Automotive Radar Interference Mitigation via Multi-Hop Cooperative Radar Communications

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***Abstract*— We investigate the interference mitigation performance of cooperative radar communications in dynamic multi-hop vehicular ad-hoc networks, where each automotive radar is not in the field of view of others. This study builds on top of our former proposed cooperative radar communications solution, RadChat, which uses a single hardware for both radar and communication purposes. Simulation results obtained for high-way traffic scenarios show that RadChat functions with quite a low latency while decreasing the interference significantly.**

***Keywords*— cooperative radar communications, FMCW, automotive radar interference, vehicular communication.**

I. Introduction

Although automotive radar sensors have distinguished features compared to other sensors, such as high localization sensitivity (e.g., up to 3 cm for 76–81 GHz operating radars) and robustness against a variety of conditions (snow/fog/rain or optical illusions), these sensors still have one safety problem: mutual interference. The automotive radar interference is expected to impact driving safety by creating ghost targets or hiding low radar cross sectioned targets, such as cyclists and pedestrians due to an increased noise floor [1]–[3]. The automotive radar interference is expected to impact driving safety when the number of vehicles with increased number of radars with advanced/autonomous driving functions increases. Furthermore, the propagation of mutual interference signals via reflections as well as line of sight (LoS) paths, is a factor that increases its possibility (Fig.1).

Frequency modulated continuous-wave (FMCW) based automotive radar has been the most common, cheap and robust radar format used in the automotive sector today [4]. Among several solutions proposed for solving the radar interference problem for the FMCW based automotive radars [1], [2], cooperative radar communications based solutions are effective, simple and least demanding in terms of hardware. Moreover, the information, which is shared among radar sensing and vehicular communications in cooperative schemes for mitigating interference [5], has the potential to be used for any vehicular networking applications, especially for low-latency cooperative localization and mapping.

The latency in communications turns out to be high when centralized control is used for coordinating radar transmissions, leading to maximum blind duration, i.e. the maximum time duration that a radar is blinded by interference, of around 10 s with 54 km/h-low-speed 60 vehicles [6]. This maximum blind duration is shown to less than 80 ms for our proposed *distributed* cooperative radar communications based interference mitigation solution, called as RadChat, for 70 vehicles in a static single-hop scenario, where all radars are in the field of view (FoV) of all other radars [7].

In this paper, we investigate the performance of RadChat in terms of interference mitigation in dynamic high-way traffic scenarios up to 300 km/h relative speeds in a multi-hop network setting, where each radar is connected to other radars through multiple hops. The results show that the RadChat protocol convergences in 73.71 ms on the average and maximum 185.84 ms; by letting blind durations of 9.42 ms on the average and maximum 40.11 ms for ten vehicles.

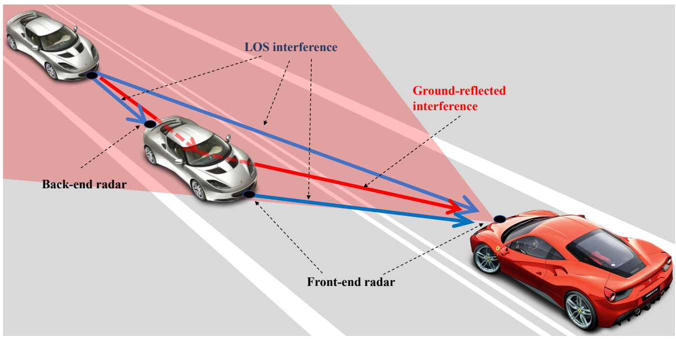


Fig. 1. An illustration of various propagation paths of mutual radar interference, including one-way LOS and one-way ground reflected interference.

II. System Model and Assumptions

A. Radar Communications Model

Vehicles are assumed to be equipped with front-end and back-end radar communication units, which have a long-range radar sensing functionality and communications capability. We assume that the receiver ADC is jointly used by radar and communications, which upper-bounds the communication band B_c, with the ADC bandwidth, i.e. $B_c < B_{\text{ADC}}$. Different radar and communication transmit powers are assumed ($P_{\text{c}} > P_{\text{r}}$) compliant to radar sensing and V2X communications based market products, which merges from the fact that the FMCW radar generally has a high processing gain G_{p} equal to product of numbers of FMCW chirps and samples per chirp.

B. Traffic Scenario and Propagation Channel Model

Two traffic scenarios given in Fig. 2 are investigated in this study: a) a fleet of vehicles in one lane, which moves in the same direction and 2) two fleets of lined vehicles, which move towards each other. In both scenarios vehicles are moving with the same speed, which leads to a dynamically changing topology for the second traffic scenario. We assume that each vehicle has one front-end and one back-end cooperative radar communications unit. This leads to spatial diversity so that we can ignore adjacent radar interference among radars mounted on the same vehicle, i.e., self-interference.

A geometry-based deterministic vehicular channel model is employed in this study due to high-frequency mmWave bands [8], [9]. We assume that both communication and radar signals propagate either through a LoS path if there exist one, or through ground-reflections. The asphalt is assumed to act as a reflector rather than a scatterer for the considered mm-Wave frequencies due to the comparable size of asphalt particles (at most 1.27 cm [10]) with the wavelengths considered (3.7-4mm). We also assume that the ground-reflected path or the LoS path are used two-way and both paths are assumed to travel the same distance.

These simplifications lead to six possible received signals at an RCU: a LoS radar return with range d_r and signal to noise ratio SNR_r, a ground-reflected radar return (d_rGR, SNR_rGR), a LoS radar interference (d_int, $\mathrm{SNR_{int}}$), a ground-reflected radar interference (d_intGR, $\mathrm{SNR_{intGR}}$), a LoS communication signal (d_c, $\mathrm{SNR_c}$) and a ground-reflected communication signal (d_cGR, $\mathrm{SNR_{cGR}}$). Assuming Friis free space propagation and radar equations [11], the signal to noise ratios (SNR) perceived at r_i for these six signals are respectively calculated as follows:

$$\mathrm{SNR_r} = \frac{P_\mathrm{r} G_\mathrm{trx} \lambda_\mathrm{r}^2 \sigma G_\mathrm{p}}{\mathrm{N_r}(4\pi)^3 \mathrm{d_r^4}}, \quad \mathrm{SNR_{rGR}} = \frac{P_\mathrm{r} G_\mathrm{trx} \lambda_\mathrm{r}^2 \beta^4 \sigma G_\mathrm{p}}{\mathrm{N_r}(4\pi)^3 \mathrm{d_{rGR}^4}}, \tag{1}$$

$$\mathrm{SNR_{int}} = \frac{P_\mathrm{r} G_\mathrm{trx} \lambda_\mathrm{r}^2 G_\mathrm{p}}{\mathrm{N_r}(4\pi)^2 \mathrm{d_{int}^2}}, \quad \mathrm{SNR_{intGR}} = \frac{P_\mathrm{r} G_\mathrm{trx} \lambda_\mathrm{r}^2 \beta^2 G_\mathrm{p}}{\mathrm{N_r}(4\pi)^2 \mathrm{d_{intGR}^2}}, \tag{2}$$

$$\mathrm{SNR_c} = \frac{P_\mathrm{c} G_\mathrm{trx} \lambda_\mathrm{c}^2}{\mathrm{N_c}(4\pi)^2 \mathrm{d_c^2}}, \quad \mathrm{SNR_{cGR}} = \frac{P_\mathrm{c} G_\mathrm{trx} \lambda_\mathrm{c}^2 \beta^2}{\mathrm{N_c}(4\pi)^2 \mathrm{d_{cGR}^2}}, \tag{3}$$

where σ is the radar cross section of the target, β is the reflection coefficient, G_p is the radar processing gain, G_trx is the multiplication of transmit and receiver antenna gains (with an assumption that it is equal for LoS and ground-reflected signals for the narrow-beam transmissions assumed in this article), λ_r and λ_c are the wavelengths of radar and communication signals, respectively; $\mathrm{NP_r}$ and $\mathrm{NP_c}$ are the thermal noise powers for radar and communication reception.

III. Multi-hop Cooperative Radar Communications via RadChat

A. Background: Basics of the RadChat Protocol

The goal of the RadChat protocol is to mitigate FMCW-based automotive radar interference. The method for achieving this goal is scheduling radars in a distributed manner via cooperative radar communications. Legacy automotive radars are replaced with RadChat Units (RCU), which have both the automotive radar and communication capability in a single hardware. All such co-located RCUs are connected to and controlled via a central unit at each vehicle.

RadChat switches between radar and communication functionality, while using separate frequency bands for communication (B_c) and radar sensing (B_r). Communication packets, which carry information about when and at which frequency radar sensing will start, are broadcast every radar frame through unacknowledged connectionless best-effort service by carrier sense multiple access (CSMA). RCUs, which receive these packets simply perform radar sensing in non-overlapping vulnerable periods and frequency bands.

Scheduling automotive radar sensing in a distributed manner requires: 1) All vehicles to employ the same time frame, which is called as the identity (ID), and 2) All RCUs to use disjoint time-frequency slots for radar sensing, called as SlotIndex (SI), for interference-free radar sensing. The maximum number of time-frequency resources or SIs is denoted by M_max, which is determined by FMCW chirp parameters (refer to [7] for a detailed explanation of RadChat).

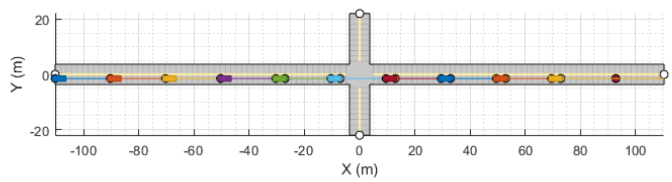
B. RadChat in a Multi-Hop Dynamic VANET

In this section, we highlight the functionalities of RadChat additional to our previous studies in [7], [12], which are specific to dynamic multi-hop VANETs.

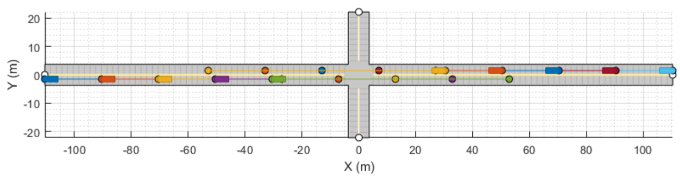
1) Connectivity

RadChat converges, i.e. solves the interference problem, when all *connected* RCUs are assigned the same ID and different SI values.

Definition 1 (Connected RCUs): Two RCUs r_i and r_j are connected, denoted by $r_i \leftrightarrow r_j$, if a radar interference signal or a communication signal transmitted by either of the RCUs is received by the other RCU with an SNR $\geq \min(\mathrm{SNR_{int}}, \mathrm{SNR_{intGR}}, \mathrm{SNR_c}, \mathrm{SNR_{cGR}})$.



(a)



(b)

Fig. 2. Traffic scenarios: a) One fleet moving in the one direction and b) 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. Scenarios are run for 2 s, resulting with 83.3 m paths.

2) Indication of widespread: Strength and identity lists

RadChat uses a *strength* variable coupled by a specific ID, which is an indication of how widespread an ID is. This strength variable ensures that the automotive radars use the ID, which is used by the majority of vehicles in order to avoid fluctuations in protocol convergence. For example, when a group of vehicles using a common time reference approach another set of vehicles, the group with the lower number of vehicles should adopt their time reference to the larger group. This is achieved through the first communicating RCU pair. Let's say the RCU r_i receives a communication packet from the RCU r_j. This packet includes the time reference of the RSU, $r_j.ID$ and the vehicle identities that use this specific ID, called as identity list and denoted by $r_j.idList$. The length of this list gives the $strength$ of this ID. If the received ID is different than the ID used by RCU ($r_i.ID \neq r_j.ID$), the RCU r_j adopts the ID with the larger $strength$, i.e. larger idList size. If ID's are the same, $r_i.ID = r_j.ID$, the two idLists are merged.

3) Keeping track of time: TTL and time stamps

A time-to-live (TTL) is used to delete a vehicle identity in case no packet is received from that specific vehicle for a long time. TTLs are coupled with the entries in the idList for RadChat to function fluently under dynamic real traffic scenarios, where entries in the idLists make no sense after having moved to a completely different neighborhood.

Moreover, as the VANET topology changes, the SIs should be reused. This is done by time-stamping each received SI while recording in the database of a vehicle. When an RCU needs to update its SI due to a conflict and all the available SI's are used, the oldest SI in the database is reused.

IV. Performance Evaluation and Results

A. Scenario

The multi-hop performance of the proposed FMCW-based distributed cooperation based radar communications protocol RadChat is evaluated in two dynamic VANETs given in Fig.2 for vehicle 20 m spacing and speeds of $v = 150\,\mathrm{km/h}$, being typical to a high-way scenario. A total of 10 Monte Carlo simulations of 2 s duration, with the parameters summarized in Table 1, are run to obtain the results.

We regard vehicles as extended objects and use the dimensions of a Volvo XC90, assuming that the RCUs are placed above the windshields, with the centre of the car being taken as the back overhang point. The elevation angle is assumed as $\pm 5°$, whereas the azimuth angle is $\pm 10°$. The mean value for the radar cross section of a car σ is taken as $10\,\mathrm{dBsm}$ [13].

All of the front- and back-end RCUs mounted on vehicles use the same FMCW sawtooth radar waveform parameters. The chirp sequence is designed so as to meet the maximum detectable relative velocity $v_{\max} = 300\,\mathrm{km/h}$, the maximum detectable range, $d_{\mathrm{r}} = 200\,\mathrm{m}$ and range resolution smaller than 1 m and velocity resolution of 0.5 m/s, which are typical for a front-end long-range radar. The radar transmit power is taken

Table 1. Simulation parameters.

	Parameter	Value
Radar	Radar bandwidth (B_{r})	210 MHz
	ADC bandwidth (B_{ADC})	50 MHz
	Carrier frequency (f_{r})	79.145 GHz
	Modified duty cycle (U')	1/4
	Chirp duration (T)	11.35 µs
	Frame duration (T_f)	20 ms
	Number of chirps per frame (N)	339
Communication	Communication bandwidth B_{c}	40 MHz
	Communication carrier frequency (f_{c})	79.02 GHz
	Modulation	16-QAM
	SlotTime δ	10 µs
	Maximum contention window size (W_0)	48
	Maximum backoff stage (B)	3
Joint	Thermal noise temperature T_0	290 K
	Receiver's noise figure	10 dB
	Antenna gain G_{trx}	30dBi
	Reflection Coefficient for asphalt (R)	0.2814

as 11 dBm, the minimum SNR required by radar γ_{r} is set as 10 dB and the radar processing gain as $G_{\mathrm{p}} = 51.75$ dB. Noise is assumed to emerge from only thermal noise at the receiver. These power settings lead to $d_{\mathrm{r}} = 200$ m for LoS and $d_{\mathrm{rGR}} = 56$ m for ground-reflection sensing ranges for the automotive radar, whereas a direct LoS radar interference can come from $d_{\mathrm{int}} = 45$ km away and a ground-reflected radar interference from $d_{\mathrm{intGR}} = 12.7$ km away. However, in practice, the road and earth curvatures together with the possibility of blocking objects within kilometers, lead to a smaller maximum distance d'_{int}, from where direct LoS and reflected interference may come. Hence, we assume a $d'_{\mathrm{int}} = 1$ km in this study. From [7, Eq.(12)], it follows that the maximum number of RCUs, which can be scheduled so as to mitigate interference is $M_{\max} = 8$. Note that $M_{\max}$ is not high since we consider a high duty cycle, low radar bandwidth and aim to mitigate interference within a 1-km-range. Using spatial diversity, we assign the same SI to both RCUs co-located on the same vehicle. Hence, we have a total of 10 vehicles but 8 available slots. But at the same time, maximum 5 vehicles are connected in Scenario 1 and maximum 9 in Scenario 2 due to FoV.

The communication parameters are adjusted to comply to IEEE 802.11p. For example, the transmit power P_{c} is taken as 23dBm compliant to Class A and B. The minimum SNR required for communication γ_{c} is taken to be 15 dB at these high speeds based on measurements of IEEE 802.11p in vehicular environments [14]. This leads to the following ranges for communication signals: $d_{\mathrm{c}} = 600$ m for LoS and $d_{\mathrm{cGR}} = 169$ m for ground-reflection (1). The communication packet size is assumed to be 100 bytes and channel bandwidth is taken as 40 MHz, in order to utilize the radar ADC sampling rate for lower latency. This bandwidth is more than the maximum bandwidth of 20 MHz allowed for the IEEE 802.11p, but it is reasonable to assume higher bandwidths at mmWave frequencies.

Table 2. Latencies (unit: ms)

		Mean	Max	Min
t_{final}	Scenario 1:	37.96	73.16	25.41
	Scenario 2:	73.71	185.84	30.84
Blind duration	Scenario 1:	7.93	26.48	0.18
	Scenario 2:	9.42	40.11	0.05

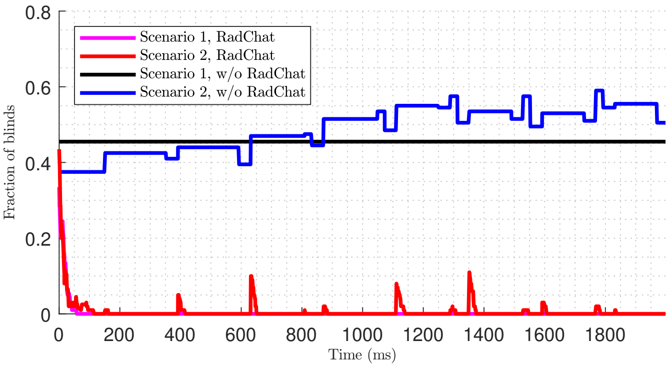


Fig. 3. The fraction of blinds for the two scenarios with and without RadChat (averaged over 10 realizations).

B. *Results and Discussion*

Table 2 summarizes the mean, maximum and minimum time it takes for RadChat to schedule all the RCUs in the network (assign the same ID and disjoint SIs), i.e., the convergence time of RadChat, and is denoted by t_{final}; as well as the blind durations. It is observed that the second scenario has slightly higher latencies than the first scenario. This is due to the changing connectivity of Scenario 2, which delays convergence of the cooperative radar communications protocol RadChat.

The fraction of blinds introduced [6], which is defined as the ratio of the number of interfering RCUs and the total number of RCUs, is shown in Fig. 3. Note that, without RadChat, around 40% of automotive radars are blinded by interference and this ratio remains the same for Scenario 1 and increases above 50% as the two fleets approach each other in Scenario 2. With RadChat, all RCUs are assigned disjoint slots within $t_{\text{final}} < 185.84$ ms. None of the RCUs are blinded after t_{final} for Scenario 1, whereas for Scenario 2, the fraction of blinds becomes nonzero after RadChat converges (after t_{final}) and interference pops up as the connectivity graph changes, since the number of available slots M_{max} is less than the number of RCUs. As a result, RadChat continues to solve the conflicts and mitigate interference as the topology changes. It is observed that RadChat mitigates these occuring interferences totally by assigning all connected RCUs disjoint slots.

V. Conclusion

Performance of the formerly proposed cooperative radar communication protocol RadChat is investigated in dynamic multi-hop high-way traffic scenarios. The results show that the protocol convergences in less than 185.84 ms, whilst blind durations do not exceed 40.11 ms for ten vehicles.

Extensions to more complex dynamically changing topologies, as well as power control, which adapts transmit powers independently for all RCUs, are left for future work. Furhermore, Radchat may be a promising tool for adapting radar parameters according to changing traffic conditions for an even more efficient ITS.

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References

[1] C. Aydogdu, G. K. Carvajal *et al.*, “Radar interference mitigation for automated driving,” *IEEE Signal Processing Magazine, accepted*, 2020.

[2] W.Buller, B. Wilson *et al.*, “Radar congestion study,” (Report No. DOT HS 812 632). Washington, DC: National Highway Traffic Safety Administration, Tech. Rep., Sept. 2018.

[3] I. M. Kunert, “Project final report, MOSARIM: More safety for all by radar interference mitigation,” 2012. [Online]. Available: http://cordis.europa.eu/docs/projects/cnect/1/248231/080/deliverables/001-D611finalreportfinal.pdf

[4] S. M. Patole, M. Torlak *et al.*, “Automotive radars: A review of signal processing techniques,” *IEEE Signal Processing Magazine*, vol. 34, no. 2, pp. 22–35, 2017.

[5] B. Paul, A. R. Chiriyath, and D. W. Bliss, “Survey of RF communications and sensing convergence research,” *IEEE ACCess*, vol. 5, pp. 252–270, 2017.

[6] J. Khoury, R. Ramanathan *et al.*, “RadarMAC: Mitigating radar interference in self-driving cars,” in *2016 13th Annual IEEE International Conference on Sensing, Communication, and Networking (SECON)*, June 2016, pp. 1–9.

[7] C. Aydogdu, M. F. Keskin *et al.*, “RadChat: Spectrum sharing for automotive radar interference mitigation,” *IEEE Transactions on Intelligent Transportation Systems*, pp. 1–14, 2019.

[8] L. Liang, H. Peng *et al.*, “Vehicular communications: A physical layer perspective,” *IEEE Transactions on Vehicular Technology*, vol. 66, no. 12, pp. 10 647–10 659, Dec 2017.

[9] W. Viriyasitavat, M. Boban *et al.*, “Vehicular communications: Survey and challenges of channel and propagation models,” *IEEE Vehicular Technology Magazine*, vol. 10, no. 2, pp. 55–66, June 2015.

[10] K. Sarabandi, E. S. Li, and A. Nashashibi, “Modeling and measurements of scattering from road surfaces at millimeter-wave frequencies,” *IEEE Transactions on Antennas and Propagation*, vol. 45, no. 11, pp. 1679–1688, Nov 1997.

[11] A. Al-Hourani, R. J. Evans *et al.*, “Stochastic geometry methods for modeling automotive radar interference,” *IEEE Transactions on Intelligent Transportation Systems*, vol. 19, no. 2, pp. 333–344, 2017.

[12] C. Aydogdu, N. Garcia *et al.*, “Radar communication for combating mutual interference of FMCW radars,” in *IEEE Revolutions in Radar, Boston, USA*, 22-26 Apr. 2019.

[13] S. Lee, S. Kang *et al.*, “Radar cross section measurement with 77 GHz automotive FMCW radar,” in *IEEE 27th Annual International Symposium on Personal, Indoor, and Mobile Radio Communications (PIMRC)*, Sept 2016, pp. 1–6.

[14] A. Paier, D. Faetani, and C. F. Mecklenbräuker, “Performance evaluation of IEEE 802.11p physical layer infrastructure-to-vehicle real-world measurements,” in *2010 3rd International Symposium on Applied Sciences in Biomedical and Communication Technologies (ISABEL 2010)*, Nov 2010, pp. 1–5.