# Universal Spectrally Agile Non-periodic Arrays and Transmitter Architectures at Millimeter-Wave

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***Abstract*—Future communication and sensing utilizing multiple spectral bands distributed across 30-100 GHz provides new opportunities for 6G networks for more optimal spectrum utilization. However, adaptive operation and spectral agility needed across all the licensed/unlicensed/shared bands for phased array is extremely challenging. This work addresses two key challenges for development of a mmWave universal frequency-agile array interface: 1) Limitations of conventional antenna array bandwidth. 2) High efficiency ultra-broadband transmitter. We propose strategies of designing and optimizing aperiodic sparse antenna arrays geometries that are capable of beamforming across an extremely large continuous bandwidth that is currently impossible with conventional antenna arrays. In addition, we describe novel design methodology enabling an ultra-wideband (30-100 GHz) beamformer transmitter element for large-scale arrays, with highlight on power amplifiers and phase shifters.**

***Index Terms*—Aperiodic, beamformer, frequency-agile, mmWave, phased array, ultra-broadband.**

## I. Introduction

To keep up with the growing demand for various new applications and services, frequency agility is expected to play a significant role in the next generation wireless systems. The wireless network must be capable of rapidly adapting to changing spectral environments to avoid interference and maintain optimal performance. While there is no current array that allows such spectral agility, one way to achieve this is through the use of multiple frequency-static front-ends, which are designed as in-dependent phased arrays each operating across a different center frequency with narrow operation fractional bandwidth roughly 15-25%. This is limited by both antenna array and RFIC bandwidth [1]–[3]. However, this approach is not scalable, as the number of spectral bands for communication and sensing has been expanding rapidly across 30-100 GHz. Therefore, we propose a new class of universal frequency-agile array interfaces and RFICs to address the available spectrum across all the licensed/unlicensed and shared bands (Fig. 1). Such a system can be a natural platform for future integrated sensing and communication that enables simultaneous dual task with more optimal spectrum resource utilization and environmental awareness. The large bandwidth of this system also boosts the throughput by supporting concurrent multi-band operation [4] where more than one bands can be transmitted or received at the same time. All these benefits comes with a unified single antenna array aperture and a single set of broadband circuit hardware for substantially low cost and footprint. In this report, we propose ultra-broadband antenna array and circuit techniques to enable such a universal array front-end.

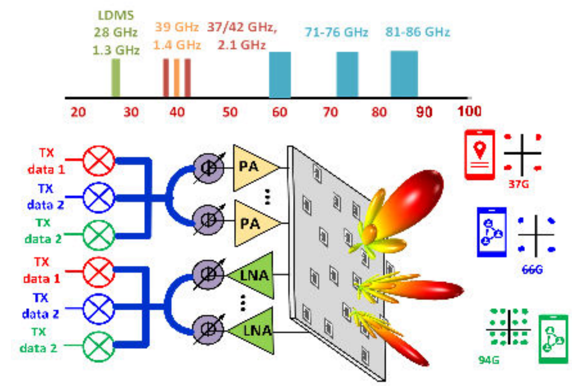


Fig. 1. Proposed frequency agile array and constituent circuits featuring a low cost, universal array interface.

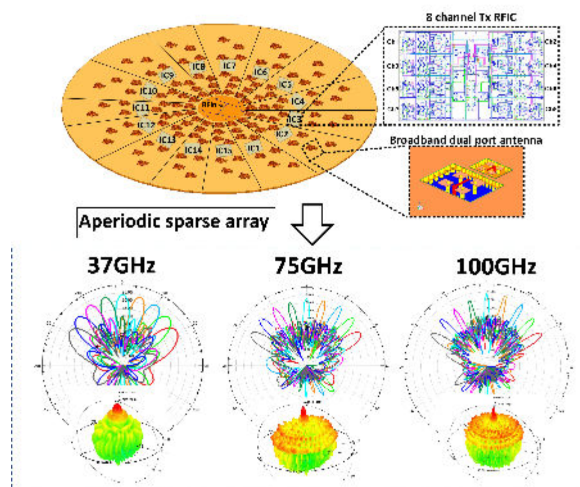


Fig. 2. Proposed 120 element aperiodic array and its full-wave simulation exhibiting low side lobe level across 3:1 frequency range and across large steering angle.

## II. Project Outcomes

Conventional uniform linear arrays (ULAs) are fundamentally incapable of operating across a wide range of frequencies extending beyond an octave without spatial aliasing (grating lobes). The element spacing (done at Nyquist rate of the wavelength of operation) creates spatial aliasing when the spacing exceeds half a wavelength, making them unusable for frequency agile system. In this work, we develop an optimized non-uniform 2D sparse array with broadband antenna element achieving beamforming capability and low side-lobe-levels (<-10 dB) over extremely wide >3:1 frequency range covering +-60$^{o}$ elevation scanning angles, while removing the undesired

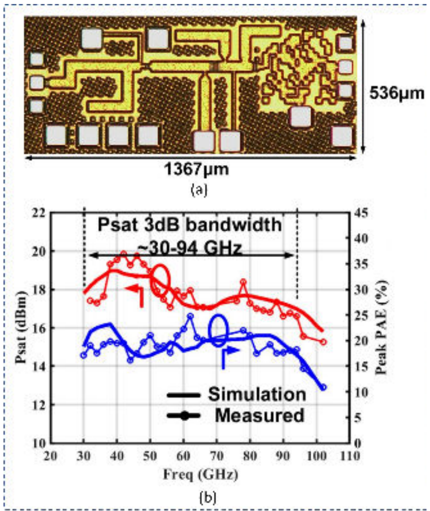


Fig. 3. Inverse designed ultra-broadband PA prototype (a) Layout (b) Measured power and efficiency performance across 30-100 GHz.

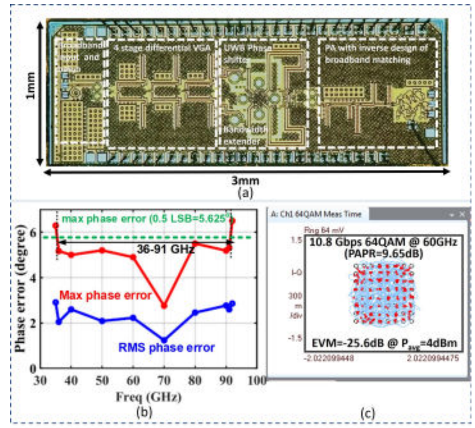


Fig. 4. Ultra-wideband beamforming transmitter layout and performance.

coupling between elements (Fig. 2). The design method relies on nature inspired array initial geometries and proposed highly efficient 2D algorithm for element location optimization. The resultant array leads to a fundamentally different method of broadband beamforming, enabling a quantum leap bandwidth improvement than conventional topology. For the proposed non-uniform array, the sparsity is guaranteed such that the minimal distance between any of two elements is larger than $0.5\lambda$ at lowest frequency to eliminate the element coupling issue, allowing for easy design of antenna element hardware.

From circuits perspective, we propose novel design methodologies for power amplifiers, phase shifters and other circuit blocks to allow ultra-wideband operation of a beamforming transmitter covering from 5G FR2 to W band frequencies with a 90% fractional bandwidth. Fig. 3 (a) presents the broadband 3-stage PA architecture using common-base PA cell, implemented in 90nm SiGe. The non-intuitive, pixelated output matching network design exploits the deep learning-enabled inverse design method we proposed in [5], which utilizes the deep learning model as a fast electromagnetic (EM) solver such that a desired output matching performance (low loss and load-pull target) can be optimized across 30-100 GHz within the large design space of nearly all random EM structures. Between 30 and 94 GHz, the PA achieves between 16.5 and 19.5 dBm Psat with sharp compression and 16%–24.7% peak PAE (Fig. 3 (b)). By the novel matching network design technique, the $P_{sat,3dB}$ bandwidth is higher than all reported mmwave silicon PAs which have peak PAE $>$ 20% and demonstrates for the first time concurrent multiband (triple-band) transmission with superior performance at multi-Gb/s. As another key enabler, we design the IQ modulator phase shifter based on an input $90^o$ hybrid-based network. Conventional differential quadrature generation network suffers from limited fractional bandwidth (23%) of amplitude imbalance. In this design, a bandwidth extender is proposed to generate each output by combining two signals generated by 'through' and 'couple' path of a narrowband quadrature hybrid respectively. Given the property of the inverse amplitude response between 'through' and 'couple' paths, the gain compensation across frequency results in a more broadband amplitude response. The beamformer transmitter chain consists of broadband PA, phase shifter and VGA (Fig. 4(a)) . The measured rms gain error of 0.24-0.35 dB, the 5 bit extremely low rms phase error of 1.24-2.8$^o$ are achieved across the 87% bandwidth (Fig. 4(b)). The beamformer is measured with a 1.8 GHz bandwidth 64QAM signal. Without pre-distortion, the Tx chip demonstrates the EVM/ACLR of -25.6 dB/-31.9 dBc with average output power of 4 dBm at 10.8 Gbps at 60 GHz (Fig. 4(c)).

## III. Career Plan and Fellowship Imapct

I would like to thank the IEEE MTT-S community for awarding me this prestigious award. I also sincerely thank my supervisor Kaushik Sengupta for the supportive guidance during my Ph.D research journey. Currently, I am preparing the thesis for my doctoral studies. After graduation, I am planning to work for industry and return to academia in the future where I can directly contribute to the MTT-S. This award has a positive impact on my motivation and confidence to continue pursuing my research in the field of mmWave/THz technologies, and it also provided me an opportunity to attend various conferences such as IMS2022, learning and keeping interactions with best experts in the field.

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