Passive Non-Cooperative Millimeter-Wave Imaging Using 5G Signals of Opportunity

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***Abstract*— We present an approach for high-resolution millimeter-wave imaging by capturing non-cooperative communications signals scattered off a scene. Advances in fifth generation (5G) communications are creating an increasingly crowded spectrum at millimeter-wave frequencies, leading to greater interest in spectrum coexistence for functions like sensing and communications. While most research has sought to minimize interference between the two modalities, in this work we exploit a highly dense signal environment where 5G communications transmitters generate a spatio-temporally incoherent signal incident on the scene. We capture the scattered signal in the spatial frequency domain, from which the scene image is reconstructed via inverse Fourier transform. Using four 5G transmitters emitting independent 256-QAM signals, we capture the scattered signals with a 24-element 38 GHz sparse millimeter-wave receiving aperture with no coordination with the transmitters. We demonstrate image reconstruction of multiple targets by implementing this non-cooperative approach.**

***Keywords*— 5G, millimeter-wave imaging, incoherent imaging, interferometry, antenna arrays, software-defined radio**

I. Introduction

Joint sensing and communications is becoming an increasingly important aspect of wireless networks, and particularly with the anticipated ubiquity of wireless nodes, it can provide significant benefits [1]. Sensing can enable tracking of people to mitigate blockage, home health monitoring for detecting elderly fall and other problems [2], IoT [3], human-computer interaction [4], and security sensing, among other applications. The number of wireless connections is expected to rapidly increase as 5G technologies continue to develop, making the coexistence of sensing and communications an increasingly important challenge. Many research efforts focus on interference mitigation, and others have attempted to combine sensing and communications into a joint waveform or system. While the former approach is challenged by filter technology limitations, or capacity degradation through time or frequency duplexing, the latter suffers from the fact that traditional communications and radar waveforms are designed for largely opposite functions, leading to waveforms and transceiver hardware that are significantly different albeit in nuanced ways. Whereas communications signals are instantaneously broadband to maximize capacity, radar signals are generally instantaneously narrowband to exploit time-varying phase information. Communications hardware is typically operated well below the saturation point due to the use of amplitude modulated signals, while radar transmitters prefer phase over amplitude modulation so that signals can always operate close to the saturation point for maximum signal-to-noise ratio (SNR). Although these differences may become less distinct in the future, their impact nonetheless has presented a significant challenge to joint sensing and communications.

We present a method of imaging at millimeter-wave frequencies that uses non-cooperative emissions of 5G communications signals for future joint sensing and communications. Using a 24-element 38 GHz interferometric antenna array, we capture signals of opportunity from multiple 256-QAM 5G transmitters. By sampling the scattered radiation in the spatial frequency domain, a sparse aperture with an order of magnitude less aperture area than traditional imaging antenna arrays can be used. In the literature some works have shown localization, tracking, and activity recognition using existing indoor wireless networks, or by transmitting signals at the existing ISM microwave frequencies [5]–[8]. Imaging in general is a more complicated measurement and can be performed using two elements that are manually moved to synthesize a larger array [9], which, however, is not feasible for real-time imaging. More recent works have showed three-dimensional millimeter-wave imaging using coordination between a transmitting 5G basestation and an auxiliary receiving phased array [10], [11]. This work presents the first full array millimeter-wave imaging system using non-cooperative signals of opportunity. This means that our approach requires no synchronization between transmit and receive, providing an opportunity for future joint sensing and communications in dense signal environments.

II. Non-Cooperative Millimeter-wave Imaging

Interferometric imaging has long been used in radio-astronomy and earth remote sensing, and has many benefits including the use of sparse antenna arrays, often with at least an order of magnitude less aperture area than filled arrays with the same resolution [12]. Since each element in an interferometric array samples information from the entire scene, the imagers operate in a staring mode and do not require scanning; furthermore, if elements in the array fail, the image degrades gracefully [13]. Interferometric imagers measure spatial frequency information by capturing the scattered electric field E at various antenna elements. The correlations between every antenna element pair give a sampled version of the scene visibility, which is the 2-D spatial Fourier transform of the scene. According to the Van Cittert-Zernike theorem [12], [14], the correlations of the fields $\langle E_i(t)E_j(t)\rangle$ collected by antenna elements i and j at

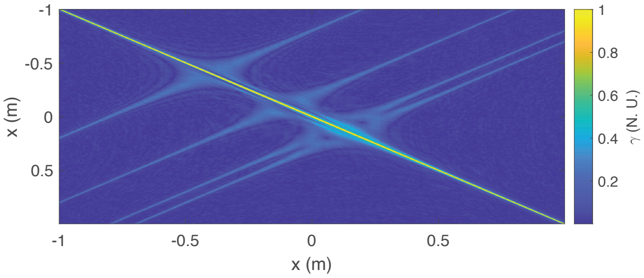


Fig. 1. Simulation of the mutual coherence matrix γ for $N = 4$ incoherent sources emitting independent information with 20 MHz bandwidth. The main diagonal shows strong self-coherence, while the unwanted partial coherence lines shows partial incoherence.

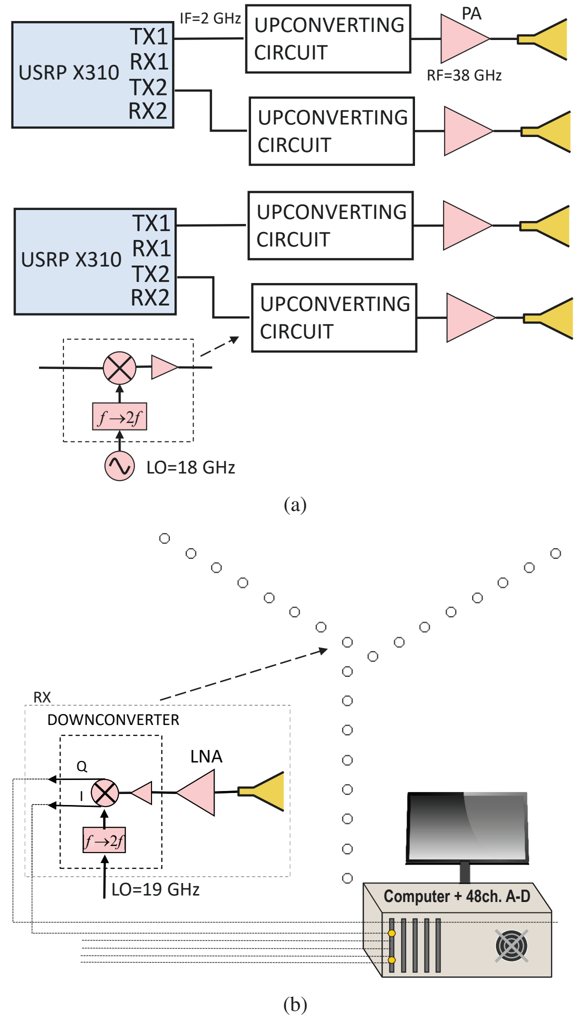


Fig. 2. (a) Schematic of the 4 38 GHz transmitting nodes employing USRP X310 SDRs. (b) Schematic of the 24-element 38 GHz receive imaging array.

locations (x_i, y_i), (x_j, y_j) give rise to the visibility samples $V_s(u = \frac{x_i - x_j}{\lambda}, v = \frac{y_i - y_j}{\lambda})$, where u and v are the two spatial frequency dimensions and λ is the corresponding wavelength. The reconstructed scene intensity I_r is then obtained through an inverse Fourier transform

$$I_r(\alpha, \beta) = \iint_{-\infty}^{\infty} V_s(u, v) e^{-j2\pi(u\alpha + v\beta)} du dv \tag{1}$$

where α and β are the direction cosines in the azimuth and elevation plane.

The use of the Van Cittert-Zernike theorem requires the scattered fields to be spatio-temporally incoherent. Passive radiation emitted by all objects inherently satisfies this constraint, however at millimeter-wave frequencies such signals are so low in power that receiver gains and integration times must be large [15], yielding expensive receivers and slow image formation time. Previous work has utilized transmission of noise signals from multiple locations in order to mimic the properties of thermal radiation and satisfy the Van Cittert-Zernike theorem requirements [16], [17], however, this requires additional transmit signal emitted in an already crowded environment.

The use of multiple independent 5G signals incident on a scene satisfies the Van Cittert-Zernike theorem requirements for spatio-temporal incoherence such that Fourier domain imaging can be performed. Effectively, if enough transmitters are in a local area, the resultant signals scattered off a scene appear sufficiently similar to random noise, such that a scene image can be reconstructed if enough spatial frequency samples are collected. Additionally, multiple 5G transmitters lead to improved spatial incoherence with the worst case scenario represented in the far field of the transmitter array (thus, very far outside the wireless network). In a 2-D space (x, y) the field from N transmitters at a carrier frequency f_c with bandwidth Δf as a function of time can be given as

$$E(x, y, t) = \sum_{i=1}^{N} \int_{f_c - \frac{\Delta f}{2}}^{f_c + \frac{\Delta f}{2}} s_{TX_i}(t) * \frac{\delta(t - R_i/c)}{R_i} \, df \tag{2}$$

where $s_{TX_i}(t)$ is the transmit signal from the i-th transmitter, and $R_i = \sqrt{(x - x_i)^2 + (y - y_i)^2}$ is the distance of each point (x, y) from the transmitters' locations (x_i, y_i). A useful metric to find the suitability of the transmit fields for passive incoherent imaging is the mutual coherence γ which describes the spatial coherence, or how much the phase of each spatial point is similar with the other. The mutual coherence can be written in matrix form where each matrix element γ_{ij} is the dot product of the spatial point responses ϵ_i and ϵ_j

$$\gamma_{ij} = \frac{|\epsilon_i \epsilon_j^H|}{||\epsilon_i|| ||\epsilon_j||}. \tag{3}$$

When γ_{ij} is close to 1, the spatial points i and j are coherent, while when γ_{ij} is close to 0, the points i and j are incoherent or partially incoherent [18]. To validate the spatio-temporal incoherence of a set of transmitters, simulations were run in MATLAB for a 38 GHz linear array with $N = 4$ sources spaced randomly in a 55 cm baseline, each emitting independent information. The results can be seen in Fig. 1 for a 1-D scene with 1 m length, at a distance 5 m away from the array. Far field is the worst case scenario for incoherent wave propagation as even incoherent sources start to appear partially coherent. Nevertheless, we can observe

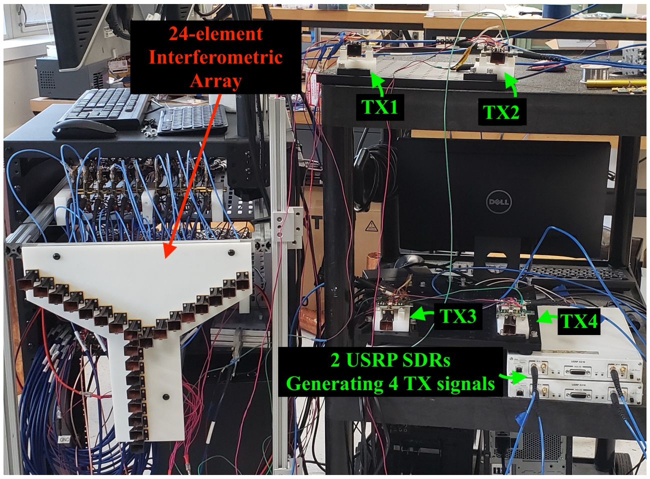
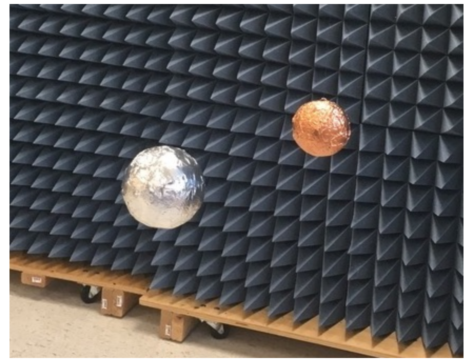
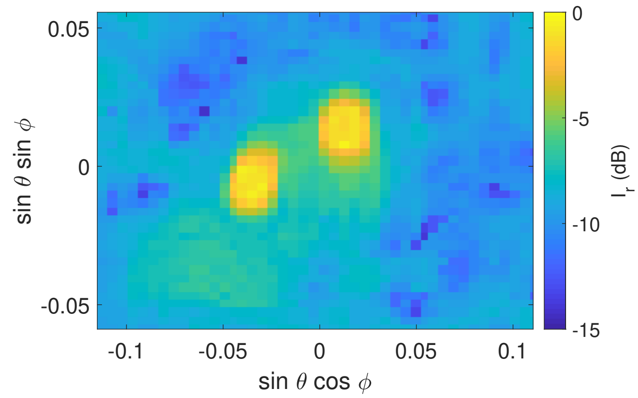


Fig. 3. Experimental millimeter-wave imaging configuration. (left) 24-element interferometric array and (right) 5G SDR-based testbed with 4 independent transmitters.



(a)



(b)

Fig. 4. (a) Photograph of the two spheres used for the experimental measurements. (b) Passive millimeter-wave image reconstruction of the two spheres. The two responses can be clearly resolved.

good incoherence results where the main diagonal line shows that every point is coherent with itself, as expected, however most of the other points show incoherence (values close to 0), with some partial coherence lines with maximum mutual coherence value approximately $1/4$. This shows that the radiation superposition does not behave coherently and can satisfy the Van Cittert-Zernike theorem requirements and therefore can be used for interferometric image reconstruction.

III. Experimental Measurements

The 5G transmitters configuration can be seen in Fig. 2a. The transmitted 256-QAM 5G signals were generated using two dual-channel USRP X310 software-defined radios (SDRs) with LabVIEW. The two SDRs were not frequency locked and all four transmitters started transmitting independent information at a random time. An IQ sampling rate of 20 MS/s was used with 2 samples per symbol configuration, giving a symbol rate of 10 MSymbol/s. The intermediate frequency carrier was set to 2 GHz, which was upconverted using an 18 GHz local oscillator (LO) and Analog Devices (ADI) HMC6787 upconverters. The boards had an integrated frequency doubler thus the resulting RF frequency was 38 GHz, the same as the operating frequency of the array. Different LOs can be used between transmit and receive in incoherent systems, which enables the passive imaging potential from third-party sources.

The millimeter-wave imaging array, shown in Fig. 2b, consisted of 24 elements placed in an asymmetric Y-array formation. Each receiver had a 15-dBi 3D-printed horn antenna, an ADI HMC1040 low-noise amplifier (LNA) and an ADI HMC6789 quadrature downconverter with integrated frequency doubler. Direct downconversion with a 19 GHz LO was used and both I and Q channels of every receiver (48 in total) were captured using three 16-channel ATS9416 14 bit, 100 MS/s, AlazarTech waveform digitizers installed on a computer in master-slave mode. The three digitizers had frequency locked clocks and time triggering took place using a common 1 kHz signal. The integration time was 50 μs. The computer had an Intel i9-9820x processor with 64 GB of RAM and performed the signal processing in real-time in MATLAB. Because the image reconstruction process is based on Fourier transforms and matrix multiplications, the processing is fast and can produce video-rate imagery.

Experimental measurements were conducted inside a semi-anechoic environment. The passive array was located next to a rack that had the 4 5G transmitters as shown in Fig. 3. The target scene was two spheres, as shown in Fig. 4a. The aluminum sphere was placed at a distance of 1.55 m, while the copper sphere was placed at a distance of 1.3 m from the imager. Fig. 4b shows the millimeter-wave image reconstruction, presenting an accurate reconstruction, clearly differentiating the responses of the two spheres.

IV. Conclusion

A millimeter-wave imaging system that can generate passive imagery of a scene using stray reflections from 5G transmitters was demonstrated. No coordination between the receive array and any transmitting node was used, demonstrating the ability to reconstruct images using signals of opportunity. These results may provide a framework for research into future joint sensing and communications in 5G networks.

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