Distributed Interferometric Radar for Radial and Angular Velocity Measurement

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***Abstract*—In this work we present a fully wireless coherent distributed interferometric radar for sensing the radial and angular velocities of dynamic targets. We build upon prior work on wireless coordination in both time and frequency by utilizing a high accuracy two-tone frequency transfer method for frequency syntonization and global navigation satellite system-based pulse-per-second timing alignment. The interferometric radar is based on software-defined radios and uses a continuous-wave 3.3 GHz signal to measure the Doppler and interferometric frequency shifts of signals scattered from moving targets. The two nodes in the array are separated by 91 cm (10λ). Coordination between the nodes was implemented wirelessly at 4.3 GHz, and received radar signals were transferred for joint processing at one node at 5.8 GHz. We demonstrate the performance of the distributed interferometric radar by measuring the instantaneous radial and angular velocities of a pedestrian carrying a corner reflector tangentially past the array.**

I. INTRODUCTION

Wireless coordination of separate antennas to create coherent distributed aperture antenna arrays has been a growing topic of interest recently [1, TA 5.6.7], [2]–[5]. Distributed apertures have the potential to enable significant improvements in performance and robustness in sensing and communications applications by enabling the deployment of dynamically scalable arrays with significantly larger apertures than previously practical for many scenarios. Because the nodes in a wireless distributed array are typically mobile, a wide range of potential array configurations is possible with many being sparse, producing grating lobes in the array pattern. While this is a challenge for some applications, prior studies have shown that the fringe pattern produced by sparse arrays can be employed in radar applications to derive useful information such as the angle and angular rate of moving objects by correlating the received radar signals at the spatially separated antennas [6]. In this paper we demonstrate a fully wireless distributed antenna array operating coherently to perform radial and angular velocity estimation of a walking person. Coordination of the distributed array was implemented using a high-accuracy two-tone frequency transfer technique based on that in [7] along with a global navigation satellite system (GNSS)-based pulse-per-second (PPS) timing synchronization method.

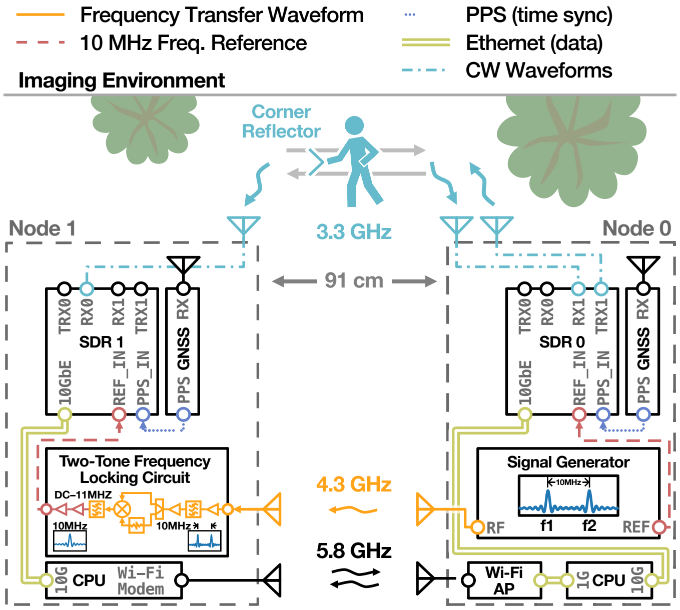

Fig. 1. Distributed interferometric radar schematic. A pedestrian holding a corner reflector jogged tangentially to the radar while their radial and angular velocity was measured. Nodes were frequency syntonized using a two-tone frequency transfer waveform transmitted by a signal generator on Node 0 and received by a self-mixing frequency locking circuit on Node 1. Data was transferred from Node 1 to Node 0 for correlation. Time alignment was performed using a GNSS-based PPS signal.

II. EXPERIMENTAL CONFIGURATION

A schematic of the fully wireless distributed interferometric radar is shown in Fig. 1; a photograph of the experimental configuration is shown in Fig. 2. Two nodes were separated by 91 cm, or 10 λ at the center frequency of 3.3 GHz of the array. Each node utilized an Ettus X310 software-defined radio (SDR) connected to a computer running an Intel i7-8700 processor. The desktops were networked via TCP/IP using a wireless 802.11ax link to stream the samples from Node 1 to Node 0 for correlation. The two nodes were synchronized in time using a GNSS-based PPS signal and syntonized in frequency using a two-tone self-mixing frequency transfer circuit described in [7]. A Keysight E8267D vector signal generator was used to generate the reference frequency for the system; its 10 MHz output was connected to the reference input of SDR 0 while its radio frequency output was configured to generate two tones separated by 10 MHz at a carrier frequency of 4.3 GHz. The two-tone signal was received by Node 1, self-mixed, and filtered, producing the 10 MHz to discipline the local oscillator on SDR 1. The scene was illuminated by a 3.3 GHz continuous-wave (CW) signal transmitted from Node 0 and received on Nodes 0 and 1. The transmitter and receivers utilized separate L-Com HG2458-08LP-NF 8-dBi vertically-polarized log-periodic antennas stacked vertically to minimize self-coupling. The frequency transfer utilized the same log-periodic antennas while the Wi-Fi link used standard dipole antennas.

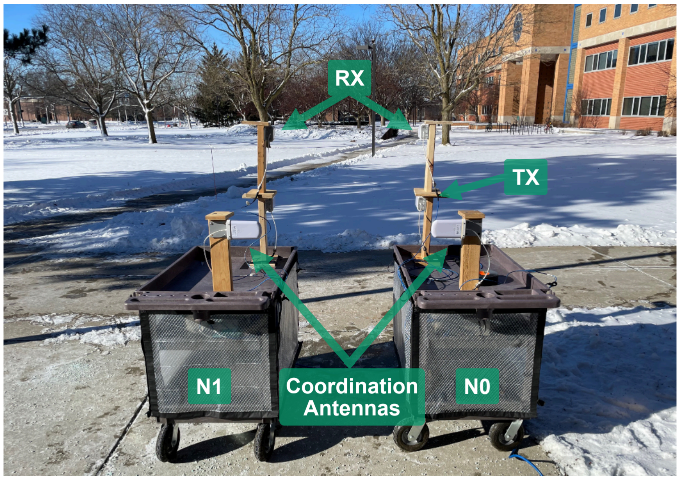

Fig. 2. System configuration photograph. Two nodes were implemented on plastic carts and physically separated. The frequency transfer coordination antennas were on the back of each cart while the transmit and receive antennas were located on the front on wooden antenna masts. Node N0 transmitted while both nodes received.

Each SDR was operated at rate of 1 MSa/s and SDR 0 transmitted a CW tone with an intermediate frequency (IF) of 100 kHz. The monostatic and bistatic radial velocities of the pedestrian were measured at nodes 0 and 1, respectively, and the tangential velocity was measured by digitally cross-correlating and low-pass filtering the received signals from each node as described in [6]. After correlation, a beat frequency proportional to the angular velocity of the subject is produced

$$f_\omega = \omega D_\lambda \cos \omega t \tag{1}$$

where ω is the angular velocity of the target and D_λ is the receive antenna baseline in wavelengths. When the target is near broadside the small angle approximation $\cos\theta \approx 1$ is valid; thus, using $v = \omega R$, where v is the linear velocity and R is the distance of the subject from the center of the interferometer, the tangential velocity may be given as

$$v_\top = \frac{f_\omega R}{D_\lambda}. \tag{2}$$

III. EXPERIMENTAL RESULTS

During the experiment a pedestrian was imaged jogging tangentially from left-to-right, then right-to-left across the path of the interferometer at a range of $\sim$10 m at the point of closest approach with a speed of $\sim 2.5\,\mathrm{m\cdot s^{-1}}$, resulting in an expected interferometric frequency response of $\sim$2.5 Hz for the given system parameters. The results of the experiment are shown in Fig. 3 with the top two plots showing the monostatic and bistatic Doppler shift of the subject passing tangentially to the array, respectively; the bottom plot is the estimated tangential velocity of the subject passing the array. The radial velocity spectrograms were produced by digitally down-converting the scattered signal from the 100 kHz IF, bandpass filtering from 1–440 Hz, and applying a short-time Fourier Transform (STFT) with a 250 ms window duration and 75% overlap. The correlation spectrogram was produced by bandpass filtering the recorded real-time correlated signal from 0.1–220 Hz and applying an STFT with a 1000 ms window duration and 90% overlap. The sign of the correlation response indicates the direction of motion. Because the subject is moving in a straight path past the array, the component of tangential velocity relative to the array creates a crescent shape peaking in intensity near ±2.5 Hz, as predicted by (2), validating the operation of the distributed interferometric radar.

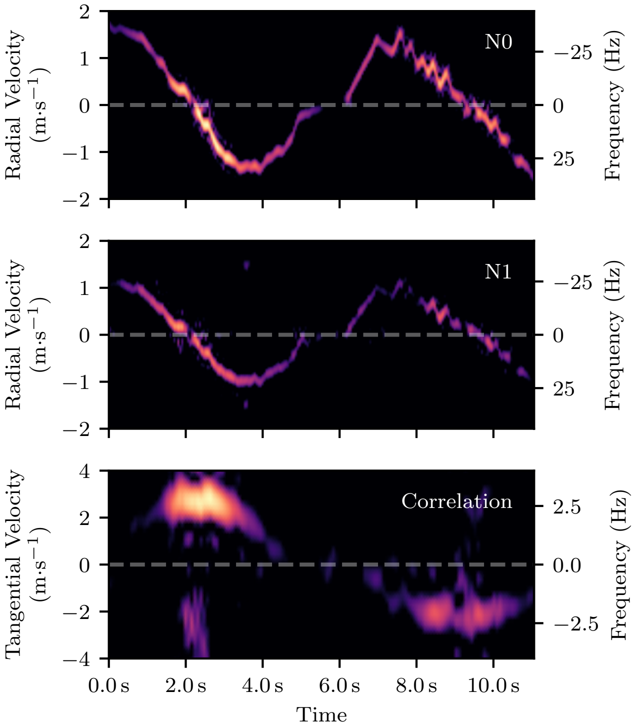

Fig. 3. Measured radial and tangential velocity spectrograms of the pedestrian jogging. The pedestrian first moved left-to-right past the interferometer, generating a positive interferometric frequency response, then returned to the starting location, producing a negative interferometric response.

REFERENCES

[1] "2015 NASA technology roadmaps," National Aeronautics and Space Administration, Tech. Rep., July 2015.

[2] O. Abari, H. Rahul, D. Katabi, and M. Pant, "Airshare: Distributed coherent transmission made seamless," in *2015 IEEE Conference on Computer Communications (INFOCOM)*, 2015, pp. 1742–1750.

[3] H. Yan, S. Hanna, K. Balke, R. Gupta, and D. Cabric, "Software defined radio implementation of carrier and timing synchronization for distributed arrays," in *2019 IEEE Aerospace Conference*, 2019, pp. 1–12.

[4] M. B. Quadrelli, R. Hodges, V. Vilnrotter, S. Bandyopadhyay, F. Tassi, and S. Bevilacqua, "Distributed swarm antenna arrays for deep space applications," in *2019 IEEE Aerospace Conference*, 2019, pp. 1–15.

[5] S. Prager, M. S. Haynes, and M. Moghaddam, "Wireless subnanosecond rf synchronization for distributed ultrawideband software-defined radar networks," *IEEE Transactions on Microwave Theory and Techniques*, vol. 68, no. 11, pp. 4787–4804, 2020.

[6] J. A. Nanzer, "Millimeter-wave interferometric angular velocity detection," *IEEE Transactions on Microwave Theory and Techniques*, vol. 58, no. 12, pp. 4128–4136, 2010.

[7] S. R. Mghabghab and J. A. Nanzer, "Open-loop distributed beamforming using wireless frequency synchronization," *IEEE Transactions on Microwave Theory and Techniques*, vol. 69, no. 1, pp. 896–905, 2021.