Performance Analysis on Access Collision in Semi-Persistent Scheduling of C-V2X Mode 4

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***Abstract*—For autonomous vehicles and smart transportation services, information exchange and fusion with low latency and high reliability is critical. The 3rd Generation Partnership Project has released the cellular vehicle-to-everything (C-V2X) Mode 4 to enable direct vehicle-to-vehicle communications regardless of the cellular coverage. Mode 4 uses the sensing-based semi-persistent resource scheduling (SPS) to support autonomous resource selection by vehicles. However, channel access collisions lead to packet losses, especially in crowded scenarios. Thus, an accurate analytical model is essential to quantify the system performance, reveal how to mitigate collision and ensure system reliability and scalability. This paper focuses on the analytical modeling of the SPS and derives the access collision ratio considering both the sensed and hidden terminals in V2X. Extended simulations are conducted to verify the correctness of the analytical framework. In addition, we investigate the impact of system parameters on performance, which provides important guidelines for improving the system configuration.**

***Index Terms*—C-V2X Mode 4, SPS, performance analysis.**

I. Introduction

Future intelligent transportation systems are anticipated to involve autonomous vehicles and various smart transportation services, where a wide range of information exchange and fusion with low latency and high reliability is critical. Recently, there have been increasing interests in the vehicle-to-everything (V2X) communications. With V2X communications, the vision of a vehicle can be improved beyond the range of equipped sensors as messages are exchanged between a vehicle and any entity that may affect or be affected by it [1]. Nevertheless, how to provide reliable and scalable communications for advanced V2X services is still an open issue [2].

Over the last decade, the Dedicated Short Range Communications has been regarded as an enabling radio technology for V2X communications [3]. On the other hand, the new cellular vehicle-to-everything (C-V2X) standard established by the 3rd Generation Partnership Project (3GPP) has shown to provide improved communication range and reliability for enhanced V2X services. Two new sidelink transmission modes have been introduced in C-V2X to enable direct V2X communications, which are the network-controlled mode (Mode 3) and the autonomous mode (Mode 4) [5]. Mode 4 uses the sensing-based semi-persistent scheduling (SPS) as its distributed media access control (MAC) protocol, which supports autonomous resource selection by vehicles for beacon broadcasting regardless of the cellular coverage. The main reason behind the choice is that SPS benefits cyclic transmissions of packets of constant size and with predictable resource requirements [6].

However, SPS encounters serious resource allocation conflict problems especially for broadcast/multicast when there is no feedback from the receivers [7], [8]. Despite that the 5G New Radio standardization aims to support more advanced vehicular applications, the proposed new autonomous mode, Mode 2 (a), is expected to be based on the same resource scheduling procedure of Mode 4. As a result, the MAC layer design poses a great threat to the reliability and scalability of the coming C-V2X networks.

To better deploy C-V2X Mode 4 in reality, there has been substantial work analyzing its performance, while much of this effort has focused on simulations [9]–[13]. For example, authors in [9] and [10] both introduced an open-source C-V2X simulator and investigated the impact of key SPS parameters on the scheduling performance. Similarly, a system-level simulation platform was set up in [11] and [12] to evaluate the transmission performance of C-V2X. A link-level event-based simulator was implemented in [13] using the ns-3 simulation environment.

In addition to simulations, analytical modeling is essential for C-V2X in terms of exploring how system parameters and network conditions influence performance. Motivated by this, increasing efforts have been devoted to C-V2X physical and MAC analysis in recent years [14]–[16]. Authors in [14] presented the average packet delivery ratio as a function of the distance between transmitter and receiver. They also investigated four different types of transmission errors in C-V2X Mode 4. A multi-dimensional Markov model was proposed in [15] to evaluate the MAC layer performance of C-V2X Mode 4, providing insights on the average delay, the collision probability, and the channel utilization in Mode 4. Nevertheless, most previous work either obtained the channel access collision probability by simplifying the MAC protocol or neglecting the influence of hidden terminals.

To overcome the above challenges, this paper develops an analytical model for studying access collision in the SPS scheme adopted by 5G New Radio. We derive the access

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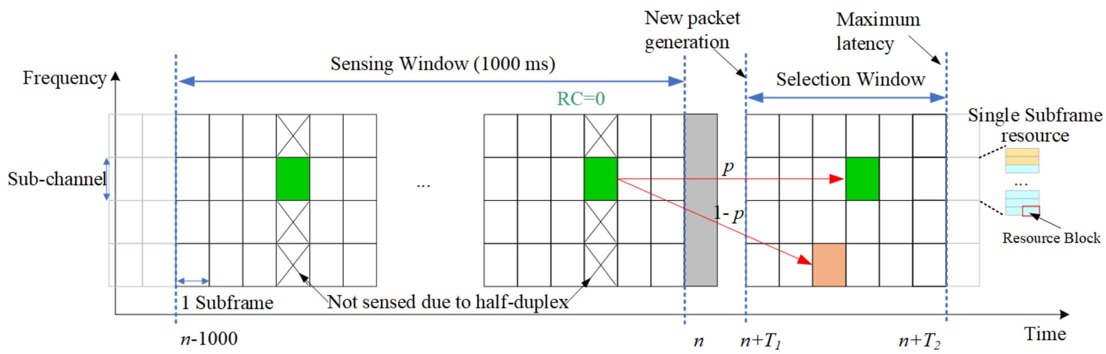

Fig. 1. Sensing-based semi-persistent scheduling scheme in C-V2X Mode 4.

collision probability of a vehicle under C-V2X Mode 4. Based on the analytical framework, the effect of physical and MAC configurations on the access collision ratio is analyzed. The contributions of this paper are summarized as follows

- We present an analytical model for the SPS scheme in C-V2X Mode 4. This model illustrates the relationship between the configuration parameters and the system performance in terms of access collision probability.
- Extensive simulations are conducted to verify the efficiency of the proposed analytical modeling. The reliability for different coverage range is also analyzed.
- Based on the verified analytical model, we further explore the impact of several key protocol parameters on the system performance. The results provide important guidelines for improving the system configuration.

The rest of this paper is organized as follows. Section II describes the system model and the PHY and MAC layers of C-V2X Mode 4. Section III provides the performance analysis. Section IV presents extensive simulation results to validate the analysis and evaluates the system performance with different configurations, followed by the concluding remarks in Section V.

II. System model and C-V2X

A. System model of vehicle-to-vehicle communications

We consider the scenario where connected vehicles exchange beacon messages on a bi-directional road. The vehicles are denoted by $\mathcal{V} = \{v_1, v_2, v_3, \dots, v_m\}$. Each vehicle needs to keep a safe distance from others through precise control on the throttle and brake. The transmit power is assumed the same for all vehicles and the maximum value is 23 dBm according to the LTE configuration.

The transmitter is denoted by v_i and the receiver is denoted by v_j. The distance between the transmitter v_i and receiver v_j is denoted by $d_{i,j}$. The transmit power of vehicle v_i is denoted by P_i^{t}. The received signal power of vehicle v_j, denoted by $P_{i,j}^r$, is a function of $d_{i,j}$, as follow

$$P_{i,j}^{\mathrm{r}} = P_i^{\mathrm{t}} K_0 d_{i,j}^{-\gamma}, \tag{1}$$

where K_0 is a constant that depends on the antenna characteristics and the average channel attenuation, and γ is the path-loss exponent.

For the transmitter v_i and receiver v_j, the signal to interference plus noise ratio of v_j can be represented by

$$SINR_{i,j} = \frac{P_{i,j}^{\mathrm{r}}}{\sum_{v_k \in \mathcal{V}_i, k \neq j} P_{k,j}^{\mathrm{r}} + N}, \tag{2}$$

where k is the vehicle index that accesses the same resources as v_i within the vehicle set $\mathcal{V}$. N is the noise power received by v_j. The beacon message can be delivered successfully only when the SINR is larger than a pre-given threshold $SINR_{\mathrm{TH}}$, i.e.,

$$SINR_{i,j} > SINR_{\mathrm{TH}}. \tag{3}$$

B. C-V2X PHY and MAC layers

C-V2X utilizes the Single Carrier-Frequency Division Multiple Access (SC-FDMA) at the PHY and MAC layers. 10 and 20 MHz channels are supported on the 5.9 GHz ITS band. The time-frequency domains are organized into orthogonal wireless resources, i.e., resource blocks (RBs). An RB is 180 kHz wide in frequency which contains 12 sub-carriers with an inter-spacing of 15 kHz. The time duration of each RB is 1 ms, corresponding to 14 OFDM symbols. Among them, 9 symbols are used to carry data, 4 symbols for channel estimation, and one for timing adjustments and possible transmitter-receiver switch.

The channel is divided into several sub-channels, and each sub-channel consists of a group of RBs in the same sub-frame which is 1 ms long. The sub-channels are used to transmit data and control information. To be specific, the data packet, also known as the transport blockis associated with the control message, denoted as sidelink control information.

To enable vehicles to autonomously select radio resources, the sensing-based SPS has been specified in Rel-14 as the distributed resource scheduling protocol for C-V2X Mode 4 by 3GPP. Fig. 1 illustrates the process of the sensing-based SPS. The resource selection/reselection of a vehicle at time n is based on the received data from other vehicles in the immediate past 1000 subframes ($= 1000$ ms), denoted as the sensing window. Through resource occupation estimation, the vehicle reserves sub-channels for a number of consecutive Reselection Counter (RC) packet transmissions. RC is randomly selected in a range $[C_1, C_2]$ according to the number of packets transmitted per second. The range can be set as $[5, 15]$, $[10, 30]$ and $[25, 75]$ when the beacon rate is 10 Hz, 20 Hz and 50 Hz, respectively. Once a packet is transmitted, the value of RC is decremented by one. When its value becomes zero, new resources will selected and reserved with probability $1 - p_0$ from the 20% least interfered resources within the selection window. The vehicle selects the same single-subframe resources for the next packet transmission with probability p_0.

III. Performance analysis on access collision

The transmit vehicle is denoted by v_i and the corresponding receiver is v_j. The interference vehicle is denoted by v_k, and it can be within or out of the sensing range of v_i. When v_k is out of the sensing range of v_i, it's regarded as a hidden terminal. For a transmitter-receiver pair (v_i, v_j), the probability of access collision is denoted by $P_{\text{c}}(d_{i,j})$.

The selection window size of v_i is $T = T_2 - T_1 + 1$ according to Section III. All vehicles are assumed to share the same sensing range, denoted by d_{sen}, which can be derived given the sensing power threshold P_{sen} as follow

$$d_{\text{sen}} = \left[\frac{P_i^{\text{t}} K_0}{P_{\text{sen}}}\right]^{1/\gamma}. \tag{4}$$

Suppose that all vehicles have the same transmit power, and we have $P_i^{\text{t}} = P^{\text{t}}$, where $i = 1, 2, ..., n$. Given the SINR threshold $SINR_{TH}$, the interference range from the receiver can be obtained as

$$d_{\text{int}} = \left[\frac{P^{\text{t}} K_0}{\frac{P^{\text{t}} K_0 d_{i,j}^{-\gamma}}{SINR_{\text{TH}}} - N}\right]^{1/\gamma}. \tag{5}$$

For the transmitter v_i, the value of RC is denoted by C, which is randomly selected from $[C_1, C_2]$. Thus, the expected resource counter equals to $(C_1 + C_2)/2$. The vehicle density is denoted by λ. For v_i, the vehicles within its sensing range is denoted by a set $\mathcal{V}_i^s$ and their total number is $N_{\text{s}} = \lambda d_{\text{sen}}$. Let N denote the total number of subchannels within one second in the system. The beacon rate of vehicles is $R\,[\text{s}^{-1}]$, and the transmission interval is $t_0 = 1/R$. Then the number of subchannels in each transmission interval is denoted by N_{subch}, which equals N/R. Let CBR denote the portion of subchannels whose RSSI exceeds a preconfigured threshold sensed by v_i. The number of resources in the candidate list is denoted by N_{rc}. As 20% least interfered resources are selected as resource candidates, $N_{\text{rc}} = N_{\text{subch}}/5$. According to the configuration in C-V2X Mode 4, we have $1 - CBR \geq 20\%$, thus $CBR \leq 80\%$.

For any vehicle, the probability that the value of RC decreases to zero can be represented by

$$N_0 = \frac{1}{E[C]} = \frac{2}{C_1 + C_2}. \tag{6}$$

The probability that v_i and v_k select the same resources is denoted by $p_{\text{c}}(d_{i,k})$. To compute this, we need to figure out how many resources are in the candidate resource lists of both vehicles, which depends on the common excluded resources. If no collision occurs within the common sensing range, then $\lambda(2d_{\text{sen}} - d_{i,k})$ common resources are excluded. However, it is possible that two vehicles select the same resources. The number of resources occupied by the vehicles within the common sensing range is denoted by N_{c}, and $N_{\text{c}} \leq \lambda(2d_{\text{sen}} - d_{i,k})$.

The above problem of computing N_c is approximately modeled as distributing $\lambda(2d_{\text{sen}} - d_{i,k})$ distinguishable balls among N_{subch} distinguishable baskets and figuring out the expected number of baskets containing at least one ball, which is denoted by N_{cr}. Thus, for each basket, the probability that it contains at least one ball is $\left[1 - \left(1 - \frac{1}{N_{\text{subch}}}\right)^{\lambda(2d_{\text{sen}} - d_{i,k})}\right]$. When $2d_{\text{sen}} < d_{i,k}$, we have $N_{\text{cr}}(d_{i,k}) = 0$. When $2d_{\text{sen}} \geq d_{i,k}$, the expected number of baskets containing at least one ball is

$$N_{\text{cr}}(d_{i,k}) = N_{\text{subch}}\left[1 - \left(1 - \frac{1}{N_{\text{subch}}}\right)^{\lambda(2d_{\text{sen}} - d_{i,k})}\right]. \tag{7}$$

Similarly, the expected number of resources occupied by the vehicles within the sensing range of a vehicle can be computed by

$$N_{\text{sr}} = N_{\text{subch}}\left[1 - \left(1 - \frac{1}{N_{\text{subch}}}\right)^{2\lambda d_{\text{sen}}}\right]. \tag{8}$$

Let $M(d_{i,k})$ denote the average number of resources selected by vehicles in the sensing range of v_i but out of the common sensing range of v_i and v_k, and $K(d_{i,k})$ as the total number of resources within one transmission interval minus the average number of resources selected by vehicles in common sensing range. We have $M(d_{i,k}) = N_{\text{sr}} - N_{\text{cr}}(d_{i,k})$ and $K(d_{i,k}) = N_{\text{subch}} - N_{\text{cr}}(d_{i,k})$. Therefore, the common candidate resources of v_i and v_k can be represented as

$$N_{\text{R}}(d_{i,k}) = [K(d_{i,k}) - M(d_{i,k})]\left[1 - \frac{1}{K(d_{i,k})}\right]^{M(d_{i,k})}. \tag{9}$$

The probability that any interference vehicle v_k within the interference range chooses the same resource as v_i does is denoted by p_c, which can be calculated by

$$p_c(d_{i,k}) = \begin{cases} \frac{N_0(1-p_0)N_{\text{R}}(d_{i,k})}{N_{\text{rc}}(N_{\text{subch}} - N_{\text{sr}})}, & d_{i,k} \leq d_{\text{sen}}, \\ \frac{(1-p_0)N_{\text{R}}(d_{i,k})}{N_{\text{rc}}(N_{\text{subch}} - N_{\text{sr}})}, & d_{i,k} > d_{\text{sen}}, \end{cases} \tag{10}$$

where N_{rc} is the number of candidate resources, which equals 20% of N_{subch}. According to Section II, $(1 - p_0)$ is the probability that the interference vehicle v_k selects a new resource when the value of RC decreases to zero. Then the probability that at least one vehicle in the interference area selects the same resource as v_i does can be computed by

$$P_{\text{c}}(d_{i,j}) = 1 - \prod_{d_{i,j} - d_{\text{int}} \leq d_{i,k} \leq d_{i,j} + d_{\text{int}}} [1 - p_{\text{c}}(d_{i,k})]. \tag{11}$$

The overall access collision ratio of the transmitter v_i is denoted by P_i^c, which can be calculated by

$$P_i^{\mathrm{c}} = \int_{-d_{\mathrm{sen}}}^{d_{\mathrm{sen}}} P_{\mathrm{c}}(r) dr. \tag{12}$$

IV. Numerical results

In this section, extended simulations are conducted to verify the proposed performance analysis model for the C-V2X Mode 4 SPS scheme and investigate the impact of system parameters on performance. The simulation settings are as follows. For simplicity, vehicles are assumed to share the same length $d_v = 4$ m. Vehicle density is set in the range of 10 to 100 per km. The size of beacon messages is 190 bytes, with the modulation mechanism configured as QPSK and the number of resource blocks to broadcast one message as 20. The system bandwidth is 10 MHz, so two subchannels are provided in a subframe. Vehicles share the same beacon rate $R \in [10, 50]$. The probability for vehicles to remain the same single-subframe resources for the next packet transmission in the selection window is set as $p_0 = 0.8$. The value range of RC is set as $[10, 30]$ if not specifically mentioned.

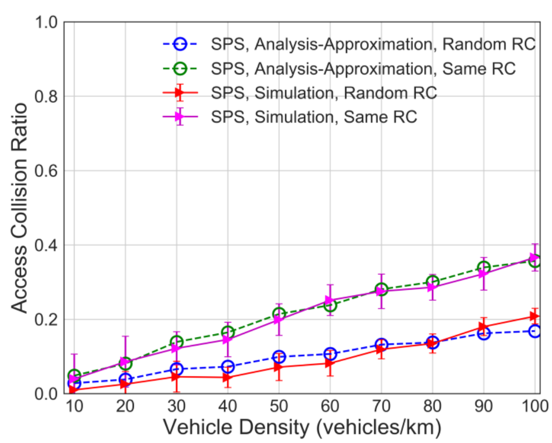

Fig. 2. Comparison between simulation and theoretical results in terms of access collision ratio for different number of vehicles.

First, we verify the correctness of the analytical model of access collision probability given in Section III. The comparison between analytical results and the simulation ones for different vehicle densities are shown in Fig. 2. Here the coverage distance is set as 247 m, which equals the theoretical sensing range. The beacon rate is set as 20 Hz so the total number of available resources is 100. The simulations are run 100 times for 5 s. For different vehicle densities, the mean values and the standard deviations of the access collision ratio are both given. It is found that the theoretical values are basically within one standard deviation from the mean. Moreover, to inspect whether the individual and random selection of RC values configured in C-V2X Mode 4 benefits the transmission reliability, the results with the same RC are also given in the figure. It can be seen that the access collision ratio with random RC is substantially lower than that with the same RC.

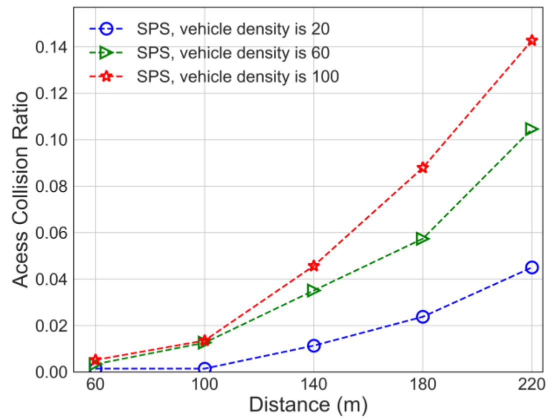

Fig. 3. Relation between packet collision ratio and transmission distance requirement under different settings of vehicle density.

Next, the broadcast reliability curves for different coverage ranges are plotted in Fig. 3. When the transmission distance is within 100 m and the vehicle density is 20 per km, the access collision ratio is below 0.02, indicating relatively high reliability under C-V2X Mode 4. However, when the distance increases over 140 m, the access collision ratio grows dramatically. Meanwhile, the access collision becomes more serious with a higher vehicle density.

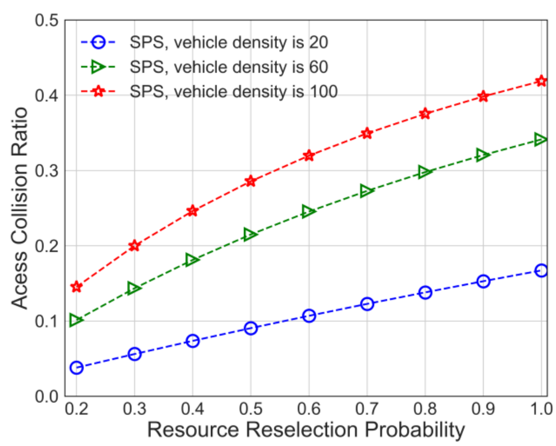

Fig. 4. Impact of resource reselection probability on the access collision ratio when vehicle density is 20, 60 and 100, respectively.

Finally, the effect of configuration parameters on the system performance is analyzed, as shown in Figs. 4-6. We focus on two parameters, the resource reselection probability and the value range of RC. Fig. 4 plots how the access collision ratio is influenced by the resource reselection probability. In a relatively stable traffic condition, a smaller reselection probability leads to less access collision. Moreover, how the RC range impacts the access collision probability is shown in Fig. 5 and Fig. 6. We can find the superiority of the range $[25, 75]$ in terms of collision reduction, compared with the ranges $[5, 15]$ and $[10, 30]$, especially when the vehicle density is high. When the beacon rate is increased from 20 Hz to 50 Hz, the access collision problem becomes more

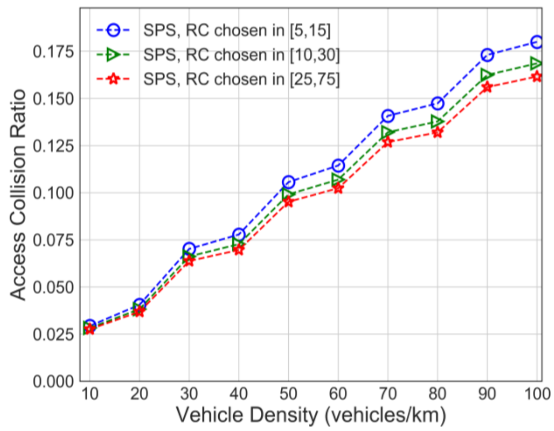

Fig. 5. Impact of RC range on the communication reliability when the beacon rate is 20 Hz.

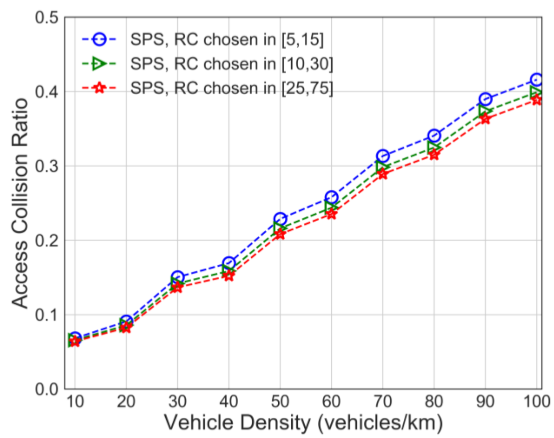

Fig. 6. Impact of RC range on the communication reliability when the beacon rate is 50 Hz.

serious, especially in dense scenarios. Therefore, adaptively adjusting the beacon rate as well as the RC range with varying vehicle density is beneficial for collision reduction and channel utilization improvement.

V. Conclusion

In this paper, the performance of the semi-persistence scheduling utilized in C-V2X Mode 4 is analyzed. Extensive simulations have verified the efficiency of the proposed analytical models. Then the relationships between the system performance and several key configuration parameters are investigated, indicating the benefits of adaptively adjusting the configuration parameters. The analytical results motivate further investigation on the performance enhancement methods to make the SPS MAC protocol more reliable and scalable.

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