

# Closed-Loop Multi-Stage DSP-Free Beam-Formers with Full-FoV Dynamic and Autonomous Unknown Blocker Rejection and Signal Tracking for Mm-Wave Wideband MIMO Transceiver System

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**Abstract**— We present an 8-element 23-30 GHz scalable full-FoV MIMO receiver array with hybrid beam-forming by using closed-loop multi-stage cascadable DSP-free mm-Wave/RF beamformers and digital beamforming. The multi-closed-loop beamformers autonomously create spatial notches on multiple in-band blockers and perform beam-forming on the desired signals with 1-2us dynamic response time. The array rejects wideband in-band blocker and receives desired signal with 6Gb/s 64QAM and 1.6Gb/s 256QAM over full FoV.

**Keywords**—Adaptive phased-array, beamforming, blocker-resilient receiver, Field of View (FoV), interference cancellation, negative feedback, retro-directive array, self-steering.

## I. INTRODUCTION

Mm-Wave massive MIMOs leverage large array size to enhance the link budget and spatial selectivity, but their resulting narrow beamwidth substantially complicates the transmitter-receiver (TX-RX) alignment. Unlike most existing “static” applications (e.g., mm-Wave HDTV transmission), many future mm-Wave links will operate in highly “dynamic” environments, such as wireless AR/VR and vehicle-/drone-/machine-based links, necessitating rapid and precise beamforming-/tracking for high link reliability and low latency. Densely deployed mm-Wave nodes will also result in future congested/contested environment, requiring spatially tracking/rejecting unknown blockers (unknown frequency, angle-of-arrival AoA, or modulation). Most existing RF/analog beamformers (BFs) are open-loop circuits *per se*, which require phase control signals from extensive baseband computation, while digital beamforming relies even more on the baseband DSP. A recent mm-Wave link in an almost idealistic setting requires 45ms for beamforming and cannot meet <1ms 5G latency target. Self-steering arrays (SSA) perform closed-loop and rapid frontend beamforming without DSP. However, existing SSAs mostly use PLL-/coupled-oscillator-architectures that are inherently narrow band with limited Field-of-View (FoV) and cannot support multi-beams or blocker suppression. In parallel, although array-based spatial filtering is extensively studied, most are open-loop circuits, whose notch syntheses require prior knowledge of the blockers or complete phase/amplitude controls from DSP.

We present a broadband scalable full-FoV MIMO RX array with hybrid beamforming using mm-Wave/IF front-end SSA BFs and baseband digital beamforming (Fig. 1). The SSA BFs achieve DSP-free beamforming with DLL-like phase domain negative feedback loops to cover broad bandwidth and full FoV [1]. They are cascadable for rapid yet accurate multi-beam operations to reject unknown blockers and align desired signals. The digital beamforming is for fine beam alignment. A proof-of-concept 8-element RX array chip includes two 4-element SSA unit arrays, scalable for massive MIMOs (Fig. 1). Each SSA unit array is composed of two parallel mm-Wave SSA BFs (1<sup>st</sup>-stage) and one IF SSA BF (2<sup>nd</sup>-stage). During the array receiving, the received signals in the adjacent two paths exhibit certain phase difference, which is then detected by the PD to generate DC feedback control voltages to adjust the phase shifters. This creates a DLL-like phase-domain negative feedback loop that autonomously equalizes the output phases. After the phase alignment, if the output combiner/ subtractor is selected, the BF will perform constructive beam-forming of the desired signal/ spatial notching of the blocker [2].

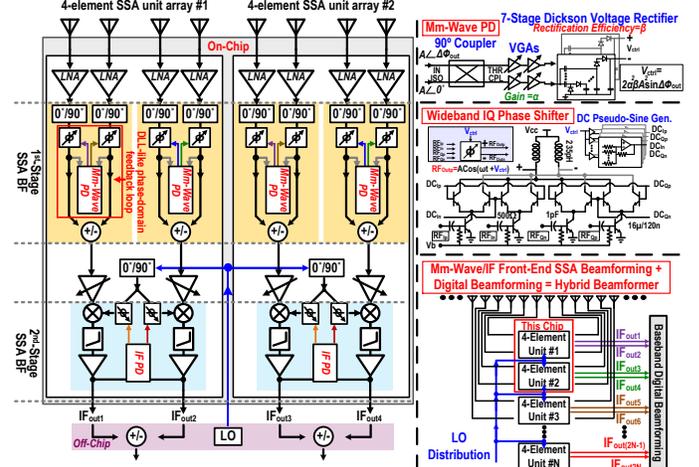


Fig. 1. System architecture of the 8-element full FoV MIMO RX array with hybrid beamforming using mm-Wave/IF front-end SSA beamformers and baseband digital beamforming. Schematic of the mm-Wave power-aware phase detector (PD), the wideband IQ phase shifter with I/Q modulator and built-in pseudo-sine generation circuits, and the proposed hybrid beamforming RX arrays in a MIMO system.

## II. VARIOUS OPERATION MODES OF THE RX ARRAY

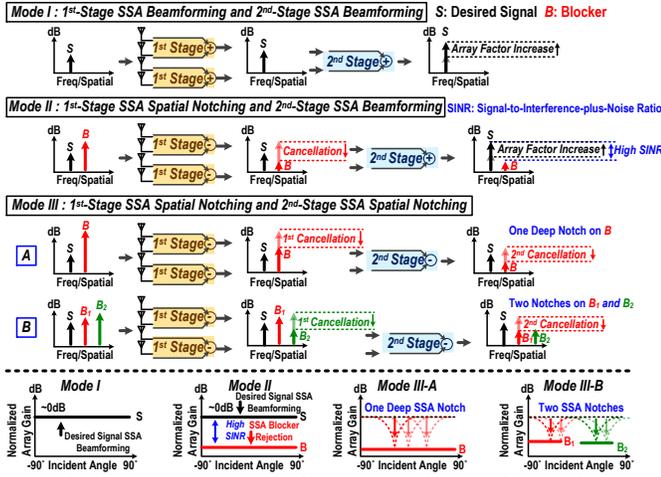


Fig. 2. Various operation modes of the RX array by reconfiguring the output combiners or subtractors in the 1<sup>st</sup> and 2<sup>nd</sup> SSA front-end BF stages.

The 2-stage front-end SSA BFs support various operation modes (Fig. 2). Mode I: The 1<sup>st</sup> and 2<sup>nd</sup> BFs both use output combiners. The RX array serves as an 8-element SSA per chip and autonomously tracks one desired signal by beamforming over full FoV. Mode II: The 1<sup>st</sup> BF uses subtractor, and the 2<sup>nd</sup> BF uses combiner. The RX array first creates a spatial notch to autonomously reject one unknown in-band blocker, and then performs beamforming for one desired signal. The power-aware PD ensures that the 1<sup>st</sup> BF only tracks and cancels the blocker, not the desired signal. Mode III: The 1<sup>st</sup> and 2<sup>nd</sup> BFs both use subtractors. The RX array can reject one strong in-band blocker twice by a deep spatial notch (Mode III-A), or it can create two independent spatial notches to reject two in-band blockers (Mode III-B). In Modes II and III, spatial filtering largely suppresses the in-band blockers, relaxes the following RX dynamic range, and enables digital beamforming.

## III. MEASUREMENT RESULTS

The 1<sup>st</sup> and 2<sup>nd</sup> SSA BFs are first tested individually (Fig. 3a~3d). Over 23-30GHz and full FoV, the 1<sup>st</sup> SSA BF achieves

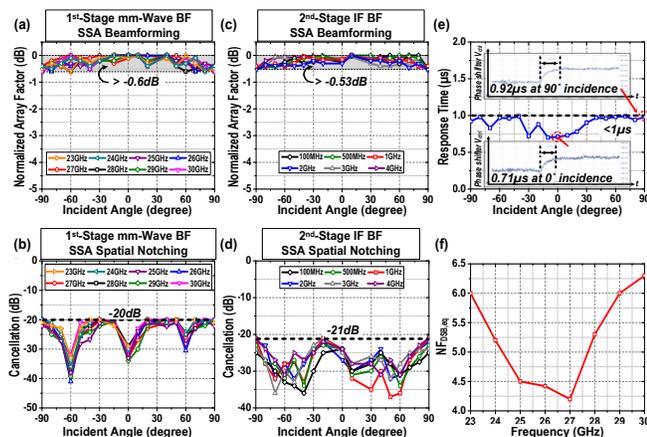


Fig. 3. (a)~(d) Measured wideband and full-FoV autonomous desired signal beamforming and blocker rejection in the 1<sup>st</sup> mm-Wave SSA BF and 2<sup>nd</sup> IF SSA BF. (e) Measured dynamic response time over full FoV. (f) Measured  $NF_{DSB,eq}$  with the 2-stage SSA BFs both turned on. (g) Mode-II demonstration with 4-element SSA for blocker rejection and desired signal beamforming when the blocker and desired signal are both broadband modulated at the same scheme and speed. After the 2-stage SSA BFs are enabled, desired signal is successfully demodulated, showing autonomous spatial cancellation of co-channel blocker.

a flat normalized array factor  $> -0.6$ dB for the desired signal beamforming and a 20-41dB spatial notch for blocker rejection. The 2<sup>nd</sup> SSA BF also achieves a flat normalized array factor  $> -0.53$ dB for desired signal beamforming and a 21-36dB spatial notch for blocker rejection over full FoV and a wide 0.1-4GHz IF range. The full FoV and wide bandwidth enable autonomous beamforming of in-band signals or cancellation of co-channel blockers, even if their carrier frequency, AoA, and modulations are unknown. The response time of each closed-loop SSA BF stage is  $< 1\mu s$  over full FoV (Fig. 3e), which ensures rapid beamforming/-tracking in dynamic low-latency applications and is 100~1000 $\times$  faster than existing DSP-controlled BFs. The equivalent single-element double-sideband noise figure is 4.2-6.3dB over 23-30GHz (Fig. 3f). We also test the RX array (Mode-II) under a wideband modulated co-channel blocker and desired signal with no digital beamforming. In Fig. 3g, after enabling the 2-stage SSA BFs for autonomous blocker rejection and signal beamforming, the desired signal is successfully demodulated with -27.2dB EVM for 3Gb/s 64QAM and -33.9dB EVM for 0.8Gb/s 256QAM. The results for various signal/blocker incident angle differences and frequency offsets clearly demonstrate beamforming and spatial filtering.

## IV. CAREER PLAN AND FELLOWSHIP IMPACT

I'm honored to receive the prestigious MTT-S Graduate Fellowship for the year 2018. The award is a great recognition of my research for the next-generation extreme-wideband ultra-low-latency communication networks. I believe that it will inspire myself to pursue and explore more advanced research fields and make future technology better. To further facilitate my ideas in real world, I will firstly work in industry, with the possibility of returning to academia in the future.

## REFERENCES

- [1] M. Huang, *et al.*, "An all-passive negative feedback network for broadband and wide field-of-view self-steering beam-forming with Zero DC power consumption," *IEEE JSSC*, vol. 52, no. 5, pp. 1260 - 1273, May 2017.
- [2] M. Huang, *et al.*, "A 23-30GHz hybrid beam-forming MIMO receiver array with closed-loop multi-stage front-end beam-formers for full-FoV dynamic and autonomous unknown signal tracking and blocker rejection," *IEEE ISSCC 2018*, pp. 68-70.

