SideSeeker: Contention-Based Distributed Relay Finding for Sidelink Mesh Networks

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***Abstract*—Sidelink relays are critical for enabling multi-hop peer-to-peer communications and ensuring connectivity of 6G sidelink mesh networks. To find proper sidelink relays without centralized coordination, a scheme of distributed relay discovery and selection named *SideSeeker* is designed with two key mechanisms. First, a two-dimensional contention scheme in time and frequency dimensions is designed based on short-term sensing, such that the collision of control signals is alleviated. Second, a mechanism of source-relay pair selection is developed, which prevents data congestion at a certain relay. With *SideSeeker*, the throughput over sidelinks outperforms those of baseline schemes by 19.4 – 36.9%.**

***Index Terms*—Sidelink mesh, relay discovery and selection.**

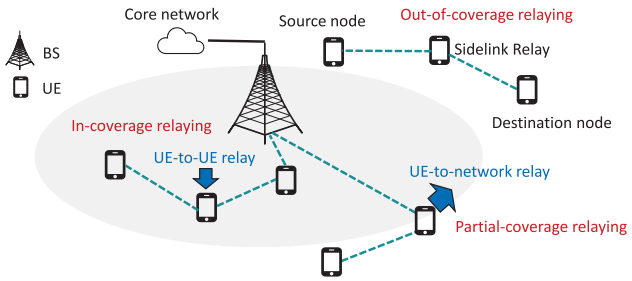


Fig. 1. A sidelink mesh network.

I. Introduction

SIDELINK communication has been introduced as one of the key enablers for future wireless networks in the Third Generation Partnership Project (3GPP) standards [1], [2]. With peer-to-peer direct communication enabled, the sidelink communication paradigm supports various scenarios of ***sidelink mesh networks***, such as automotive networks and massive Internet-of-Things (IoT) networks [3].

In sidelink mesh networks, ***sidelink relays*** forward data between the base station (BS) and user equipment (UE) (UE-to-network), or between UE and UE (UE-to-UE), as shown in Fig. 1. To enhance network connectivity and combat unpredictable link blockage and failures, sidelink relays must be efficiently discovered and selected, and the corresponding sidelinks must be established. As shown in Fig. 1, several types of sidelink relaying are supported: in-coverage, partial, and out-of-coverage relaying, depending on whether the sidelink relays are within the coverage of BS. For in-coverage relaying, relay discovery and selection can be determined in a centralized way by BS [1]. For partial and out-of-coverage relaying, however, sidelink relays need to be discovered and selected in a distributed way to maintain high transmission efficiency.

This letter is focused on how to design an efficient distributed relay finding mechanism (i.e., relay discovery and selection mechanism) for sidelink mesh networks. Existing distributed relay finding solutions have limited performance for the following two reasons.

First, as the control signals involved in distributed relay finding are generally aperiodic and spontaneous, the existing mechanisms [3], [4], [5] suffer from low transmission efficiency of these control signals. In the 3GPP standards [4] for sidelink communications, both control and data packets are transmitted by an autonomous resource selection scheme named *Mode 2*. However, Mode 2 is proved to be inefficient in transmitting aperiodic packets [3], as only long-term sensing (LTS) is conducted to alleviate collisions. In [5], short-term sensing (STS) used in Listen Before Talk (LBT) schemes is first applied in sidelink networks to facilitate more aperiodic transmissions. However, transmissions cannot multiplex in frequency since STS occurs only in the time dimension [5], leading to low transmission efficiency. Additionally, the contention-based transmission protocols such as carrier sensing multiple access (CSMA) in 802.11 systems [6] cannot be directly used for sidelink networks, as their system configurations are different in the aspects of time synchronization, wireless resource structures, and frame formats.

Second, there exists a node pairing problem between the nodes requesting for relays (i.e., source nodes in Fig. 2) and the candidate relays: how a relay node selects the desired source nodes to send responses, and how a source node selects the best relay for subsequent data transmission. This node pairing problem is also termed as source-relay pairing or bi-directional relay selection in this letter. In [7], only one source-destination pair is considered in an 802.11 network, and a relay is randomly selected out of all the relays with successful contention. The existing selection schemes [8], [9], [10] assume that contention only exists among the source or relay nodes. In these schemes, the node pairing is only determined on one side, i.e., the source node selects the relay based on signal strengths, while relays are unable to filter requests from source nodes on their own. This can cause congestion

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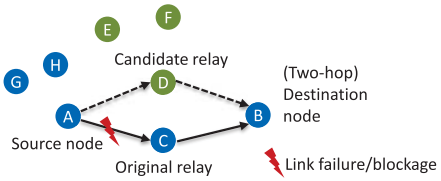


Fig. 2. Two-hop sidelink relaying scenario.

at a certain relay during data transmission if many densely-distributed source nodes select the same relay.

In this letter, a scheme of distributed relay discovery and selection named ***SideSeeker*** is designed. To fully resolve the above issues, two key mechanisms are developed. First, to reduce the collision ratio of aperiodic control signals and the delay of accessing a relay, a two-dimensional contention mechanism in both time and frequency dimensions is designed based on STS. The two-dimensional random backoff and priority-based contention window determination are designed for sidelink control signal transmission. Due to different system configurations compared with 802.11 protocols, the designed mechanism is distinct in the following aspects: 1) each sidelink contention conforms to time slot alignment; 2) the backoff process fits in the sidelink resource pool; 3) the carrier sensing requires the detection of sidelink reference signals; 4) the contention window size is decided based on the priority of control signals. With the designed contention mechanism, the collisions in sidelink relay discovery and selection can be significantly alleviated. Second, to fulfill bi-directional relay selection, a mechanism of selecting transmission pairs is designed. Upon receiving requests from source nodes, a relay prioritizes the requests, and selects the high-priority source nodes to send responses. For a source node, it matches itself with the relay with the highest link quality. In this way, congestion can be alleviated at each relay during sidelink data transmission, and throughput is improved for the sidelink mesh network.

The rest of this letter is organized as follows. The overall framework is presented in Section II, and two key mechanisms are stated in Section III. The designed scheme is evaluated in Section IV, and the conclusions are drawn in Section V.

II. System Model and Overall Framework

As shown in Fig. 2, a two-hop sidelink relaying scenario is investigated, consisting of source nodes (node A, G, and H), sidelink relays (node C, D, E, and F), and destination nodes (node B). The designed mechanisms can be extended to the multi-hop case by dividing multi-hop links into groups of two-hop links. Specifically, node D, E, and F serve as partial/out-of-coverage candidate relays, while node C is the operating relay connecting the source node A to the destination node B. When operating sidelinks, such as link A-C (from node A to C), encounter blockage or failures, new sidelink relays must be discovered and selected to maintain connectivity of sidelink mesh. There may exist multiple source nodes such as node G and H requiring to find new relays as well. It is assumed that the two-hop destination node is pre-known by the source nodes [11], and single-path forwarding is adopted. In this letter, we focus on semi-static and low-mobility networks

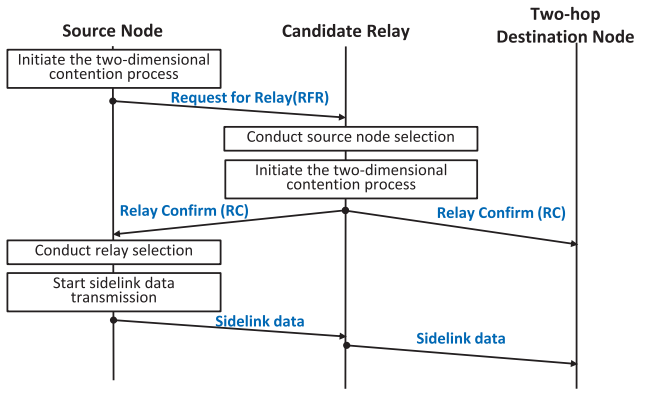


Fig. 3. Overall signaling framework.

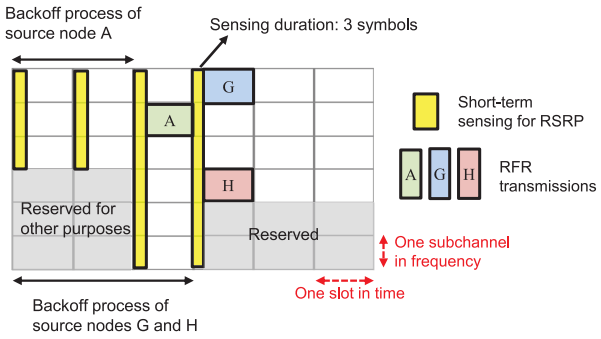


Fig. 4. Two-dimensional contention for transmitting RFR signals.

(e.g., pedestrian networks) where the two-hop information does not require frequent updates. Node mobility can be ignored in the relay finding process that is on the timescale of milliseconds. How to reduce protocol overheads and two-hop information updating costs in high-mobility sidelink networks (e.g., vehicular networks) is left for future investigation.

The overall signaling framework is illustrated as in Fig. 3. First, when the source node is in need of a new relay, it initiates the two-dimensional contention mechanism to broadcast *Request for Relay (RFR)* signal. Second, after the candidate relay receives multiple RFR signals from different source nodes, it selects the appropriate source nodes to respond to. The selection result as well as the local long-term sensing results is encoded into *Relay Confirm (RC)* signal. The candidate relay initiates the contention process to broadcast RC, such that potential collisions among relays can be alleviated. Third, upon receiving RC signals, the source node can select the proper relay to form a transmission pair. Then the source node starts periodic sidelink data transmission based on the standard Mode 2 scheme. Furthermore, the source node integrates the piggybacked long-term sensing results from the relay with its own long-term sensing data, so as to alleviate hidden node problems during the sidelink data transmission phase. Such an inter-node coordination mechanism in Mode 2 is elaborated in [1], [3].

Regarding the radio resources carrying sidelink signals, there exists a resource pool occupying a number of slots in time and subchannels in frequency, as shown in Fig. 4. Each subchannel is composed of physical resource blocks (PRB) [1].

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Each transmission of RFR and RC signals can occupy one or multiple subchannels in the resource pool [2]. Before the contention process of transmitting RFR and RC, those resources reserved for sidelink data transmission or other purposes are already excluded from the resource pool (as shown in Fig. 4). Aligning with the standards [1], reference signal received power (RSRP) can be obtained by detecting sidelink reference signals, which is used as a critical measurement of resource occupation.

III. SideSeeker: Design of Distributed Relay Discovery and Selection

The design of *SideSeeker* includes two interleaving parts: 1) the mechanism of two-dimensional contention with STS for transmitting RFR and RC signals; 2) the mechanism of source-relay pairing. Note that the selection results are encoded into RFR and RC signals. Therefore, the pairing process is conducted along with RFR and RC transmission. The two mechanisms are elaborated in the following.

A. Two-Dimensional Contention With Short-Term Sensing

Short-term sensing is viewed as a common practice in LBT mechanisms, where the transmitter senses the channel right before it transmits the signal. The sensing duration is as short as tens of microseconds [5]. On the contrary, long-term sensing (LTS) in Mode 2 incorporates the sensing window that lasts for hundreds or even thousands of milliseconds before transmission [3]. The sensing results from LTS are used to exclude resources in the resource selection window, which comes subsequently after the sensing window. In the resource selection window, resources are randomly selected without instantaneous sensing. It is evident that LTS can hardly benefit aperiodic transmission of control signals, as the information extracted from the long sensing window is outdated. Therefore, STS is adopted for RFR and RC transmission, where the priority-based contention windows and two-dimensional random backoff are specially designed for sidelink transmissions. As shown in Fig. 4, the two-dimensional contention mechanism means that the resources are contended in both the time and frequency dimensions of a resource pool. Note that the detailed contents of control signals will be presented in Section III-B.

Regarding RFR transmission, as shown in Fig. 4, multiple source nodes, such as node A, G, and H, initiate the relay discovery process by broadcasting RFR signals. In the resource pool as described in Section II, each source node n determines its adaptive contention window size W_n based on its priority indicator p_n. Specifically, a monotonically decreasing function f can be applied on p_n to obtain W_n, i.e., $W_n = f(p_n)$, such that a node with a higher priority has a smaller contention window size. In practice, p_n is affected by service requirements, delay budgets, and among other factors [6].

With the contention window determined, the source node initiates the two-dimensional random backoff process, which is specially designed to fit in the resource pool. It includes 1) short-term sensing; 2) exponential backoff control. For short-term sensing, the source node's sensing duration is set to three OFDM symbol time, i.e., $3T_{\mathrm{s}}$, at the beginning of each slot, and RSRP is measured for each subchannel and also each slot. The reason for setting a three-symbol sensing duration is that the sidelink reference symbols are inserted into the first three symbols of each OFDM frame [1]. If the measured RSRP over these reference signals is larger than the predetermined threshold, the corresponding subchannel in the current slot is deemed as busy, and otherwise it is idle. For backoff control, a random integer is uniformly generated within $[0, W_n]$ at source node n as the initial value of backoff counter. In each slot, the backoff counter value decreases by the number of idle subchannels based on STS. Let $c[t]$ be the backoff counter value at slot t, and $s[t]$ be the number of idle subchannels detected at slot t. Then the updating rule of backoff control is expressed as $c[t] = \max(c[t-1] - s[t], 0)$. When the counter value is equal to 0, the source node randomly selects one subchannel to broadcast RFR signal in the following slot. If this source node does not receive any eligible response in the future N_{S} slots (i.e., the time-out period), then its contention window size will be doubled and retransmission is initiated. It is noted that the waiting time before RFR transmission depends on the contention window size as well as resource occupation over the resource pool. If a source node has a smaller contention window and senses more idle subchannels locally, there exists a higher probability that its RFR signal will be sent out earlier than other peer nodes.

The transmission of RC signals is also based on two-dimensional contention mechanism with STS. However, compared with the above process, the relay nodes adopt the same fixed contention window size W_{R}. It is not necessary to set diverse contention window sizes for RC transmission as all RC signals should share the same priority, i.e., they need to be sent back to source nodes as soon as possible. With a proper choice of the contention window size W_R, setting the same window size for RC transmission will not have a negative impact on the collision ratio, which will be evaluated in Section IV. RC signals are only re-transmitted upon the reception of RFR, and thus there is no time-out period being set up.

B. Selection of Source-Relay Pairs

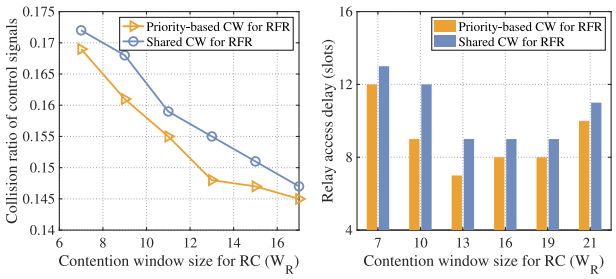
With RFR and RC transmissions, source-relay pairs need to be selected among multiple source nodes and candidate relays. This selection process is divided into two steps: 1) upon receiving RFR signals, a candidate relay needs to select the appropriate source nodes to respond to; 2) upon receiving RC signals, a source node needs to select a single relay for subsequent sidelink data transmission. The information carried by control signals is stated as follows. The RFR broadcasting signal sent by source node n contains: 1) self-ID n; 2) priority indicator p_n; 3) the pre-known two-hop destination node ID. The RC broadcasting signal sent by the candidate relay includes: 1) self-ID m; 2) the selected source node IDs; 3) the local long-term sensing results as stated in Section II that will be used in the phase of sidelink data transmission.

For the selection of source node by a candidate relay, the received RFR signals in slot t are evaluated based on the following two criteria. First, the RSRP of RFR signal needs to be higher than the predetermined threshold. Second, the destination ID contained in the RFR signal is examined, and

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the candidate relay checks whether the destination node can be reached. Such information can be historically saved in the relay's neighboring node table [11]. The relay then selects the source node whose RFR satisfies the above criteria. On one hand, if no received RFR in the current slot satisfies these two criteria, the candidate relay will discard the received ones and continue RFR detection in the next slot, i.e., slot $(t+1)$. On the other hand, if multiple received RFR signals satisfy the criteria simultaneously, the candidate relay will further compare the priority indicator p_n specified in RFR, and select the source nodes with the highest priority. After this selection step, the relay initiates the two-dimensional contention process and discards any other RFR signals.

For the selection of relay by a source node, there also exist two criteria for evaluating the received RC signals. First, the RSRP needs to surpass the pre-determined threshold. Second, the selected source ID contained in RC signal is compared against the source node self-ID, and the received RC is considered as eligible if they are the same nodes. Otherwise, the received RC will be discarded. The source node will keep receiving RC signals in each slot until the above criteria are met. When there exist multiple received RC signals that are eligible that all destined for this source node, the source node selects the relay whose RC has the highest signal strength. Then, the source node initiates sidelink data transmission via the selected relay.



(a) Collision ratio (b) Relay access delay

Fig. 5. Collision ratio and relay access delay in slots with various contention window sizes W_{R}.

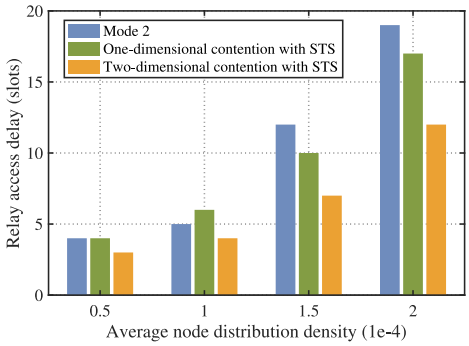


Fig. 6. Relay access delay with various node distribution densities.

IV. Performance Evaluation

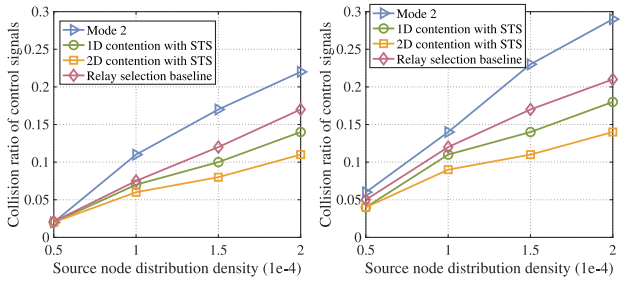
The two-hop sidelink relaying scenario with multiple source and relay nodes as shown in Fig. 2 is considered. The carrier frequency is 4 GHz, and the resource pool configured for sidelink transmission consists of 13 PRBs [1]. Each subchannel occupies one PRB bandwidth, i.e., 12 subcarriers with 15 kHz spacing, and each slot has 14 OFDM symbols. The time-out period for the source node N_{S} is 5 slots. The source node priority p_n is set proportional to the number of flows congested at source node n, and it is normalized into $(0,1]$. As p_n approaches 1, the priority becomes higher. The contention window size W_n follows $W_n = W_{\mathrm{S}}/p_n$, with the smallest window value $W_{\mathrm{S}} = 13$. The common contention window size for relays W_{R} is set to 13. The transmit power of each source or relay node is set as 24 dBm [2]. The path loss model follows $PL = 36.85 + 30log_{10}(d) + 18.9\log_{10}(f_c)$ [3], where d is the distance between two nodes and f_c is the carrier frequency. The shadowing standard deviation is set as 7 dB log-normal, and the fast-fading model adopts 3GPP TDL-A channel model [12]. The source nodes and candidate relays are distributed based on two independent spatial homogeneous Poisson Point Processes (PPP). The simulation area is set as $500m \times 500m$ with a square unit region of $1m^2$. The node distribution density is defined as the constant intensity in spatial PPP. The noise power spectrum density is -168 dBm/Hz. The interfering range is 300 m, and the received signal detection threshold is set to 10 dB. Only one retransmission of RFR is allowed, aligning with the evaluation guidelines of sidelink transmission in 3GPP standards [1].

Four baselines are considered: 1) standard Mode 2 scheme [1]; 2) one-dimensional contention with STS only in the time dimension [5]; 3) the one-side-contention-based relay selection baseline by adapting key features in [8], [10] to the sidelink set-up; 3) the variant of *SideSeeker* with RSRP-based relay selection only at the source nodes. The relay access delay is defined as the average number of slots for a source node to successfully receive the matched RC signal, considering all the source nodes. In addition, the collision ratio of control packets is defined as the ratio of control packets that are not successfully received due to collision. The severity of contention is characterized by the source node distribution density and relay node distribution density in the interfering region, varying from 0.5×10^{-4} to 2×10^{-4} per m^2. The following results are averaged over 100 random realizations.

First, the ablation study on various contention window (CW) sizes are shown in Fig. 5. As CW size for RC transmission W_R increases from 7 to 17, the collision ratio decreases monotonically. However, the relay access delay first decreases and then increases. This is because small contention window sizes incur high collision probabilities, while too large window sizes induce unnecessary backoff time, both leading to a higher delay. The impact of W_n is evaluated by comparing the performance with priority-based CW against that without them. By using priority-based CW (i.e., the design in *SideSeeker*) instead of the same shared CW, the collision ratio is further reduced by $1.36 - 4.52\%$, and the delay is reduced by $9.09 - 25.0\%$. Note that the source and relay node densities are both $2 \times 10^{-4} m^{-2}$.

Next, the impact of node densities on the relay access delay and collision ratio is studied. As shown in Fig. 6, when the average node density of source and relay nodes increases,

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(a) $D_{\mathrm{R}} = 0.5 \times 10^{-4} m^{-2}$ (b) $D_{\mathrm{R}} = 1.0 \times 10^{-4} m^{-2}$

Fig. 7. Collision ratio with various node distribution densities (D_{R} as relay distribution density).

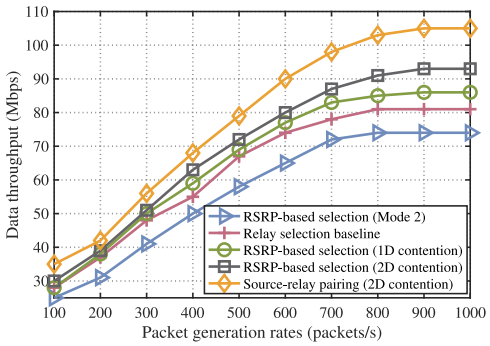


Fig. 8. Data throughput with various packet generation rates.

the relay access delay gradually increases. The designed contention mechanism, i.e., two-dimensional (2D) contention with STS, achieves a significant reduction on the relay access delay, by 24.6% and 29.4% compared with Mode 2 and time-dimension contention respectively. Specifically, the designed mechanism can exploit time-frequency resources more efficiently by enabling frequency multiplexing compared to time-domain contention. As the node distribution becomes denser, the designed scheme can significantly alleviate the collision via STS compared to Mode 2. This is also validated in Fig. 7, as the 2D contention scheme reduces the collision ratio by $4.76 - 32.7\%$ compared with the relay selection baseline for various relay node densities and source node densities.

Finally, to evaluate the overall performance of two mechanisms, the data throughput is defined as successfully received data bits per second in the two-hop sidelink relaying scenario. In this case, we assume that RFR retransmission is disabled, so it is likely that relays cannot be properly added to the network under severe collision. Data flows with constant packet generate rates are generated at each source node. Here, the underlying assumption is that the buffer length at the source or relay node will not exceed the buffer size (i.e., the total capacity of the buffer). This is because flow control on the network layer [13] can limit the number of packets entering the network and discard those excessive packets when the network is saturated. The source nodes are distributed with the density $2 \times 10^{-4}\ m^{-2}$, and the packet size is aligned with [1]. As shown in Fig. 8, when the RSRP-based relay selection is adopted at the source nodes, the 2D contention scheme outperforms the others by $8.14 - 25.6\%$ in saturation throughput, since candidate relays are more likely to be successfully added without collisions. If the designed source-relay pair selection scheme in *SideSeeker* is conducted instead of the RSRP-based baseline, the sidelink throughput witnesses an additional gain by up to 11.3%. Specifically, the saturation throughput achieved with *SideSeeker* is 28.6% higher than that achieved with the relay selection baseline. Overall, via the design of two key mechanisms, the throughput is boosted by $19.3 - 36.9\%$ compared with the baselines (i.e., Mode 2 and one-dimensional contention).

V. Conclusion

A distributed relay discovery and selection scheme, named *SideSeeker*, has been developed. Through the design of a two-dimensional contention scheme based on short-term sensing, both the collision of control signals and relay access delay have been significantly reduced. Besides, by carefully selecting source-relay pairs to reduce congestion, sidelink throughput has been improved by more than 19%. *SideSeeker* stands out as the first scheme to integrate the two-dimensional random backoff and priority-based contention windows into sidelink communications. As for future studies, there is potential to extend this scheme to multi-hop sidelinks. Additionally, investigating how to further alleviate the hidden node problem presents another interesting avenue for exploration.

Acknowledgment

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