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Citation for the original published paper (version of record):
Aydogdu, C., Wymeersch, H., Rydstrom, M. (2020). Can Automotive Radars Form Vehicular Networks?. IEEE National Radar Conference - Proceedings, 2020-September: 1-6.
http://dx.doi.org/10.1109/RadarConf2043947.2020.9266540

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Can Automotive Radars Form Vehicular Networks?

Canan Aydogdu*, Henk Wymeersch*, Mats Rydström†
*Department of Electrical Engineering, Chalmers University of Technology, Gothenburg, Sweden
†Veoneer Sweden AB, Gothenburg, Sweden
Email: {canan,henkw}@chalmers.se, mats.rydstrom.external@veoneer.com

***Abstract*—Radar communications (RadCom) is a spectrally efficient way for removing automotive radar interference and thereby enhancing reliable radar sensing, via a single hardware for both radar and communications. When interference coordination does not use all the RadCom resources, opportunities for communicating additional data arise. We propose a new communication protocol, termed RadNet (for radar network), which forms a vehicular ad-hoc multi-hop network by automotive radars in a distributed manner. Simulation results obtained for high-way use cases show that RadNet can enable several Mbps data links without degrading the radar performance.**

I. Introduction

Vehicular networking is a necessity for future intelligent transportation systems (ITS) to enhance safety beyond the range of automotive sensors and beyond the human driver capabilities. Several safety-critical applications such as dissemination of warning messages (future collision warning, blind spot warning, braking ahead warning [1]) and vehicular cooperation for enhancing sensor accuracy or detection of security threats depend on feasibility of a vehicular networking technology.

There are currently two options for connecting vehicles: either via the cellular infrastructure (e.g., 4G Long-Term Evolution for Vehicle (LTE-V) or 5G) or through short-range solutions, such as the WiFi-based IEEE 802.11p used in Dedicated Short-Range Communications (DSRC) in the USA and ITS-G5 in Europe [2]. Vehicular networking through the cellular infrastructure is suitable for Internet of Things (IoT) like applications, such as long-term traffic information (e.g., route suggestions), whereas short-range is specifically dedicated to form vehicular ad-hoc networks (VANETs) that provide low-latency transmissions whereas moving the dependency on infrastructure. Recently, a third option for vehicular networking has been proposed, whereby communications occurs via automotive radars that implement radar communications (RadCom) [3]. Vehicular networks can use for example, the unlicensed 60 GHz or so-called mmWave band (57–66 GHz) for dual purpose under restrictions in terms of power emissions [4], [5]; or the 76-81 GHz radar band together with a separate suitable communication channel. When multiple vehicles use such RadCom technology to connect a network of vehicles, we obtain a radar network (RadNet), which is the natural result of convergence of the mm-Wave frequency bands used by wireless communications and automotive radars. RadNets can be used for short-range communications as well as integrated into the mm-Wave cellular communication infrastructure. Although the concept of 'radar networks' was used for integrated radars for environmental mapping or cooperative sensing in military or weather-forecasting [6], it was not considered as an alternative for vehicular communications [2]. Possible forms of co-existence and co-design of automotive radar sensing and cellular communications reviewed in [7] and a radar communications unit employing OFDM for short-range vehicular communications proposed in [8] provide several examples for communication over automotive radars.

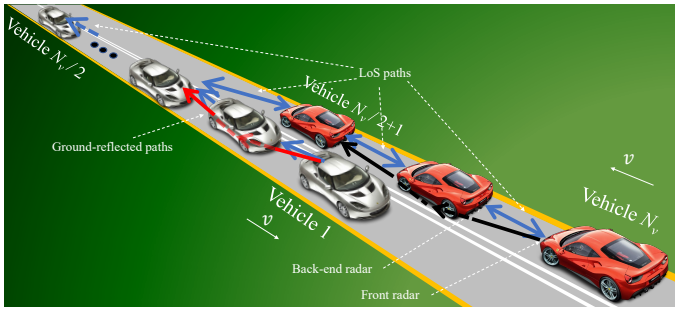

Fig. 1. An illustration of a scenario with example propagation paths of mutual radar interference and communication links, including LOS and ground reflected links.

There are three distinguished features of a RadNet, which deserves a thorough investigation to find out its suitability for a vehicular networking option. First of all, a highly reliable and low-latency communication system is a missing part of the puzzle of the safe and efficient transportation vision [9]. If a RadNet is formed by replacing radars with radar communication units (RCU) in the next generation of Advanced Driver Assistance (ADAS) and Autonomous Drive (AD) vehicles, V2V communication beams will become directed and more reliable (due to less collisions and increased SINR) and will have lower latency (due to reduced dual function single-on-chip processing delays and reduced delays in the wireless channel). Secondly, improved road [10] and parking capacity [11] expected from a future ITS, can only be achieved through high-sensitive localization and the inherent automotive radar sensors offer high localization sensitivity (e.g., up to 3 cm for 76–81 GHz operating radars), together with robustness against a variety of conditions like snow/fog/rain [12] or optical illusions. Finally, compared to the existing vehicular networking options, a RadNet is more efficient in various aspects: i)

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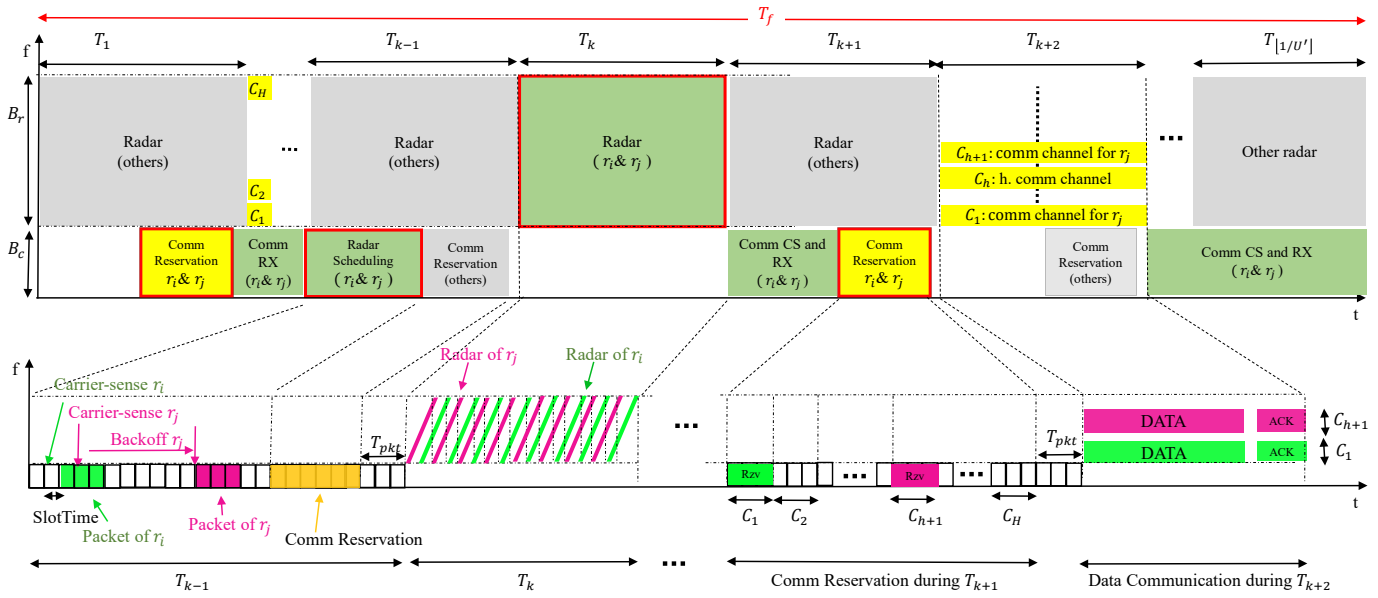


Fig. 2. Illustrates the utilization of frequency-time resources for the RadNet protocol w.r.t. two specific RCUs r_i and r_j. Scheduled radars by RadChat occur over green colored resources, whereas data communications occur over yellow colored resources.

spectrum-efficient, since the underutilized automotive radar spectrum is used by communications; ii) energy-efficient: two functions combined in one SoC; iii) hardware-efficient, since the hardware in a vehicle is reduced from two separate systems to a single dual function hardware.

In this paper, we propose RadNet as a vehicular ad-hoc multi-hop networking technology and investigate its communication capabilities in terms of data rate for high-way traffic. We build on top of our earlier work on the basic communication protocol, RadChat protocol, which coordinates radar transmissions in order to address the mutual interference problem [13], [14], leading to reduced ghost targets [15] and improved pedestrian detections [16]. We show that, cooperative radar communications can also be used to achieve data communication among vehicles on the order of tens of Mbps with a reasonable latency besides eliminating mutual radar interference.

II. System Model

All automotive radars are assumed to be replaced with RCUs, which have an additional communication plus interference mitigation capability, such as the RadChat RCUs [14]. RCUs thus have both the automotive radar and communication capability within a single hardware and are controlled via a central unit in each vehicle. And radar transmission is considered successful if it is received without any in-band interference.

All vehicles use FMCW-type radars with the same bandwidth B_{r}, same chirp duration T, and same frame time T_f, comprising N chirps per frame.

RCUs switch between radar and communication functionality. However, interference-free radar sensing is always prioritized over communication. In order to achieve this, the total system bandwidth is divided in band B_{c} used for control packets (communication reservation and radar scheduling packets), and in band B_{r} radar transmissions occur, as well as data communication for external applications (such as warning messages, see-through driving data, sensor fusion data).

Two types of communication packets are used: control and data packets. Control packets are unacknowledged broadcast messages by RadChat for interference mitigation and are sent over a separate frequency band B_{c}, which lies out of the radar sensing frequency band B_{r}. Data packets are used for vehicular communication, such as warning messages, see-through driving data, sensor fusion data, and are sent over frequency bands within B_{r} if this band is free from radar sensing.

III. RadNet: Protocol Description

RadNet is a distributed vehicular networking protocol based on cooperative FMCW-based radar communications. The goal of RadNet is to provide data communication, such as distributing warning messages, radar map data, see-through driving data, etc., in a mutual radar interference-free channel. Interference-free radar sensing is always prioritized over communication in a RadNet; and communication takes place only when the radar sensor becomes idle during a radar frame. In this section, we describe the proposed RadNet protocol.

A. Division in Time Slots

Time division is a necessary feature for the operation of RadNet for enabling cooperative radar communications since the same hardware is used for both functionalities. Fig. 2 illustrates the utilization of frequency-time resources for the RadNet protocol w.r.t. two specific RCUs r_i and r_j. The RCUs r_i and r_j transmit radar signals during time slot T_k, where a

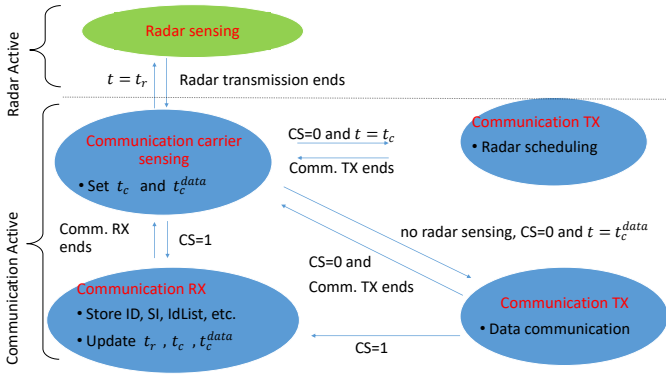


Fig. 3. Flowchart for RadNet operation.

time slot is a portion of a periodically repeated radar frame. We divide a radar frame T_f into $\lfloor 1/U' \rfloor$ time slots, where $U' = (N+1)T/T_f$, corresponding to a modified duty cycle with one extra chirp added to a chirp sequence in order to allocate more than one radar sequence to the same time slot. This slotted time within a radar frame is set to maximize the non-overlapping chirp sequences within a radar frame. Other RCUs in the VANET are allowed to transmit their FMCW chirp sequences during other time slots, except T_k, over the band B_r in Fig. 2 (colored in grey). Communication control packet transmission over the band B_c is also adjusted according to these time slots. For example, the RCUs r_i and r_j do send broadcast control packets for mutual radar interference-free operation, i.e., RadChat, during T_{k-1}.

This division in time results in a certain maximum number of RCUs with no mutual interference in the vehicular network, which is denoted by $M_{\max}$. $M_{\max}$ is the maximum size of the disjoint time-frequency resources that a radar can be scheduled at for interference-free vehicular communication. Note that a maximum of $\lfloor B_{\rm r}/((1+\alpha_d)B_{\rm c}) \rfloor$ radars can be sent during one time slot without interfering each other, where α_d is a constant for determining the maximum range of a direct interferer taken into account [14]. Hence, $M_{\max} \leq \lfloor 1/U' \rfloor \lfloor B_{\rm r}/((1+\alpha_d)B_{\rm c}) \rfloor$.

B. Services Provided

The RadNet protocol provides two services:

- *Radar scheduling service:* mutual radar interference is mitigated by the RadChat protocol [14], by scheduling radars to non-interfering time-frequency resources.
- *Data communication service:* vehicular data communication takes place during unused time-frequency resources in the band $B_{\rm r}$, without compromising radar performance.

These services are implemented on top of a single RadCom hardware using different medium access control (MAC) techniques described next. A flowchart for the operation of RadNet is given in Fig. 3, where t_r is the starting time of radar transmission, t_c is starting time of communication control packet for radar scheduling and $t_c^{\rm data}$ is the starting time of data packet.

1) Radar Scheduling Service: In order to provide interference-free automotive radar sensing, RCUs should transmit their chirp sequences in non-overlapping time slots over the radar band $B_{\rm r}$ and non-conflicting vulnerable periods within a time slot [15]. The value of such resources is called as SlotIndex (SI), where SIs range from 1 to $M_{\max}$. Hence, each RCU needs to schedule its radar transmission in a specific SI, which should be different than the SIs employed by other vehicles. The RadChat protocol [14] explained next, provides this in a distributed manner over both single-hop and multi-hop VANETs.

Prior to radar chirp sequence transmission, each RCU broadcasts a packet over a separate communication channel with carrier sense multiple access (CSMA) with random binary exponential backoff (BEB). For example, let the RCU r_i have a radar chirp sequence transmission during T_k in Fig. 2 within the radar frame T_f. This RCU broadcasts a control packet during T_{k-1} (green-coloured rectangle on the bottom left corner). Let us assume that another RCU r_j receives this control packet. The control packet includes the identity (ID: the reference time employed), the SlotIndex (SI: randomly selected index for one of the disjoint time-frequency resources) and the idList (the list of vehicles using the same ID). RCU r_j, which plans to radar sense during T_k, does not send an acknowledgement, but updates its own ID, SI and idList according to this received control packet, so that its radar transmission is scheduled to a different and possibly non-conflicting SI. Any conflicts or collisions of control packets are resolved in other radar frames since BEB is employed. The radar chirp sequences of RCU r_j lie in T_k but use a non-conflicting vulnerable period after these adjustments. RCU r_j broadcasts its radar information by a control packet during T_{k-1} (pink-coloured rectangle on the bottom left corner).

As a result, RadChat avoids mutual radar interference by scheduling radar sensing to non-overlapping vulnerable periods, avoids communication packet collisions by CSMA with BEB for communications, while radar and communication cross-interferences are avoided by using a different communication band than radar (refer to [14] and [17] for a detailed explanation of single-hop and multi-hop operation of RadChat).

2) Data communication service: This service is an extension to the radar scheduling service and constitutes the primary contribution of this article. The goal of data communication service of RadNet is to coordinate data communication, which is achieved by a reservation-based random MAC technique. The RCUs, which radar sense during T_k, do carrier-sense the control channel starting T_{k+1}. If no activity is sensed during T_{k+1} in the control channel, these RCUs are allowed to utilize a portion of the radar band B_r during the time slot T_{k+2} (and also other time slots except T_{k-1} and T_k) with data communication. The radar band is divided into data communication channels C_h, for $1 \leq h \leq H_{\max}$, where $H_{\max} = \lfloor B_{\rm r}/B_{\rm c} \rfloor$ is the maximum number of available data communication channels that don't mutually overlap. For example, the RCUs r_i and r_j carrier-sense and receive packets

over the control channel as long as radar is inactive in order to cope with dynamic vehicular topologies during the green coloured durations over the control band in Fig. 2. If no radar scheduling takes place during T_{k+1} in the control channel, a communication reservation interval in the control band is used for allocation of the data communication channels (indicated by yellow in the right bottom of Fig. 2). An RCU willing to transmit data to one or more destinations sends a ready-to-send (RTS) packet during a randomly selected reservation slot, say $C_h \in T_{k+1}$. The recipient RCUs tune their RF circuitry to the corresponding channel C_h in the next time slot T_{k+2}. Data is transmitted during T_{k+2} over channel C_h, which is acknowledged. This way, RadNet provides an acknowledged connectionless service, with either unicast or multicast transmissions depending on the intended destinations.

C. Random versus Packed Assignment

Since we prioritize radar, data communication can never take place if radar sensing occurs at every time slot in a radar frame. In our previous studies [14], [15], [17], radars are scheduled randomly to the available slot indices (SIs). We call this *Random Assignment (RA)*. However, it is possible to assign radar sensing to one or few time slots, i.e., packing radar sensing in time, which we call as *Packed Assignment (PA)*. After convergence of RadChat, a packed assignment of SIs can be distributed over the control packets to vehicles, either controlled by a clusterhead RCU or in a distributed manner. The details of the protocol for PA are omitted for space reasons.

IV. Performance Evaluation and Results

A. Evaluation Scenario

Two high-way traffic scenarios are investigated, where one fleet of vehicles moves in the same direction in Scenario-I and two fleets of vehicles move in opposite directions in Scenario-II (see Fig. 4). A geometry-based deterministic vehicular channel model is employed owing to high-frequency

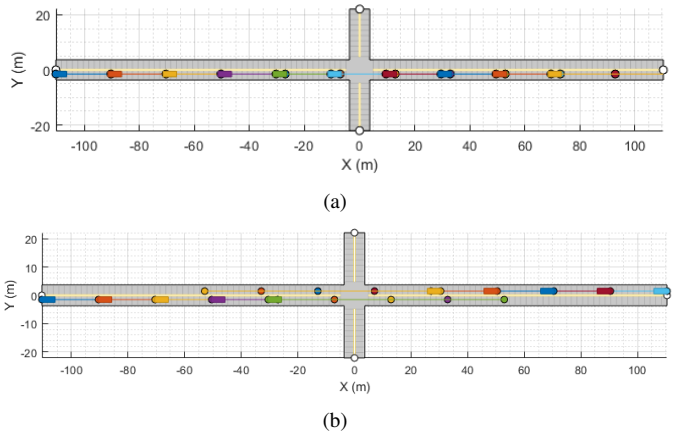


Fig. 4. Traffic scenarios: a) Scenario-I, one fleet moving in one direction and b) Scenario-II, two fleets approaching each other. Vehicles are represented by rectangles, whereas waypoints, i.e., starting and ending paths, of each vehicle is indicated by dots with same color.

TABLE I
Simulation Parameters [14]

	Parameter	Value
Radar	Radar bandwidth (B_{r})	800 MHz
	ADC bandwidth (B_{ADC})	15 MHz
	Carrier frequency (f_{r})	79.15 GHz
	Modified duty cycle (U')	1/5
	Vehicle radar cross sections σ	10 dBsm
	Radar transmit power P_{r}	12 dBm
	Radar processing gain G_p	53.76 dB
	Radar signal to noise ratio threshold γ_{r}	7 dB
	Chirp duration (T)	77.51 µs
	Frame duration (T_f)	50 ms
	Number of chirps per frame (N)	129
Communication	Communication bandwidth B_{c}	15 MHz
	Communication carrier frequency (f_{c})	79.02 GHz
	Packet size (N_{pkt})	100 bytes
	Modulation	16-QAM
	Communication transmit power P_{c}	23 dBm
	SlotTime δ	10 µs
	Maximum contention window size (W_0)	48
	Maximum backoff stage (B)	3
Joint	Maximum range of LoS interference	1 km ($\alpha_d = 6.56$)
	Thermal noise temperature T_0	290 K
	Receiver's noise figure	2
	Antenna gain G_{trx}	30dBi
	Reflection Coefficient for asphalt (R)	0.2814
	Antenna FoV	$\pm 10^\circ$ (azimuth), $\pm 5^\circ$ (elevation)

mmWave bands [18], [19] and we assume that signals propagate either through a LoS path if not blocked, or through ground-reflections. The signal to noise ratios (SNR) perceived at RCUs are computed using Friis free space propagation and radar equations [20]. The values of α_d is assigned so that the maximum range of a direct interferer taken into account is set as 1 km. Communication links with a data rate equal to $2B_c$ are assumed to be available if a bit error rate of at most 10^{-5} is achieved for the 16-QAM signals over the AWGN channel.

We ignore interference among radars within a single vehicle since each vehicle is assumed to be equipped with one front-end and one back-end RCU with long-range radar sensing functionality. All vehicles are assumed to be equally spaced and have the same speed. The achievable data rate performance of the distributed cooperation-based radar communications protocol RadNet is evaluated in two dynamic VANET fleets scenarios for 20 m vehicle spacing and speeds of $v = 150\,\mathrm{km/h}$, which provides us a communication performance at a regime where we push the limits of automotive radar performance at reasonable maximum relative velocities. A total of 10 Monte Carlo simulations of 2 s duration were performed, with the parameters summarized in Table I.

B. Discussion

Scenario-I (one fleet): We first evaluate the impact of the number of vehicles in the fleet on the convergence time of RadChat (denoted by t_{final}) and the achieved rate upon convergence of RadChat. The data rate per vehicle versus the convergence time of interference mitigation for Scenario-I is

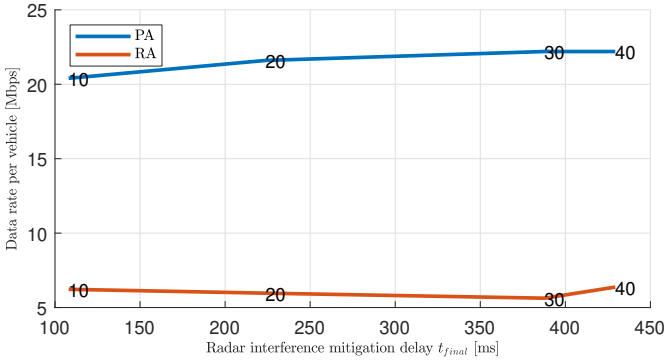
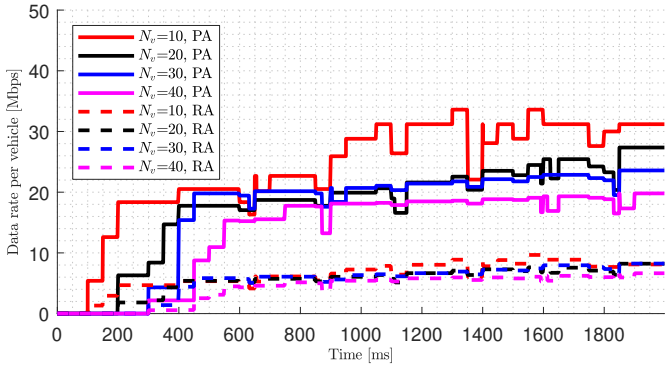
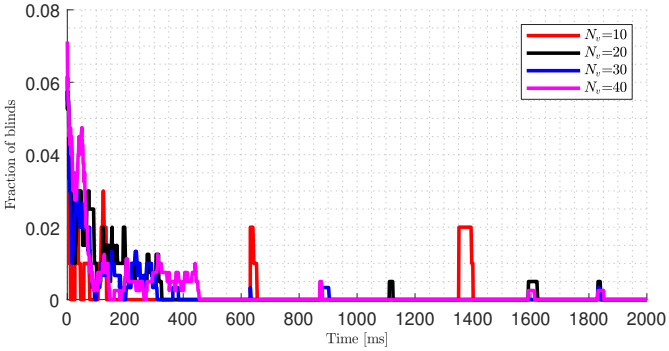


Fig. 5. Scenario-I performance for the radar interference mitigation convergence time t_{final} versus communication data rate per vehicle for random assignment (RA) and packed assignment (PA).



(a)

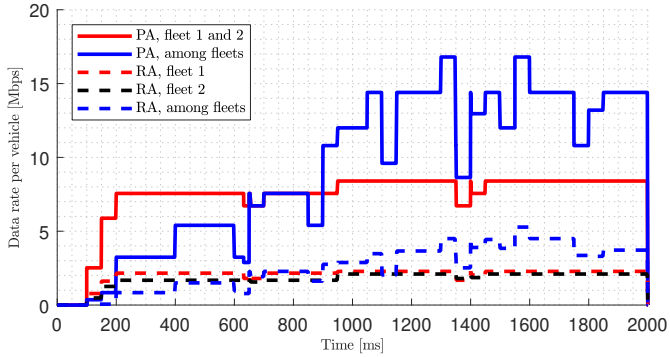


(b)

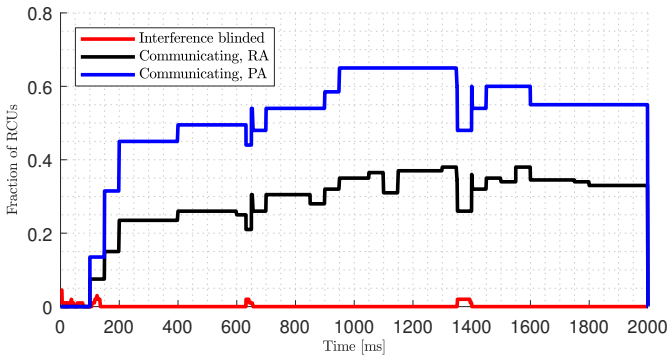
Fig. 6. Scenario-II performance for $N_v = \{10, 20, 30, 40\}$: a) communication data rate with random assignment (RA) and packed assignment (PA) with RadChat and b) fraction of radar blinds.

given in Fig. 5 for various number of vehicles N_v denoted on the curves.

Note that each vehicle is connected to up to 4 other vehicles, 2 through LOS links and 2 through ground-reflected links. Hence, the number of communication links is linear with the number of vehicles, which makes data rate per vehicle almost constant. It can be observed that RA provides about 6.05 Mbps, whereas PA provides 21.6 Mbps data rate per vehicle on the average. This suggests that a RadNet provides data



(a)



(b)

Fig. 7. Scenario-II performance for $N_v = 10$ vehicles: a) communication data rate, b) fraction of blind and communicating RCUs with random assignment (RA) and packed assignment (PA) with RadChat.

rates comparable to DSRC by reusing radar spectrum during radar idle times. These rates are enough for dissemination of warning messages, while see-through driving data might be relayed by doubling the radar ADC bandwidth for the considered fleet of vehicles on a high-way scenario.

Scenario-II (two approaching fleets): For two approaching fleets, the network topology will change continuously, so the achieved rate varies over time. For that reason we evaluate communication and radar performance as a function of time, for a varying number of vehicles. Fig.6-a) shows the data rate per vehicle. The data rate starts off low, as the RadChat protocol takes most resources to coordinate radar interference (this takes about 100-400 ms), after which the rate increases. The rates are higher than in Scenario-I, since a vehicle may connect to more surrounding vehicles via LoS or ground reflection. As in Scenario-I, the packed assignment leads to rates about 3 to 4 times higher than under random assignment. The radar performance in shown in Fig.6-b), in terms of the fraction of radar blinds (i.e., non-functioning due to interference) as a function of time. Observe the correlation between increased blinds and reductions in rate. Again, the convergence of RadChat is visible within 400 ms, with small adjustments around 600 and 1400 ms, due to the changing topology. Note that RadChat operates in a distributed manner and each individual vehicle experiences a different convergence latency

which is lower than the maximum value reported here. Hence, RadChat convergence latency is determined by the number of neighboring RCUs rather than the number of RCUs in the whole VANET. as shown in Fig. 6(b).

When two fleets approach, there is both intra-fleet and inter-fleet communication. In order to understand the rates for each type of communication, Fig. 7-a) depicts the data rate per vehicle within each fleet and between fleets, for $N_v = 10$, while Fig. 7-b) shows the fraction of communicating vehicles, as well as the fraction of radar blinds. We see that up to 60% of vehicles are able to send data with almost 15 Mbps across a fleet moving with a 300 km/h relative speed with RadNet, whereas the data rate per vehicle within the fleet is almost constant around 8 Mbps. About half of the RCUs do communicate while radar sensing is not affected at all.

V. Conclusion

When radar hardware is reused for communication purposes, it enables not only interference coordination, but also additional data services. We have proposed a distributed radar networking solution, which we evaluated in a case study to assess the achievable data rate. This solution, named as RadNet, builds on the existing RadChat protocol and provides low radar interference and high-rate communications. Based on realistic radar parameters and a geometric channel model, we achieve data rates comparable to the widespread short-range vehicular solution DSRC.

Acknowledgment

This research was supported by Vinnova grant 2018-01929 and the Chalmers Transport Area of Advance project IRIS.

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