High Angular Resolution Digital Beamforming Method for Coherent FMCW MIMO Radar Networks

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***Abstract*—This manuscript describes the research results undertaken under the 2021 IEEE MTT-S Graduate Fellowship. In particular, we investigate the feasibility of a high angular resolution digital beamforming method for coherent frequency-modulated continuous-wave (FMCW) multiple-input multiple-output (MIMO) radar networks. The proposed coherent radar network system consists of two separate FMCW radars, where each radar unit comprises N_{TX} transmit and N_{RX} receive antennas. The proposed method will combine two separate FMCW radars to an FMCW radar network with $2N_{\mathrm{TX}} \times 2N_{\mathrm{RX}}$ virtual antennas for MIMO applications. Compared to existing work, the proposed method does not depend on the distance between two separate radars. The distance is arbitrary and this will enable us to increase the number of radars in coherent FMCW MIMO radar networks in the future.**

***Index Terms*—Automotive radar, mono-static, bi-static, FMCW, MIMO, networks.**

I. Introduction

The application of cooperative multiple-input multiple-output (MIMO) radar networks achieved a lot of interest in the past few years. Theoretical concepts of cooperative MIMO radar networks have been investigated in [1]–[3]. In our proposed coherent radar network which is shown in Fig. 1, we use two separate FMCW radar stations. The proposed method will combine N_{TX} and N_{RX} signals from station 1 with N_{TX} and N_{RX} signals from station 2. This will make two separate FMCW radars become an FMCW radar network with $2N_{\mathrm{TX}} \times 2N_{\mathrm{RX}}$ virtual antennas for MIMO application. Additionally, in this proposed method, the processing of virtual antennas does not depend on the distance d of the separated radars. Therefore, d can be arbitrary and this will enable the coherent FMCW MIMO radar networks with more than two separate radars in the future.

II. Proposed Method and Measurement

The proposed method exploits the two-dimensional (2-d) structure after calculating a 2-d fast Fourier Transform (FFT) from the ADC data. In each station, we use a single TX antenna and four RX antennas to demonstrate our approach. Fig. 2 shows the antenna setup for the coherent FMCW radar network. TX_0 from station 1 radiates N_{s} chirps with a constant carrier frequency phase. TX_0 from station 2 applies an alternating binary phase-shift keying (BPSK) modulation that changes the carrier frequency phase between 0° and 180° from chirp to chirp [4].

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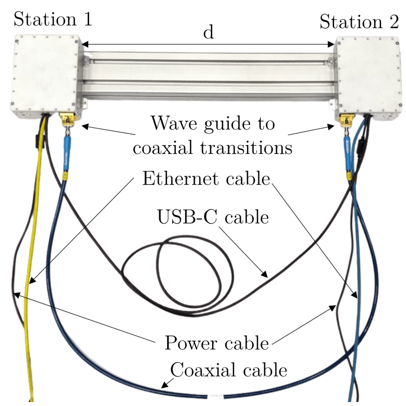

Fig. 1. Coherent radar networks using two separate FMCW radar.

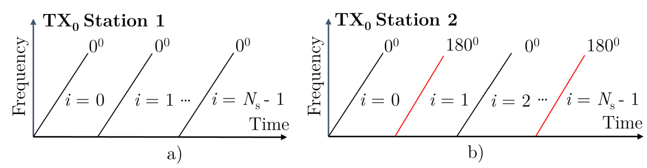

Fig. 2. (a) Chirp signals with phase setup of TX_0 at station 1. (b) Chirp signals with phase setup of TX_0 at station 2.

For our coherent radar network, the frequency synthesizer from station 1 generates the FMCW signal, then this signal is up-converted and is transmitted by TX_0 at station 1. At the same time, this FMCW signal is also transmitted through the coaxial cable to station 2, then it is up-converted and is transmitted by TX_0 at station 2. The signals which are transmitted from TX_0 at station 1, are reflected at a target, and are received at RX antennas at station 1 where they form the mono-static signals. The RX of station 1 also receive signals which are reflected at a target after being transmitted from TX_0 of station 2. These signals are known as bi-static signals.

The proposed method is measured with a coherent FMCW radar network system in an anechoic chamber. Each radar transmits in a loop with 48 fast chirps. Each chirp has a duration T_{sw} of 0.1 ms with a bandwidth B of 1 GHz and start frequency f_0 = 76.5 GHz. With this setup, the system has v_{max} = 9.74 m/s. The length of the coaxial cable is 1.3 m and the distance between the two stations is d = 5 cm. The processing of virtual antennas do not depend on d so that d can be arbitrary. The measurements are carried out with two static targets and one moving target. Each target is a cylindrical pole with a diameter of 5 cm and length of 1 m. The static targets are positioned at 2.4 m at an angle of 18° and 4 m at an angle of -25°. The moving target, which is mounted on a linear rail, has v = -1.5 m/s at an angle of 7°. Fig. 3a shows the mono-static and bi-static signals at station 1. It can be

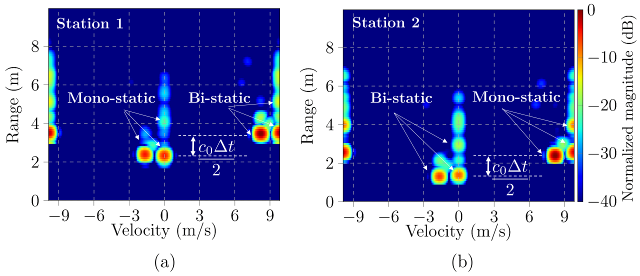

Fig. 3. (a) Mono-static and bi-static signals from RD map in station 1. (b) Mono-static and bi-static signals from RD map in station 2.

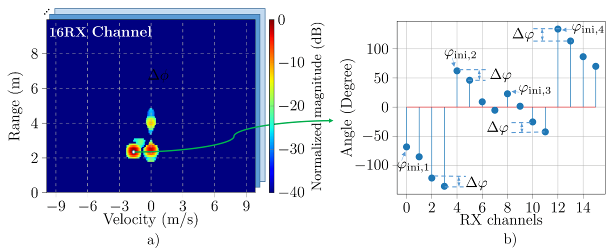

Fig. 4. (a) 16 RD maps after applying binary mask from station 1 and station 2. (b) Phase information of a single target along 16 RX channels.

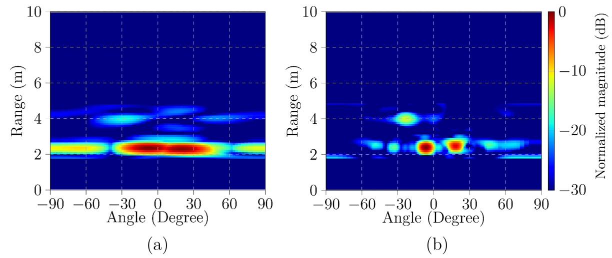

Fig. 5. (a) RA map result uses single FMCW radar with 1TX and 4 RX antennas. (b) RA map result after applying proposed method using coherent FMCW MIMO radar network, each radar uses 1TX and 4 RX antennas.

seen that the bi-static signals appear at location $v_{\max}$ in the RD map due to the BPSK modulation. The distance between mono-static and bi-static signals is 1 m which is explained in section II. Conversely, Fig. 3b shows mono-static and bi-static signals at station 2.

First of all, the proposed method shifts the bi-static signals at the RD map of station 1 to the location of mono-static signals. Secondly, the original and shifted RD map are converted to binary versions by thresholding. Thirdly, since we use N_{RX} = 4 antennas, we have 4 original RD maps and 4 shifted RD maps. By taking the Hadamard product between these RD maps and the binary mask, we form 8 RD maps with the correct position of targets. Fourthly, we apply the same method for station 2. Totally, we then have 16 RD maps for the next processing steps. Fig. 4 shows 16 RD maps and the example of the phase of 1 target. Since the 16 RD map is the combination of all mono and bi-static signal, the phase of the target is not linear.

To enhance the angular resolution, we construct the linear array with 16 channels. The detail for this step is show in [5] which is the publication for this research in IMS 2021. Fig. 5a shows the range-angle (RA) map result when using single FMCW radar with 1 TX and 4 RX antennas. Fig. 5b shows the range-angle (RA) map result with coherent radar network, each radar uses 1 TX and 4 RX antennas. The result shows that the method can detect the angle-of-arrival (AoA) with $2N_{\mathrm{TX}} \times 2N_{\mathrm{RX}}$ virtual antennas of both static and moving targets without applying motion compensation as it would be required for a time-division multiplexing (TDM) FMCW radar and achieve better angular resolution compared to single FMCW radar.

III. Conclusion

In this paper, we have presented a method to combine two separable FMCW radars with arbitrary distance d, each radar using 1 TX and 4 RX antennas, to an FMCW radar network with 16 virtual antennas. The results confirm that this method can be used to realize the MIMO functionality. Future work will exploit the application of more TX by exploiting other modulation schemes.

IV. Career Plan And Impact Statement

I am currently completing my doctorate dissertation and preparing for graduation. My current research involves both radar signal processing and deep leaning to increase angular resolution for FMCW MIMO radar. I am truly honored to receive the 2021 IEEE MTT-S Graduate Fellowship. I deeply appreciate this prestigious award from the MTT-Society. Although I did not have the chance to attend the IMS 2021 due to the pandemic, I have submitted a paper for IMS 2022 and get accepted. Therefore, I hope I can join IMS 2022 to talk and discuss with other researchers around the world.

Acknowledgment

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