An Improved Clear Channel Assessment Technique for Interference Mitigation in FMCW Radars

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***Abstract* – This paper explores the differences between the *real-only* and *complex baseband* mixer architectures used in Frequency Modulated Continuous Wave (FMCW) radars. It proposes an improved Clear Channel Assessment (CCA) technique based on the complex baseband architecture for mitigating *narrowband* interference in a network of FMCW radars. The proposed technique employs the Carrier Sense Multiple Access (CSMA) protocol that performs the CCA at different reference frequencies to improve the throughput. The effectiveness of the proposed CCA improvement technique is shown by simulations. It is also shown that the use of complex architecture can increase the throughput up to 3.28 times.**

***Keywords* –** *FMCW radar, narrowband interference, CSMA, complex baseband mixer*

I. Introduction

The Frequency Modulated Continuous Wave (FMCW) radar technology has become a critical sensing component in modern Advanced Driver Assistance Systems (ADAS) and autonomous vehicle platforms [1]-[3]. An FMCW radar operates by transmitting a frequency modulated radio signal, whose instantaneous frequency increases linearly with time, and processing the received signal which is reflected from the objects in the environment. By analyzing the frequency shift between the transmitted and received signals, an FMCW radar can detect objects and determine their range, relative speed, and direction relative to itself [4]. The FMCW radar technology offers many advantages over traditional radar systems, including higher accuracy, longer range, and better resolution. It is also less affected by weather conditions and can detect both stationary and moving objects in real-time.

In real-world scenarios, several FMCW radars operate in close proximity to each other, resulting in a network of radars [5], [6], where the transmissions of one radar interfere with the receptions at other radars. Simultaneous transmissions may cause *wideband* interference if different parameters are used by different radars, or *narrowband* interference if all radars use the same parameters [7], [8]. The radars must use smart signal processing methods and Medium Access Control (MAC) protocols to reduce the interference [9].

There has been prior work in the area of MAC protocols for interference mitigation in FMCW radar networks. The use of a multiple access technique has been proposed for the mitigation of narrowband interference [8]. A statistical approach to characterization of interference with the Unslotted Aloha protocol has been provided in [10]. Various MAC protocols such as the Slotted Aloha and Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) have been analyzed and compared in [9]-[11].

In the CSMA protocol, carrier sensing is performed before transmission. This is done by a Clear Channel Assessment (CCA) procedure in which the radar listens the medium for the duration of one slot to check if any other transmission is already present. The CCA is done by setting one input of the mixer to a *reference frequency*, f_r, and the other input to the receiver's feed. The transmission starts after the completion of the CCA slot only if the medium is found to be 'free'[12]. In [11], the authors propose to use two consecutive CCAs (hereinafter called the *CSMA-2CCA* scheme) to achieve better interference mitigation compared to a single CCA (hereinafter called the *CSMA-1CCA* scheme).

The type of architecture of the mixer (viz., *real-only* vs. *complex baseband*) plays an important role in determining the sensitivity of interference detection [13]. A discussion on real-only vs complex baseband architectures for FMCW radars is provided in [14]-[15]. When compared to the real-only design, the complex baseband architecture offers several performance advantages in FMCW radars. One such advantage has been leveraged in this paper to propose an improved CCA.

The main contribution of the paper are as follows:

- We study and compare the joint impact of: (i) the choice of the reference frequency, f_r, and (ii) the type of mixer architecture (real-only vs. complex baseband), on the performance of an FMCW radar network with both CSMA-1CCA and CSMA-2CCA schemes under narrowband interference.
- We show that a complex baseband mixer architecture provides better performance with both CSMA-1CCA and CSMA-2CCA compared to a real-only mixer.
- We propose that the first CCA in the CSMA-2CCA scheme should be performed by setting $f_r = f_{max} - f_{LPF}$ and show that this choice provides better performance compared to the alternative choice $f_r = f_{max}$.

The contents of the remainder of the paper are organized as follows. Section II discusses the system model used in the paper, drawing on the fundamental concepts of FMCW radars. Section III discusses how the CCA schemes help in avoiding narrowband interference and when they fail. In Section III-C, we explain why using $f_{max} - f_{LPF}$ as the reference frequency provides certain performance benefits. Section IV explains why using the complex baseband architecture could provide better performance. Section V compares the simulation results to substantiate these explanations. Section VI concludes the paper summarizing the findings and outlining future work.

II. System Model

We consider a network of FMCW radars with identical parameters, making them vulnerable primarily to narrowband interference, also known as *packet collision*, which can cause false identification of ghost objects. As shown in Fig. 1, each FMCW radar consists of a synthesizer that generates a linear frequency modulated sinusoid, called a *chirp* [16]. The chirp is transmitted by an antenna which is then reflected off the target object. The reflected chirp is received at the receiver antenna. A mixer takes the transmitted and the received chirps as inputs and gives an Intermediate Frequency (IF) signal, also known as the *beat frequency*, as the output. This mixer can either be a so-called *real-only* mixer, which is widely used in automotive radars, or a *complex baseband* mixture. The IF signal is then passed through a low-pass filter (LPF), the output of which is then digitized. A Fast Fourier Transform (FFT) is performed on the Analog to Digital Converter (ADC) data to determine the range of the target object.

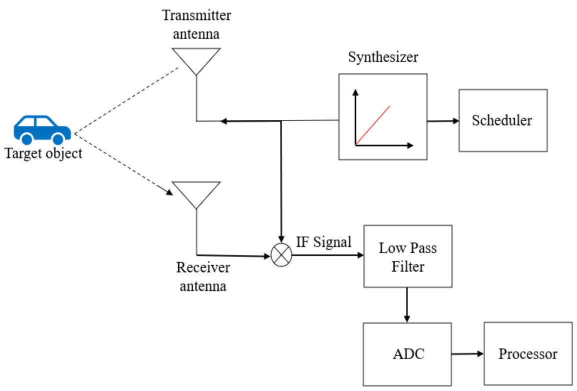

Fig. 1. Block diagram for an FMCW radar.

Each radar transmits L chirps per packet. The starting and ending frequencies of the chirps are at f_{min} and f_{max}, respectively, and hence the bandwidth B is given by

$$B = f_{max} - f_{min}.$$

The duration of each chirp is T_c and the slope, $h = B/T_c$. The radar uses an LPF with a cutoff frequency f_{LPF}. The packet transmissions by each radar follows a slotted time structure, with slot duration $\Delta = f_{LPF}/h$ and $T_c = K\Delta$, where K is a positive integer representing the number of slots per chirp. Fig. 2 illustrates an example packet. An intermediate frequency signal, $f_{IF} = 2dB/cT_c$ is generated by the transmitted and reflected chirps when the target is situated at a distance d from the radar, where c denotes the speed of light. The target is detected if f_{IF} is smaller than f_{LPF} [17].

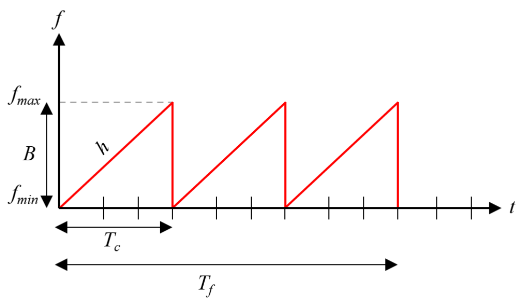

Fig. 2. Transmission of packet with $K=3$ and $L=3$.

It is assumed that the parameters (such as K, L, T_c, f_{LPF}, f_{min} and f_{max}) associated with each radar in the network are equal *but their clocks are not in sync*. Let the clock offset and distance between Radars i and j, be denoted by δ_{ij} and d_{ij}, respectively. If

$$-\Delta \le T_{ij} := \delta_{ij} + \frac{d_{ij}}{c} < \Delta, \quad (1)$$

then the IF signal generated at Radar i has a frequency smaller than f_{LPF}. This results in Radar i making a false detection of the target at a distance $(T_{ij}\times c)/2$. In such a scenario, we say that Radar j is causing interference to the packet transmitted by Radar i.

Each radar uses the CSMA protocol to control the access to the shared communication medium. The CCA is done by listening to the medium for one slot of duration, Δ, setting one input of the mixer to a *reference frequency*, f_r, and the other input to the receiver's feed. The output of the LPF is observed at the end of the CCA slot. In CSMA-1CCA (see Fig. 3), if a carrier is detected, we say that *'the CCA has failed'*. Then, the radar waits a random amount of time before performing the CCA again. These silence periods are termed as *backoffs* [18]. Else, if no signal is observed at the conclusion of a CCA slot, then it is assumed that *'the CCA has succeeded'* and the transmission of the packet starts after the completion of the CCA slot.

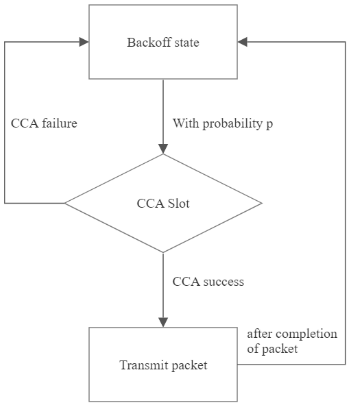

Fig. 3. Flowchart illustrating the functioning of CSMA-1CCA.

CSMA-2CCA is an enhancement of CSMA-1CCA [11] and is performed as illustrated in Fig. 4. In this scheme, a radar performs the CCA twice, consecutively, before transmitting its packet. Packet transmission starts after a successful second CCA. The radar enters the backoff state with a probability of $1 - p$ after the completion of packet transmission, or on failure of either of the CCAs. The process is repeated until the packet is transmitted successfully.

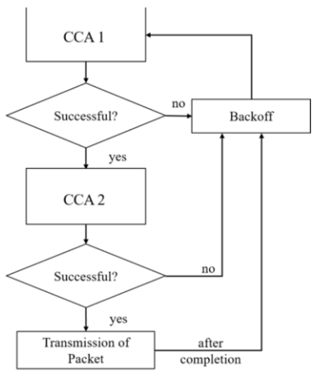

Fig. 4. Flowchart illustrating the functioning of CSMA-2CCA.

Both real-only and complex baseband mixer architectures are considered in the paper. As illustrated in Fig. 5, a mixer with real-only architecture may interpret a received signal to be a reflected signal without regard to it being *delayed* or *advanced* with respect to its transmitted chirp. A mixer with complex baseband architecture, however, interprets a received signal to be a reflected signal only if it is delayed, and not advanced, with respect to its transmitted chirp.

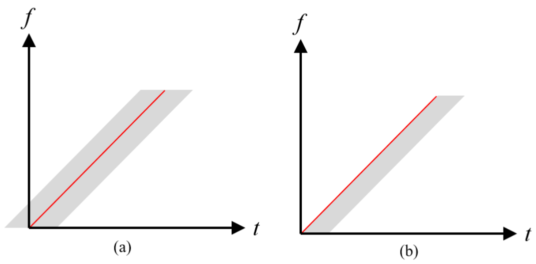

Fig. 5. Interference region using (a) real-only and (b) complex baseband architecture.

III. MAC Based Interference Avoidance

For the case of CSMA-1CCA, the value of the reference frequency recommended in the literature is $f_r = f_{min}$. For the case of CSMA-2CCA, no such recommended values could be found. In this paper, we propose and compare two different choices of f_r for the first CCA in CSMA-2CCA, viz., $f_r = f_{max}$ and $f_r = f_{max} - f_{LPF}$. The implications of the choice of f_r are discussed next under various scenarios.

A. Collocated Radar Network

First consider the idealized case of a network of *collocated* radars, i.e., when $d_{ij} = 0$ for every pair i and j of radars. Their clocks, however, are assumed to be not in sync. Suppose the number of chirps per packet is equal to 1, i.e., $L = 1$. In this case, the radars do not suffer any collisions using CSMA-1CCA, except for the case when two radars start doing the CCA within the same slot. This is because the transmission by any other radar must have begun at least Δ time before the conclusion of the CCA slot for a successful CCA at the victim radar. There would be no collision as the start times of transmission are separated by at least Δ [19]. When $L > 1$, however, the packets may experience interference under CSMA-1CCA [19]. It is known that CSMA-2CCA can eliminate packet collisions when the radars are collocated, except for the case when both the victim and the interfering radars start doing their first CCA in the same slot [11]. Note that CSMA-2CCA can still avoid collisions if the first CCA of the victim radar and the second CCA of an interfering radar are done in the same slot.

B. Non-Collocated Radar Network

Next, let us consider the realistic case of a network of non-collocated and asynchronous radars. This case has not been sufficiently studied in the literature. A radar using CSMA-1CCA in this case would experience packet collisions even when $L = 1$. If the radars are at a distance of d from each other, then the delayed radar transmits its packets with a delay equal to d/c. The observed delay is by one slot when $d/c = \Delta$, as illustrated by Fig. 6. Assuming that the victim radar starts the CCA at slot t_1, it would not result in a CCA failure even if the delayed radar starts transmitting its packet in slot t_1. This is due to the delay that is caused by the distance between the radars. Hence, the former radar would start its transmission at slot $t_1 + 1$ as its CCA would be successful. But it would suffer interference with the delayed radar's packet as shown in Fig. 6.

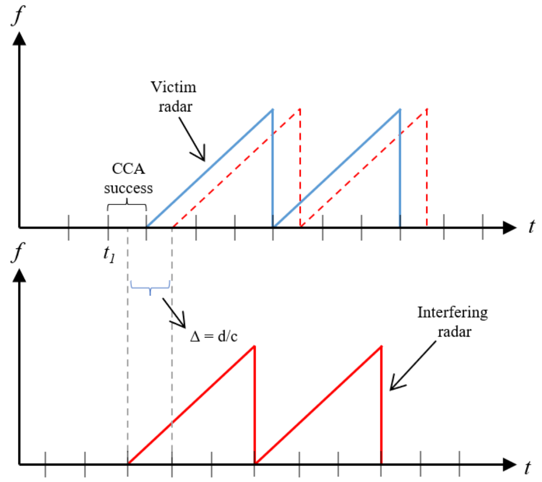

Fig. 6. Illustration of interference in a non-collocated asynchronous radar network. BLUE indicates victim radar and RED indicates interfering radar.

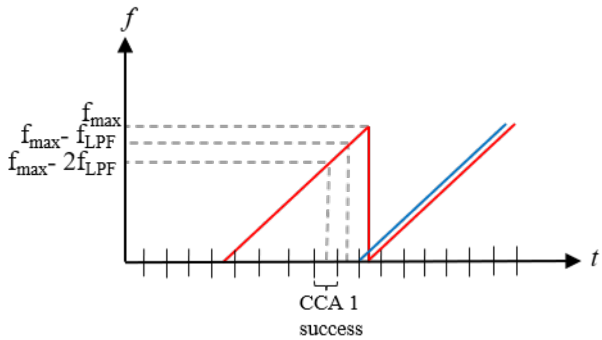

Fig. 7. Illustration of interference using f_{max} followed by f_{min} as the reference frequencies for performing carrier sensing. BLUE indicates victim radar and RED indicates interfering radar.

C. Choice of Reference Frequency

Let us consider the case when $L>1$. Note that even though $L=1$ may suffice for distance estimation, the estimation of relative speed and direction requires $L>1$. In this case, we focus on CSMA-2CCA as it can eliminate many collisions when $L>1$. Here, one plausible choice of f_r when doing CCA 1 is f_{max}. This is because it can protect against collisions in EVENT 1, i.e., if the victim radar does CCA 1 in the last slot of the last chirp of the interfering radar's packet. However, as explained below, using $f_{max} - f_{LPF}$ as the reference frequency instead of f_{max} can protect against collisions in EVENT 2, i.e., if the victim radar does CCA 1 in the last but one slot of a chirp which is not the last chirp of the interfering radar's packet. This is explained further in the following using Fig. 7.

When CCA 1 is performed at reference frequency f_{max} in the last but one slot as shown in Fig. 7, it would result in a success. Subsequently, CCA 2 is performed in the next slot. The reference frequency in CCA 2 must be f_{min} to detect the next chirp of the interfering radar, if present, when CCA 1 is done in the last slot of a chirp of the interfering radar's packet. Since we have $f_r = f_{min}$ during CCA 2 (see Fig. 7), and the received frequency is close to f_{max}, this would result in a (overall) successful CCA and the victim radar would start transmitting its packet in the next slot. However, if the interfering radar has further chirps remaining in its packet, then it would result in a collision with the victim radar's chirp. In contrast, if the reference frequency used to perform CCA 1 is $f_r = f_{max} - f_{LPF}$, it would result in a failure. Therefore, using $f_r = f_{max} - f_{LPF}$ for CCA 1 followed by $f_r = f_{min}$ for CCA 2 would result in better collision avoidance in EVENT 2. As L increases, the probability of EVENT 2 gets larger than that of EVENT 1. Therefore, for large L, $f_r = f_{max} - f_{LPF}$ is a better choice than $f_r = f_{max}$. Simulation results to support this logical explanation are provided in Section V.

Note: Since the received frequency cannot be more than f_{max}, the use of real-only and complex baseband architecture would provide identical performance when the reference frequency is set to f_{max}. Thus, the impact of using different mixer architectures is discussed next with $f_r = f_{max} - f_{LPF}$.

IV. Real-Only vs Complex Baseband Architecture

The frequency of the received signal, f_{RX}, is given as input to the mixer along with the reference frequency, f_r. The output of the mixer is the difference of these two inputs. When a real mixer is used to perform CCA, the output is given as $|f_r - f_{RX}|$. Thus, CCA 1 would fail if the output of the mixer falls in the range of 0 to f_{LPF} as given in (2).

$$0 < |(f_{max} - f_{LPF}) - f_{RX}| < f_{LPF} \tag{2}$$

Therefore, it can be said that CCA 1 would fail when f_{RX} satisfies either of the following two conditions:

$$f_{max} - 2f_{LPF} < f_{RX} < f_{max} - f_{LPF} \tag{3}$$

$$f_{max} - f_{LPF} < f_{RX} < f_{max} \tag{4}$$

When f_{RX} satisfies (3), it results in a positive difference between the reference and the received frequencies, whereas, when f_{RX} satisfies (4), it results in a negative difference.

A. $L = 1$

We first consider the case when the radars transmit packets with $L = 1$. When CCA 1 is performed as shown in Fig. 8, it results in a failure as f_{RX} lies in the range given by (3). The radar enters backoff state and interference is avoided.

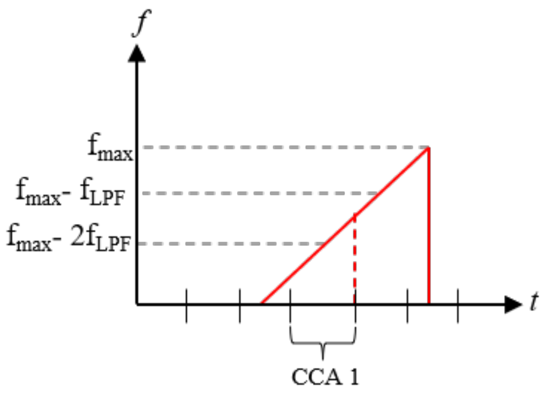

Fig. 8. Illustration of CCA failure with positive difference between reference and received frequencies.

When CCA 1 is performed as shown in Fig. 9, the CCA fails, and the radar enters backoff state. It can be observed that such a backoff is unnecessary as the victim radar can transmit its packet without any interference after the next CCA slot even in the absence of a silence period (the blue dotted line in Fig. 9 indicates the transmission of packet by the victim radar after a successful double CCA). Such unnecessary backoffs can be avoided with the use of complex baseband architecture.

The output of a complex mixer when used to perform carrier sensing is given by $f_r - f_{RX}$. The CCA would fail when $f_r - f_{RX}$ lies between 0 and f_{LPF}. Subsequently, CCA 1 only fails when:

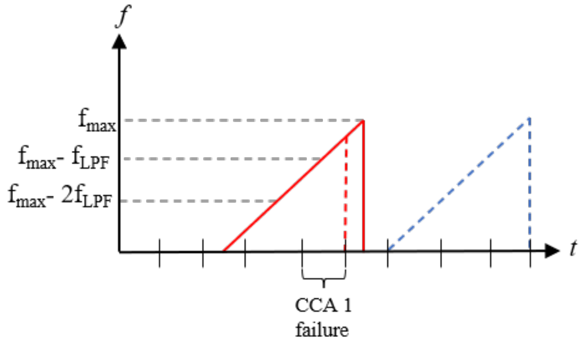

Fig. 9. CCA failure with negative difference between reference and received frequencies. BLUE indicates victim radar and RED indicates interfering radar.

$$0 < (f_{max} - f_{LPF}) - f_{RX} < f_{LPF} \tag{5}$$

Therefore, in the previous case (illustrated in Fig. 9), CCA 1 would be successful and the radar proceeds to perform CCA 2 with $f_r = f_{min}$. Since the packet has only one chirp, CCA 2 would also be successful and the radar can transmit its packet without any backoff.

Note: It must be noted that the same is applicable if the interfering radar is transmitting the last chirp of its packet.

B. $L > 1$

The use of complex architecture for both CCA 1 and CCA 2 can be disadvantageous when $L > 1$ and the chirp being transmitted by the interfering radar is not the last chirp of the packet. This has been illustrated by Fig. 10.

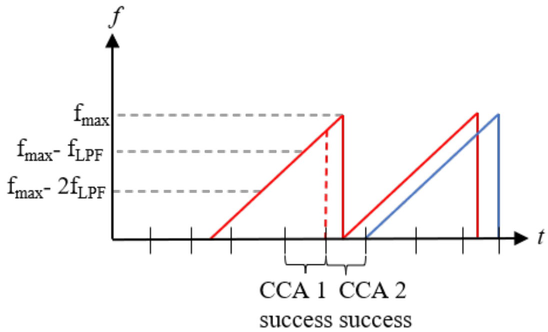

Fig. 10. Interference despite successful double CCA with the use of complex architecture. BLUE indicates victim radar and RED indicates interfering radar.

To avoid such interferences, CCA 2 must fail in the case of both positive and negative frequency differences. To achieve so, the MAC protocol is modified to ignore the phase information of the output obtained after performing CCA 2, and thus resulting in a CCA failure in such cases.

Note: The use of phase information during CCA 1 using a complex baseband architecture and ignoring the phase information during CCA 2 results in higher performance in both CSMA-1CCA protocol as well as CSMA-2CCA protocol even though our discussion in this section is based on the CSMA-2CCA protocol.

V. Numerical Results

In this section, we provide simulation results for various scenarios and analyze the results. We consider a network with N radars with identical parameters. Each radar transmits L chirps per packet. The radars' clocks are not synchronized, but are in sync with a hypothetical global clock. We consider both collocated and non-collocated radar networks. In the case of non-collocated radar networks, the propagation delay D directly maps to the distance between each pair of radars in the network, which is given by $D \times c$ where c is the speed of light, e.g., when $D = 2$ µs, then the distance between each pair of radars is $2 \times 10^{-6} \times 3 \times 10^{8} = 600$ meters. The backoffs are sampled from a geometric distribution. The bandwidth of a chirp is given by $K \times f_{LPF}$. The exact values of K and f_{LPF} do not impact the protocol. We have set $N = 50$ and $K = 40$ for our simulations and all the simulations have been carried out for 10,000 slots. A packet is considered to have experienced a collision even if one of the constituent chirps collides.

A. CSMA-1CCA

As proposed in [8], we use f_{min} as reference frequency for performing the carrier sensing for the CSMA-1CCA protocol. As mentioned in Section IV, using complex architecture provides better performance. The nature of architecture used does not affect the performance when $L = 1$. However, using the complex architecture provides much better performance when $L = 28$ due to the reduced number of unnecessary collision detections. Fig. 11 and Fig. 12 illustrate the performance in collocated and non-collocated networks.

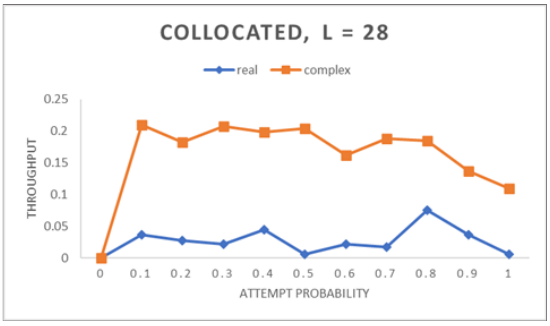

Fig. 11. Throughput vs attempt probability in a collocated network with $L = 28$ and with 1CCA.

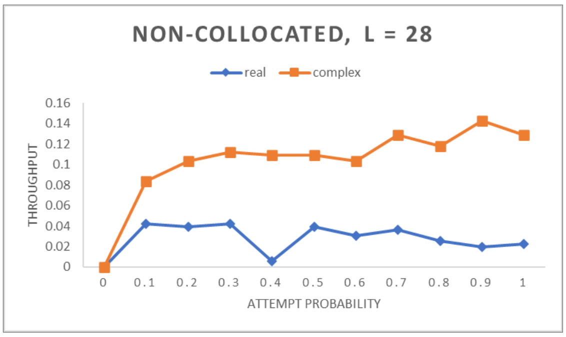

Fig. 12. Throughput vs attempt probability in a non-collocated network with $L = 28$ and with 1CCA.

As shown in Fig. 11, for a collocated radar network, the complex architecture achieves an average throughput of 0.178 chirps/slot, whereas the real architecture achieves only 0.029 chirps/slot for a collocated radar network. Similarly, as shown in Fig. 12, for a non-collocated radar network, the complex architecture achieves 0.113 chirps/slot, which is much greater than 0.03 chirps/slot obtained using the real architecture.

B. CSMA-2CCA

We first consider a network of collocated radars and plot the throughput as functions of the attempt probability p for CSMA-2CCA in the following cases:

- Using $f_r = f_{max}$ followed by $f_r = f_{min}$
- Using $f_r = f_{max} - f_{LPF}$ followed by $f_r = f_{min}$ with real architecture
- Using $f_r = f_{max} - f_{LPF}$ followed by $f_r = f_{min}$ with complex architecture

Fig. 13 and Fig. 14 illustrate the throughputs of a network of collocated radars in the case of $L = 1$ and $L = 28$ respectively. It can be observed that using $f_r = f_{max} - f_{LPF}$ instead of $f_r = f_{max}$ gives better throughput. For $L = 1$, the average throughput obtained by using $f_r = f_{max}$ for CCA 1 is 0.285 chirps/slot, which is much lesser when compared to the average throughput 0.388 chirps/slot obtained using $f_r = f_{max} - f_{LPF}$ for CCA 1, using the real-only mixer and 0.633 chirps/slot using the complex baseband mixer.

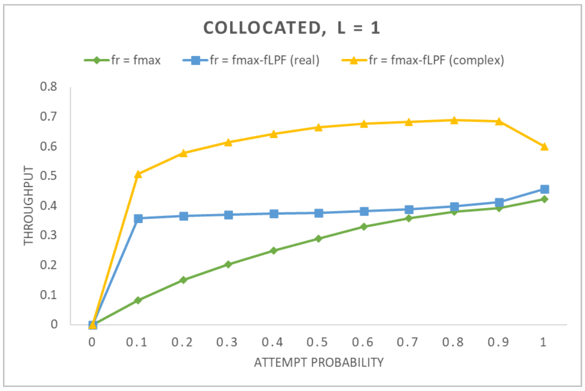

Fig. 13. Throughput vs attempt probability in a collocated network with $L = 1$ and with 2CCA.

For $L = 28$, using complex architecture with $f_r = f_{max} - f_{LPF}$ provides an average throughput of 0.759 chirps/slot, which is greater than 0.738 chirps/slot obtained using real architecture. However, the increase in the performance due to complex architecture is just 2.84%. This is because the probability of CCA 2 being performed in the last slot of the packet is very small in the case of collocated radar network with a large packet length. On the other hand, using $f_r = f_{max}$ resulted in far lesser average throughput at only 0.032 chirps/slot.

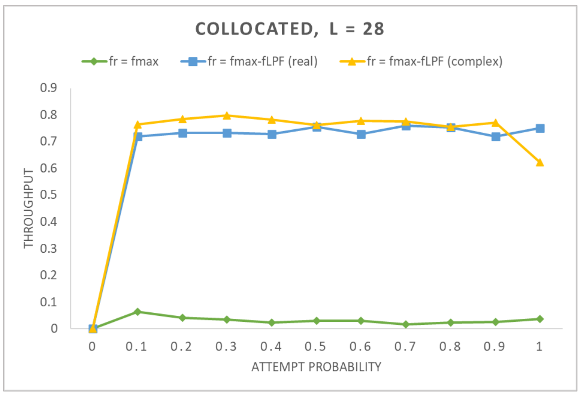

Fig. 14. Throughput vs attempt probability in a collocated network with $L = 28$ and with 2CCA.

Next, we consider a network of non-collocated radars. The radars are spatially distributed with the maximum pairwise propagation delay of 2 μs, which corresponds to a distance of 600 meters. The throughput vs attempt probability graphs with packet lengths $L=1$ and $L=28$, are as illustrated in Fig. 15 and Fig. 16, respectively. In this case, the MAC protocols provide lower throughputs than the collocated case.

When $L = 1$, the protocols deliver around 0.29 chirps/slot of throughput. Both real and complex architecture provide almost same performance with only 1.38% difference as the number of CCA slots after packet completion is almost equal to the additional backoffs due to CCA failure. Using $f_r = f_{max}$ continues to provide much lower performance as expected with only 0.027 chirps/slot.

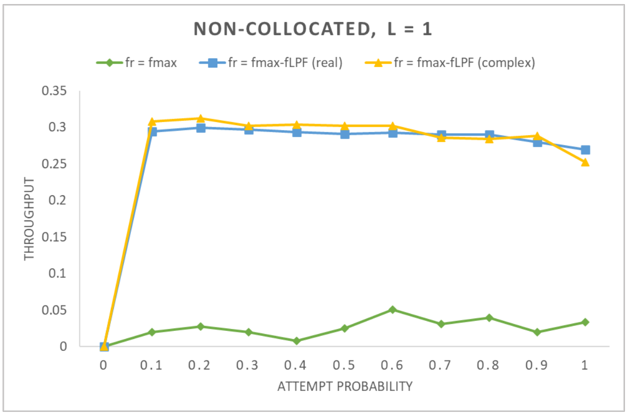

Fig. 15. Throughput vs attempt probability in a non-collocated network with $L = 1$, $D = 2$ and with 2CCA.

Fig. 16 pertains to a realistic case where the radars are in a non-collocated network and use a large packet length. Using real architecture resulted in an average throughput of 0.107 chirps/slot. On the other hand, using complex architecture provided a much better throughput performance with an average of 0.351 chirps/slot resulting in an increase of 3.28 times. Whereas, using $f_r = f_{max}$ results in a throughput of only 0.005 chirps/slot.

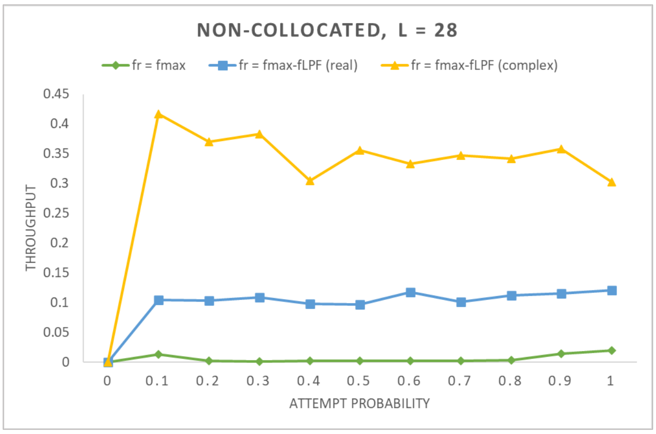

Fig. 16. Throughput vs attempt probability in a non-collocated network with $L = 28$, $D = 2$ and with 2CCA.

It can be observed from the above results that the use of $f_r = f_{max} - f_{LPF}$ to perform the first carrier sensing followed by using $f_r = f_{min}$ provides much better performance in all the cases. A packet is considered to have experienced a collision even if one of the constituent chirps collides.

VI. Conclusions and Future Work

We presented analysis and simulations to compare the impact of mixer architecture on performance. The use of a complex baseband mixer for performing CCA as part of the CSMA protocol can help avoid certain unnecessary backoffs and subsequently provide better performance with both CSMA-1CCA and CSMA-2CCA protocols. It was shown that the use of complex architecture can increase the throughput up to 3.28 times. We also proposed that using $f_{max} - f_{LPF}$ as the reference frequency for performing CCA 1 would result in better collision avoidance compared to when f_{max} is used, which is supported by the simulation results presented.

Future work includes studying the impact of wideband interference on heterogenous FMCW radar networks and modifying the MAC to support mitigation of both narrowband and wideband interference.

References

[1] J. Savithry, Ortega, A. G., Dr. Anju Pillai S., Balbastre, P., and Crespo, A., “Design of Criticality-Aware Scheduling for Advanced Driver Assistance Systems”, 2019 24th IEEE International Conference on Emerging Technologies and Factory Automation (ETFA). 2019.

[2] Hemaanand, M., Rakesh Chowdary, P., Darshan, S., Jagadeeswaran, S., Karthika, R. and Parameswaran, L., 2020. Advanced driver assistance system using computer vision and IOT. In Computational Vision and Bio-Inspired Computing: ICCVBIC 2019 (pp. 768-778). Springer International Publishing.

[3] Lee, K.M., Lee, I.S., Shin, H.S., Ok, J.W., Youn, J.H., You, E.N., Yang, J.R. and Kim, K.T., 2023. Reconstruction of Range-Doppler Map Corrupted by FMCW Radar Asynchronization. Sensors, 23(12), p.5605.

[4] Eser, D., Demır, Ş. and Koç, S., 2023. A Compound ECCM Technique for FMCW Radars. IEEE Access.

[5] Aydogdu, C., Keskin, M.F., Garcia, N., Wymeersch, H. and Bliss, D.W., 2019. RadChat: Spectrum sharing for automotive radar interference mitigation. IEEE Transactions on Intelligent Transportation Systems, 22(1), pp.416-429.

[6] Khoury, J., Ramanathan, R., McCloskey, D., Smith, R. and Campbell, T., 2016, June. RadarMAC: Mitigating radar interference in self-driving cars. In 2016 13th Annual IEEE International Conference on Sensing, Communication, and Networking (SECON) (pp. 1-9). IEEE.

[7] Makino, Y., Nozawa, T., Umehira, M., Wang, X., Takeda, S. and Kuroda, H., 2019. Inter-radar interference analysis of FMCW radars with different chirp rates. The Journal of Engineering, 2019(19), pp.5634-5638.

[8] Kurosawa, M., Nozawa, T., Umehira, M., Wang, X., Takeda, S. and Kuroda, H., 2019. Proposal of multiple access FMCW radar for inter-radar interference avoidance. The Journal of Engineering, 2019(21), pp.7304-7308.

[9] Haritha, K., Sukumaran, V.B. and Singh, C., 2021, July. Slotted Aloha for FMCW Radar Networks. In 2021 National Conference on Communications (NCC) (pp. 1-6). IEEE.

[10] Jin, S. and Roy, S., 2020. Cross-layer interference modeling and performance analysis in FMCW radar multiple access network. In 2020 IEEE 92nd Vehicular Technology Conference (VTC2020- Fall) (pp. 1-6). IEEE.

[11] Ishikawa, S., Kurosawa, M., Umehira, M., Xiaoyan, W.A.N.G., Takeda, S. and Kuroda, H., 2019, September. Packet-based FMCW radar using CSMA technique to avoid narrowband interefrence. In 2019 International Radar Conference (RADAR) (pp. 1-5). IEEE.

[12] Huang, Y. and Chin, K.W., 2023. A Hierarchical Deep Learning Approach for Optimizing CCA Threshold and Transmit Power in WiFi Networks. IEEE Transactions on Cognitive Communications and Networking.

[13] Murali, S., Subburaj, K., Ginsburg, B. and Ramasubramanian, K., 2018, April. Interference detection in FMCW radar using a complex baseband oversampled receiver. In 2018 IEEE Radar Conference (RadarConf18) (pp. 1567-1572). IEEE.

[14] Rao, S. and Mani, A.V., 2020, September. Interference Characterization in FMCW radars. In 2020 IEEE Radar Conference (RadarConf20) (pp. 1-6). IEEE.

[15] Ramasubramanian, K. and Instruments, T., 2017. Using a complex-baseband architecture in FMCW radar systems. Texas Instruments, 19.

[16] Koivumäki, P., 2017. Triangular and ramp waveforms in target detection with a frequency modulated continuous wave radar.

[17] S. Sundaresan, Anjana, C., Tessy, Z., and Gandhiraj R., “Real Time Implementation of FMCW Radar for Target Detection using GNU Radio and USRP”, in 4th IEEE International Conference on Communication and Signal Processing-ICCSP'15, Department of Electronics and Communication Engineering, Adhiparasakthi Engineering College, Chennai, 2015.

[18] Jayasree M. Oli, Boppa, S., Bandi, S., and Krothapalli, V., “Comparative Performance Evaluation for DCF and CONTI MAC Schemes”, 2017 International Conference on Computer Communication and Informatics, ICCCI 2017, 2017.

[19] Sukumaran, V.B. and Singh, C., 2022. Slotted ALOHA and CSMA Protocols for FMCW Radar Networks. arXiv preprint arXiv:2201.09030.