Millimeter-Wave Sparse Digital Array for Imaging at More Than 250 Frames per Second

Stavros Vakalis, *Student Member, IEEE* and Jeffrey A. Nanzer, *Senior Member, IEEE*

***Abstract*—This project report summarizes the accomplished work that was supported in part by the 2021 IEEE MTT-S graduate fellowship award. A new 38 GHz digital array incoherent imaging system has been designed and built, both hardware and software, that can achieve image reconstruction at 652 frames per second. This is achieved by a novel design using incoherent noise illumination, enabling the use of passive interferometric image reconstruction. Design considerations and experimental high-speed imaging measurements of a sphere moving in a pendulum motion are presented.**

***Index Terms*—Digital arrays, high-speed imaging, interferometry, incoherent imaging, millimeter-wave imaging, noise signals**

I. Introduction

IMAGING is crucial in scientific and consumer applications due to the high information density of images and the human ability to rapidly interpret visual data. Millimeter-wave imaging is useful in applications such as security screening [1], remote sensing [2], and automotive radar [3], among others, in part because of the good penetration of millimeter-waves through clothing, clouds, fog, and smoke. One of the biggest challenges in millimeter-wave imaging is the slow imaging speed of current systems. Mechanically scanned antennas [1] are generaly slow to form images, and while electronically scanning phased arrays can increase the data acquisition speed, they necessitate a large amount of active hardware and therefore the total system cost can be high [3]. Computational imaging can reduce the number of active components, but at the cost of increased computational complexity [4]. This project thus sought to explore a new method for millimeter-wave imaging, one that leverages interferometric imaging, that has the potential for very high speed image formation.

Interferometric imaging was first developed in radio astronomy, where large antenna arrays are used to observe signals emitted from stars and other stellar objects. A few principal benefits of interferometry are that the antenna arrays are sparse and the image reconstruction is fast. The drawback is that most interferometric techniques rely on incoherent signals, according to the Van Cittert-Zernike theorem. Therefore, interferometric systems have to rely on naturally-generated thermal signals, which have extremely low power at millimeter-wave frequencies, and therefore require very high receiver sensitivity and long integration times, limiting the image formation speed. Active incoherent millimeter-wave imaging mitigates these requirements by illuminating the scene with incoherent noise signal transmission from multiple locations, and thus supports high-speed image formation [5].

S. Vakalis and J. A. Nanzer are with the Department of Electrical and Computer Engineering, Michigan State University, East Lansing, MI, USA (email: vakaliss@msu.edu).

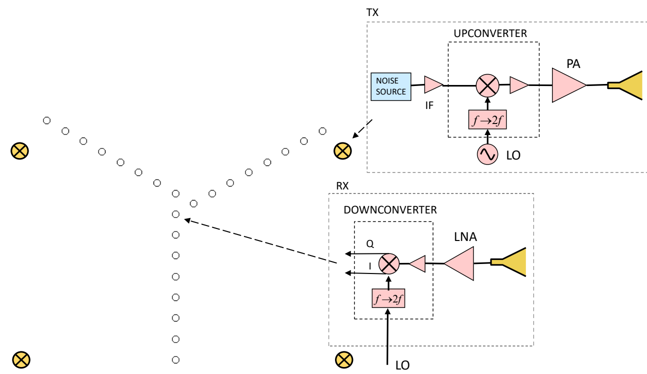

Fig. 1. Interferometric imaging system architecture; 24 receivers (represented by white circles) are located in the locations of a Y-array and 4 transmitters (represented by the yellow circles with crosses) are placed just outside the receiving array [6].

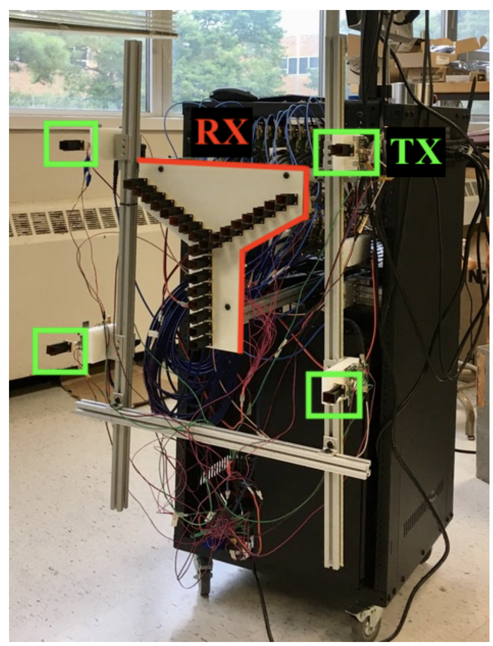

Fig. 2. Photograph of the millimeter-wave imaging system. The transmitters are shown in the green boxes, while the receive array is outlined with red. The millimeter-wave hardware, power supplies, digital hardware, and computer are hosted inside the rack [6].

II. Project Outcome

The use of active illumination decreases the integration time and bandwidth compared to other interferometric ap-

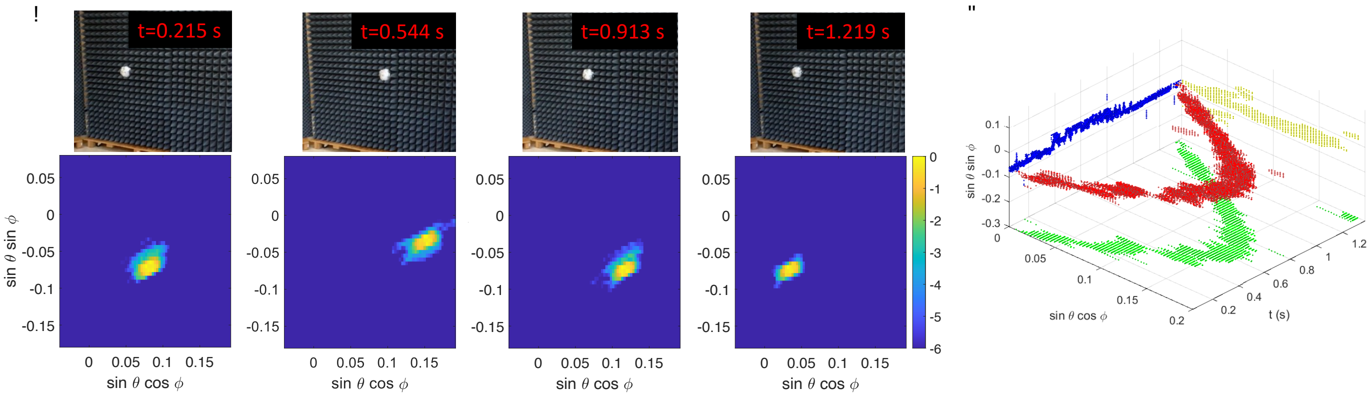

Fig. 3. (a) High-speed imaging results. Four different frames of the optical video of the pendulum can be seen (top) along with the millimeter-wave image reconstructions (bottom). The colorbar values correspond to the normalized reconstructed image intensity I_r and are in dB. (b) Three dimensional plot showing the pendulum movement as a function of the two direction cosines $\sin\theta\cos\phi$ and $\sin\theta\sin\phi$ and time [6].

proaches, thus the image reconstruction algorithms can be run quickly in the time-domain using multi-channel digitizers and a consumer-grade computer, without the need for dedicated processing hardware like field programmable gate arrays (FPGAs). Furthermore, the reconstruction algorithm does not require an iterative solver or computationally expensive matrix inversions found in computational imaging techniques. The digital array architecture of the system that was built can be seen in Fig. 1. The 4 transmitters (TX) utilized 0.1-2 GHz calibrated noise sources with 15 dB excess noise ratio (ENR), that were upconverted to 38 GHz using Analog Devices (ADI) HMC6787A upconverters. At 38 GHz the noise signal was amplified using ADI HMC7229 power amplifiers. Both transmitters and receivers utilized 15 dBi 3D-printed horn antennas that were fabricated at Michigan State University. The 24 receivers (RX) were placed in asymmetric Y-array formation, and the spacings between neighboring receive antenna elements was 24 mm (3.04λ). For the receivers, each antenna was followed by a 20 dB gain ADI HMC1040 low-noise amplifier (LNA) before being downconverted to baseband using an ADI HMC6789 I/Q downconverter. The same 19 GHz local oscillator (LO) was used for all the downconverters after being split into 24 ways. A photograph of the 38 GHz imaging system can be seen in Fig. 2. The digital array architecture was first presented in [7]. In order to increase the frame rate, the data acquisition and image formation took place in a parallel setting, which significantly reduced the fixed time delays for synchronizing, arming, and stopping the data acquisition [6].

III. Experimental Millimeter-Wave Measurements

Four time-lapse screenshots of the millimeter-wave image reconstructions of the pendulum sphere and the corresponding optical frames can be seen in Fig. 3(a). The optical images are shown on top, while the millimeter-wave images are shown in bottom. Total variation denoising was used on the millimeter-wave images. The experimental imaging frame rate was calculated by using an optical video camera with time stamps as ground truth. The millimeter-wave frame rate was 652 fps, more than an order of magnitude faster than other reported millimeter-wave imaging systems. A slow motion video can be found in the supplemental material of [6]. These results were also cross-validated with the pendulum oscillation period $T = 2\pi\sqrt{\frac{L}{g}}$, where L is the line length and g is the gravity acceleration constant. In Fig. 3(b), a three-dimensional plot of the sphere motion is shown as a function of time. The red color corresponds to the oscillatory movement of the sphere as a function of time. Blue, yellow, and green colors represent the projection in the different planes.

IV. Fellowship Impact and Career Plans

As my PhD journey is coming to an end, I consider the MTT-S Graduate Fellowship to be one of its biggest milestones. This award has been an honor and a big help for me and has enabled me to keep pursuing my research in an academic or industry setting. The fellowship also serves as an amazing proposal and grant writing experience for PhD students, which I definitely recommend.

Acknowledgement

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