Distributed Interferometric Radar for Radial and Angular Velocity Measurement

College of Engineering
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WE-A6.1P.1 | Focused session on challenges, advances and future trends on emerging applications of radar imaging

delta Distributed Electromagnetics Theory and Applications
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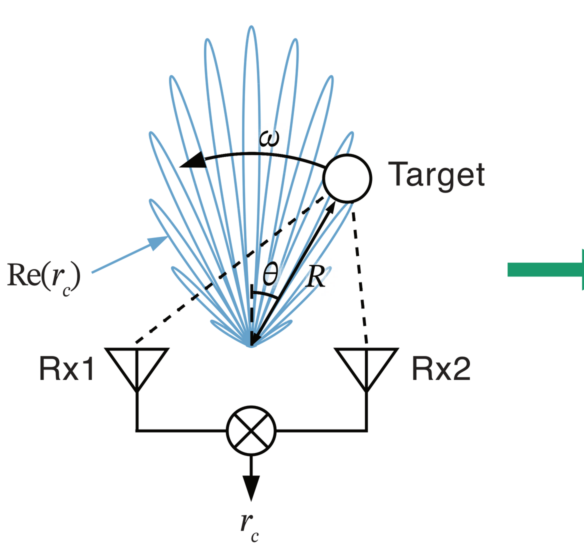
Abstract

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.

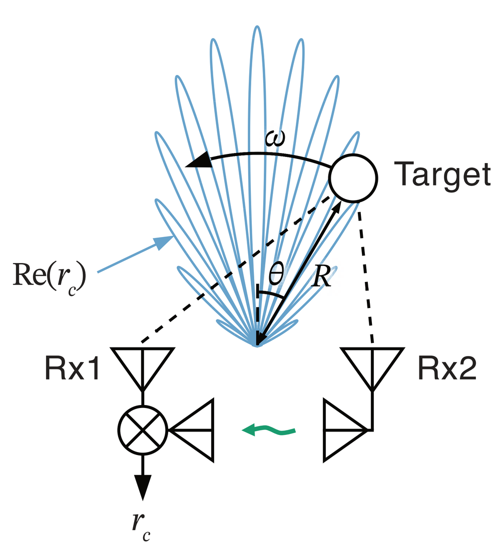
Introduction and Motivation

In this work, we lay the foundation for enabling interferometric aperture array processing in a distributed wireless manner. Single baseline aperture interferometers, shown below, can detect a single spatial frequency; however, arrays of diverse baseline interferometers can detect many spatial frequencies enabling detection of complex scenes.

Traditional Aperture Interferometer



Wireless Aperture Interferometer



Applications of aperture interferometers

- Instantaneous angular velocity for traditional radar sensing and tracking
- Scene spatial frequency intensity for incoherent microwave/millimeter-wave imaging

In this work, we focus on the tracking and sensing applications of single-baseline aperture interferometers with wireless coordination. Multi-baseline interferometer arrays have been shown previously to enable multi-target tracking in radars and imaging of complex scenes.

Benefits of wirelessly coordinating antenna elements

- Many small element nodes may be used to make up the interferometer array
  - Reduced deployment cost
  - Decreased thermal management requirements
  - Resilient to antenna / node failures
  - Increased number of interferometer baselines possible
    - Increased number of targets possible to track in a radar operation
    - Increased number of spatial frequencies for imaging operation
- Larger physical aperture sizes possible
  - Improved angular velocity sensing sensitivity for radar operation
  - Increased highest spatial frequency possible to detect for imaging

Challenges of wirelessly coordinating antenna elements

- Stringent coordination requirements for
  - Time
  - Frequency
  - Element Position

Coordination must be performed at the wavelength of the carrier frequency to a fraction of a wavelength to achieve high performance in sensing and imaging applications.

Radial and Angular Velocity Estimation

Continuous-wave transmit signal:

$$s_{\mathrm{tx}}(t) = A(\theta)\exp(j2\pi f_0 t)$$

Baseband signals after downconversion:

$$r_{\mathrm{d}n}(t) = A(\theta)\exp(-j2\pi f_0 \tau_{\mathrm{d}n})$$

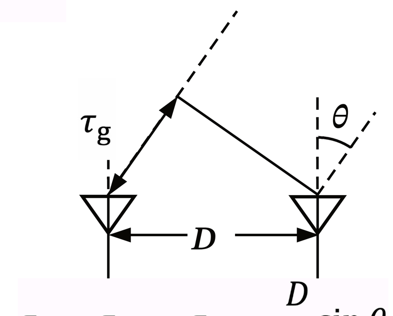
Radial rate measurement (Doppler):

$$f_{\mathrm{d}n}(t) = \frac{1}{2\pi}\frac{d\phi_{r_{\mathrm{d}n}}(t)}{dt} = -\frac{d}{dt} f_0 \tau_{\mathrm{d}n} = \frac{2v_{rn}}{c}$$

$$\Rightarrow \boxed{\hat{v}_{rn} \approx -f_{\mathrm{d}n}\frac{\lambda}{2}\ (\mathrm{m/s})}$$

Correlator output:

$$\begin{aligned} r_c(t) &= r_{\mathrm{d}1}(t)\cdot r_{\mathrm{d}2}^*(t) \\ &= A(\theta)\exp(j2\pi f_0 \tau_g) \\ &= A(\theta)\exp(j2\pi D_\lambda \sin\theta) \end{aligned}$$



$$\tau_g = \tau_{\mathrm{d}2} - \tau_{\mathrm{d}1} = \frac{D}{c}\sin\theta$$

Angular rate measurement:

$$\text{Using } \omega = \frac{d\theta}{dt} \implies \theta = \omega t + \theta_0$$

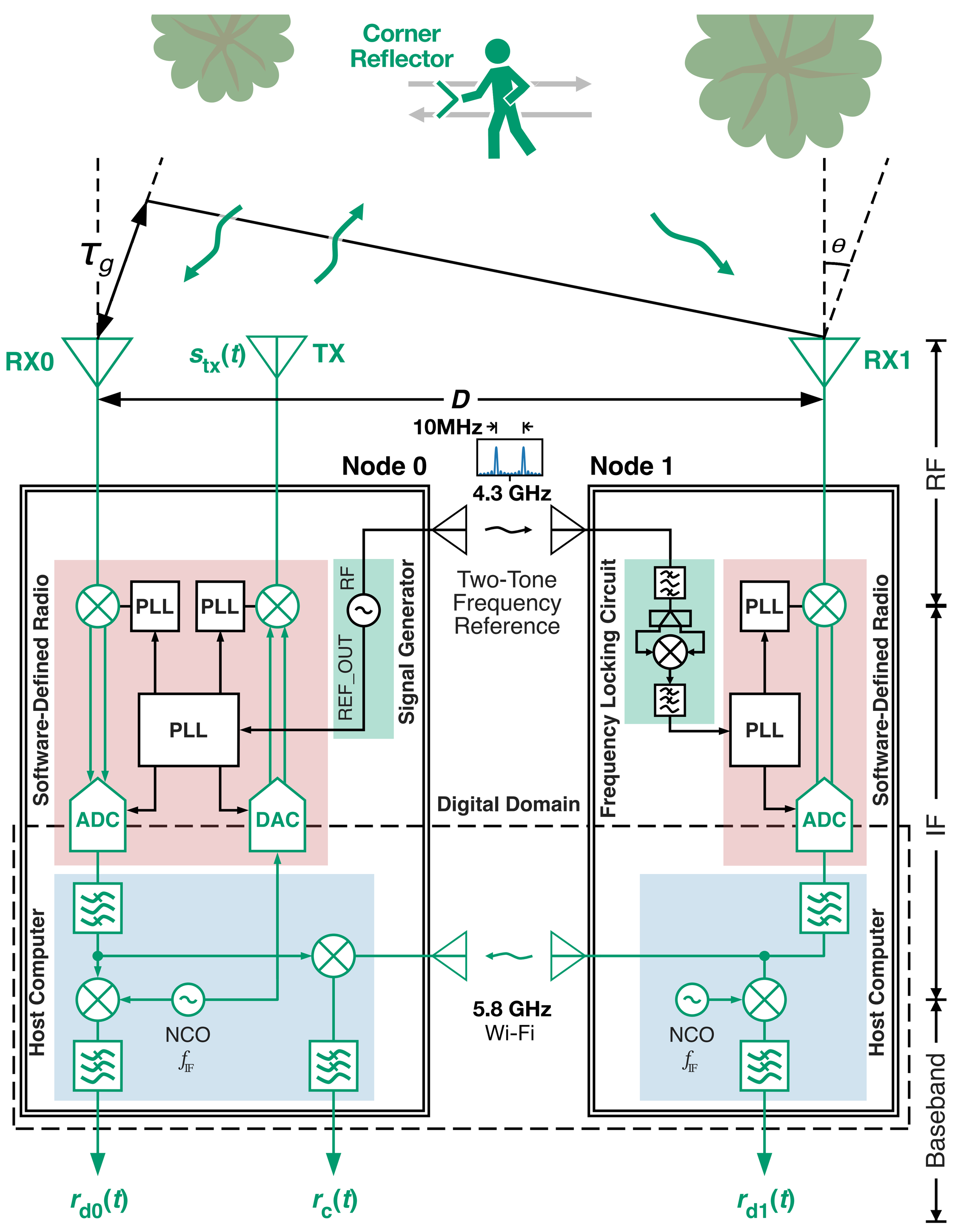
$$f_\omega = \frac{1}{2\pi}\frac{d\phi_{r_c}(t)}{dt} = \omega D_\lambda \cos\theta$$

$$\Rightarrow \boxed{\hat{\omega} \approx \frac{f_\omega}{D_\lambda}\ (\mathrm{rad/s})}$$

System Configuration and Coordination

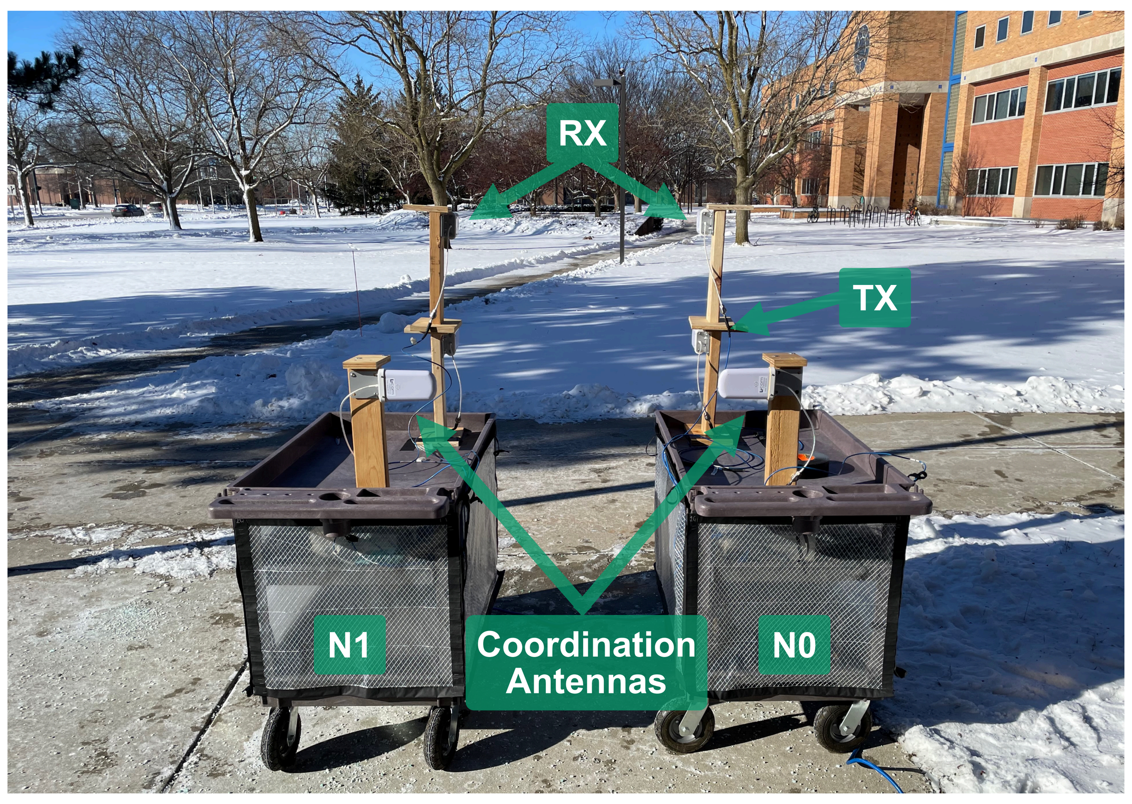
- System utilizes two spatially separated nodes consisting of a software-defined radio and a computer
- Node 0 contains a signal generator for local frequency reference and to broadcast the two-tone frequency reference waveform
- Node 1 contains a self-mixing frequency locking circuit to demodulate the two-tone frequency reference waveform

System Schematic



- Data is shared between hosts running GNU Radio via TCP/ZeroMQ
- Radial velocity processing performed on each respective platform
- Correlation processing performed at a centralized location

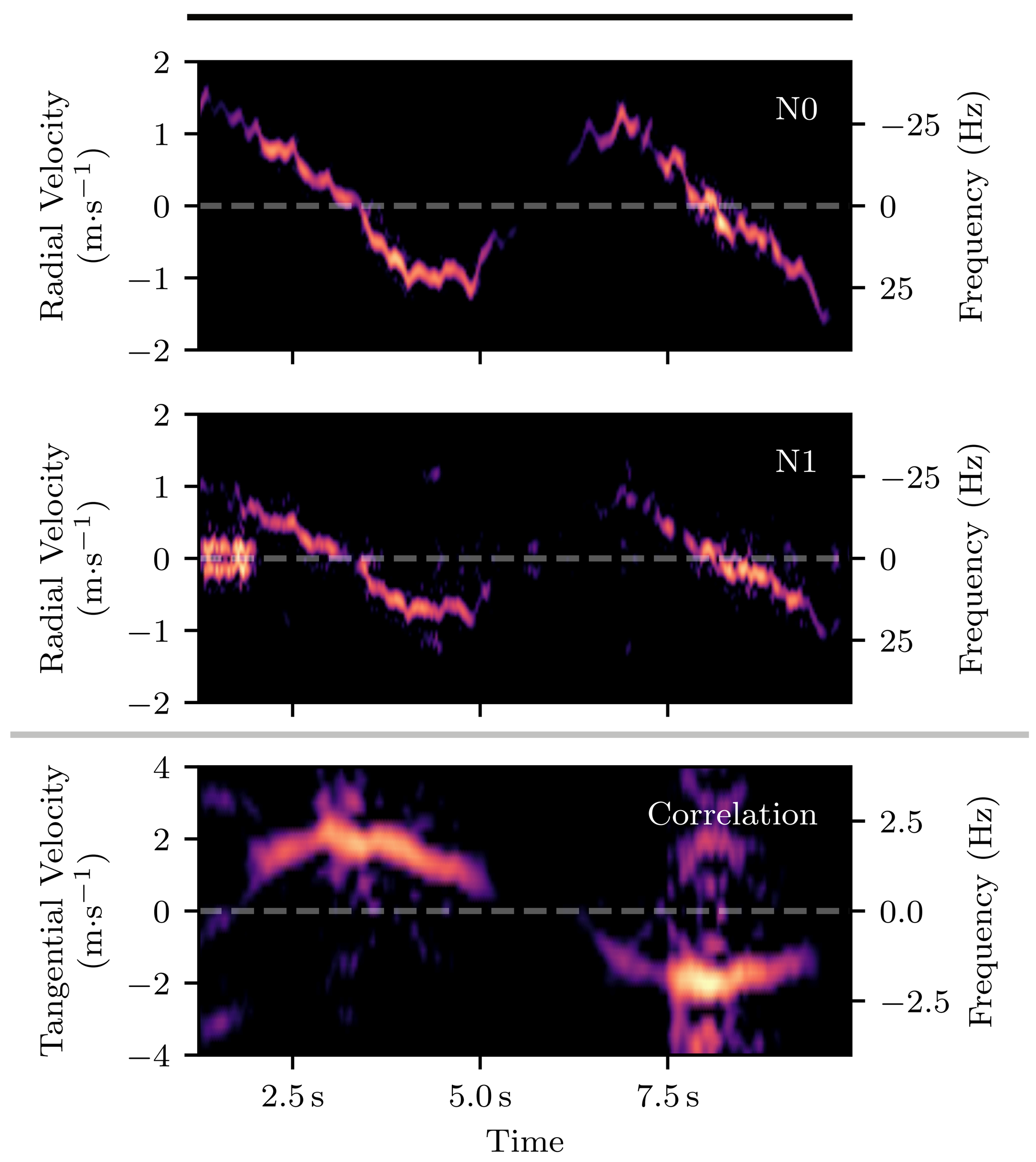
Experimental Configuration



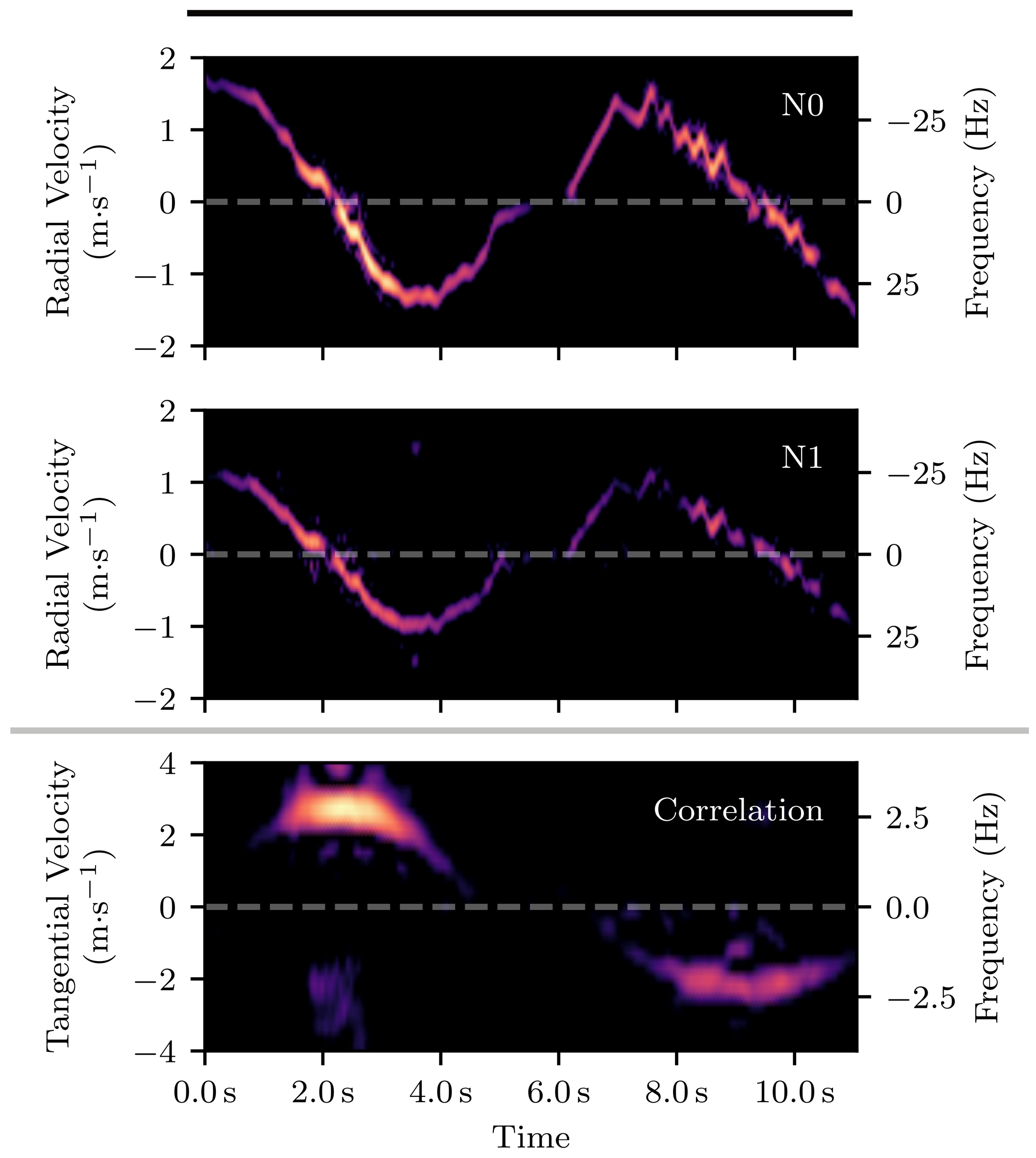
Experimental Measurements of Pedestrian Walking

Radial and Tangential Velocity Measurement of Pedestrian

Pass 1



Pass 2



- Pedestrian was imaged jogging tangentially from left-to-right, then right-to-left
- Range of ~10 m at the point of closest approach, speed of ~2.5 m/s (expected interferometric frequency response of~2.5 Hz for the given system parameters).
- Measured radial and tangential velocities shown in a waterfall plot below
- The radial velocity spectrograms 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

Conclusions

- Demonstrated a wireless distributed aperture interferometer simultaneously measuring both radial and tangential motion of a point scatterer carried by a pedestrian
- Results show a promising step towards larger distributed interferometric arrays