-1}^{\infty} K \cdot p(n). \quad (9)$$

The first term indicates the situations when the number of packets arriving at RS does not reach K but the waiting time of the

first packet reaches T_{\max} . The second term indicates the situation when the number of awaiting packets in the transmit queue reaches K before the waiting time of the first packet reaches T_{\max} .

The expectation of MAC service time is given as

$$E[T_s] = P'_s(1) = T_p^r + \alpha_c T_{bo}, \quad (10)$$

where T_{bo} is the average time period for the backoff process and is expressed as

$$T_{bo} = \frac{CW - 1}{2} \times \left\{ \delta + \frac{\alpha_{col}(\bar{T}_{col} + \text{DIFS}) + (\alpha_c - \alpha_{col})(T_p + \text{DIFS})}{1 - \alpha_c} \right\}. \quad (11)$$

Obviously, T_{bo} does not depend on relaying scheme employed at RS. Some other observations can be obtained from the expression of T_{bo} . When $\alpha_c = 0$ (and thus $\alpha_{col} = 0$), T_{bo} is equal to $(CW - 1)\delta/2$. This is the average backoff time in case that the channel is clear after the backoff procedure is evoked until the timer reaches zero. When $\alpha_c \rightarrow 1$, T_{bo} converges to the infinity. It means that the channel is saturated and RS cannot transmit any packet.

In order to obtain the average time period for the backoff process T_{bo} , we need to derive α_c and α_{col} . Let N_{CS} be the number of VSs in the carrier-sensing range of RS. Knowing that the channel is sensed busy at RS if there is at least one of N_{CS} VSs transmitting its packet, the expression of α_c (the channel-in-use time ratio at RS) can be basically derived as

$$\alpha_c = 1 - \left(1 - \frac{T_p + \text{DIFS}}{T_f}\right)^{N_{CS}}. \quad (12)$$

To calculate α_{col} (channel-in-use time ratio due to collision process), we make an assumption that at most two packets collide at RS [5]. This results in the maximum T_{col} to be $2T_p$, which gives the average value \bar{T}_{col} of $3T_p/2$. We focus on a T-VS in the sensing range of RS that is transmitting a packet. If there is another VS in the range that fails to sense the transmission of T-VS of interest, RS will sense the channel as busy due to collision process (contrary to collision-free process). Let N_{HT} be the number of HTs on the sensing range of RS. The expression of α_{col} can be derived as

$$\alpha_{col} = \alpha_c N_{HT} \left(\frac{2T_p + \text{DIFS}}{T_f} \right) \left(1 - \frac{2T_p + \text{DIFS}}{T_f} \right)^{N_{HT}-1}. \quad (13)$$

3.2 Expression of Packet Transmission Rate at RS

We consider the packet lifetime of relay packets equal to T_f . Assuming that each relay transmission is independent on the previous transmission at RS. It means that RS has the same opportunity to transmit every relayed packet. By using the MAC service time, we can calculate the maximum number of relayed packets that RS can transmit in a transmission interval T_f as

$$n_t^i = \left\lfloor \frac{(1 - \alpha_c)T_f}{E[T_s^i]} \right\rfloor, \quad (14)$$

where T_s^i with $i \in \{\text{RL}, \text{PCRL}\}$ is the MAC service time of RS. $\lfloor x \rfloor$ is the largest integer less than or equal to x .

Then, the packet transmission rate at RS for PCRL scheme is

expressed as

$$\xi_{RS}^{\text{PCRL}} = \begin{cases} \bar{k} \cdot n_t^{\text{PCRL}} / \lambda, & \text{for } \lambda > \bar{k} \cdot n_t^{\text{PCRL}} \\ 1, & \text{otherwise.} \end{cases} \quad (15)$$

Note that the arrival rate λ is also the average number of V2V packets that RS receives in a T_f and basically does not depend on the packet forwarding scheme employed at RS. The packet transmission rate at RS for RL scheme can be similarly calculated as Eq. (15) by substituting n_t^{PCRL} and \bar{k} by n_t^{RL} and 1, respectively. It can be seen that the packet drop happens when λ exceeds $\bar{k} \cdot n_t^{\text{PCRL}}$ and n_t^{RL} for PCRL and RL schemes, respectively. The proposed PCRL scheme sends \bar{k} V2V data payloads in a transmission opportunity, and thus can accommodate larger λ .

4. Numerical Results

4.1 Vehicle Stations Layout and Evaluation Parameters

In order to validate the analysis model and evaluate performance of the proposed scheme for various traffic conditions, computer simulations using the Scenargie network simulator [18] were conducted. The vehicle stations layout is shown in Fig. 4. Each street of the crossroads has 20 m width and 600 m length. One RS is placed at the center of the intersection. The total number of VSs M is varied from 50 to 300, and all VSs are equally divided into four groups on the streets (we call them north group, west group, south group and east group, respectively). Each street group spreads between 20 m and 300 m from center of the intersection and VSs in each group are uniformly distributed. For example, if M is 200, all VSs in each group are placed on two lanes with 25 VSs per lane, as illustrated in Fig. 4. Each VS independently generates packets and then broadcasts them to other VSs by CSMA/CA.

In this paper, we consider the balanced vehicle distribution among the streets. However, we may encounter the cases where the vehicle distribution is unbalanced in the practical scenarios. For example, let us consider a scenario when the number of VSs on a certain street (e.g., north street) is much larger than those on the other streets. Since carrier-sensing within a street group may succeed with high probability, the opportunity for a T-VS to get channel access becomes lower, especially when traffic is high. However, from the viewpoint of an R-VS and RS, the collision probability becomes lower due to the successful carrier-sensing among T-VSs in the street groups. This may result in either higher or lower PDR of the direct V2V communication depending on the number of VSs. This phenomenon happens irrespective of the use of RS. For packet relay transmission, the opportunity for RS to obtain channel access also becomes lower than that in an uniform vehicle distribution. However, even in such a situation, PCRL can efficiently utilize limited chance of channel access. Therefore, PCRL can still improve the PDR performance of V2V communications irrespective of vehicle distribution.

The radio transmission parameters and V2V traffic conditions are shown in **Table 1** and **Table 2**, respectively. The 700 MHz frequency band is employed because of its low diffraction loss and propagation loss [19]. The propagation environment is represented by both LOS and NLOS propagation loss models that take into account shadowing for NLOS caused by buildings around

Table 1 Radio transmission parameters.

Frequency (Bandwidth)	700 MHz (10 MHz)	
Tx power	18 dBm	
Propagation model	ITU-R P.1411-6 LOS + Rayleigh fading	
Access protocol	IEEE 802.11p (CSMA/CA)	
Data rate/Modulation	V to V, V to RS	RS to V
	6 Mbps/QPSK	12Mbps/16QAM
CINR threshold	10 dB	15 dB
Packet length (100 byte payload)	264 μ s	152 μ s
Carrier sense threshold	-82 dBm	
Receiver noise figure	11.8 dB	
Contention window size	64	
VS antenna Height/gain	1.5 m/0 dBi	
RS antenna height/gain	6 m/0 dBi	

Table 2 V2V traffic conditions.

Packet Type	UDP broadcast packet
Packet Payload Size	100 byte
Packet Generation Interval: T_f	100 ms

intersection. Rayleigh fading is used as fading model.

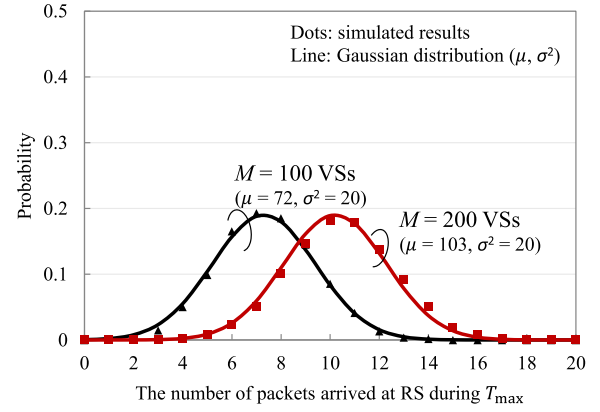
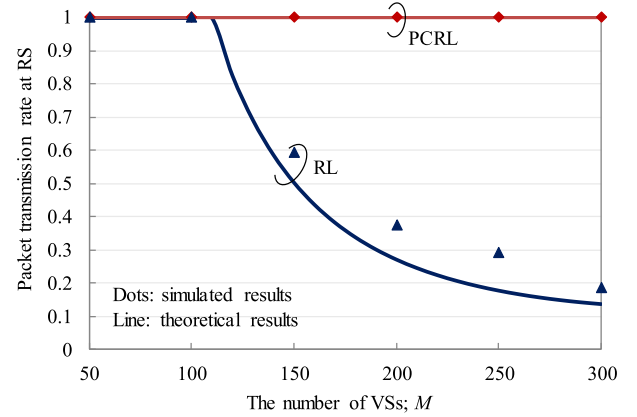
We focus on the R-VSs on the north street for evaluation. Since the layout of the VSs and RS is rotation symmetric by 90 degrees and its multiples, this condition does not lose generality. On the contrary, this condition lets us know what combination of the transmitting and receiving vehicles has good or bad performance. For performance evaluation, we adopt a general quality measure of average broadcast packet delivery rate (BPDR) as the performance metric to provide a general view about performance of the proposed schemes. The BPDR is calculated for a T-VS to the evaluated R-VSs on the north street, and then the average BPDR is obtained by averaging in location of the T-VS. More details about the impact of the location of R-VS on the performance of PDR is out of the scope of this paper and is left as a future study.

4.2 Packet Arrival Process at RS

Figure 6 shows packet arrival probability at RS for $T_{\max} = 10$ ms. We consider two traffic conditions of $M = 100$ and $M = 200$. The solid lines are calculated from the Gaussian distribution given in Eq. (8) with the mean μ of 72 and 103 arrivals for the M of 100 and 200 vehicles, respectively. The variance σ^2 is 20, which is obtained by least square algorithm to match with the simulated results. Figure 6 clearly shows that the Gaussian distributions well agree with the simulated ones. Thus, we conclude that the packet arrival process at RS can be modeled as a Gaussian process and hence it is used in the following evaluations.

4.3 Packet Transmission Rate at RS

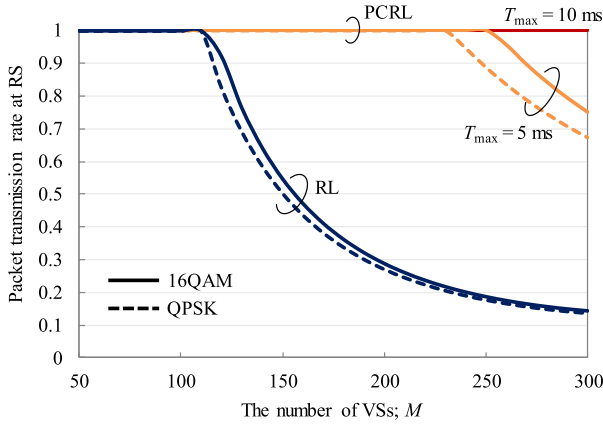
Figure 7 shows the theoretical and simulated results of the packet transmission rate at RS for PCRL and RL schemes. For PCRL scheme, T_{\max} is set to 10 ms. To calculate the theoretical values from Eq. (15), we use the Gaussian process with the mean

**Fig. 6** Packet arrival process at RS ($T_{\max} = 10$ ms).**Fig. 7** Packet transmission rate at RS ($T_{\max} = 10$ ms).

μ obtained from simulations and the variance σ^2 of 20. In order to calculate α_{col} in Eq. (13), we assume that VSs on different streets become HT to each other due to large propagation loss among them. As a result, N_{HT} is assumed to be equal to $3M/4$.

It can be seen from the figure that the theoretical and simulated results well agree with each other for the proposed PCRL. For RL scheme, the theoretical and simulated results agree only when M is less than or equal to 100. Although the theoretical result does not agree well with the simulated one when M is larger than or equal to 150, it describes well the declining trend of the packet transmission rate at RS. It is observed that packet drop appears for RL scheme when M is 150, and it becomes severer as M becomes larger. It decreases to less than 20% when M is 300. On the other hand, the transmission rate for the proposed PCRL scheme is 100% regardless of M . This comes from the effect of the proposed PCRL in mitigating congestion issue at RS.

Figure 8 shows the impact of T_{\max} and the modulation schemes on the packet transmission rate at RS. The value of T_{\max} is set either 5 ms or 10 ms. Packet transmission rate for RL scheme is also presented for reference. When $T_{\max} = 5$ ms, the packet transmission rate for QPSK-PCRL scheme keeps 100% until M is 230 and becomes lower for the larger M . The degradation is mitigated by employing 16QAM for relay transmission. When T_{\max} is set to 10 ms, the packet transmission rate at RS for both QPSK and 16QAM is 100% irrespective of M . Since the number of V2V payloads to be combined reaches the maximum number of K before T_{\max} counts up under high traffic conditions, the transmission rate keeps 100% for T_{\max} of 10 ms or greater. Therefore,

Fig. 8 Impact of T_{\max} and modulation scheme.

it is enough to set T_{\max} as 10 ms. It is only 10% of the transmission interval T_f that is the dominant cause of transmission delay. Hereafter we use T_{\max} of 10 ms in the evaluation.

4.4 Broadcast Packet Delivery Rate (BPDR)

For ITS safety application, V2V cumulative packet reception rate should satisfy 95% during a vehicle moves 10 m [21]. If vehicle speed is 70 km/h, there are at most 5.14 chances of the reception during the move. Then average packet reception ratio should keep more than 44.2%.

4.4.1 Effect of packet payload combining and 16QAM modulation

In order to evaluate the effect of packet payload combining and 16QAM modulation, average BPDRs of direct V2V communication without relaying (Without RL), RL and packet combining relay (QPSK-PCRL and 16QAM-PCRL) schemes were compared.

Figure 9 shows average BPDRs from T-VSSs on the west and east streets. Note that the T-VSSs are in NLOS conditions with the evaluated R-VSSs on the north street. Average BPDR of the non-relay system is less than 20%, which is caused by shadowing due to buildings at the corner. Addition of an RS around the intersection can effectively mitigate the shadowing issue and thus remarkably increases the BPDR. Performance of relay-assist is further improved by PCRL schemes. Especially, the improvement for large M is more significant, which comes from the effect in improving the packet transmission rate at the RS.

Figure 10 shows average BPDRs from T-VSSs on the south street. Average BPDRs of the relay-assisted V2V schemes are higher than that of the direct scheme. This proves that using RS can effectively compensate attenuation loss due to node distance. Same as on the west and east streets in Fig. 9, PCRL schemes further improve the relaying performance. However, BPDR of relaying schemes for the south street is higher than that of the west and east streets. The gain comes from the path diversity effect between direct and relayed paths. The diversity effect is further obtained by using 16QAM for relaying transmission. With 16QAM, the probability of packet collisions among V2V packets is lowered.

Note that the average BPDRs from T-VSSs on the north street are high for all V2V schemes because of the low propagation loss due to LOS condition between the T-VSSs and R-VSSs. Fig-

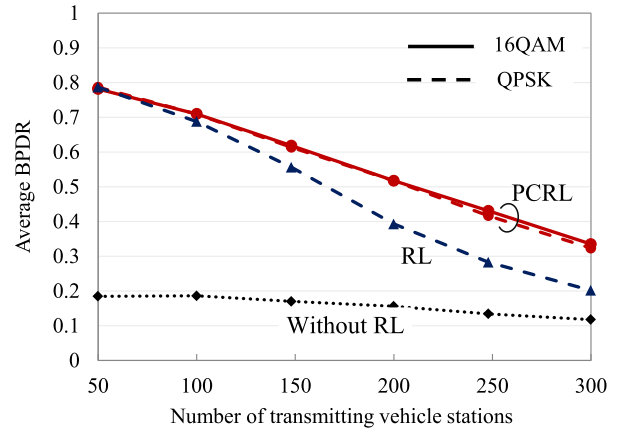


Fig. 9 Average BPDR from T-VSSs on east and west streets.

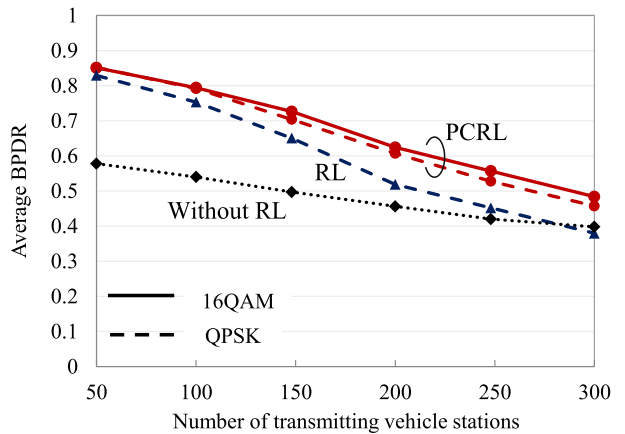


Fig. 10 Average BPDR from T-VSSs on south street.

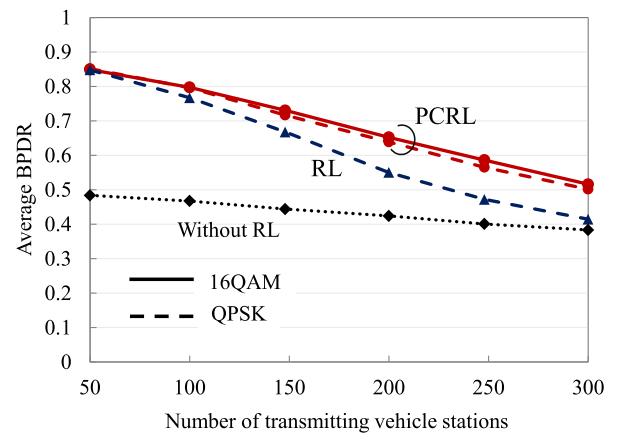


Fig. 11 Average BPDR from T-VSSs on all streets.

ure 11 shows average BPDRs from T-VSSs on all streets. In general, relay-assist improves performance of V2V communication. PCRL schemes further improve performance of relay-assist by mitigating the congestion issue, especially under high traffic conditions.

4.4.2 Improvement by combination of PCRL and TDG

Figure 12 shows average BPDRs of direct V2V communication, RL with and without TDG, and PCRL with TDG schemes for all streets. When M is small, Both RL and PCRL with TDG remarkably improve the average BPDRs. This is because the HT problem among different groups (streets) can be effectively alleviated by TDG. As M increases, the average BPDR of RL with

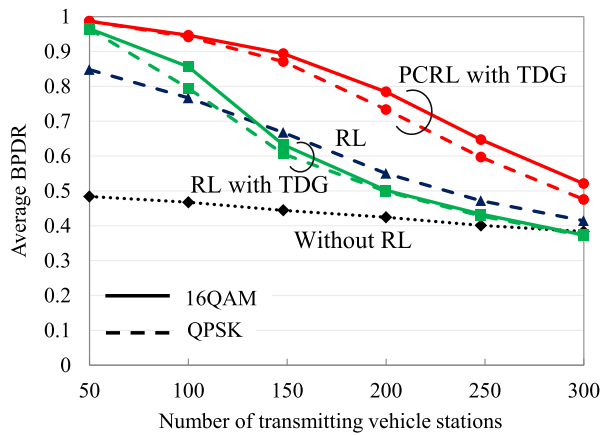


Fig. 12 Average BPDR from T-VSs on all streets with TDG.

TDG significantly degrades due to the packet congestion issue. On the other hand, PCRL with TDG scheme still provides large improvement over RL with TDG when M is large.

The improvement is more significant if 16QAM data modulation is adopted for the proposed PCRL-TDG. When M is larger than 100, average BPDR of 16QAM-PCRL with TDG becomes higher than that of QPSK-PCRL with TDG. Therefore, we consider $M = 100$ as the threshold to switch from QPSK modulation to 16QAM modulation. By converting $M = 100$ to the corresponding number of observed packets μ of 72 shown in Fig. 6, RS can choose the appropriate modulation scheme. AMC-PCRL with TDG scheme can provide the highest average BPDR performance regardless of M . When M is 300 or less, average BPDR of the scheme is 52% or higher. The proposed AMC-PCRL with TDG scheme can accommodate 300 VSs.

5. Conclusions

Reliability in ITS V2V communication is one of the most significant challenges for the deployment of V2V safety applications and the future automated driving system. Addition of a relay station (RS) at intersection improves the reliability of the system. On the other hand, packet congestion happens at the RS that decreases the packet transmission rate at RS and limits the relaying performance. This paper proposed a new payload combining relay scheme with adaptive modulation and coding at the RS to mitigate the congestion problem. The proposed scheme chooses either 6 Mbps QPSK or 12 Mbps 16QAM according to the measured traffic conditions. Analysis and simulated results show that the proposed packet combining relay scheme effectively mitigates packet congestion at RS and improves the reliability of V2V relay communication. Combination of the proposed scheme and a time division grouping method also improves the performance of relaying and can accommodate a number of vehicle stations up to 300 around intersection with higher reliability.

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