

## ABSTRACT

The emergence of millimeter-wave 5G/NextG technology has driven significant interest in real-time analog signal processing, which offers compelling advantages over conventional digital approaches. Unlike digital techniques that depend on analog-to-digital converters (ADCs) and complex processing chains, analog systems enable analog computing for real-time signal manipulation directly in the native waveform, reducing latency, lowering power consumption, and minimizing reliance on high-speed ADCs. At the forefront of this paradigm is radio frequency (RF) analog signal processing - a method defined by the direct manipulation of signals in their pristine high-frequency waveforms. This approach unlocks critical capabilities for microwave and millimeter-wave applications, including bandwidth efficiency, ultrafast operations, and seamless integration with high-frequency systems. However, current RF analog signal processing face inherent limitations. Precision and noise susceptibility in analog components (e.g., phase shifters, mixers, etc.) degrade signal-to-noise ratios (SNR) at high frequencies, while parasitic effects and design complexity hinder the integration of multi-functional circuits into compact systems. Additionally, analog systems lack the programmability of digital counterparts, limiting their adaptability to dynamic communication standards like 5G/NextG. These limitations underscore the need for innovative RF front-end circuit design that balances architectural simplicity, functional versatility, and compatibility with emerging standards.

Firstly, a frequency-reconfigurable RF Hilbert transformer (RFHT) has been presented to overcome the limit of conventional Hilbert transform in digital baseband processing, which requires analog-to-digital conversion and computational latency. It is a novel microwave circuit capable of performing real-time Hilber transform directly on high-frequency analog signals across a wide RF bandwidth. This breakthrough shifts traditionally digital signal processing tasks—such as edge detection, time synchronization, and spectrum discrimination—into the analog domain. Building on this design, we demonstrate three key RF analog applications operating in the Wi-Fi band: 1) an RF edge detector for real-time pulse edge detection 2) an RF time delay estimator for precise synchronization, 3) a RF spectrum sniffer for flexible spectrum management.

Monopulse tracking radar systems are widely used in applications such as wireless communications, remote sensing, imaging, and autonomous driving due to their ability to estimate the range, velocity, and direction of arrival (DoA) of objects in real time. These systems achieve

this by simultaneously receiving and comparing signal waveforms from multiple radiation beams. However, traditional monopulse receivers often rely on complex multilayer designs or expensive waveguide-based solutions, increasing cost and design complexity. To address this, we propose a low-cost monopulse receiver featuring a novel comparator network composed of two types of symmetrical couplers. This design eliminates the need for costly multilayer or waveguide structures, marking the first investigation of a cost-effective planar comparator for monopulse systems. To validate the concept, two comparator networks operating at 5.8 GHz and 2 GHz were designed, fabricated, and tested. Simulation and measurement results confirm the feasibility and performance of the proposed solution, demonstrating its potential to enable affordable and efficient monopulse tracking in next-generation radar systems.

In addition, phased array systems rely on beamforming matrices to achieve precise control over radiation patterns for a dynamic communication, but traditional designs often lack the flexibility needed for advanced beam steering applications. To address this limitation, we propose a novel  $3 \times 3$  Nolen beamforming matrix that enables flexible progressive phase differences, offering unprecedented freedom in free-space beam steering. Unlike previous designs, the proposed matrix supports two key advancements: 1) a tunable  $3 \times 3$  Nolen matrix capable of achieving a full  $360^\circ$  progressive phase shift, 2) a dual-band  $3 \times 3$  Nolen matrix that provides distinct progressive phases at two different operating frequencies. These innovations are applicable to both 1D and 2D beamforming scenarios, significantly enhancing the versatility of phased array systems. To validate the design, comprehensive simulations and measurements were conducted, evaluating both the beamforming matrix and the radiation characteristics of the integrated phased array. The results confirm the feasibility and performance of the proposed Nolen matrix, demonstrating its potential to enable advanced beamforming capabilities in next-generation communication and radar systems.