Neighbor Discovery and MAC Protocol for Joint Automotive Radar-Communication Systems

Ceyhun D. Ozkaptan, Eylem Ekici
Dept. of Electrical and Computer Engineering
The Ohio State University
Columbus, OH, USA
{ozkaptan.1, ekici.2}@osu.edu

Chang-Heng Wang, Onur Altintas
InfoTech Labs
Toyota Motor North America R&D
Mountain View, CA, USA
{chang-heng.wang, onur.altintas}@toyota.com

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Abstract—**Large-scale deployment of connected vehicles equipped with multiple automotive radar systems increases the demand on both the millimeter-wave (mmWave) automotive radar spectrum in 76-81 GHz and the vehicle-to-everything (V2X) communication spectrum in 5.9 GHz that is mainly allocated for the exchange of safety messages. To supplement V2X communication and support high data rates needed by broadband applications, the automotive radar spectrum with up to 4 GHz of contiguous bandwidth can be leveraged. For this purpose, various joint automotive radar-communication (JARC) systems have been proposed in the literature to perform both functions using the same radio-frequency (RF) signal and transceiver hardware. Combined with the high mobility in traffic, the directionality of RF transmission in mmWave spectrum and interference from other systems prevent JARC systems to achieve optimal communication and radar performance. In this work, we propose a dedicated neighbor discovery and medium access control (MAC) protocol for JARC systems to establish reliable communication links and improve the robustness of radar functionalities without requiring a separate control channel.**

I. INTRODUCTION

As an integral part of Intelligent Transportation Systems (ITS), the connected vehicle technology will promote safer and coordinated transportation through wireless communication and sensing technologies. To enable vehicle-to-everything (V2X) communication, Federal Communications Commission (FCC) dedicated 30 MHz in the 5.9 GHz band for the ITS applications and the exchange of transportation and vehicle safety-related messages. With the large-scale deployment of connected vehicles and the intelligent infrastructure, the V2X spectrum in the 5.9 GHz band will face a spectrum scarcity problem and will not be able to sustain non-safety-related and broadband applications due to limited bandwidth.

In addition, emerging cooperative sensing and autonomous driving technologies may require a large amount of raw sensor and navigation data to be exchanged for improved reliability and performance [1], [2]. However, the V2X spectrum cannot be used efficiently for much larger payloads along with high-priority basic safety messages that are crucial for life-saving applications. A solution to alleviate the scarcity problem and attain higher data rates is to leverage the underutilized millimeter-wave spectrum (mmWave).

Meanwhile, 76-77 GHz and 77-81 GHz millimeter-wave (mmWave) spectra are dedicated to the automotive long-range radar (LRR) and short-range radar (SRR) operations with the contiguous bandwidths of 1 and 4 GHz, respectively. As automotive radars are crucial for assisted driving and safety-critical systems such as collision avoidance, lane change assistance, and adaptive cruise control, allocated large bandwidth and short wavelength in the mmWave spectrum enable better estimation accuracy in terms of distance, velocity, and angle [3]. With the large available bandwidth, one prominent solution to supplement the V2X communication and enable high-throughput broadband applications is the deployment of joint (i.e., dual-function) radar-communication systems in 76-81 GHz automotive radar band.

Various joint radar-communication systems have been proposed in the literature to employ the same radio-frequency (RF) signal and transceiver hardware for simultaneous radar sensing and data transmission. Linear frequency modulated (LFM) waveform, which is widely used in conventional radar systems, is investigated as a *joint waveform* by leveraging spread-spectrum methods in [4] for simultaneous transmission, and phase-coding methods to encode data on LFM waveform [5]. However, these solutions typically offer low data rates and compromise both communication and radar performance due to interference and the arbitrary encoding of data. Radar processing methods that employ *conventional communication waveforms* have also been proposed in the literature to avoid degradation in communication performance. In [6], IEEE 802.11ad-based radar processing has been investigated by exploiting the preamble of single-carrier communication standard for range and velocity estimation. Besides single-carrier communication waveform, orthogonal frequency division multiplexing (OFDM) waveform, which is the prevalent technology for broadband wireless communication, is studied for radar processing capabilities for joint systems in [7]–[10]. Among these approaches, OFDM-based systems are attractive candidates for joint automotive radar-communication (JARC) systems considering broadband capabilities such as robustness against frequency-selectivity and low complexity equalization.

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Although the automotive radar spectrum provides up to 4 GHz of contiguous bandwidth to attain gigabit-per-second (Gbps) data rates and high-resolution radar sensing, JARC systems need to generate directional transmit beampatterns to compensate for higher propagation and penetration loss experienced in the mmWave spectrum. Combined with the high mobility in traffic, the directionality of transmission lowers the achievable communication performance in JARC networks due to limited coordination. Besides communication performance, mutual interference also significantly degrades the detection and estimation capabilities of automotive radar systems. Hence, mutual interference will be the main threat to the reliability of automotive radar systems with the deployment of many vehicles equipped with multiple radars in the next few years [11]. Various signal processing methods have been proposed to filter and mitigate interference from other automotive radar systems [12], [13]. However, the proposed approaches provide limited performance improvement for highly congested radar networks.

As an alternative, the design of medium access control (MAC) layer protocols is studied for the coordination of multiple automotive radars by leveraging omnidirectional V2X communication in 5.9 GHz spectrum [14] and by using a separate control channel in the automotive radar spectrum [15]. While the protocol proposed in [15] only provides communication capability for coordination and interference mitigation, the protocol in [14] relies on the V2X spectrum and introduces signaling overhead. In this work, we propose a dedicated neighbor discovery and medium access control (MAC) protocol for JARC systems to establish reliable communication links and form directional JARC networks while meeting the requirements of the automotive radar functionalities. Without relying on other out-of-band transmissions, the proposed framework also serves as an interference avoidance mechanism that is crucial for radar sensing performance. Through extensive simulations, we show that the proposed protocol can discover one-hop and multi-hop neighbors in a mobile environment and achieve high throughput.

II. SYSTEM MODEL

In this section, we describe our system model for the JARC networks that operate in 76-81 GHz automotive radar spectrum by defining the transceiver and timing model of the JARC nodes. Today connected and autonomous vehicles are equipped with multiple radar transceivers that face different directions of the vehicle to provide extensive sensing capabilities. To compensate for higher propagation loss in the mmWave spectrum and improve signal-to-interference-plus-noise-ratio (SINR), the transceiver generates directional transmit beampattern as shown in Fig. 1. While the radar information and transmitted/received data from multiple JARC transceivers on a vehicle are processed at a central unit, each JARC transceiver acts as *a separate node* at the network level. Therefore, each JARC node manages its own neighbor table and transmission schedule. Consequently, multiple JARC nodes that are mounted on the same vehicle may reside in the same JARC network as their transmissions can affect each other. Each JARC node uses a unique ID that is composed of VehicleID that denotes the unique ID of the vehicle and JarcID that denotes the unique ID of the JARC transceiver.

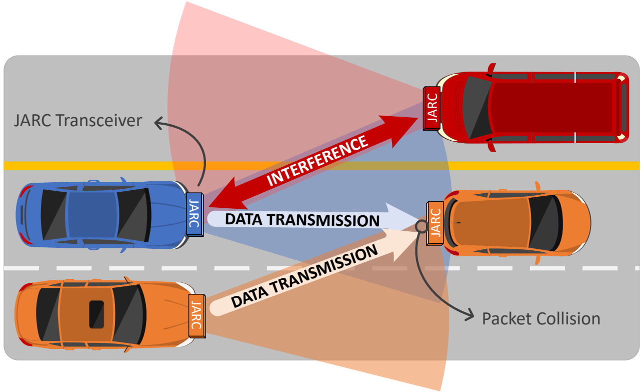


Fig. 1: A vehicular scenario for a directional JARC network with 4 nodes where the transmissions from two nodes collide while mutual radar interference is observed.

We consider JARC nodes employ OFDM waveform for physical layer (PHY) operation with joint radar and communication functionality considering its broadband capabilities. Moreover, the OFDM waveform also supports frequency division multiple access (FDMA) by dividing the available spectrum into subbands which is also known as orthogonal frequency division multiple access (OFDMA) [16]. We consider that the operating band of the JARC nodes is divided into equal sized N_{subband} subbands that are composed of a group of adjacent subcarriers. As studied in [16], subband-based subcarrier allocation allows different JARC nodes to operate in different subbands without collision or mutual-interference. Thus, the nodes employ OFDMA scheme for frequency division multiple access.

Since JARC nodes also perform radar processing with the reflections while transmitting data, they operate in full-duplex mode as illustrated in Fig. 1. However, a transmitting node cannot decode any incoming signals that are being received in the same subband since the radar processing is being performed with a self-interference component. While the self-interference can be mitigated to improve radar performance as studied in [17], other interfering signals will still degrade the radar's detection and estimation performance due to lowered radar SINR.

A. JARC Timing and Performance Metrics

Before describing the details of the proposed JARC protocol, we discuss the assumptions for the system. First, it is assumed that JARC nodes synchronize their clock with equipped Global Positioning System (GPS) technology [18]. Moreover, we assume that the time is slotted, where slot duration denoted by T_{slot} is in the order of milliseconds and all JARC nodes use the same transmission duration denoted by T_{tx}. During transmission, a JARC node transmits RF signals and simultaneously receives reflections for a duration of T_{tx} seconds in a chosen subband of the available spectrum. After the transmission, the node processes received reflections to obtain the range-Doppler-angle image (i.e., radar image) of the illuminated area and goes into an *idle period* in which it listens the channel for incoming signals.

For the safety of the vehicle and traffic, the surroundings of vehicles should be sensed periodically by the radar system. Unlike conventional communication systems that use long contention cycles to take turns in transmission, JARC systems should satisfy both the periodical update requirement of radar and the reliability of communication links. So, all JARC nodes operate in cycles for periodic transmissions and use the same cycle duration denoted by T_{cycle}. The states of operation for two JARC nodes are illustrated in Figure 2 with two subbands for two cycles. For conventional automotive radars, T_{cycle} determines the update rate of the radar image and can vary between 30 ms to 150 ms based on the operation range and velocity of the radar. While T_{cycle} is longer for long range radars, it is shorter for short range radar systems due to frequent update requirements.

Furthermore, transmission duration T_{tx} determines the velocity resolution and the energy of the reflected signals. The velocity resolution is determined by $\Delta v = c/(2T_{\text{tx}}f_c)$, where c is the speed of light and f_c is the carrier frequency. For $f_c = 77$ GHz, a radar system with $T_{\text{tx}} = 3$ ms achieves velocity resolution of $\Delta v = 0.65$ m/s which is the requirement for automotive radars [3]. Thus, while designing the timing structure of the protocol, our first constraint is $T_{\text{tx}} > 3$ ms to achieve the required velocity accuracy. However, the ratio of T_{tx} to T_{cycle} also determines the duty cycle of the system. As a JARC node also transmits data with the same signal, a high duty cycle is preferred to achieve higher communication throughput and leverage the high bitrate capabilities in mmWave radar spectrum. At the same time, transmissions from different JARC nodes should not collide at a JARC receiver to achieve a reliable exchange of messages and should not cause mutual-interference for accurate target detection and tracking as illustrated in Fig. 1.

One can observe that there is a trade-off between the communication throughput and the reliability of both communication and radar functionalities (i.e., collisions and interference) based on the system parameters T_{tx} and T_{cycle}. Therefore, inter-frame time in which the JARC node is idle can be leveraged to avoid collisions and interference. Besides the given requirements and trade-off, the hidden terminal problem is harder to solve due to the directionality and limited penetration of mmWave signals along with the high mobility of obstacles and transceivers.

III. PROPOSED MAC PROTOCOL FOR JARC

In this section, we present the distributed neighbor discovery and MAC protocol for the JARC networks considering the given system and performance requirements. A JARC transmission cycle consists of transmission states (i.e., TRANSMIT and AlternativeTX) and idle states (i.e., WAIT and IDLE) as illustrated in Fig. 2 for $N_{\text{subband}} = 2$ subbands. SYNC signal represents a synchronization trigger that is used by JARC nodes to adjust their transmission cycles. While SYNC signal provides a coarse synchronization for the slotted MAC functionalities, the time synchronization for PHY layer, which requires higher accuracy, is established with the use of preambles at the beginning of each transmission. Since the time is slotted, each cycle contains $N_{\text{time}} = T_{\text{cycle}}/T_{\text{slot}}$ slots along the time-axis. Thus, each cycle consists of $N_{\text{unit}} = N_{\text{time}}N_{\text{subband}}$ resource units in the time-frequency grid.

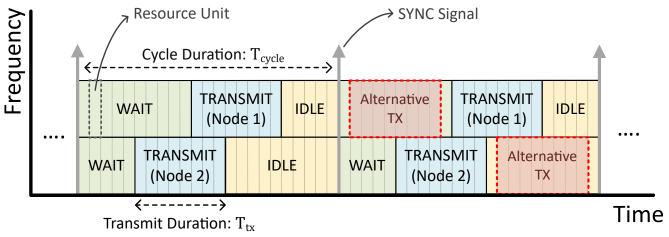


Fig. 2: The timing structure of the proposed JARC protocol.

A. *Beaconing and Neighbor Discovery*

As explained in the previous section, a JARC system is required to transmit in every cycle for periodic radar imaging. In every TRANSMIT state, JARC node transmits a Beacon message as a part of the payload with the joint signal to notify the neighboring nodes and arrange directional transmission schedules as a network. Since the bitrate is high and the transmit duration is long (i.e., at least 3 ms), a Beacon message takes up a small portion of the JARC frame.

A Beacon message contains the following information: VehicleID which is the unique ID of the vehicle; JarcID which is the unique ID of the JARC transceiver; TxBlock which indicates the starting index of the resource units as {time slot, subband} for transmission; NeighborTable which is the table of discovered nodes with their transmission schedules as shown in Fig. 3. Hence, Beacon messages are used to allocate and advertise the chosen time slot and subband for transmission. Since they also include the transmitter's neighbor table, the nodes also announce their *current reception schedules* from their discovered neighbors.

Neighbor Tables with One-Hop Indicator: The exchange of the neighbor tables with the Beacons is an important part of the distributed protocol to prevent and resolve possible collisions for the maintenance of reliable communication links. Thus, the entries in a NeighborTable contain the following information: VehicleID and JarcID, the unique ID for the JARC node;

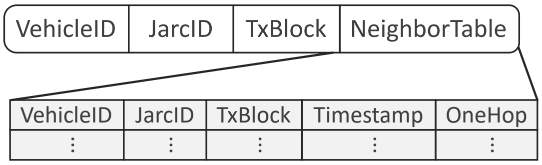


Fig. 3: The structure of the Beacon message.

TxBlock, indicates the starting index of the resource units of the node for transmission; Timestamp, indicates the latest update time of the entry; OneHop, indicates whether the node is a one-hop neighbor. Additionally, ExpireTime is locally attached to each entry to indicate the expiry time of the entry for removal.

For each entry, Timestamp field is filled with the update time of the entry to keep track of the freshness of the information. As the nodes also include an expiration time for each entry based on the timestamp, they discard outdated information. The expiration duration can be determined as a fixed duration or adaptively after an update based on the advertised location information, the obtained radar image, and the size of the neighbor table. Based on the reception of further Beacon messages, the entries in the NeighborTable and their timestamps are updated. OneHop is a Boolean variable to indicate if the discovered neighbor is a one-hop (i.e., direct neighbor) or a multi-hop neighbor. Using the information available in their NeighborTable, the nodes remove expired entries and keep track of the *available resource units* in the time-frequency grid.

B. Neighbor Table Merge and Update

In this section, we first describe the NeighborTable merge and update routines upon reception of a Beacon. Then, we explain the strategies to resolve the hidden node problem. When a node receives a Beacon, it adds the entry of the Beacon transmitter to its NeighborTable with OneHop indicator set to one and inspects the attached NeighborTable. In a future transmission, the Beacon receiver can cause interference to the Beacon transmitter and can cause collisions to the transmissions of *the transmitter's one-hop neighbors*. To prevent the collisions, Beacon receivers also add the entries of *the transmitter's one-hop neighbors*, which are likely to be hidden nodes due to directionality, to their NeighborTable with OneHop indicator set to zero. If the transmitter's NeighborTable contains a more up-to-date entry of a node that is already in the receivers' NeighborTable based on the timestamps, the receiver updates the corresponding entry.

If the transmitter node is already discovered as a one-hop neighbor and its NeighborTable does not contain the receiver's information correctly (e.g., mismatch or multi-hop), the receiver assumes that its previous transmissions are failed due to a hidden node problem. To resolve this problem and avoid further collisions, the receiver changes its resource units for future transmissions by randomly choosing another spot (i.e., time slot and subband) from available resource units based on its current NeighborTable. Conversely, if the transmitter's NeighborTable contains the receiver's information correctly, the receiver uses it as an acknowledgment for its previous transmissions. Hence, the exchange of neighbor tables is also used as an implicit acknowledgment mechanism without requiring additional signaling and overhead.

By keeping track of available resource units with the exchange of NeighborTables, the JARC nodes adjust their time slots and subbands to ensure that they will not cause interference to their one-hop neighbors and collisions to the transmissions of their multi-hop neighbors. With the proposed strategies, the nodes form directional JARC network by discovering other nodes and resolving possible hidden node problems in a distributed manner.

C. Random Resource Allocation

Upon initial start, all JARC nodes follow a *random resource allocation strategy* wherein they choose a random transmission spot (i.e., consecutive time slots and subband) in the cycle's time-frequency grid. Unless an overlap is detected, the nodes use the same resource units in future cycles.

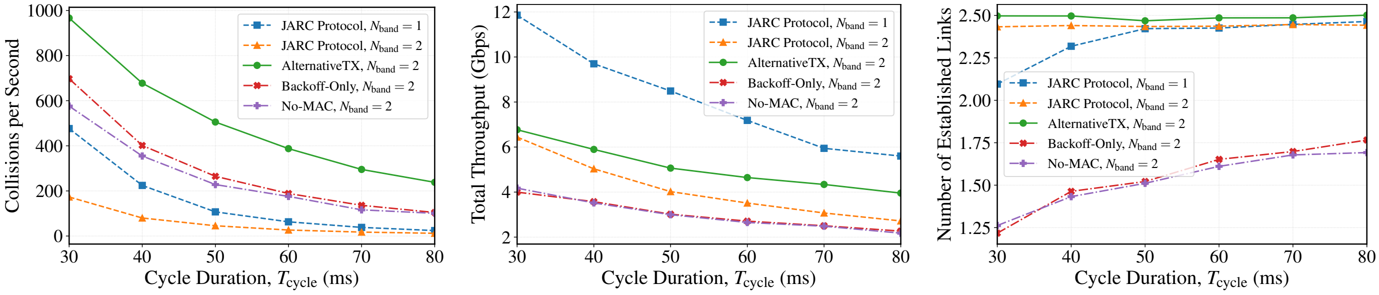
Similar to the carrier-sense multiple access with collision avoidance (CSMA/CA) method, the node that chooses the *shortest wait time* wins the channel access priority for the chosen subband and others who can sense the transmission defers from transmission in the same subband. When a node's transmission time comes and the subband is not sensed busy, the node goes into TRANSMIT state for the transmission of the joint OFDM waveform to perform both radar imaging and data transmission with a Beacon message attached. During the TRANSMIT state, the node can still receive signals in all subbands, whereas the signals received in the chosen subband will cause interference to the radar operations.

In the WAIT state, if the node starts receiving a signal that will overlap with its currently chosen resource units, it backoffs to another random spot that is chosen from all available resource units in the next N_{backoff} time slots. If no backoff units are available for the current cycle, the node will transmit at the end of the cycle and choose a random spot for the next cycle. With this strategy, the JARC nodes that are facing each other would have a lower probability of causing mutual interference and collisions.

After the TRANSMIT state, the nodes go into the IDLE state until the next cycle. If the channel is sensed busy, it waits for a transmission duration T_{tx} for reception and checks whether the received signal is an intended message or an interference. If it is a Beacon, the JARC node initiates the NeighborTable update routine described in Section III-B. Otherwise, the node stays in IDLE state until the new transmission cycle starts. At the start of a new cycle, all JARC nodes always check their NeighborTables if the current transmission units will cause interference to their neighbors. If there is an overlap, the node chooses a random transmission spot from vacant resource units to prevent collisions and interference.

D. Alternative Transmission (AlternativeTX)

While increasing T_{cycle} also increases the number of resource units and lowers the probability of collisions, it also lowers the data throughput due to unused resource units especially for low congestion networks. Furthermore, increasing the transmit duration to lower the duty cycle increases the probability of collisions and mutual interference substantially. Hence, the duty cycle of JARC transceivers introduces a trade-off between data rate and reliability of operations which is mainly affected by interference. To address this problem, we



(a) Total number of collisions per second

(b) Total achieved throughput

(c) Average number of links per node

Fig. 4: The results for communication performance.

also propose an *alternative transmission* strategy that allow nodes to transmit for a second time in a cycle.

Since each node keeps track of unused resource units with its NeighborTable, it can evaluate whether a second transmission can be performed in a cycle without any interference. Hence, at the start of each cycle, JARC nodes choose another random spot for a second transmission (i.e.,AlternativeTX) if there are enough vacant resource units as illustrated in Figure 2. However, nodes do not advertise their AlternativeTX schedule and perform AlternativeTX in a standalone manner by leveraging information distributed among nodes. If an overlap with the AlternativeTX is detected while sensing the channel, AlternativeTX is canceled for the current cycle. With this strategy, JARC nodes can improve the spectrum utilization to increase communication throughput and lower information dissemination delay.

IV. PERFORMANCE EVALUATION

In this section, we present the simulation results to evaluate the performance of the proposed JARC protocol in terms of both communication and radar performance in traffic. For comparison, we also include the results of two conventional approaches as baselines: *No-MAC* wherein nodes do not follow any protocol, and *Backoff-Only* wherein nodes only perform backoff as suggested in [11]. For the network and traffic simulations, we use Veins (Vehicles in Network Simulation) [19] that provides a framework to integrate OMNeT++, an event-based network simulator, and SUMO, a road traffic simulator.

For the simulations, we consider a 3-lane highway scenario with a speed limit of 30 m/s that is 200 meters long and we evaluate the performance with 150 vehicles generated in 60 seconds. Each vehicle is equipped with 2 JARC transceivers that are mounted on the front and rear of the vehicles and operating with the carrier frequency $f_c = 77$ GHz with 1 GHz of bandwidth that provides a constant bitrate of 1 Gbps when full bandwidth is used. So, when $N_{\text{subband}} = 2$, the bitrate of communication links drops to 0.5 Gbps. Also, transmit duration $T_{\text{tx}} = 5$ ms and slot duration $T_{\text{slot}} = 1$ ms is used for the MAC protocol. Besides the MAC protocol implementation, a PHY layer is also implemented with a directional antenna model and a blockage model due to a lack of mmWave support in Veins. Since the carrier frequency is 77 GHz, we only consider line-of-sight transmissions with full attenuation when there is a blockage. We also assume that all transceivers have identical and idealized beampatterns that provide a transmit power of 30 dBm within a beamwidth $\theta_{\text{beam}} = 30°$ and zero gain outside the beamwidth which complies with the LRR parameters in [3]. For the communication links, we use a SINR threshold of 15 dB with noise floor of -89 dBm to determine whether the signal can be decoded, which provides a communication range of 50 m when there is no interference.

With the simulations, we evaluate the impact of cycle duration T_{cycle}, the number of subbands N_{subband}, and AlternativeTX strategy on both communication and radar performances. The achieved communication performance of the approaches are shown in Fig. 4 wherein *JARC Protocol* denotes the proposed protocol without AlternativeTX strategy. As shown in Fig. 4a, higher numbers of collisions are observed with the baseline approaches compared to the proposed protocol without AlternativeTX. Increased number of collisions result in low throughput and poor neighbor discovery performance as shown in Fig. 4b and 4c, respectively. Although *Backoff-Only* approach also assists in mitigating the radar interference as shown in Fig. 5, the lack of coordination between nodes still result in lower communication performance.

Employing a single subband (i.e., $N_{\text{subband}} = 1$) enables higher total throughput due to the use of full bandwidth. However, it substantially deteriorates both neighbor discov-

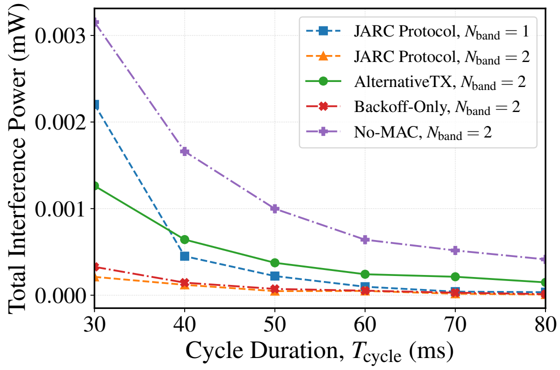


Fig. 5: Total received radar interference power.

ery and radar performance for shorter cycle duration (e.g., $T_{\text{cycle}} = \{30, 40\}$ ms) due to the limited number of resource units as demonstrated in Fig. 4 and 5. However, when the cycle duration and number of subbands are increased, the total throughput lowers considerably without AlternativeTX due to underutilized spectrum and unused resource units.

As shown in Fig. 4, AlternativeTX strategy improves the spectrum utilization that leads to better throughput and neighbor discovery performance at the expense of radar interference and collisions. Since AlternativeTX creates more transmit opportunity in a greedy manner, the number of packet collisions do not lower the throughput, unlike the baseline approaches. Furthermore, the increase in radar interference with AlternativeTX is mainly caused by the mobility of nodes since the changes in topology and transmit schedules disseminate with a delay.

V. CONCLUSION

In this work, we have proposed a dedicated neighbor discovery and MAC protocol for JARC systems to leverage the large spectrum in the mmWave automotive radar spectrum for improved communication and radar performance without using a separate communication channel. Through practical simulations, we demonstrated that the proposed protocol allows JARC transceivers to form directional communication networks in traffic with high throughput. Furthermore, we showed that reliable coordination among JARC systems improves the robustness of automotive radar operations with lowered mutual interference. In future work, we will study the adaptive approaches to adjust transmit and cycle duration based on the number of nodes and congestion in the network.

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