Millimeter-Wave Localization of Multiple Targets Using TDOA and Wideband Frequency Modulation

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***Abstract*—In this paper, a distributed radar is presented that can perform both ranging and time difference of arrival (TDOA), resulting in two-dimensional location estimation without beam-scanning. The transmitter emits a linear frequency modulated (LFM) signal, ranging from 37 to 40 GHz. The receiver is composed of two antennas separated by 80 cm (102.7λ). By performing matched filtering with the transmitted LFM signal on each individual receive element, the range information of multiple targets can be obtained using the signal leakage from the transmit signal. By comparing the two waveforms, their angles are calculated from the TDOA between them. The theory behind the technique is explained and experimental measurements of two reflecting targets are shown.**

I. Introduction

Numerous applications, from future self-driving vehicles to wireless sensor networks, will necessitate a cost-effective solution for localization of moving objects [1], [2]. Optical sensors, such as lidars, exhibit very good spatial resolution [3], but their high cost and challenges in penetrating fog, rain, and dusty environment limit the real-world applications and reliability. Microwave and mm-wave radars, on the other hand, are much cheaper and noticeably less attenuated by fog, smoke, clouds, and some building materials. In millimeter-wave frequencies, the channel response is much flatter than at microwave frequencies, particularly for wideband wireless transmission, leading to better resolution and accuracy for many radar applications, as well as aligning with ideal bands for 5G wireless systems [4]. The ability of radars to estimate range, angle, and velocity have been evolving over the decades, utilizing mechanical and, later, electrical scanning [5]. Mechanical scanning is hampered by the beam scanning speed and resolution whereas electrical scanning, often leveraged by phased arrays, is limited by the hardware cost. Recent developments in the area of sensing involve multiple small antenna elements such as multiple-input and multiple-output (MIMO) radar [6], and angle-estimation algorithms like MUSIC [7] and ESPRIT [8]. These methods mostly rely on large antenna arrays and complicated signal processing involving computationally inefficient calculation based on the different responses collected at each antenna element.

To simplify the range and angle estimation of multi-targets, a radar of only two receive and one transmit element using TDOA [9] is proposed in this paper. Similar to the angle-estimation system in [10], this approach uses a wideband chirp signal, however by appropriate time-domain processing, fast, two-dimensional detection of multiple targets is achieved.

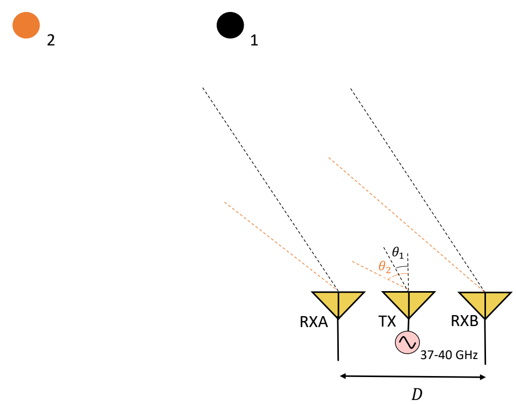

Fig. 1. Distributed radar observing two targets at angles θ_1 and θ_2. The transmit signal is an LFM signal in the 37-40 GHz range. The reflections from the two targets will arrive at both of the receivers in the same order. Coherent processing will give the range information. The TDOA between them will give their residing angle.

II. TDOA for Angle Estimation Using Signal Leakage

Consider a configuration with two receivers and one transmitter observing two targets as shown in Fig. 1. For an LFM pulse given by

$$s(t) = \cos\left[2\pi\left(f_0 t + \tfrac{K}{2}t^2\right)\right] \tag{1}$$

where f_0 is the carrier frequency, and K (Hz/s) is the chirp rate, the normalized signals received by two antennas separated by a baseline D after reflecting off of the target at angle θ are

$$v_A(t) = s(t-\tau_{A1}) + s(t-\tau_{A2}) \tag{2}$$

$$v_B(t) = s(t-\tau_{B1}) + s(t-\tau_{B2}) \tag{3}$$

where τ_{Ai} and τ_{Bi} are the time delays of arrival of the reflections from the i-th target at the A and B receiver respectively, since transmitting the LFM pulse. Assuming the targets are on a much larger range than the baseline D and the difference in their ranges is within the range resolution of the radar system, their reflections will arrive in the same order in both receivers. The $TDOA_i = \frac{D}{c}\sin\theta_i$ represents the geometrical time delay which is the time difference the

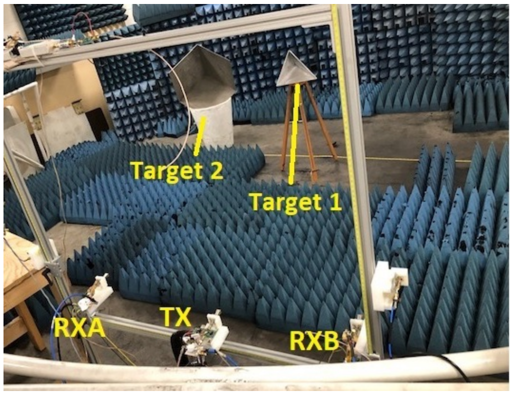

Fig. 2. Measurement setup with two reflectors inside the semi-closed arch range with two receivers and one transmitter. Target 1 was fixed and Target 2 was moved away from broadside to the receiving antennas.

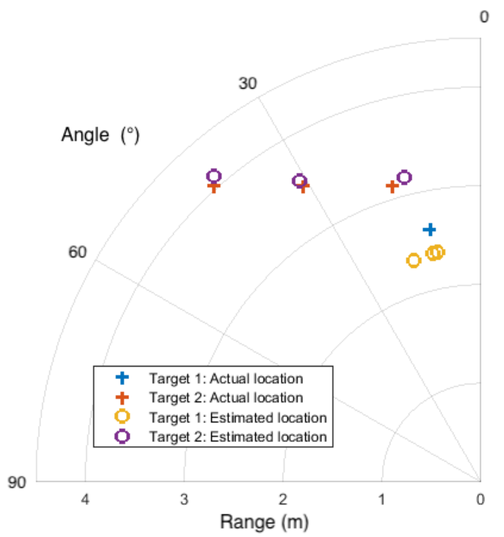

Fig. 3. Estimated locations of the two reflectors compared with their true locations. Blue cross for the true location of Target 1, red crosses for various locations of Target 2, yellow and purple circles next to the crosses are the estimated locations by the radar.

plane wavefront faces in reaching the two elements separated by D. It can be approximated for both targets responses by

$$TDOA_i = \tau_{Bi} - \tau_{Ai}. \tag{4}$$

The angle of each target can then be found through

$$\theta_i = \sin^{-1}\left[\frac{c}{D}\left(TDOA_i\right)\right]. \tag{5}$$

Estimation of the time delay, or range, to the target is accomplished using a matched filter, where each received signal is cross-correlated with $h(t) = s^*(-t)$. The range information is obtained by taking advantage of the leaked signal from the transmitter, which represents the $t = 0$.

III. Experimental measurements

The theory of multi-target detection was verified by the measurement setup shown in Fig. 2. Two trihedral reflectors were placed in a semi-closed anechoic range. Both receivers were mounted on a frame with a baseline of 0.8 m with the transmitter placed in the middle. An LFM signal of 2 μs and ranging from 1 GHz to 4 GHz was generated by a Keysight M8190 Arbitrary Waveform Generator before being upconvertered to a carrier frequency of 36 GHz with an upconverter (Analog Devices HMC6787ALC5A) and an LO of 18 GHz. The resulting chirp signal spanned between 37 and 40 GHz was boosted by a GaAs power amplifier (Analog Devices HMC7229LS6) with a gain of 24 dB and radiated by a 10-dBi horn antenna. The signals reflected off the scene were received by two 10-dBi horn antennas and then low noise amplified by the Analog Devices HMC1040LP3CE with a gain of 23 dB before being downconverted to baseband by the Analog Devices HMC6789BLC5A and the same LO of 18 GHz. The baseband signal of each receiver was then captured by an oscilloscope and processed offline with MATLAB.

The experimental results can be seen in Fig. 3 where the RX/TX were located at the origin, Target 1 was stationary (indicated by the blue cross), and Target 2 was moved in different locations (indicated by the red crosses). The measured locations of the two targets are indicated by the purple and yellow circles, showing good detection performance in down-range and cross-range. The root-mean square error between experimental and actual locations is 2.6 degrees in angle and 0.18 m in range, which verifies the potential of this method for accurate, scan-free localization.

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