Automotive Radar and Communications Sharing of the 79-GHz Band

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ABSTRACT

The spectrum scarcity problem is becoming severer in the 5.9 GHz Dedicated Short Range Communication (DSRC) band due to the rapidly increasing wireless traffic demands in vehicular networks. Meanwhile, massive bandwidth has been allocated to automotive radars in the 79 GHz band. Given its large bandwidth, radar imaging accuracy in the 79 GHz automotive radar band is still low because sequential target observations of a single radar sensor are highly correlated. Therefore, the 79 GHz band can be regarded as underutilized. Since the observations of different vehicles are less correlated, collaborative radar imaging among neighboring vehicles through vehicle-to-vehicle (V2V) communications can improve the accuracy of automotive radar imaging. More importantly, in the resulting Joint Automotive Radar-Communication (JARC) system, less bandwidth is required to achieve high radar imaging accuracy. Hence, remaining bandwidth can be utilized to alleviate the spectrum scarcity problem in the DSRC band.

In this paper, we develop a distributed JARC system to facilitate the spectrum sharing between radar imaging and V2V communications in the 79 GHz millimeter wave band. In particular, we implement the proposed JARC system by devising of a corresponding MAC layer protocol, which contributes to the future standardization of the JARC system. Moreover, the performance of the proposed JARC system is evaluated through simulation examples, which demonstrates that the JARC system is able to support high-throughput V2V communications in the 79 GHz band.

CCS Concepts

•**Networks** → **Network protocol design; Link-layer protocols; Network simulations;** *Mobile ad hoc networks;*

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Keywords

Joint automotive radar and communication system; spectrum sharing; 79 GHz millimeter wave band

1. INTRODUCTION

Tens of megahertz bandwidth in the 5.9 GHz band have been allocated to vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) communications in many countries. This band is also named the Dedicated Short-Range Communications (DSRC) band supporting intelligent transportation systems in the United States. However, many studies have shown that the DSRC band is insufficient to guarantee reliable transmissions of safety messages [8, 12, 14]. In particular, transmissions of non-safety related messages have to be severely restricted to guarantee the reliable transmissions of safety messages. For example, it is shown in [28] that less than 10% of the DSRC bandwidth remains for non-safety applications if 95% reliability of transmissions is guaranteed for safety applications at medium vehicle density.

Meanwhile, the 77 - 81 GHz millimeter wave band has been allocated to automotive radar imaging in many countries as well as at the International Telecommunication Union World Radiocommunication Conference[1], which is also referred to as the 79 GHz band. Despite the width of 4 GHz bandwidth, the accuracy of automotive radar imaging is still low due to temporal correlation between sequential target observations of a single radar sensor [4, 19]. Therefore, the 79 GHz band can be regarded as underutilized. Since the observations of different vehicles are less correlated, collaborative radar imaging among neighboring vehicles through the exchange of radar imaging results can improve the imaging accuracy. More importantly, since fewer observations are required to achieve high imaging accuracy in the resulting Joint Automotive Radar and Communication (JARC) system [13, 26], the remaining time can be utilized to alleviate the spectrum scarcity problem in the DSRC band. In particular, based on estimation theory, it is shown in [13] that V2V communications can improve radar imaging accuracy. Moreover, a resource allocation scheme is developed in [13] to maximize the remaining time for other communications after the baseline imaging accuracy of vehicles is achieved.

Although the JARC system has been studied in some existing works, most of them focus on the development of hardware platform [10, 20] and PHY layer issues [5, 9, 11, 23, 26]. For example, a software-defined radio platform is developed in [20], which allows users to implement real-time adaptive radar imaging algorithms using wideband digital communication signals. In [10], another software-defined platform is developed to support joint radar imaging and data communications. In addition, OFDM waveforms have been particularly studied in many references [5, 9, 10, 11, 23]. In contrast, few efforts have been devoted to MAC layer design issues. In this paper, we try to fill the gap by devising a MAC protocol for the JARC system. Contributions of our work are twofold. Firstly, we propose a distributed JARC system and develop a corresponding MAC protocol. Secondly, we evaluate the performance of the proposed JARC system through extensive simulations.

The remainder of this paper is organized as follows. Details of the JARC system is discussed in Section 2, followed by a simulation evaluation of the JARC system in Section 3. Conclusions and future works are discussed in Section 4.

2. DESIGN OF THE JARC SYSTEM

In this section, we propose a distributed JARC system using automotive radar sensors with both the functionality of radar imaging and communications [10, 20]. The sensing range of the radars is from 40 to 250 meters, and the typical beamwidth is 3-4 degrees in the 79 GHz band [24]. The JARC system is comprised of three core components: neighbor discovery, link establishment/maintenance and data delivery.

Before introducing details of the proposed JARC system, we discuss some assumptions that are essential to the system design. Firstly, it is assumed that vehicles can achieve synchronization through either the GPS-based technology used in IEEE 1609.4 [1] [6] or the PHY layer based technology used in IEEE 802.11ad [2] [15]. Moreover, in IEEE 1609.4, the 5.9 GHz DSRC band is divided into one control channel and six service channels [6]. In our JARC system, one of the service channels is used as the JARC control channel. Note that in Japan, only standard heartbeat messages with no other information attached are supported in the DSRC band. The proposed JARC system also applies to Japan because only vehicle identity information will be used in the system, which will be discussed in detail in Section 2.1. Finally, in addition to onboard radar sensors, a dedicated JARC control radio is used to exchange control information on the JARC control channel. Note that different from the multi-channel operation mechanism in IEEE 1609.4, this JARC control radio only operates on the JARC control channel.

2.1 System Design

As shown in Figure 1, the proposed JARC systems is comprised of the left-side control plane and the right-side data plane. Apart from the Physical Layer block on the bottom and the Network Layer block on the top, the data plane consists of three core components in the MAC layer: periodic neighbor discovery, periodic link establishment/maintenance and data delivery. Details of the all the functionality blocks in Figure 1 are as follows.

Control Plane

The core functionality block in the control plane is a JARC controller, which manages the operations of the JARC system by considering multiple factors such as distributed requirement, directional antennas, synchronization accuracy, identification of neighboring vehicles, high mobility of vehicles, QoS requirements of various wireless applications, and use of two bands for operation [3] operation requirements. It is the core of the JARC system. As an example, the JARC controller determines the multiplexing strategies in the data plane, i.e., Channel Access Scheduling blocks in Figure 1 .

Physical Layer

We consider two options for the PHY layer waveform design. The first option is to use the OFDM waveform for both radar imaging and vehicular communications [5, 9, 10, 11, 23], and the second option is to use OFDM waveform only for vehicular communications and use the conventional Frequency Modulated Continuous Wave (FMCW) for radar imaging. In addition to the waveform design, other PHY layer issues include antenna design, synchronization, beamforming etc. Similar to the fact that IEEE 802.11p is an amendment to the IEEE 802.11 standards for WLANs in the 2.4 GHz ISM band, the design of our PHY layer can also refer to the IEEE 802.11ad standard for WLANs in the 60 GHz millimeter wave band.

Network Layer

The network layer requires an on-demand routing engine, which is able to cope with distributed and directional features of the JARC system. It first makes a routing table using the input from the link establishment/maintenance block. Then, it receives routing requests from the data delivery block and sends the routing table back to the data delivery block. Since building the whole routing table for all the other vehicles at every vehicle can incur a significant amount of overhead and latency, an on-demand routing protocol is preferred.

Periodic Neighbor Discovery

The neighbor discovery block first receives channel access scheduling decisions from the control plane, which deals with multiplexing of the radar frequency band among neighboring vehicles to avoid mutual interference. Then, neighbor scanning is performed in both the DSRC band and the radar band. Specifically, the automotive radars detect neighboring vehicles through radar imaging using the 79 GHz band, and the control radio detects neighboring vehicles through overhearing their broadcast information in the 5.9 GHz band. The control radio itself also broadcasts its own identity information such that it can be detected by the control radios of neighboring vehicles. For the neighbor discovery in the radar band, a vehicle can only obtain location and mobility information of its neighbors while the neighbor discovery in the DSRC band enables the vehicle to obtain identity information of the neighbors [4]. Therefore, the vehicle can identify its neighbors by combining the detected neighbor information in the two bands. Finally, the neighbor information is sent to the link establishment/maintenance block.

[1] IEEE 1609.4 denotes the IEEE Standard for Wireless Access in Vehicular Environments (WAVE) (Multi-channel Operation) in the DSRC band

[2] IEEE 802.11ad defines PHY and MAC layer protocols for WLAN operating in the 60 GHz millimeter wave band

[3] Here, "two bands" denote the 5.9 GHz DSRC band (control channel) and the 79 GHz band (vehicular communication channels)

[4] This minimal information collection enables the use of this system world-wide, including in Japan, where DSRC channel carries only standard heartbeat messages with no additional information.

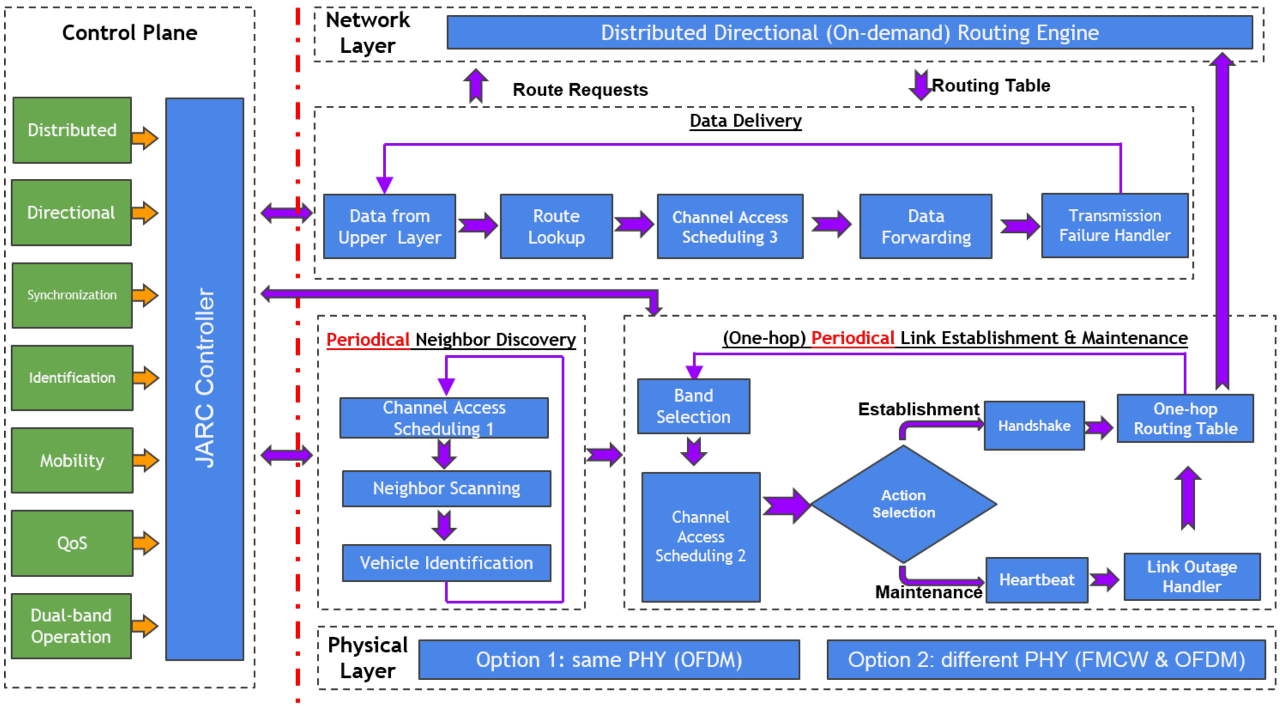


Figure 1: The proposed JARC system

Periodic Link Establishment/Maintenance

As shown in Figure 1, the operations for link establishment and maintenance depend on the operating frequency band. More specifically, in the DSRC band, a vehicle can broadcast its link establishment and maintenance information while in the radar band only directional unicast communication is supported. Moreover, multiplexing schemes are required for both bands to avoid mutual interference, which is determined by the JARC controller. In order to establish a link with one of its neighbors, the vehicle needs to start a handshake with the neighbor. To verify that the previously established channel is still alive (i.e., maintain the connection), the vehicle can use a simple heartbeat scheme. If not, a link outage handler is needed to deal with the link outage event. Finally, the vehicle makes its local one-hop routing table and sends it to the Network Layer block.

Data Delivery

As shown in Figure 1, the Data Delivery block performs route discovery, channel access scheduling, and data forwarding sequentially when transmission requests are received from the Network Layer. The routing table is acquired from the Network Layer and the multiplexing scheme is determined by the JARC controller. Moreover, if a transmission is not acknowledged by the receiver, a transmission failure handler is used to deal with the lost frames, e.g., retransmit the frames before timeout or discard the frames after timeout.

2.2 System Analysis

The development of the JARC system is faced with two main challenges: the controller design as well as the routing engine design. As shown in Figure 1, the controller design is faced with many requirements such as distributed and directional operation across two bands, as well as high mobility of vehicles. In particular, the controller must support the three JARC modules in the data plane, i.e., neighbor discovery, link establishment/maintenance and data delivery. Since the three modules can use different bands and have different requirements, it is a great challenge to provide efficient scheduling and coordination service for them.

Since current vehicular communications use the 5.9 GHz DSRC band, most existing vehicular routing protocols are for omnidirectional antennas. However, some distributed and directional routing protocols designed for general mobile ad hoc networks can provide insights into the design of our routing engine, e.g., [7, 17, 18].

2.3 MAC Protocol Design

Based on the system design in Figure 1, we continue to develop a corresponding MAC protocol. In Figure 2, two types of MAC frames are proposed. The Type 1 frame consists of three phases: neighbor discovery, link establishment, and data delivery. The first two phases require dual-band operation while the last phase solely operates in the radar frequency band. The Type 2 frame consists of two phases: link maintenance and data delivery, which both operate in the radar frequency band.

The motivation to use two types of MAC frames is that the relative speeds between neighboring vehicles can be very small compared with their absolute speeds. Therefore, vehicles may not need to discover neighbors and establish links in every MAC frame, which can be as small as 100 milliseconds as defined in IEEE 1609.4. Instead, in most frames, the previously established radar links can be still alive, in which case vehicles only need to maintain these links. Another reason of using two types of MAC frames is that using only

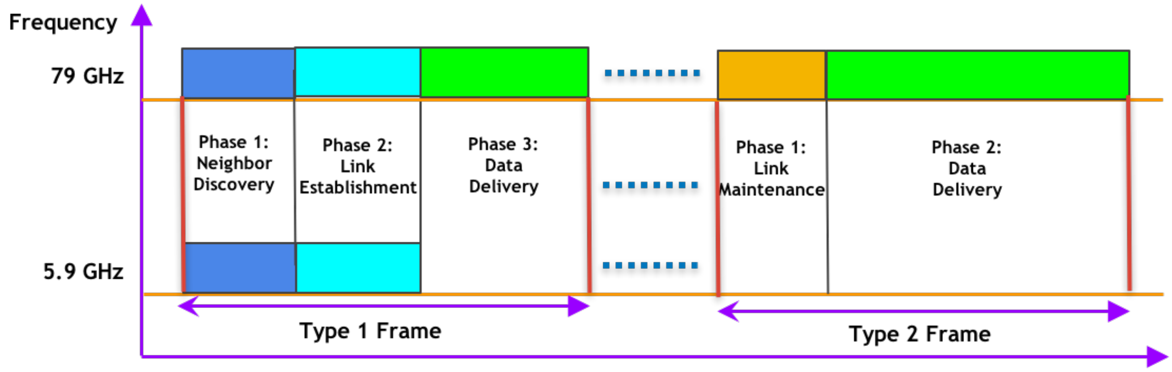


Figure 2: The proposed MAC protocol

Type 1 frames incurs a large amount of control overhead. Since both the Phase 1 and 2 intervals of the Type 1 frame are proportional to vehicle density, this can incur congestion on the JARC control channel. Hence, a large portion of the Type 1 frame needs to be allocated to the two control intervals under high vehicle density. In contrast, the control interval in the Type 2 frame is rather short because the link maintenance is only conducted in the radar frequency band. Therefore, the Type 1 frame is used if and only if a free radar interface needs to establish a link with its neighbors while Type 2 frame is used when the previously established link is still alive.

Details of the MAC protocol are as follows.

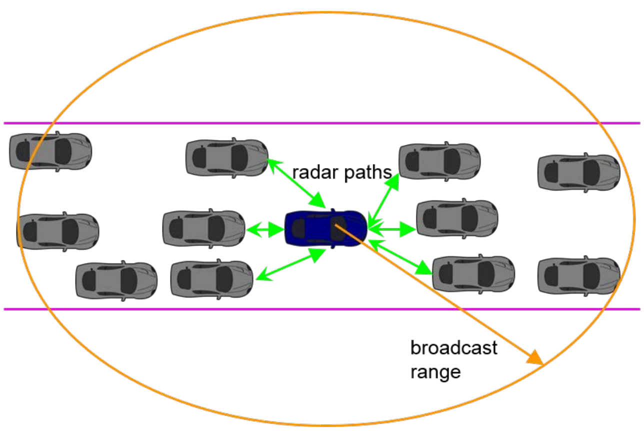


Figure 3: Neighbor discovery by radio and radars

Type 1 Frame: Phase 1 (Neighbor Discovery)

In a Type 1 frame, neighbor discovery is performed by both the control radio and radar sensors. As shown in Figure 3, the detection range of the control radio (e.g., 1 km) is much larger than that of the radar sensors (e.g., 100 m). Moreover, the detection of the radio is omnidirectional while the detection of radars is directional. Therefore, different sets of neighbors can be found by the radio and radars. Let S_1 and S_2 be the sets of neighbors discovered by the radio and radars, respectively, and the neighbors in $S_1 \cup S_2$ can be divided into three subsets:

- $S_1 \cap S_2$, i.e., neighbors that are both identified (overheard) by the control radio and sensed by the radars.
- $S_1 \setminus S_2$, i.e., neighbors that are identified by the radio but not sensed by the radars. Possible reasons are 1) there are no line-of-sight paths to these neighbors in the 79 GHz band; 2) distances to these neighbors are larger than the maximum radar sensing range; 3) mutual interference with neighboring vehicles. In the following sections, we assume that mutual interference is negligible due to small enough beamwidth and the use of efficient channel scheduling algorithms. Moreover, the first two reasons make it impossible to establish a link between two vehicles. Therefore, the neighbors in this subset are not considered for establishing links.
- $S_2 \setminus S_1$, i.e., vehicles that are not identified by the radio but sensed by the radar sensors. One reason could be the congestion on the control channel. Since communications on the radar band are coordinated by the control radio, vehicles in this subset cannot efficiently coordinate with neighboring vehicles and thus are also not considered for establishing links.

Hence, only neighbors in the subset $S_1 \cap S_2$ will be considered for link establishment in the following step.

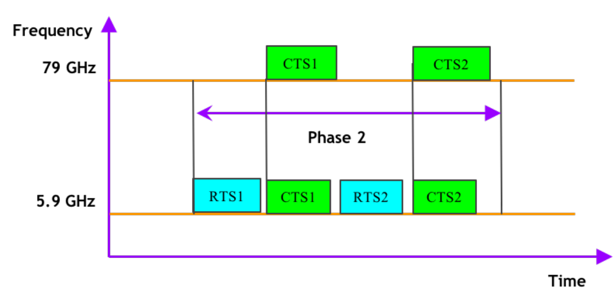


Figure 4: Dual-band RTS/CTS scheme for link establishment

Type 1 Frame: Phase 2 (Link Establishment)

As shown in Figure 4, to establish a link, a vehicular transmitter first broadcasts an RTS signal on the control channel. After receiving the RTS, the receiver not only broadcasts a CTS on the control channel but also sends a CTS on the radar band. The CTS on the control channel is to: 1) verify the RTS signal has been received; 2) broadcast information on the radar link being established; 3) broadcast resource reservation for the link being established in the upcoming data delivery phase, which will be discussed in the next paragraph. The CTS on the radar band is to: 1) verify the RTS signal has been received; 2) verify that the radar link being established is valid. Note that since one of the DSRC service channels is used as the JARC control channel, RTS/CTS exchange on the JARC control channel would be the exchange of data on the actual service channel. For the multiplexing scheme in this phase, in addition to listen-before-talk, more sophisticated schemes can be used (e.g., [22][27]).

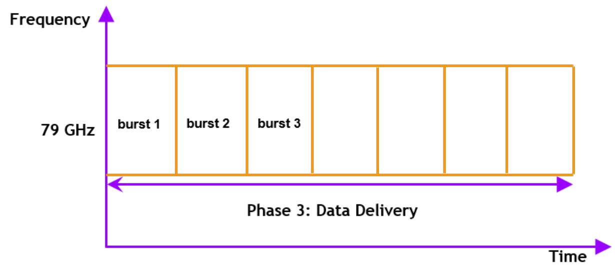


Figure 5: A TDMA-based multiplexing scheme

As shown in Figure 5, Phase 3 is divided into multiple time bursts, where a burst is defined as a resource unit in the time domain. To transmit in Phase 3, the vehicular transmitter must first reserve at least a burst through the CSMA/CA contention scheme in the DSRC band. More specifically, the burst reservation information is included in the omnidirectional RTS/CTS messages that are broadcast on the control channel. After overhearing these messages, all vehicles mark the bursts as reserved. When a vehicle wants to establish a link, it must find at least a burst that has not been reserved. Then, based on its need, it can reserve a couple of bursts starting from the first available burst. Alternatively, since all the burst reservation decisions are made by individual vehicles, every vehicle can be forced to reserve at most one burst in order to ensure fairness.

Since beamwidth of the communications links in the 79 GHz is usually quite small, concurrent communications can be adopted to leverage spatial reuse of the 79 GHz millimeter wave band. However, the mutual interference issue also becomes more complicated due to the non-zero beamwidth as well as the reflection of communication signals by neighboring vehicles and roadside obstacles. Since the mutual interference issue in millimeter wave ad hoc networks is still an important open research issue [21], as the very first step, we adopt the traditional TDMA-based multiple access scheme illustrated in Figure 5.

Type 1 Frame: Phase 3 (Data Delivery)

After a link is established, a vehicle starts transmitting data. If a neighbor cannot be reached in one hop, a routing protocol is required. For example, the directional AODV protocol can be used to find routes in on-demand manner [16]. Finally, if the data transmission is not acknowledged by the receiver within a certain time, the transmitter can: 1) retransmit the data on the control channel if they are urgent; 2) retransmit the data in the next frame if they are not urgent; 3) discard them if a timeout occurs.

Type 2 Frame

As shown in Figure 2, in Phase 1 of a Type 2 frame, a heartbeat scheme (similar to RTS/CTS) is used to maintain previously established radar links. Specifically, the transmitter simply sends a HELLO message to the receiver and the receiver sends a ACK message if it receives the HELLO message. If the link is still alive, it will continue to be used for data delivery. Otherwise, the link will not be used and the vehicle will try to establish a new link in the next frame using the Type 1 frame. Moreover, the data delivery phase is identical with the data delivery phase of the Type 1 frame.

3. SYSTEM EVALUATION

In this section, we first present details on the simulation tools used in our evaluations. Then, we explain the simulation setup such as the road topology model, the radar link model, as well as the simulation parameters. Thereafter, we evaluate the performance of the proposed JARC system through simulations. In particular, we will study two problems:

1. impact of radar link availability on the system performance;

2. impact of Type 1 frame control intervals on the system performance.

3.1 Simulation Platform

Two simulation tools are used in our evaluations: Network Simulator 3 (ns3) [2] and Simulation of Urban Mobility (SUMO) [3]. ns3 is a popular network simulator in both industry and academia because it provides models of how packet data networks work and perform, and provides a simulation engine for users to conduct simulation experiments. We implemented the proposed JARC system by developing a C++ JARC module in ns3.

SUMO is an open source, highly portable, microscopic and continuous road traffic simulation package designed to handle large road networks. SUMO allows modeling of traffic systems including road vehicles, public transport, and pedestrians. SUMO includes many supporting tools that handle tasks such as route finding, visualization, network import and emission calculation. All the road topology models used in our simulations are generated using SUMO and then ported to ns3.

3.2 Road Traffic Model

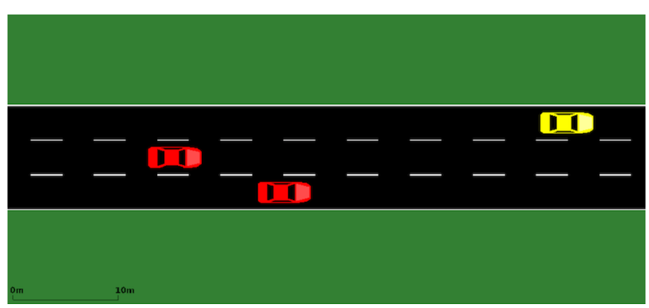


Figure 6: One-way highway model generated using SUMO

As an example shown in Figure 6, a one-way highway model is generated using SUMO. The highway is 40,000 meters long and 12 meters wide. It has three straight lanes, each of which is 4 meters wide. All vehicles must move from the west end of the highway to the east end, and the average distance between a vehicle and its front (and/or rear) vehicle is 15 meters. The number of vehicles in the network is changed multiple times to study the performance of the JARC system under different vehicle densities. Specifically, the number of vehicles is taken from $6, 12, 18 \cdots 96, 100$. Note that we also studied other road traffic models like intersections with traffic lights, which are not shown in this paper due to space constraint.

3.3 Radar Link Model

In our simulations, a radar communication link is modeled as a bi-directional point-to-point link. Main properties of the link are as follows. Firstly, a link between two vehicles can be established if and only if: 1) the distance between the two vehicles is less than the radar communication range, which is set to 150 meters in our simulations; 2) at least one line-of-sight path exists between the two vehicles. Secondly, a vehicle can establish at most four radar links simultaneously with neighboring vehicles. The reason is that in practice each vehicle only has a limited number of onboard radars, e.g., four radar sensors in the front, rear, left and right side of the vehicle. Finally, Since vehicular radar links usually have shorter lifetimes than radio-based communication links, we model the availability of a radar link as a continuous time Markov ON-OFF process. Let $E[t_{on}], E[t_{off}]$ be the average ON and OFF time, respectively, and we define the Link Availability Probability (LAP) as:

$$LAP = \frac{E[t_{on}]}{E[t_{on}] + E[t_{off}]}. \tag{1}$$

3.4 Simulation Parameters

The main system parameters of our simulations are as follows.

- JARC MAC Frame. Similar to IEEE 1609.4 where a MAC frame is 100 milliseconds long, both Type 1 and 2 frames are set to 200 milliseconds long. We run each simulation example for 10 minutes.

- Control Interval of Type 1 Frame (i.e., Phase 1 and Phase 2). Since the control interval can affect the number of established radar links, we consider three scenarios for (Phase 1, Phase 2) interval pairs: small intervals (5 ms, 15 ms), medium intervals (10 ms, 30 ms), and large intervals (20 ms, 60 ms). Therefore, Phase 3 is 180, 160 and 120 ms long, respectively.

- Control Interval of Type 2 Frame (i.e., Phase 1). Since the link maintenance is only performed on radar links, merely a short period of time is required, which is set to 2 milliseconds in our simulations.

- Link Availability Probability (LAP). Two scenarios are considered: small probability (LAP = 0.25) and large probability (LAP = 0.95).

- Wireless Applications. Whenever a radar link is established between two vehicles, UDP packets are transmitted from one vehicle to the other with Constant Bit Rate (CBR) of 3 Gbps, e.g., using QPSK or 16-QAM modulation schemes [25].

- Routing Engine. Since only one-hop transmissions are required in our simulations, no routing protocol is used. Instead, vehicles only maintain their one-hop neighbors. Note that simulation of multi-hop networks is regarded as one of our future works.

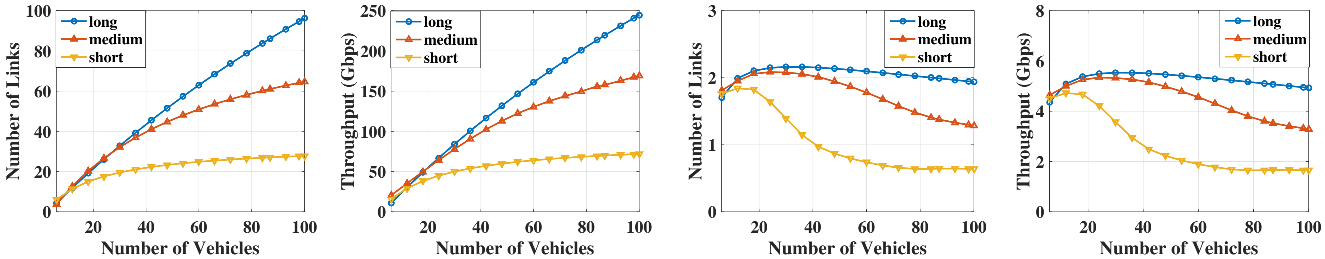
- Performance Metrics. The performance of the proposed JARC system is evaluated through four metrics: 1) the total number of established links in the network, 2) the throughput of the whole network, 3) the average number of established links at a vehicle, and 4) the average throughput at a vehicle.

3.5 Simulation Results

The performance of the JARC system is shown in Figure 7 (LAP = 0.95) and Figure 8 (LAP = 0.25). In these figures, "small", "medium" and "large" denote small, medium and large control intervals in Type 1 frames, respectively. Recall that we consider three scenarios for (Phase 1, Phase 2) interval pairs: small intervals (5 ms, 15 ms), medium intervals (10 ms, 30 ms), and large intervals (20 ms, 60 ms). Comparing Figure 7 and 8, we can find that larger LAP values lead to more established links as well as higher throughput, which is because the LAP value represents reliability of the radar links. In addition to the aforementioned four performance metrics, the ratio of Type 1 frames over the total amount of frames is also shown in Figure 9. Since the control interval of Type 1 frames is much longer than that of Type 2 frames, the radar link throughput of Type 1 frames is lower than that of Type 2 frames. Hence, the ratio of Type 1 frames affects the throughput of the network.

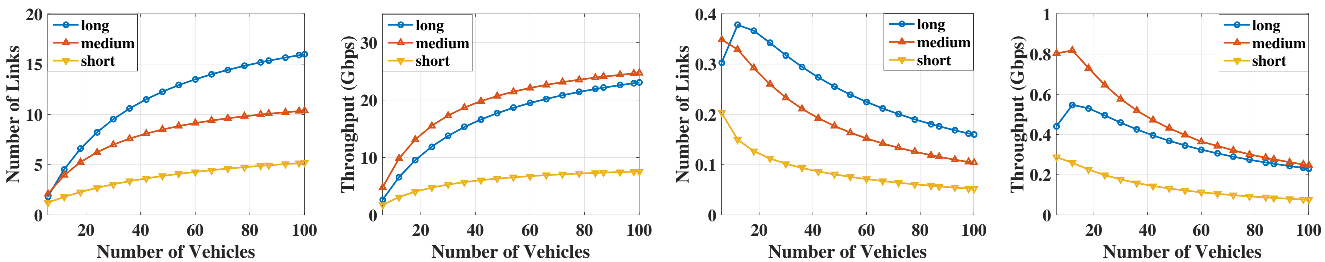
Figure 7 shows that longer control intervals in Type 1 frames lead to more established radar links as well as higher throughput. The reason for more established radar links is that more time is allocated to neighbor discovery and link establishment. The reason for higher throughput is more complicated. The trade-off of choosing the Type 1 control intervals is that longer control intervals can help establish more radar links, but also lead to shorter data delivery time (i.e., lower throughput). In contrast, the control interval of Type 2 frames is fixed, which is 2 milliseconds in our simulations. Therefore, the network throughput is not only dependent on the number of established links, but also affected by the ratio of Type 1 frames. However, Figure (9a) shows that only a small ratio of links use Type 1 frames due to the reliability of radar links (i.e., LAP = 0.95). Therefore, the throughput of the network is almost proportional to the number of established links. It can also be seen in Figure (9a) that the ratio of Type 1 frames decreases with increasing vehicle density. This is because the radar links are so stable that most of them can be successfully maintained, and thus vehicles do not need to establish new links using Type 1 frames.

Figure (8a) and (8c) show that longer control intervals in Type 1 frames lead to more established radar links and higher throughput, respectively. The reason is that more time is allocated to neighbor discovery and link establishment. Figure (8b) and (8d) show that longer control intervals in Type 1 frames not necessarily lead to higher network throughput due to the trade-off of choosing the Type 1 frame control intervals explained in the previous paragraph.



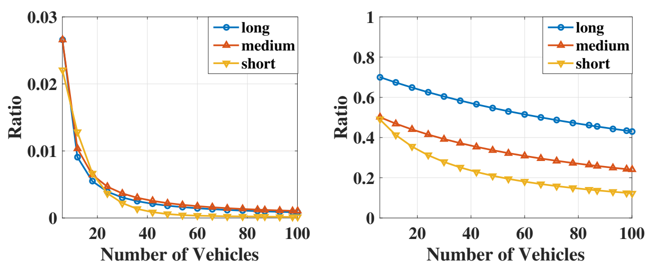
(a) Total number of links (b) Total throughput (c) Average number of links (d) Average throughput

Figure 7: LAP = 0.95



(a) Total number of links (b) Total throughput (c) Average number of links (d) Average throughput

Figure 8: LAP = 0.25



(a) LAP = 0.95 (b) LAP = 0.25

Figure 9: Ratios of Type 1 frames

Specifically, although the “long” control interval results in more established links as shown in Figure (8a), most of the links use Type 1 frames as shown in Figure (9b). In contrast, Figure (9b) shows that the “medium” control interval has lower ratios of Type 1 frames. Since Type 1 frames have much longer control intervals than that of Type 2 frames, the “long” control interval achieves lower throughput than the “medium” control interval, which is shown in Figure (8b) and (8d). Finally, Figure (9b) shows that the ratio of Type 1 frames decreases with increasing vehicle density, which is due to the congestion on the control channel.

4. CONCLUSIONS

In this paper, we propose a distributed JARC system enabling spectrum sharing between radar imaging and vehicular communications in the 79 GHz automotive radar band. The JARC system is comprised of three main functionality blocks: neighbor discovery, link establishment/maintenance and data delivery. In addition, we devise a corresponding MAC protocol that implements all the functionality of the JARC system. Moreover, we evaluate the performance of the system through practical simulation examples. The simulation results demonstrate that the proposed JARC system is able to support high-throughput data delivery in vehicular networks using the 79 GHz band. More importantly, since less bandwidth is required in the JARC system to achieve high radar imaging accuracy, remaining bandwidth can be used to alleviate the spectrum scarcity problem in the DSRC band.

One of our future works is to implement more realistic radar link models in ns3. Specifically, the current radar link model is a simple mathematical model with no consideration of physical properties of the millimeter wave signals. Hence, a more accurate model of vehicular communication links in the 79 GHz band needs to be developed. Moreover, we propose to use more realistic road traffic models (e.g., real-time road traffic on normal roads in urban and rural areas as well as highways), which can also be generated using SUMO. Another future work is to study the performance of the system in multi-hop networks and in terms of more performance metrics (e.g., average delay and packet loss ratio).

5. REFERENCES

[1] ITU World Radiocommunication Conference. https://www.itu.int/net/pressoffice/press_releases/2015/52.aspx. Geneva, November 17, 2015.

[2] NS3. https://www.nsnam.org/. NS-3.24: September 15, 2015.

[3] SUMO. http://sumo.dlr.de/wiki/Main_Page. Release: 0.25.0, 07.12.2015.

[4] F. Baselice, G. Ferraioli, G. Matuozzo, V. Pascazio, and G. Schirinzi. 3D automotive imaging radar for transportation systems monitoring. In *Environmental*

Energy and Structural Monitoring Systems (EESMS), 2014 IEEE Workshop on, pages 1–5, Sept 2014.

[5] M. Braun, C. Sturm, A. Niethammer, and F. K. Jondral. Parametrization of joint OFDM-based radar and communication systems for vehicular applications. In *Personal, Indoor and Mobile Radio Communications, 2009 IEEE 20th International Symposium on*, pages 3020–3024, Sept 2009.

[6] Q. Chen, D. Jiang, and L. Delgrossi. IEEE 1609.4 DSRC multi-channel operations and its implications on vehicle safety communications. In *2009 IEEE Vehicular Networking Conference (VNC)*, pages 1–8, Oct 2009.

[7] L. Ding, W. Wu, J. Willson, H. Du, and W. Lee. Efficient virtual backbone construction with routing cost constraint in wireless networks using directional antennas. *Mobile Computing, IEEE Transactions on*, 11(7):1102–1112, July 2012.

[8] K. Fawaz, A. Ghandour, M. Olleik, and H. Artail. Improving reliability of safety applications in vehicle ad hoc networks through the implementation of a cognitive network. In *Telecommunications (ICT), 2010 IEEE 17th International Conference on*, pages 798–805, April 2010.

[9] D. Garmatyuk and J. Schuerger. Conceptual design of a dual-use radar/communication system based on OFDM. In *Military Communications Conference, 2008. MILCOM 2008. IEEE*, pages 1–7, Nov 2008.

[10] D. Garmatyuk, J. Schuerger, and K. Kauffman. Multifunctional software-defined radar sensor and data communication system. *IEEE Sensors Journal*, 11(1):99–106, Jan 2011.

[11] D. Garmatyuk, J. Schuerger, Y. T. Morton, K. Binns, M. Durbin, and J. Kimani. Feasibility study of a multi-carrier dual-use imaging radar and communication system. In *Radar Conference, 2007. EuRAD 2007. European*, pages 194–197, Oct 2007.

[12] A. J. Ghandour, K. Fawaz, H. Artail, M. Di Felice, and L. Bononi. Improving vehicular safety message delivery through the implementation of a cognitive vehicular network. *Ad Hoc Netw.*, 11(8):2408–2422, Nov. 2013.

[13] Y. Han, E. Ekici, H. Kremo, and O. Altintas. Optimal spectrum utilization in joint automotive radar and communication networks. In *Modeling and Optimization in Mobile, Ad Hoc, and Wireless Networks (WiOpt), 2016 14th International Symposium on*, May 2016.

[14] G. Karagiannis, O. Altintas, E. Ekici, G. Heijenk, B. Jarupan, K. Lin, and T. Weil. Vehicular networking: A survey and tutorial on requirements, architectures, challenges, standards and solutions. *Communications Surveys Tutorials, IEEE*, 13(4):584–616, Fourth 2011.

[15] P. Kumari, N. Gonzalez-Prelcic, and R. W. Heath. Investigating the IEEE 802.11ad standard for millimeter wave automotive radar. In *Vehicular Technology Conference (VTC Fall), 2015 IEEE 82nd*, pages 1–5, Sept 2015.

[16] A. N. Le, D.-W. Kum, S.-H. Lee, Y.-Z. Cho, and I.-S. Lee. Directional AODV routing protocol for wireless mesh networks. In *Personal, Indoor and Mobile Radio Communications, 2007. PIMRC 2007. IEEE 18th International Symposium on*, pages 1–5, Sept 2007.

[17] A. Nasipuri, J. Mandava, H. Manchala, and R. Hiromoto. On-demand routing using directional antennas in mobile ad hoc networks. In *Computer Communications and Networks, 2000. Proceedings. Ninth International Conference on*, pages 535–541, 2000.

[18] C. Papathanasiou, N. Dimitriou, T. Samios, and L. Tassiulas. On the use of distributed directive antenna arrays in mobile OFDMA networks. In *Vehicular Technology Conference (VTC Spring), 2011 IEEE 73rd*, pages 1–5, May 2011.

[19] M. Rockl, T. Strang, and M. Kranz. V2V communications in automotive multi-sensor multi-target tracking. In *Vehicular Technology Conference, 2008. VTC 2008-Fall. IEEE 68th*, pages 1–5, Sept 2008.

[20] C. W. Rossler, E. Ertin, and R. L. Moses. A software defined radar system for joint communication and sensing. In *Radar Conference (RADAR), 2011 IEEE*, pages 1050–1055, May 2011.

[21] H. Shokri-Ghadikolaei and C. Fischione. Millimeter wave ad hoc networks: Noise-limited or interference-limited? *arXiv preprint arXiv:1509.04172*, 2015.

[22] S. Singh, R. Mudumbai, and U. Madhow. Distributed coordination with deaf neighbors: Efficient medium access for 60 GHz mesh networks. In *INFOCOM, 2010 Proceedings IEEE*, pages 1–9, March 2010.

[23] Y. L. Sit and T. Zwick. MIMO OFDM radar with communication and interference cancellation features. In *Radar Conference, 2014 IEEE*, pages 0265–0268, May 2014.

[24] C. Sturm and W. Wiesbeck. Waveform design and signal processing aspects for fusion of wireless communications and radar sensing. *Proceedings of the IEEE*, 99(7):1236–1259, July 2011.

[25] X. Tie, K. Ramachandran, and R. Mahindra. *Passive and Active Measurement: 13th International Conference, PAM 2012, Vienna, Austria, March 12-14th, 2012. Proceedings*, chapter On 60 GHz Wireless Link Performance in Indoor Environments, pages 147–157. Springer Berlin Heidelberg, Berlin, Heidelberg, 2012.

[26] M. Uchida, Y. Kagawa, and A. Okuno. A vehicle-to-vehicle communication and ranging system based on spread spectrum technique-SS communication radar. In *Vehicle Navigation and Information Systems Conference, 1994. Proceedings., 1994*, pages 169–174, Aug 1994.

[27] J. Wang, Y. Fang, and D. Wu. SYN-DMAC: a directional MAC protocol for ad hoc networks with synchronization. In *Military Communications Conference, 2005. MILCOM 2005. IEEE*, pages 2258–2263 Vol. 4, Oct 2005.

[28] Z. Wang and M. Hassan. How much of DSRC is available for non-safety use? In *Proceedings of the Fifth ACM International Workshop on VehiculAr Inter-NETworking*, VANET '08, pages 23–29, New York, NY, USA, 2008. ACM.