This article has been accepted for publication in IEEE Transactions on Vehicular Technology. This is the author's version which has not been fully edited and content may change prior to final publication. Citation information: DOI 10.1109/TVT.2022.3223414

Performance Analysis and Optimization for Semi-Persistent Scheduling in C-V2X

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***Abstract*—For periodical beacon broadcasting in cellular vehicle-to-everything (C-V2X) networks, a distributed reservation media access control (MAC) protocol, the sensing-based semi-persistent scheduling (SPS), is adopted. However, how to quantify the communication reliability and latency is an open issue, which is critical for low-latency and high-reliability services. In this paper, an analytical model for SPS is presented, based on which the impacts of beacon rate, range settings and system configuration on access collision probability and delay outage probability are quantified. The analytical model provides important insights and guideline to adapt and optimize protocol parameters including the sensing range, transmit power and resource reservation. The enhanced MAC protocol can maintain high-reliability and low-latency services with a wide range of vehicle density. Simulations are conducted to validate the analysis and the results demonstrate that the proposed MAC enhancement solution can reduce collision probability while ensuring the delay outage probability based on service requirements.**

***Index Terms*—beacon broadcasting, media access control (MAC), semi-persistent scheduling (SPS), cellular vehicle-to-everything (C-V2X).**

I. Introduction

CONNECTED vehicles are anticipated to enhance road safety and efficiency by periodically exchanging beacon messages on their position, speed, acceleration and other status information. With real-time beacon messages, the perceptive region of the vehicles can be improved beyond the range of equipped sensors [1]. When multiple vehicles broadcast their beacon messages simultaneously, the message transmission is limited by the available channel bandwidth. Thus, it is essential to improve the performance of medium access control (MAC), which specifies the bandwidth sharing mechanism among multiple vehicles [2].

The IEEE 802.11p and cellular vehicle-to-everything (C-V2X) are two main wireless communication technologies for beacon broadcast with different MAC solutions. The IEEE 802.11p, also known as dedicated short-range communication (DSRC), is a standard extending the 802.11 standard to vehicular communication systems [3]. In this standard, each vehicle uses the carrier sense multiple access/collision avoidance (CSMA/CA) mechanism to access the shared medium [4]. The adoption of CSMA/CA helps prevent packet collisions and brings high spectrum utilization. However, the communication reliability is hard to guarantee under high vehicle densities [5].

Compared with DSRC, C-V2X has shown to provide improved communication range and reliability for crowded scenarios [6]. Specially, a sensing-based semi-persistent scheduling (SPS) algorithm was developed for distributed resource reservation in the C-V2X MAC layer [7], which is beneficial for periodical transmissions of packets with constant sizes [8]. There are many researches to improve the communication performance of connected vehicles based on the SPS algorithm.

SPS still confronts the following difficulties. First is the resource allocation conflict problem, in which multiple vehicles are allocated with the same resources. Second, consecutive collisions and long delay between beacons can be caused once a vehicle has a conflicting reservation with others. As a result, the communication reliability and timeliness are hard to guarantee in C-V2X networks.

In the related literature, many efforts have been devoted to analyzing SPS [9] and designing a more effective MAC protocol, focusing on collision reduction or fair channel access [10]. These researches provided guidance for mitigating collision and ensuring system reliability and scalability. In fact, the delay is the same important as the reliability for beacon broadcasting. The work in [11] further studied how to mitigate long delay due to collisions. However, how to ensure both high reliability and low latency for delay-sensitive beacon broadcasting considering the negative impact of the hidden terminals remains an open issue, which motivated this work.

In our preliminary work presented in [12], an analytical model was established to investigate the access collision probability in semi-persistent scheduling. The model reveals the relationship of the access collision probability and the key system parameters, considering the impacts of hidden terminals. In this paper, we further extend the model to evaluate the delay performance of beaconing, as long delay caused by conflicting resource reservation affects the timely information exchange among vehicles, and thus increases the risk of traffic accidents.

The contributions of this paper are three-fold. First, the analytical model in [12] is extended to evaluate the delay performance of SPS. Specifically, the delay outage probability is derived given a delay threshold which is related to the prac-

This work was supported in part by the National Natural Science Foundation of China under Grants 61873353 and 62172448, in part by the Natural Sciences and Engineering Research Council of Canada, in part by the Fundamental Research Funds for the Central Universities of Central South University under Grant 2018zzts172, and in part by the China Scholarship Council. *(Corresponding author: Zhiwu Huang.)*

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tical requirements of driving assistance for vehicles. Second, based on the model analysis, protocol parameters, including the sensing range, transmit power and resource reservation are optimized. The practical factors are incorporated, such as the vehicle density and the service requirements including reliability, latency and beacon range. Third, extensive simulations have been conducted to verify the accuracy of the analysis and the effectiveness of the proposed adaptation and optimization solution. The results demonstrate the superior performance of the proposed sensing range and transmit power adaptation compared to the legacy SPS using a constant sensing range and fixed transmit power and other adaptive SPS solution. They also show the advantages of our proposed RC range adaptation, which can maintain high-reliability and low-latency services and outperforms the legacy SPS and other delay reduction solution.

The rest of this paper is organized as follows. Related work is presented in Section II. Section III describes the system model and the sensing-based SPS. Section IV provides the performance analysis. Section V presents the adaptation and optimization for SPS. In Section VI, extensive simulation results are provided to validate the analysis and evaluate the proposed MAC enhancement solution, followed by the concluding remarks in Section VII.

II. Related Work

The MAC protocol plays an important role in sharing wireless resource among vehicles. DSRC and C-V2X are two main wireless communication technologies for beacon broadcasting, with different MAC solutions. Recently, many efforts have been devoted to the design of reliable and scalable MAC protocols.

A. MAC Protocol for DSRC

DSRC provides the services of beacon broadcasting by adopting the random access mechanism based on CSMA/CA. Each vehicle transmits beacon messages only if the medium is sensed idle, otherwise it takes a random backoff to reduce collision probability. It supports rapid changes in network topology caused by the high mobility of vehicles, but the backoff scheme brings the unbounded delay and unfair access [13].

To address these issues of CSMA, many works tried to optimize the channel configuration or to improve the reliability by combining the contention-based and contention-free MAC protocols. The orthogonal frequency-division multiple-access was adopted in [14] for contention-free transmission, based on a resource negotiation phase supported by CSMA. Similarly, a novel MAC protocol was proposed in [15], which consists of two centralized sessions and one distributed session. However, the above hybrid protocols request coordination of the roadside units, which demands wide deployment of infrastructures [16]. It remains an open issue to enable distributed and reliable MAC for beacon broadcasting for vehicles.

B. MAC Protocol for C-V2X

As for C-V2X, it adopts a distributed reservation MAC protocol, which is the sensing-based SPS [7]. Each vehicle senses the channel to determine suitable transmission opportunities, and stays in the same channel and time slot in each period for a number of periods. The number of periods is determined by the reselection counter (RC). The initial value of RC is randomly chosen from a given range. Once a packet is transmitted, the value of RC is decremented by one. Only when its value becomes zero, a new resource can be selected and the RC is reset. Thanks to the periodicity and predictable packet size in beacon broadcasting, once a beacon is transmitted successfully, all neighboring vehicles will not use the same resource to avoid collision, so resources can be used efficiently with the distributed reservation approach by SPS. However, if two vehicles select the same resource to transmit, the reservation collision will lead to consecutive packet collisions.

To address the above concerns, performance analysis is critical to provide guidance for system configuration by investigating the relationship between key parameters and system performance. Analysis of SPS can be classified into simulation evaluation and analytical modelling. For simulation efforts, [17] and [18] each introduced an open-source simulator and investigated the impact of key SPS parameters on the scheduling performance. Similarly, a system-level simulation platform was set up in [19] to evaluate the transmission performance. Simulations provide results for specific use cases, while analytical models help obtain performance results under more general assumption.

In recent years, increasing efforts have been devoted to analysis on C-V2X physical and MAC layers. Authors in [9] presented an analytical model to formulate the average packet delivery ratio as a function of the distance between transmitter and receiver. They investigated four different types of transmission errors in simple scenarios. On this basis, the analytical model was further developed in [20] to evaluate the performance of SPS when supporting a particular scenario, i.e., collective perception service. A multi-dimensional Markov model was proposed in [21] to evaluate the MAC performance, providing insights on the successful transmission probability, the collision probability, and the channel utilization.

The theoretical analysis enables the parameter adaptation to improve SPS operation. In particular, an adaptive-transmit power control algorithm was presented in [22] to avoid interference among neighboring vehicles. In additional to the power control, authors in [23] proposed an adaptive transmission power and message interval control scheme to reduce channel contention for improved reliability and latency. Moreover, to reduce the collision caused by imperfect sensing, some enhanced MAC protocols were proposed. In [24], a short sensing unit was added right before resource selection to reduce collision. Negative feedback was used in [25] and [26] before transmission to mitigate collision probability, while it led to longer delay. For delay-sensitive beacon broadcasting, the reliability and timeliness are both important. New approaches are in need for maintaining high-reliability and low-latency services.

To decrease the delay of beacon broadcasting in SPS, RC is regarded as a critical tunable factor. The setting of RC indicates how long the resources are reserved for suc-

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cessive beacon transmissions. Resource reservation benefits the predictable beacon broadcasting, while the long delay caused by conflicting reservation may lead to potential safety hazard in vehicular environment. To address the long delay issue, a resource alternation selection algorithm was proposed to guarantee non-continuous collisions even if collisions do occur [27]. Similarly, an enhancement to SPS was proposed in [11], where a limitation value was set to the number of consecutive resource-keeping time, avoiding delay of many seconds. It was suggested in [28] that the reservation duration should be controlled as it impacts collision probability.

According to the above analysis, the resource reservation not only impacts the collision probability but also affects the delay performance, while how to fulfill both the reliability and delay requirements has not been fully addressed. In this paper, we propose to optimize the resource reservation by tuning the RC range for high-reliability and low-latency services.

III. Preliminary and System Model

In this section, we present the system model of beacon broadcasting among connected vehicles. The network model and the channel model are both given. Then the performance of SPS for beacon broadcasting is analyzed in terms of access collision and delay.

A. Network Model

In this paper, we focus on the beacon broadcasting using C-V2X technology for connected vehicles. As shown in Fig. 1, vehicles are distributed randomly on a bi-directional road, periodically exchanging beacon messages for safety and coordination purposes. Beacon messages contain the vehicle's status information, such as position, speed and direction. They should be received by all those vehicles that are within a given range, so that awareness of the neighboring vehicles is enabled. According to the C-V2X standard [29], broadcasting is considered as the communication mode for beacon messages. The key notations and definitions used throughout this paper are summarized in TABLE I.

The vehicles are denoted by a set $\mathcal{V} = \{v_1, v_2, v_3, \ldots, v_m\}$ and they share the same beacon range, denoted by d_{br}, which indicates how far the beacon messages are to be delivered. For the sake of situational-awareness among vehicles, beacon messages must be delivered with high reliability and low latency.

B. Channel Model

In a C-V2X system, the single carrier-frequency division multiple access (SC-FDMA) is used in the PHY and MAC layers, with 10 MHz or 20 MHz channels supported on the 5.9 GHz band [30]. 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 subcarriers with an inter-spacing of 15 kHz. The time duration of each RB is 1 ms, corresponding to 14 orthogonal frequency division multiplexing (OFDM) symbols. One RB is the smallest resource unit for a C-V2X user.

TABLE I
Notations and Definitions

Symbol	Definition
$\mathcal{V}$	Set of vehicles
P^{t}	Transmit power
$P^{\text{r}}_{i,j}$	Received signal power of v_j from v_i
$d_{i,j}$	Distance between v_i and v_j
γ	Path-loss exponent
K_0	Path-loss constant
N	Noise power
$SINR_{\text{th}}$	Minimum SINR
$SINR_{i,j}$	SINR for the transmitter-receiver pair (v_i, v_j)
R	Beacon rate
t_0	Transmission interval
N_{a}	Number of resources within one second
N_{subch}	Number of resources in each transmission interval
d_{br}	Beacon range
λ	Vehicle density
D	Delay, which is the time duration till receiving a beacon from a neighbour vehicle
D_{th}	Delay threshold
T_1	Lower bound of section window
T_2	Higher bound of selection window
C_1	Lower bound of the RC range
C_2	Higher bound of the RC range
$\overline{C}$	Average value of the RC range
T_{s}	Size of sensing window
T	Size of selection window
P_{th}	Sensing power threshold
d_{sen}	Sensing range
s	Ratio between the number of candidate resources and that of all resources within one selection window
N_{rc}	Number of candidate suchannels
P_{sen}	Sensing power threshold
d_{int}	Interference range
p_0	Probability of resource keep
p_{r}	Probability that RC equals zero for any vehicle in any transmission interval.
N_{s}	Number of vehicles within the sensing range
N_{sr}	Number of resources occupied by vehicles within the sensing range
$N_{\text{cr}}(d_{i,k})$	Number of resources occupied by vehicles within the common sensing range of v_i and v_k
P^{c}	Access collision probability of any vehicle
P^{d}	Delay outage probability of any vehicle
P^{c}_{th}	Threshold of access collision probability
P^{d}_{th}	Threshold of delay outage probability

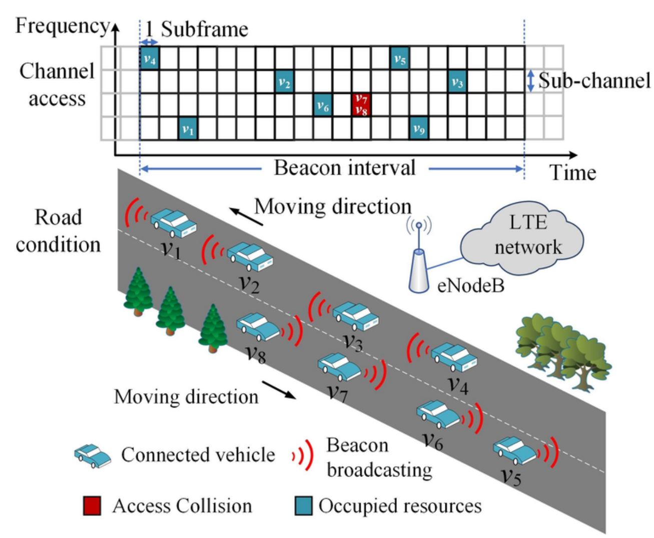

Fig. 1. System model of periodical beacon broadcasting among connected vehicles, which are equipped with C-V2X technology.

In the C-V2X network, the sub-channel is defined as a group of resource blocks in the same sub-frame [30]. The number of resource blocks per sub-channel can vary. It is assumed that each beacon transmission occupies one sub-channel (also called one resource) [28]. The sub-channels are used to transmit data and control information. Each data packet carried on the transport block (TB) follows the control message, denoted as sidelink control information (SCI). The SCI contains important information such as the modulation and coding scheme (MCS), the RBs used to transmit the TB and the corresponding sub-channels periodically used for subsequent transmissions. One SCI is always transmitted with two resource block pairs, while the number of resource block pairs used for the TB depends on the size of the message. TBs can be transmitted using 16-QAM or QPSK and turbo coding. For any vehicle $v_i \in \mathcal{V}$, the index of the sub-channel chosen by v_i is denoted by r_i, where i is the index of the vehicle, ranging from 1 to m.

The channel model is presented as follow. We consider a transmitter-receiver pair (v_i, v_j), where v_i is the transmitter and v_j is the receiver. Let P^{t} denote the transmit power of vehicles. The transmit power is assumed the same for all vehicles, whose maximum value is 23 dBm according to the LTE configuration. The distance between v_i and v_j is denoted by $d_{i,j}$, and $0 < d_{i,j} \le d_{\text{br}}$. The received signal power of vehicle v_j, denoted by $P^{\text{r}}_{i,j}$, is a function of $d_{i,j}$, as follows

$$P^{\text{r}}_{i,j} = P^{\text{t}} K_0 d_{i,j}^{-\gamma}, \tag{1}$$

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-receiver pair (v_i, v_j), the signal to interference plus noise ratio can be represented by

$$SINR_{i,j} = \frac{P^{\text{r}}_{i,j}}{\sum_{v_k \in \mathcal{V}, k \neq j, r_k = r_i} P^{\text{r}}_{k,j} + N}, \tag{2}$$

where v_k is the vehicle that accesses the same resources as v_i does within the vehicle set $\mathcal{V}$. N is the noise power received by v_j. For each transmission, the beacon message can be decoded successfully only when the SINR value is no less than a pre-given threshold $SINR_{\text{th}}$, i.e.,

$$SINR_{i,j} \ge SINR_{\text{th}}. \tag{3}$$

C. SPS for Connected Vehicles

The sensing-based SPS is utilized for sharing the wireless resource among vehicles. By doing this, connectivity of vehicles is guaranteed regardless of cellular coverage. Fig. 2 illustrates the process of the sensing-based SPS scheme. 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 estimating which resources have not been used by other vehicles, the vehicle reserves sub-channels for a period of time based on its RC.

Generally, 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 the value becomes zero, a new resource will be selected and reserved with the probability $(1 - p_0)$. The new resource is randomly selected from the pool of the 20% least interfered resources [11]. The ratio of 20% is set by the C-V2X standard to provide enough accessible resources for low collision, and the selection from the least interfered resources is to avoid interference with the ongoing nearby transmissions.

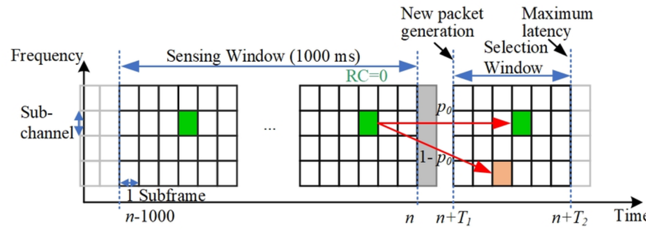

Fig. 2. Procedure of sensing-based semi-persistent scheduling.

The vehicle selects the same single-subframe resources for the next packet transmission with probability p_0, as shown in Fig. 2. In addition, the lower bound T_1 of the selection window depends on the time of packet generation. The higher bound T_2 is the maximum latency of the new packet.

SPS encounters resource allocation conflict problems, especially for broadcast/multicast without any feedback from receivers. It cannot prevent two or more vehicles from accessing the same resource, causing mutual interference with consecutive collisions. If the collision lasts for a long period of time, it will lead to potential safety hazard. From the above analysis, the reliability and delay performances are both important for beacon broadcasting. We define two performance metrics to evaluate them. One is the access collision probability, which the probability that a neighbor vehicle fails to receive the beacon due to collision, denoted by P^{c}. The other is the delay outage probability, which is the probability that the time duration till receiving a beacon from a neighbor vehicle exceeds a given delay upper bound, denoted by P^{d}. Both of the two probabilities will be derived in the next section.

IV. Analytical Model for SPS

In this section, an analytical model is presented to evaluate the performance of the sensing-based SPS. To be specific, we derive the probability of conflicting resource selection for a transmitter-receiver pair, in Section IV-A. Next, the average access collision probability is obtained considering all the receivers within the beacon range in Section IV-B. The delay outage probability is further derived in Section IV-C.

A. Resource Selection Conflict

The access collision is caused by conflicting resource selection between vehicles. We consider a transmitter-receiver pair $(v_i,\ v_j)$, and the interfering vehicle is denoted by v_k. As shown in Fig. 3, v_k can be within or out of the "sensing

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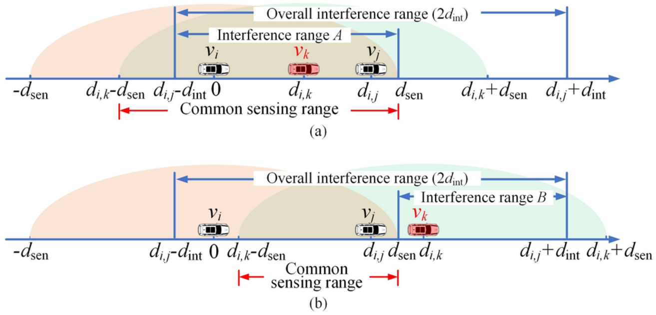


Fig. 3. Different interference conditions. (a) The interfering vehicle v_k is within the sensing range of the transmitter v_i. (b) The interfering vehicle v_k is out of the sensing range of the transmitter v_i.

range"[1] of v_i. The range of interfering vehicles is denoted as the interference range, which is divided into two parts, A and B, according to whether or not v_k is within the sensing range of v_i.

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 below,

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

Let N_{a} denote the number of resources within one second in the system. The beacon rate of vehicles is $R\,[\text{s}^{-1}]$, and the transmission interval is $t_0 = 1/R\,[\text{s}]$. The number of sub-channels (i.e., resources) in each transmission interval is denoted by N_{subch}, which equals N_{a}/R. Those sub-channels whose Reference Signal Received Power (RSRP) level exceeds a preconfigured threshold are excluded, and the rest are in the candidate list. Let s denote the ratio between the number of candidate resources and that of all resources within one selection window. Then the excluded resources account for $(1-s)$ of the number of total resources.

Within the sensing range, vehicles can sense each other. Thus, the number of selected resources is approximately the number of vehicles in the sensing range. Then we have

$$d_{\text{sen}} = \frac{(1-s)N_{\text{subch}}}{2\lambda}, \tag{5}$$

where λ is the vehicle density. As a result, the sensing range d_{sen} is jointly determined by s, λ and N_{subch}.

Let N_{rc} denote the number of resources in the candidate list for any vehicle, then we have $N_{\text{rc}} = sN_{\text{subch}}$. According to the configuration of C-V2X, s is set as 20% so the RSRP threshold will be adjusted accordingly in real time.

Given the SINR threshold $SINR_{\text{th}}$, the interference range from the receiver can be obtained as

$$d_{\text{int}} = \left[\frac{P^{\text{t}} K_0}{\frac{P^{\text{t}} K_0 d_{i,j}^{-\gamma}}{SINR_{\text{th}}} - N}\right]^{1/\gamma}. \tag{6}$$

[1]Note that the "sensing range" used in this paper is different from the physical layer sensing range. In our analysis, the defined sensing range is that if any resource is sensed to be used by a neighbor vehicle in this range, this resource will be excluded in the resource selection process.

For a transmitter-receiver pair (v_i, v_j), the interference range d_{int} indicates the farthest distance from the receiver v_j that one interfering vehicle can cause enough interference leading to access collision.

p_{r} is defined as the probability that RC equals zero in any transmission interval. According to the definition, p_{r} is the reciprocal of the average duration between two consecutive events when RC equals zero, meaning that $p_{\text{r}} = 1/\overline{C}$, in which $\overline{C}$ denotes the average duration. In our paper, the initial value of RC, denoted by C, is randomly selected from a given range $[C_1, C_2]$. Then the average duration $\overline{C} = (C_1 + C_2)/2$. Thus, $p_{\text{r}} = 2/(C_1 + C_2)$.

The probability that v_i and v_k select the same resource is denoted by p_{c}. Given the system parameters such as vehicle density λ, sensing range d_{sen} and transmit power P^{t}, $p_{\text{c}}()$ is a function of the distance $d_{i,k}$ between v_i and v_k. $p_{\text{c}}(d_{i,k})$ depends on whether v_k is in the range of A or B. When v_k is in the range of A (i.e., $d_{i,k} \leq d_{\text{sen}}$), access collision occurs when their RC values are both decreased to zero. When v_k is in the range of B, as a hidden terminal for v_i (i.e., $d_{i,k} > d_{\text{sen}}$), access collision may happen no matter whether they choose new resources simultaneously or not. Therefore, for $d_{i,k} \leq d_{\text{sen}}$, the collision occurs on the premise of simultaneous resource selection, whose probability is p_{r}.

According to the semi-persistent scheduling, each vehicle only selects one resource from its 20% least interfered ones, whose quantity is N_{rc}. Let $N_{\text{R}}(d_{i,k})$ denote the number of common candidate resources of v_i and v_k. More common candidate resources lead to a higher resource selection conflicting probability. For each one of the $N_{\text{R}}(d_{i,k})$ common candidate resources, the probability that the resource is selected by v_i and v_k simultaneously is $\frac{1}{N_{\text{rc}}^2}$. Then the probability of selecting the same resource is $\frac{N_{\text{R}}(d_{i,k})}{N_{\text{rc}}^2}$. Based on the above analysis, $p_{\text{c}}(d_{i,k})$ can be derived by

$$p_{\text{c}}(d_{i,k}) = \begin{cases} \frac{p_{\text{r}}(1-p_0)N_{\text{R}}(d_{i,k})}{N_{\text{rc}}^2}, & d_{i,k} \leq d_{\text{sen}}, \\ \frac{(1-p_0)N_{\text{R}}(d_{i,k})}{N_{\text{rc}}^2}, & d_{i,k} > d_{\text{sen}}. \end{cases} \tag{7}$$

Since the relationship between $p_{\text{c}}(d_{i,k})$ and $N_{\text{R}}(d_{i,k})$ is given in (7), the key point is to derive $N_{\text{R}}(d_{i,k})$. $N_{\text{R}}(d_{i,k})$ is determined by many factors like the vehicle density, the resource quantity, the distance between v_i and v_k. The derivation details are provided in the appendix.

B. Access Collision Probability

Based on the above analysis, the resource selection conflict probability $p_{\text{c}}(d_{i,k})$ is derived. For the transmitter-receiver pair (v_i, v_j), the probability of access collision is denoted by P_{c}, which equals the probability that at least one vehicle in the interference area selects the same resource as v_i does. Here, the interference area is determined by the distance $d_{i,j}$ between v_i and v_j, so $P_{\text{c}}()$ is a function of the distance $d_{i,j}$. Therefore, we have

$$P_{\text{c}}(d_{i,j}) = 1 - \prod_{v_k \in \mathcal{V}, d_{i,j} - d_{\text{int}} \leq d_{i,k} \leq d_{i,j} + d_{\text{int}}} [1 - p_{\text{c}}(d_{i,k})]. \tag{8}$$

The average access collision probability of any vehicle considering all receivers within the beacon range is denoted by P^{c}, which can be calculated by

$$P^{\mathrm{c}} = \frac{1}{2d_{\mathrm{br}}} \int_{-d_{\mathrm{br}}}^{d_{\mathrm{br}}} P_{\mathrm{c}}(r) dr, \tag{9}$$

where r of $P_{\mathrm{c}}(r)$ indicates the distance between the transmitter and any receiver within the beacon range.

Combining (7), (8) and (9), the access collision probability P^{c} will decrease by decreasing of p_{r}, i.e., by increasing the initial value of RC, C. However, RC is the persistent time to keep the communication resources for one vehicle. Thus, the great value for C increases the risk of long delay caused by consecutive collisions. In the following, the impact of the RC range on the delay outage probability is analyzed.

C. Delay Outage Probability

Using SPS, consecutive collisions and long delay between beacons can be caused once a vehicle has a conflicting reservation with others. The delay bound is denoted by D_{th}. Let P_{d} denote the delay outage probability for (v_i, v_j), and P^{d} denote the overall delay outage probability of any vehicle considering all receivers within its beacon range. In the following, we will prove that $P_{\mathrm{d}}()$ is a function of $P_{\mathrm{c}}(d_{i,j})$, so $P_{\mathrm{d}}()$ is also a function of the distance $d_{i,j}$. P^{d} is computed by

$$P^{\mathrm{d}} = \frac{1}{2d_{\mathrm{br}}} \int_{-d_{\mathrm{br}}}^{d_{\mathrm{br}}} P_{\mathrm{d}}(r) dr. \tag{10}$$

To derive the delay outage probability, the consecutive collision problem is studied. In the sensing-based SPS scheme, resources are reserved for several transmission opportunities once selected. The reservation duration is Ct_0, determined by the initial value of RC, C. For a transmit-receiver pair (v_i, v_j), once v_i suffers from resource selection conflict with an interfering vehicle v_k, all the packets from v_i to v_j will be lost until the conflict ends. The conflict ends when the RC of either v_i or v_k is decreased to zero, triggering resource reselection. Therefore, the duration of consecutive collisions is determined by the lower initial RC value of v_i and v_k. Let C_0 denote the expectation of the lower value of two variables randomly selected from the range $[C_1, C_2]$. Using the probability theory, C_0 is computed by

$$C_0 = \sum_{i=C_1}^{C_2} \frac{2i(C_2 - i + 1)}{(C_2 - C_1 + 1)^2}. \tag{11}$$

In the following, we consider the channel access upon resource reselection. The channel access trials are independent, and the number of failed channel access times before successful access is denoted by X. Then X follows a geometric distribution, i.e.,

$$P_r\{X = x\} = P_{\mathrm{c}}^x(d_{i,j}) \left[1 - P_{\mathrm{c}}(d_{i,j})\right], \ x = 0, 1, \ldots \tag{12}$$

where $P_r\{X = x\}$ is the probability that it takes x failed channel access trails till v_j receives a beacon from v_i. $P_{\mathrm{c}}(d_{i,j})$ is the access collision probability obtained in (8).

If the interfering vehicle always has a greater RC value than v_i, conflict ends only when v_i reselects a new resource without conflict, and we can use (12) to obtain the delay distribution and further derive the delay outage probability; Otherwise, the conflict ends when the interfering vehicle reselects a new resource. The delay distribution is derived considering both conditions. Let k_{th} denote the maximum value of failed channel access trials, then we have

$$k_{\mathrm{th}} = \left\lfloor \frac{D_{\mathrm{th}}}{C_0 t_0} \right\rfloor. \tag{13}$$

We assume that the probability that v_k has a greater RC value than v_i is $\frac{1}{2}$. If $k_{\mathrm{th}} = 0$, $P_{\mathrm{d}}(d_{i,j}) = 1 - P_{\mathrm{c}}(d_{i,j})$. Otherwise, $P_{\mathrm{d}}(d_{i,j})$ can be computed by

$$P_{\mathrm{d}}(d_{i,j}) = P_{\mathrm{c}}(d_{i,j}) - \sum_{k \in \mathbb{N}, k \le k_{\mathrm{th}}} \left[\frac{1}{2} P_{\mathrm{c}}(d_{i,j})\right]^k \left[2 - P_{\mathrm{c}}(d_{i,j})\right]. \tag{14}$$

Substituting (14) into (10), the overall delay outage probability for beacon broadcasting of a vehicle is obtained.

Based on the above analytical model, the access collision probability and the delay outage probability are derived, which provides important guidance for system configuration. Through analysis in the next section, the sensing range, transmit power and RC are key parameters for performance improvement in the MAC layer. Therefore, we further investigate adaptive MAC design for beacon broadcasting in C-V2X.

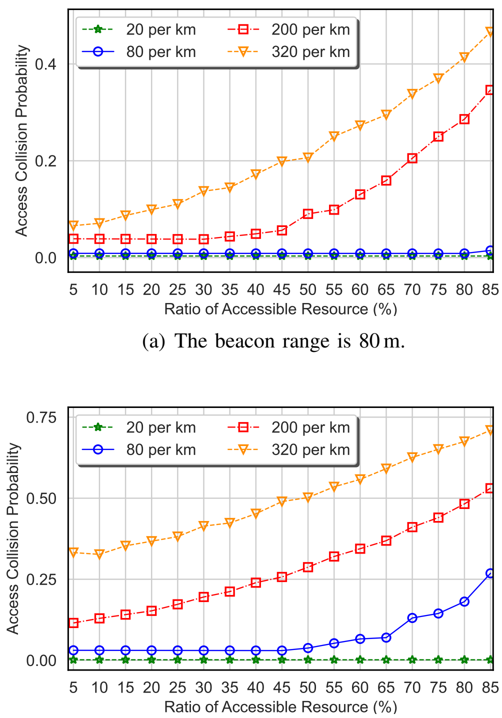
V. Adaptation and Optimization for SPS

In this section, the adaptation and optimization for SPS is presented, aiming to ensure reliable and timely beacon broadcasting. Based on the above analytical model, the sensing range and transmit power are adapted to the vehicle density and beaconing requirements to improve the communication reliability and save power. Furthermore, an optimization problem is formulated and solved to achieve the optimal RC range for maintaining high-reliability and low-latency services.

A. Sensing Range

Different from the existing SPS, we propose that the sensing range varies according to the requirements. The sensing-based SPS requests that the number of resource candidates must be no less than 20% of the total available resources. In other words, there must be at least 20% resources with RSRP lower than the given threshold. If the ratio of accessible resources is lower than 20%, the vehicle will increase the RSRP threshold by 3 dB, and repeat this process until the constraint is met. Under such configuration, vehicles may exclude too few resources in dense scenarios. Ensuring 20% resources accessible will lead to a small sensing range, where hidden terminals may be ignored. Intuitively, reducing the ratio of accessible resources can exclude more potential interference.

Fig. 4 shows how the ratio of accessible resources impacts access collision for different vehicle densities. The beacon rate is set as 20 Hz. We consider four different vehicle densities, which are 20, 80, 200, and 320 vehicles per km. The results are obtained based the proposed analytical model. Figs. 4 (a) and 4 (b) differ in required transmission range. In Fig. 4 (a), the transmission range is 80 m. When as few as 20 vehicles are



(a) The beacon range is 80 m.

(b) The beacon range is 150 m.

Fig. 4. Access collision probability versus the ratio of accessible resources for different vehicle densities based on the proposed analytical model. The beacon rate is 20 Hz.

within the range of 1 km, no matter what the ratio of accessible resources is, the beacon broadcasting shows high reliability. Comparatively, for scenarios involving 80 or 200 vehicles per km, great s above a certain value results in high collision probability. Therefore, setting s as 20%, as the standard does, is a reasonable choice for the cases with $\leq$ 200 vehicles/km. The results of a larger transmission range of 150 m are shown in Fig. 4 (b). Here, setting 20% as the ratio of accessible resources becomes undesirable for the cases with 200/320 vehicles/km.

According to the above analysis, it's necessary to tune s for beacon broadcasting in high-density scenarios when a large beacon range is requested. Given the beacon range, we define σ as the approximate change rate of access collision probability with respect to s, represented by

$$\sigma = \frac{P^{c}(s=0.20,\lambda,d_{br}) - P^{c}(s=0.19,\lambda,d_{br})}{0.20-0.19}. \quad (15)$$

For different vehicle densities and beacon range requirements, s has variable impact on access collision probability. Greater σ indicates the necessity of tuning s. Therefore, by substituting the vehicle density and the beacon range into (15), we check whether the result exceeds a pre-given threshold σ_{th}. To improve the reliability of beacon broadcasting in high density scenarios, we propose a sensing range adaptation scheme for SPS, as shown in Algorithm 1.

In the algorithm, the accessible resource ratio s is adjusted only when $\sigma > \sigma_{th}$. Moreover, the value of s is decreased by Δs for each iteration. The loop ends until it exceeds the minimal value s_{min} or the collision probability is lower than the required value P^{c}_{th}. Empirically, the threshold of σ_{th} can be set as 1. Moreover, $\Delta s = 1/N_{subch}$. Let s_{min} denote the minimal value of s. We set the lower bound of s because conflicted vehicles tend to reselect the same resource from a limited accessible resource pool. The value of s_{min} depends on the resource quantity N_{subch}. For example, when $N_{subch} = 100$, s_{min} can be set as 5%. If N_{subch} is as small as 40 because of a high beacon rate, 10% is chosen empirically.

Algorithm 1 Sensing Range Adaptation Algorithm

Input: Vehicle density λ;
Beacon range d_{br};
Transmit Power P^{t}

Output: Optimal ratio of accessible resources s^{*};
Optimal sensing range d^{*}_{sen}

Compute the approximate change rate σ using (15)
if $\sigma \leq \sigma_{th}$ **then**
  $s^{*} = 20\%$
else then
  while $s \geq s_{min}$ **and** $P^{c} \leq P^{c}_{th}$ **do**
    $s = s - \Delta s$
  $s^{*} = s$
compute d^{*}_{sen} using Equation (5)
return s^{*}, d^{*}_{sen}

B. Transmit Power

For autonomous driving, the beacon range is expected to be increased for a more comprehensive surrounding situation, which brings new demands on communication system design. Setting the transmit power at a high level is an intuitive solution.

Let P^{t}_{min} denote the minimal transmit power needed so that the received signal to noise ratio (with the transmission distance equal to the beacon range d_{br}) is above the threshold for successful transmissions. Given the required beacon range d_{br}, the value of P^{t}_{min} can be derived using the following equation.

$$P^{t}_{min} = \frac{SINR_{th} N d^{\gamma}_{br}}{K_0}. \quad (16)$$

Based on the proposed analytical model, the relationship between transmit power and access collision probability is illustrated in Fig. 5. Figs. 5 (a) and 5 (b) only differ in the beacon range requirements. When the beacon range is set as 80 m, only a slight increase in collision probability is found when the transmit power decreases from 23 dBm to 10 dBm. In other words, once above a threshold, the transmit power has little impact on reliability. The threshold can be obtained by (16) given the required beacon range from the application layer. For 150 m beacon range in Fig. 5 (b), a dramatic increase of access collision can be seen when the transmit power is decreased below 19 dBm as $P^{t}_{min}|_{d_{br}=150\,\text{m}} \approx 19\,\text{dBm}$. Therefore, instead of fixing the transmit power at 23 dBm, we propose to adjust the transmit power to vehicle density and service requirement for power saving.

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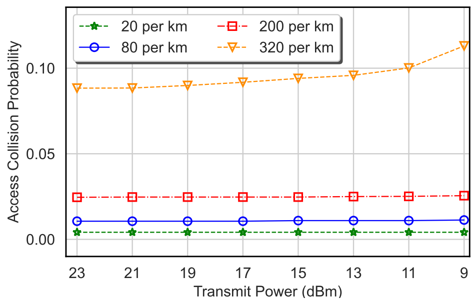
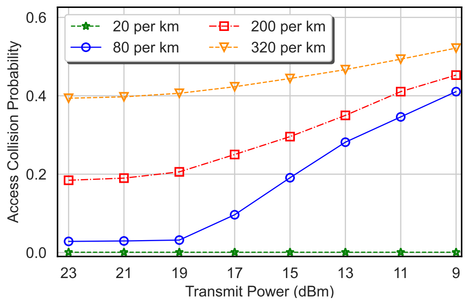
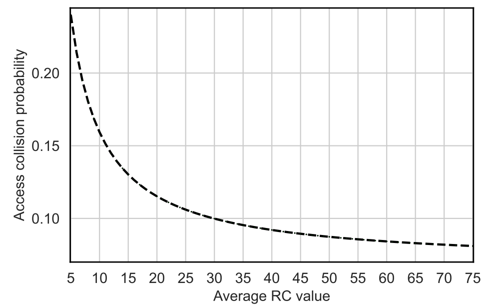


(a) The beacon range is 80 m

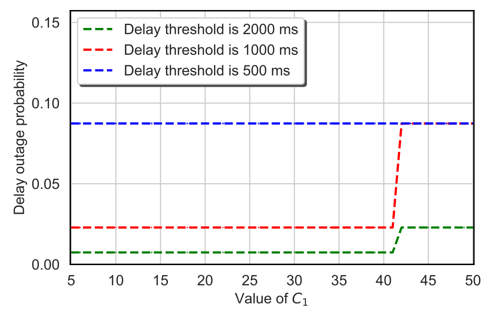


(b) The beacon range is 150 m.

Fig. 5. Impact of transmit power on access collision probability for different vehicle densities when the beacon rate is 20 Hz.



(a) The impact of the average RC value $\overline{C}$ on access collision probability.



(b) The impact of C_1 on delay outage probability when the avearge RC value $\overline{C} = 50$ with different threshold values of delay.

Fig. 6. The impact of two RC parameters ($\overline{C}$ and C_1) on access collision probability and delay outage probability, based on the proposed analytical model. The beacon rate is 50 Hz, the vehicle density is 100 per km and the delay threshold is 2000 ms, 1000 ms and 500 ms.

From the analytical model, setting a high transmit power is beneficial for reliability improvement when vehicles are crowded in C-V2X. This is because the transmitters always choose a resource from the least 20% interfered ones. In this case, the sensing range is adapted to vehicle density in C-V2X, different from the DSRC system which has fixed sensing range. Thus, in crowded networks, for DSRC, the transmit power must be reduced to decrease the interference and sustain the communication reliability.

C. Resource Reservation

In the sensing-based SPS scheme, RC is used as an indicator for resource reservation and re-selection. The beacon rate is determined by the application layer with service requirements. According to the C-V2X standard, the RC range is set based on the beacon rate. Specifically, the range is set as $[5, 15]$, $[10, 30]$ and $[25, 75]$ when the beacon rate is 10 Hz, 20 Hz and 50 Hz. However, such system configuration does not fully consider the delay requirements of beacon broadcasting.

An example is presented with Fig. 6 to illustrate how RC impacts the access collision probability and delay outage probability. In the case, the beacon rate is 50 Hz, so $t_0 = 20$ ms. The vehicle density is 100 per km, and three delay thresholds are studied, which are 2000 ms, 1000 ms and 500 ms. As shown in Fig. 6 (a), the access collision probability decreases with the increase of $\overline{C}$ as RC determines how long a vehicle should reselect a new resource.

The curves of delay outage probability in Fig. 6 (b) have several step changes. This is because that the tolerable time of resource reselection is expected to be reduced by one to keep delay below a given threshold D_{th}. For instance, when $C_1 = 30$, $C_2 = 2\overline{C} - C_1 = 70$. By substituting C_1 and C_2 into (11), we have $C_0 \approx 44$. Then the value of k_{th} is 0, 1, 2 when D_{th} is 500 ms, 1000 ms and 2000 ms, respectively, obtained from (13). This further leads to their difference in delay outage probability. However, a lower value of C_1 results in a higher risk of long delay. A long duration of disconnection between two vehicles is intolerable for some delay-sensitive vehicular services in autonomous driving. Therefore, the RC range needs to be tuned to meet both the high reliability and low latency requirements. For this purpose, an adaptive reservation scheme for SPS is designed. Instead of fixing the RC range as the standard does, we propose to tune the RC range, i.e., jointly optimize $\overline{C}$ and C_1 according to the reliability requirements.

The optimization problem can be formulated as follows.

$$\min_{\overline{C}, C_1} P^{\text{c}}, \tag{17}$$

$$\textbf{s.t.} \quad P^{\text{d}} \le P^{\text{d}}_{\text{th}}, \tag{17a}$$

$$P^{\text{c}} \le P^{\text{c}}_{\text{th}}, \tag{17b}$$

$$C_{\min} \le \overline{C} \le C_{\max}, C \in \mathbb{N}, \tag{17c}$$

$$C_{\min} \le C_1 < \overline{C}, C_1 \in \mathbb{N}, \tag{17d}$$

$$(2\overline{C} - C_1)t_0 \le D_0. \tag{17e}$$

In (17e), D_0 is a strict delay upper bound of most beacon transmission, determined by the vehicular application. (17a) and (17b) are the constraints of delay outage probability and access collision probability, determined by the application. (17c) and (17d) are the constraints of two configuration parameters of RC ranges. C_1 is the lower bound of RC range, so it must be smaller than the average value $\overline{C}$. Note that $C_1 = \overline{C}$ is not considered as it increases the risk of consecutive collision when two vehicles reserve the same resource. The last constraint in (17e) indicates the upper bound of delay caused by a failure of channel access.

Algorithm 2 is designed to find the ideal RC range which maintains both the access collision and delay requirements. The optimal solution can be obtained by performing exhaustive searching through all possible combinations of $\overline{C}$ and C_1, so the computational complexity is $\mathcal{O}((C_{\max} - C_{\min})^2)$, which is not impacted by the vehicle density or beacon range. The decision variables $\overline{C}$ and C_1 are two integers with a limited range. Since $C_{\min} = 5$ and $C_{\max} = 75$, the computation burden is acceptable for the optimization problem. In this way, the scalability of **Algorithm** 2 is guaranteed.

Algorithm 2 Adaptive Resource Reservation Algorithm

Input: Vehicle density λ;
Delay threshold D_{th};
Threshold of access collision probability P_{th}^{c};
Threshold of delay outage probability P_{th}^{d};
Strict upper bound of delay D_0
Output: Optimal RC average $\overline{C}^*$;
Optimal RC lower bound C_1^*

initialize $\overline{C}^* = \text{NULL}$, $C_1^* = \text{NULL}$
for $\overline{C} = C_{\max}$ **to** $C_{\min}$ **do**
  get $\overline{C}$
  compute access collision probability P^{c} using (9)
  if $P^{\text{c}} > P_{\text{th}}^{\text{c}}$ **then**
    continue
  end if
  for $C_1 = C_{\min}$ **to** $\overline{C} - 1$ **do**
    get C_1
    if $(2\overline{C} - C_1)t_0 > D_0$ **then**
      continue
    end if
    compute delay outage probability P^{d} using (10)
    if $P^{\text{d}} \leq P_{\text{th}}^{\text{d}}$ **then**
      $\overline{C}^* = \overline{C}$
      $C_1^* = C_1$
    end if
  end for
end for
return $\overline{C}^*$, C_1^*

In the algorithm, (9) and (10) are used to estimate the access collision probability P^{c} and delay outage probability P^{d}, respectively. (17a) and (17b) are used to check whether or not $\overline{C}$ together with C_1 meets the reliability requirements from the application layer. The access collision probability P^{c} is computed when $\overline{C}$ is gradually decreased from $C_{\max}$ to $C_{\min}$. These two bounds can be set as 5 and 75, respectively. If P^{c} is no greater than the given threshold P_{th}^{c}, the collision probability meet the application requirements. Under this condition, we first evaluate whether or not the upper bound C_2 exceeds the strict delay threshold. If not, C_1 is gradually incremented from $C_{\min}$ to $\overline{C} - 1$. The delay outage probability P^{d} is computed. If the obtained P^{d} does not exceed the given threshold P_{th}^{d}, both $\overline{C}$ and C_1 are regarded as tolerable. Although there may be more than one value of $\overline{C}$ satisfying both conditions, the first combination of $\overline{C}$ and C_1 we find satisfying all conditions is the output. If no $\overline{C}^*$ or C_1^* is found, NULL is returned by the algorithm, indicating that the application-layer demand on reliability and delay are infeasible. It is suggested to relax reliability and delay requirements or narrow the target beacon range for performance improvement.

Different mobility patterns will result in different levels of dynamics of the network topology and thus mobility pattern of vehicles plays an important role on network performance. Nevertheless, adapting the protocol parameters to network dynamics is beneficial. In the proposed MAC design, protocol parameters, including the sensing range, transmit power and resource reservation, are optimized periodically to deal with changing topology. As a result, high-reliability and low-latency services can be maintained in networks with different mobility patterns.

VI. Performance Evaluation

In this section, we verify the correctness of the proposed analytical model for SPS and evaluate the performance of the proposed adaptive sensing and reservation MAC design. The traffic flow is generated with SUMO [31]. The distributed resource scheduling and beacon broadcasting process are simulated using Python. The developed simulator is available as open-source[2]. The test cases involve beacon broadcasting in both urban and highway scenarios. Overall, we consider a 4-km two-way road, where at most three lanes are in each direction. Parameters regarding road condition and the C-V2X network are given in TABLE II. The road condition, channel condition, and beacon requirements are set following [22] and [23]. Since we investigate the adaptation and optimization of the sensing range, transmit power, and resource reservation, the suggested values in the 3GPP standard are considered, and we further tune them to compare the performance.

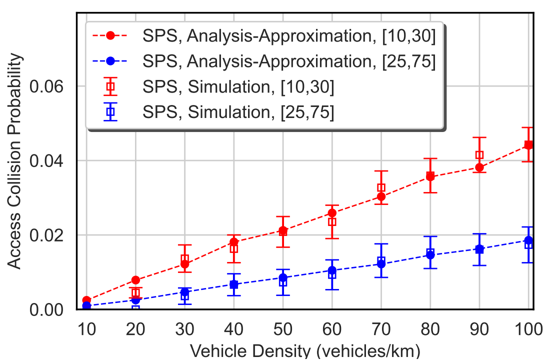
A. Analysis Verification

First, we verify the correctness of the presented analytical model in Section IV. The comparison between analytical results and the simulations for different vehicle densities are shown in Fig. 7. Here, the beacon range is set as 150 m, which is smaller than the theoretical maximal transmission distance of 200 m. The beacon rate is set as 50 Hz so the total number of available resources is 40. The simulations have been run 100 times for 10 s. For different vehicle densities, the mean values and the standard deviations of the access collision probability and delay outage probability are given. It is found that the theoretical values are basically within one standard deviation from the mean. Hence, the correctness of the proposed analytical model is validated.

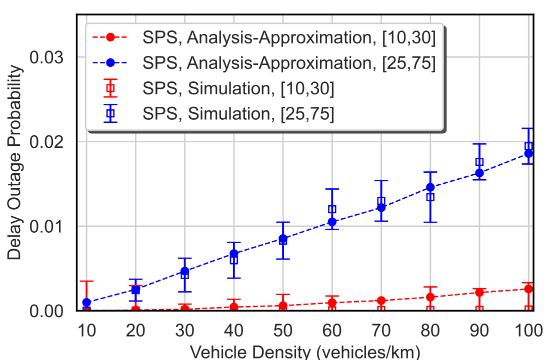
[2]https://github.com/xinuvic/Simulators-for-SPS

TABLE II
PARAMETER SETTINGS

Parameters	Value
Road length l	4 km
Vehicle density λ	10∼320 vehicles/km
Vehicle speed v	10∼30 m/s
Transmit power P^{t}	23 dBm, variable
Path-loss exponent γ	3.68
Path-loss constant K_0	$10^{-4.38}$
Channel Bandwidth	10 MHz
Noise PSD N_0	-174 dBm/Hz
Minimum SINR $SINR_{\mathrm{th}}$	2.76 dB
Beacon rate R	10 Hz, 20 Hz, 50 Hz
Beacon size b	300 bytes
Beacon range d_{br}	80 m, 100 m, 150 m, 180 m
Delay threshold D_{th}	100∼1000 ms
Selection window lower bound T_1	≤4 ms
Selection window higher bound T_2	$1/R$
Modulation and coding scheme	MCS-4
RC range $[C_1, C_2]$	$[5, 15]$, $[10, 30]$, $[25, 75]$, variable
Size of sensing window T_{s}	1 s
Power level threshold P_{th}	-110 dBm, variable
Sensing range d_{sen}	variable
Probability of resource keep p_0	0



(a) Access collision probability.

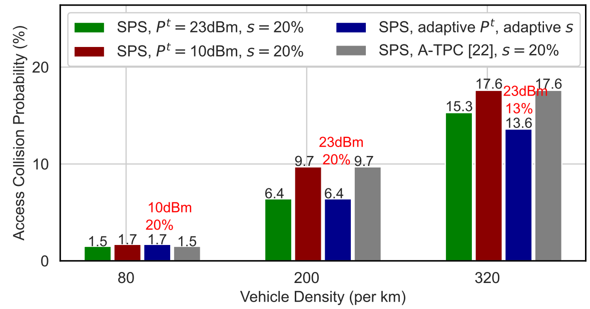


(b) Delay outage probability.

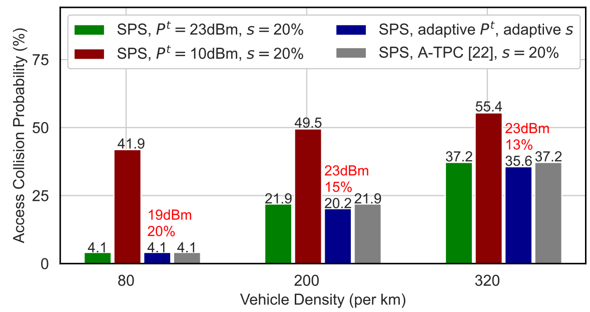
Fig. 7. Comparison between simulation and theoretical results in terms of access collision probability and delay outage probability for different number of vehicles, where the beacon rate is 20 Hz, the beacon range is 150 m and the delay threshold is 1000 ms.

B. Evaluation of Adaptive Sensing and Power Control

Next, we evaluate how the proposed sensing range adaptation and power control benefit reliability and power saving.



(a) The beacon range is 80 m.



(b) The beacon range is 150 m.

Fig. 8. SPS collision probability with and without sensing range adaptation and power control and with adaptive-transmit power control (A-TPC) in [22] for different beacon range requirements. The beacon rate is 20 Hz.

Simulations are conducted to compare the access collision probability obtained by SPS with and without the sensing range adaptation and power control, and that obtained by SPS with the adaptive-transmit power control (A-TPC) algorithm in [22]. To handle the congestion problem in the traffic scenarios with high vehicle density, the A-TPC was proposed to lower the transmit power to reduce interference for a desired transmission distance. The comparison results for the above three solutions are shown in Fig. 8. Two scenarios are investigated with varying traffic densities (80, 200, and 320 vehicles per km), where the beacon range is 80 m and 150 m, respectively. The beacon rate is set as 20 Hz in these two scenarios.

As shown in Fig. 8, the green and red bars represent the results obtained with the fixed P^{t} and s in SPS, and the blue bars represent the results obtained with the adaptive P^{t} and s. The adapted values are also given and marked in red. The grey bars represent the results obtained with the A-TPC algorithm in [22]. When the parameters are fixed, P^{t} is set to 23 dBm or 10 dBm. s is set to 20% according to the 3GPP configuration.

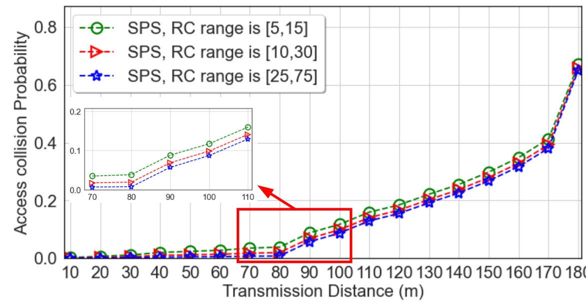
Fig. 8 (a) shows the simulation results when the beacon range is 80 m. When the vehicle density is low (80 vehicles per km), the access collision probability has only a slight decrease when P^{t} is reduced from 23 dBm to 10 dBm. Following the adaptation rules in Section V-B, the transmit power is adjusted to 10 dBm for power saving. When the vehicle density is higher (200 or 320 vehicles per km), setting the transmit power as 10 dBm is not a good choice as the access collision probability is dramatically increased when the transmit power varies from 23 dBm to 10 dBm. Therefore, the transmit power is set as the maximal value, 23 dBm in our design, which corresponds to the analytical results in Section V-B. Moreover, the sensing range is adjusted to 13% when the vehicle density is as high as 320 vehicles per km according to Section V-A. As shown in Fig. 8 (a), with the transmit power as 23 dBm, the access collision probability is reduced from 15.3% to 13.6% thanks to the adapted s. When the A-TPC algorithm is adopted, the power is set as 23 dBm for the low density (80 vehicles per km) scenario. However, the power is adjusted to 10 dBm to control interference if density is increased up to or over 200 vehicles per km. This is because the A-TPC algorithm guarantees the communication reliability for the transmission at a distance of 80 m instead of the overall communication performance for all receivers within the beacon range.

Fig. 8 (b) shows the comparison of the simulation results obtained by different sensing range and power settings when the beacon range is 150 m. With a larger beacon range, the access collision probability in Fig. 8 (b) is higher than that in Fig. 8 (a) with the same P^t and s. Moreover, the transmit power has a great impact on communication reliability. For example, the access collision probability is increased from 4.1% to 41.9% when P^{t} is reduced from 23 dBm to 10 dBm for the density of 80 vehicles per km. To enable high reliability in this case, the transmit power is set as 19 dBm based on (16) in our adaptation solution. From Fig. 8 (b), we can also find that the access collision probability is decreased thanks to the adapted s when the vehicle density is 200 or 320 vehicles per km. When the A-TPC algorithm is adopted, as the gray bars show, the maximal transmit power 23 dBm for transmission at a distance of 150 m. Our proposed adaptation outperforms the A-TPC algorithm for high-density scenarios, thanks to the sensing range adaptation. Overall, Fig. 8 shows the effectiveness of our proposed sensing range adaptation and power control in terms of access collision reduction and power saving.

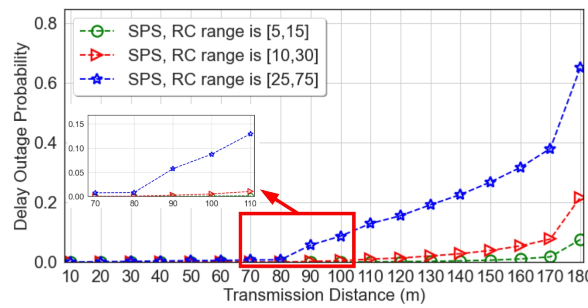
C. Evaluation of Resource Reservation Optimization

Furthermore, we investigate how resource reservation impacts the system performances in terms of both collision and delay. In the SPS scheme, the RC is an indicator for the duration of resource reservation, and its range affects both access collision probability and delay outage probability. In the following, we first study the performance of three RC ranges provided by the standard, i.e., $[5, 15]$, $[10, 30]$, $[25, 75]$, and then compare our proposed resource reservation adaptation against the standard.

The broadcast performance curves for different beacon ranges are plotted in Fig. 9. The access collision probability and delay outage probability are presented in Fig. 9 (a) and (b), respectively. When the transmission distance is within 80 m, the access collision probability is below 5%, indicating relatively high reliability with C-V2X SPS. However, both the access collision probability and delay outage probability grow dramatically if the distance increases over 80 m. The comparison among three standard RC ranges can also be observed in the figure. The range $[25, 75]$ brings about the lowest access collision probability, compared to the other two ranges. Nevertheless, it leads to very high delay outage



(a) Access collision probability.



(b) Delay outage probability.

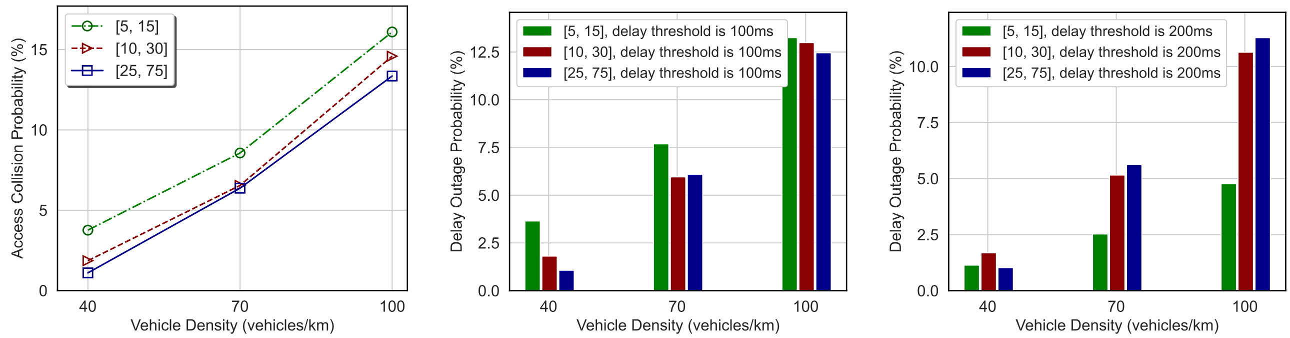
Fig. 9. Performance versus the transmission distance in terms of access collision probability and delay outage probability. The beacon rate is 50 Hz.

probability for the long-distance beacon transmission. Once the access collision probability is high enough, consecutive collision is more likely to happen with a long period of resource reservation. When it comes to autonomous driving, it's necessary to control the delay outage probability for beacon exchange between vehicles no matter whether they are very close or more than 100 m apart.

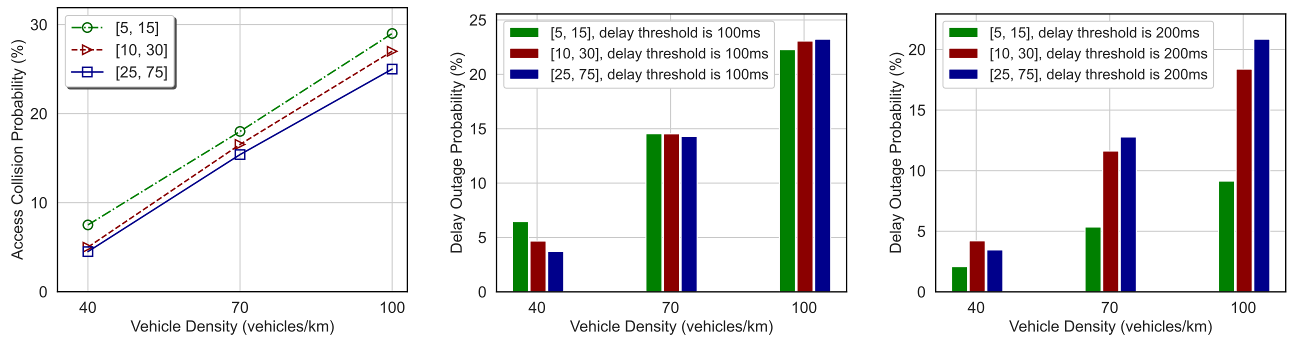
From the above discussion, it's necessary to study the average delay outage probability over all transmission distances. In Fig. 10, comparison of the simulation results obtain by three standard RC ranges are provided. In the simulations, the beacon rate is set as 50 Hz. Figs. 10 (a), 10 (b) and 10 (c) show the results of beacon transmission within 100 m, while Figs. 10 (d), 10 (e) and 10 (f) are corresponding to 150 m. Figs. 10 (a) and 10 (d) both plot the access collision probability in the case of three different RC ranges. Figs. 10 (b) and 10 (c) show the delay outage probabilities with different delay thresholds, i.e., 100 ms and 200 ms.

Overall, it is found that the largest RC range $[25, 75]$ is superior to other two ranges in terms of access collision probability. However, the largest RC range does not always result in the lowest delay outage probability. When $d_{\mathrm{br}} = 100$ m and $D_{\mathrm{th}} = 100$ ms, the performance of $[25, 75]$ is generally the best, because delay less than 100 ms means no resource reservation conflict. Nevertheless, no matter when d_{br} equals 100 m or 150 m, the smaller RC ranges $[5, 15]$ and $[10, 30]$ outperform $[25, 75]$ when the delay threshold is 200 ms for most densities. We also study the scenarios where the delay threshold is 500 ms and 1000 ms, finding that the delay outage probability obtained by $[25, 75]$ is more than three times of that obtained by $[10, 30]$. In this respect, the ranges $[5, 15]$ and $[10, 30]$ are more desirable than $[25, 75]$.

This article has been accepted for publication in IEEE Transactions on Vehicular Technology. This is the author's version which has not been fully edited and content may change prior to final publication. Citation information: DOI 10.1109/TVT.2022.3223414



(a) Access collision probability, $d_{\text{br}} = 100\,\text{m}$. (b) $d_{\text{br}} = 100\,\text{m}$, $D_{\text{th}} = 100\,\text{ms}$. (c) $d_{\text{br}} = 100\,\text{m}$, $D_{\text{th}} = 200\,\text{ms}$.



(d) Access collision probability, $d_{\text{br}} = 150\,\text{m}$. (e) $d_{\text{br}} = 150\,\text{m}$, $D_{\text{th}} = 100\,\text{ms}$. (f) $d_{\text{br}} = 150\,\text{m}$, $D_{\text{th}} = 200\,\text{ms}$.

Fig. 10. Performance comparison of three standard RC ranges, $[5, 15]$, $[10, 30]$, $[25, 75]$, considering different delay thresholds provided by the application layer. The beacon rate is 50 Hz. (a) and (d) are the access collision probability when the beacon range is 100 m and 150 m, respectively. (b)-(c) and (e)-(f) are the delay outage probability when the beacon range is 100 m and 150 m, respectively. The delay threshold is 100 ms in (b) and (e), and 200 ms in (c) and (f).

The RC range $[25, 75]$ is a good choice for beacon broadcasting when delay above 100 ms is intolerable. However, safety issues may arise when disconnection between vehicles lasts for a long time, especially for autonomous driving services highly depending on beacon broadcasting. Our proposed resource reservation adaptation aims to cope with the above challenges by adapting the RC range to delay requirements under dynamic density conditions.

Our proposed adaptive resource reservation (ARR) algorithm aims to obtain low access collision probability on the premise of satisfying delay requirement, by optimizing the RC range. To verify the superiority of our adaptation design, the SPS with ARR (SPS-ARR) is compared with two methods in simulations. One is the legacy SPS using the RC ranges given in the standard, and the other is a resource alternation selection (RAS) algorithm presented in [27]. By reserving and allocating multi-resources alternatively, the RAS algorithm was proposed to solve the continuous collision problem in SPS, so that long delay was avoided. In the simulations, three different cases are studied, denoted by Cases 1, 2, and 3. The comparison results are shown in TABLE III. Two performance metrics are observed, which are access collision probability and delay outage probability, denoted by ACP and DOP, respectively.

Instead of fixing the beacon range, we set the number of receiving vehicles to 10 on a six-lane highway for all the three cases. The first two cases indicate the common vehicular service scenario, where vehicles in the neighborhood exchange beacon messages for safety purpose. The beacon rate is 10 Hz and 20 Hz in Cases 1 and 2, respectively. We pay attention to the reliability of beacon delivery to the closest 10 neighbor vehicles with the delay threshold set as 300 ms and the vehicle density as 60 vehicles per km. The third case corresponds to an advanced vehicular service scenario, which requests more frequent beacon exchange among vehicles. The beacon rate is 50 Hz. The vehicle density is 180 vehicles per km. The delay threshold is set as 500 ms in Case 3.

TABLE III
ACCESS COLLISION PROBABILITY (ACP) AND DELAY OUTAGE PROBABILITY (DOP) OBTAINED BY SPS WITH AND WITHOUT THE ARR ALGORITHM, AND OBTAINED BY THE RAS ALGORITHM [27]

Beacon rate	Performance metric	SPS	SPS-ARR	RAS [27]	RAS-ARR
Case 1 (10 Hz)	ACP	1.57%	0.82%	2.58%	1.80%
	DOP	1.57%	0.82%	0.08%	0.03%
Case 2 (20 Hz)	ACP	1.84%	0.93%	2.65%	2.18%
	DOP	1.84%	0.93%	0.14%	0.07%
Case 3 (50 Hz)	ACP	12.78%	12.89%	19.77%	19.41%
	DOP	6.94%	4.07%	2.26%	1.12%

As shown in TABLE III, the access collision probability and delay outage probability can be reduced below 1% when SPS is implemented with ARR, in Cases 1 and 2. Using the ARR algorithm, the RC range is optimized as $[5, 23]$ for Case 1 and as $[10, 42]$ for Case 2. When the beacon rate is 10 Hz, the transmission interval is 100 ms. Delay of no longer than 300 ms means continuous collisions of no more than 3 times.

Since the lower bound of the RC range is 5 for both SPS and SPS-ARR, the delay is to exceed 500 ms once collision occurs. As a result, the delay outage probability equals the access collision probability in Case 1.

For Case 2, the access collision probability also equals the delay outage probability when SPS or SPS-ARR are adopted. However, for the RAS algorithm, the delay outage probability is much lower than the access collision probability. The RAS algorithm brings about the lowest delay outage probability among the three MAC schemes. This is owing to the alternative selection of multiple resources for one vehicle to use, lowering the risk of consecutive collisions. However, the delay performance is improved at the cost of reliability. We can find that RAS leads to the highest access collision probability. In addition, we evaluate the reliability and delay performances when RAS [27] is combined with our proposed ARR. The combination MAC scheme is denoted by RAS-ARR, as shown in TABLE III. Compared with the RAS algorithm, the combination algorithm leads to reduction in both access collision probability and delay outage probability.

For Case 3, the application-layer requirements are set as follows. The vehicular service requests less than 500 ms delay with the outage probability lower than 5%, and the access collision probability should be no more than 15%. Performance comparison is illustrated in TABLE III. Although the RC range $[25, 75]$ is suggested by the C-V2X standard to support beacons transmitted every 20 ms, the obtained delay outage probability is 6.94%, above the maximal tolerable value 5%. By adopting the proposed ARR algorithm, the optimal RC range $[5, 61]$ is derived. Compared to $[25, 75]$, $\overline{C}$ is decreased by 14 while only a minor change is seen in the range width. In this way, the delay outage probability can be reduced from 6.94% to 4.07%, satisfying the delay requirement.

By adapting the resource reservation to the required beacon rate, dynamic traffic density, and demand for beaconing reliability, the variable RC range outperforms those given by the current C-V2X standard. When the RAS algorithm is adopted, the delay outage probability is reduced to 2.26% while the access collision probability is increased up to 19.77%, which exceeds the upper bound of 15%. For the RAS algorithm in combination with ARR, the delay outage probability can be further reduced to 1.12% and the combination brings a slight decrease of access collision probability.

Compared to the legacy SPS and the RAS algorithm [27], the proposed adaptive MAC design is superior in maintaining high reliability and low latency services in dynamic vehicle density scenarios. The simulation results also show that our proposed ARR has the potential to be combined with other MAC enhancement solutions to further improve the broadcasting performance.

VII. Conclusion

To address the reliability and timeliness concerns on SPS, this paper has presented an analytical model for SPS and identified those factors that impact the performance and are relevant to the standard configuration. The system performance has been evaluated by the access collision probability and delay outage probability, which are both important for advanced services like autonomous driving. Furthermore, we proposed to enhance the MAC design by adapting and optimizing protocol parameters, including the sensing range, transmit power and resource reservation. Our proposed scheme has taken into account vehicle density as well as various requirements on the beacon rate and the beacon range. With the enhance MAC, trade-off between high reliability and low latency can be made. Extensive simulations have verified the accuracy of the proposed analytical model. The results have shown that the enhanced MAC design benefits the reduction of collision and delay, compared with the existing SPS configuration. Overall, the analytical model as well as the optimization solution provides important guidelines for improving the system configuration in C-V2X.

The proposed analytical model is suitable for performance analysis of SPS for periodical beacon broadcasting, while event-driven emergency messages may be transmitted aperiodically on the same shared channel requiring extremely low latency. How to coordinate the radio resource allocation for both beacon and event-driven messages with the differentiated service priorities should be further investigated. For example, the transmit power for periodic beacons can be decreased to improve the communication reliability of event-driven messages when they coexist. Also, the SPS can be implemented with pre-emption to accommodate aperiodic event-driven messages.

Appendix

The derivation of $N_{\text{R}}(d_{i,k})$ is given in the following. For v_i, the number of vehicles in its sensing range is $2\lambda d_{\text{sen}}$. The number of vehicles within the common sensing range of v_i and v_k is $\lambda(2d_{\text{sen}} - d_{i,k})$. Let N_{cr} denote the number of resources occupied by the vehicles within the common sensing range of v_i and v_k, and N_{sr} denote that within the sensing range of any vehicle.

The problem of computing N_{cr} 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. We have

$$N_{\text{cr}}(d_{i,k}) = N_{\text{subch}} \left[1 - \left(1 - \frac{1}{N_{\text{subch}}} \right)^{\lambda(2d_{\text{sen}} - d_{i,k})} \right]. \quad (18)$$

Similarly, N_{sr} can be computed by

$$N_{\text{sr}} = N_{\text{subch}} \left[1 - \left(1 - \frac{1}{N_{\text{subch}}} \right)^{2\lambda d_{\text{sen}}} \right]. \quad (19)$$

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. Thus, $M(d_{i,k}) = N_{\text{sr}} - N_{\text{cr}}(d_{i,k})$. Let $K(d_{i,k})$ denote the total number of resources within one transmission interval minus the average number of resources selected by vehicles in the common sensing range. Thus, $K(d_{i,k}) = N_{\text{subch}} - N_{\text{cr}}(d_{i,k})$. The number of candidate resources of v_i equals the difference between $K(d_{i,k})$ and $M(d_{i,k})$. For any candidate subchannel of v_i, the probability that it is also in the candidate list of

v_k equals $\left[1-\frac{1}{K(d_{i,k})}\right]^{M(d_{i,k})}$. Therefore, $N_{\rm R}(d_{i,k})$ can be computed by

$$N_{\rm R}(d_{i,k}) = [K(d_{i,k}) - M(d_{i,k})]\left[1-\frac{1}{K(d_{i,k})}\right]^{M(d_{i,k})}. \quad (20)$$

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This article has been accepted for publication in IEEE Transactions on Vehicular Technology. This is the author's version which has not been fully edited and content may change prior to final publication. Citation information: DOI 10.1109/TVT.2022.3223414

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