

# A Wideband 27-41GHz N-Input-N-Output MIMO Receiver Using Scalable Cascadable Autonomous Array-Based High-Order Spatial Filters for Instinctual Full-FoV Multi-Blocker Suppression and Signal Beamforming

Min-Yu Huang and Hua Wang

School of Electrical and Computer Engineering, Georgia Institute of Technology, Atlanta, GA 30332 USA

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**Abstract**— This is the proposal supported by DARPA MIDAS (Millimeter Wave Digital Arrays) project. We present a wideband 27-41GHz RX array for N-input-N-output MIMO systems. It employs scalable cascadable array-based high-order Autonomous Spatial Filters (ASFs) with high spatial selectivity as a “smart” spatial filter bank for instinctual multi-blocker/signal management to assist digital beamforming. The array autonomously rejects multiple wideband modulated in-band blockers and receives desired signal with 3Gb/s 64QAM and 0.8Gb/s 256QAM over full FoV.

**Keywords**—Adaptive phased-array, beamforming, blocker-resilient receiver, Field of View (FoV), interference cancellation, low-latency, MIMO, N-input-N-output, negative feedback, retro-directive array, self-steering, scalable large-scale phased array.

## I. INTRODUCTION

Rapidly growing deployment of mm-wave links in commercial (e.g., 5G/automotive) and defense (e.g., fast-moving drones) applications [1]-[4] often exposes the transceiver (TX/RX) frontends in complex EM environments

with multiple fast-changing yet unknown blockers (Angle-of-Arrival AoA/frequency/modulation). To preserve full field-of-view (FoV) and multi-beam/MIMO operations, digital arrays often skip FoV-limited frontend beamforming and rely on digital backends for spatial filtering [1]. However, the RXs and ADCs need high dynamic range (DR) to handle all the aperture information and avoid array saturation by strong signals/blockers that may hinder digital beamforming. Therefore, to aid digital arrays and reduce RX/ADC DR, there is a critical need for agile spectral-spatial frontend filtering for instinctual blocker suppression and “power-equalizing” of desired signals.

In digital arrays, frontend spectral filtering, e.g., by mixers/filters, suppresses out-of-band blockers but not in-band spatial blockers. Most existing frontend spatial filters use analog beamformers (BFs) as spatial notches. As a fundamental limitation, these approaches require the signal/blocker knowledge *a priori* for open-loop spatial notching or use digital backend for on-the-fly coefficient computation for the analog BFs, limiting them in dynamic use with unknown and fast-changing signals/blockers.

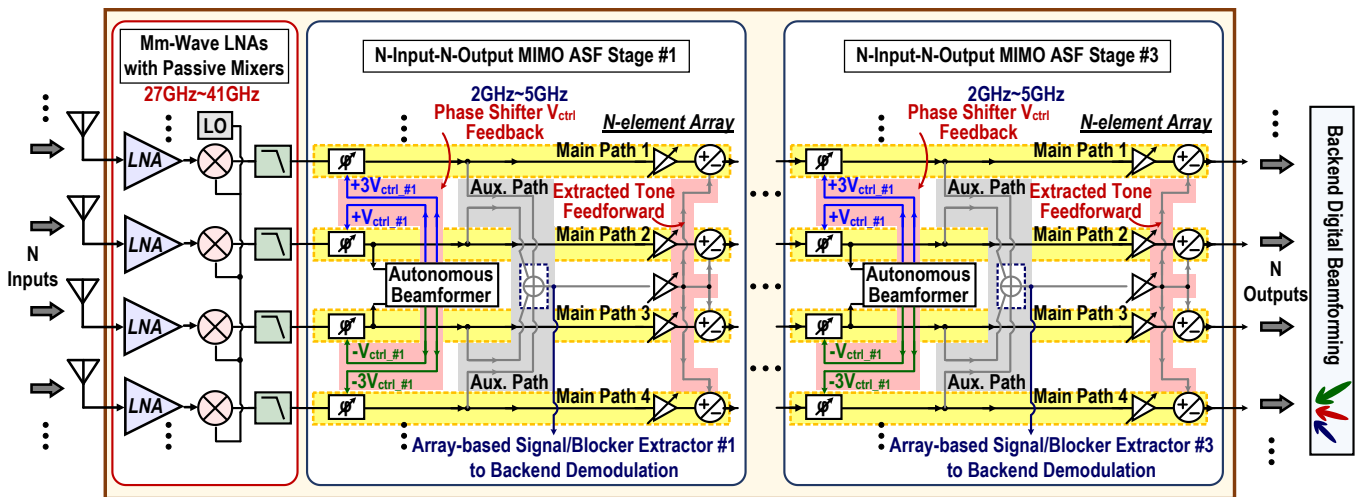


Fig. 1. System architecture of the 27-41GHz N-Input-N-Output MIMO RX with scalable cascadable array-based high-order ASFs for instinctual full-FoV signal/blocker management.

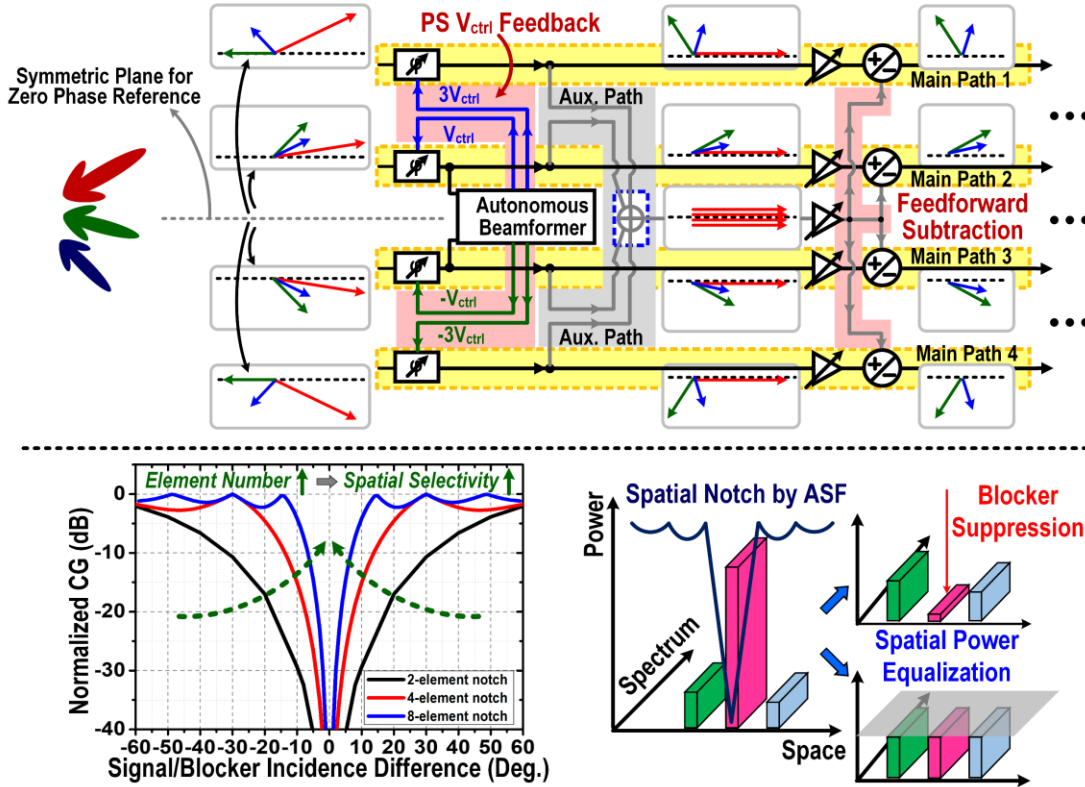


Fig. 2. Conceptual diagram for the operation of the autonomous N-Input-N-Output array-based high-order ASF with a 4-element ASF example shown for spatial notching, multi-blocker suppression, and desired signal power equalization in various dynamic MIMO operation cases to relax dynamic range requirement for RXs/ADCs.

Conventional self-steering BFs automatically align RX array towards the incident beam without backend computation. However, they either use Van-Atta-like simple reflectors, or employ coupled oscillators/PLLs autonomous BFs that are inherently narrow-band and not scalable to large arrays due to loop stability. Moreover, its intrinsic nonlinearity cannot support multi-beams or Gbit/s complex modulations. Recently, shows DLL-like autonomous BFs to suppress unknown strong signals/blockers and support Gbit/s signals. However, its array size reduces by 2 after each beamforming stage and cannot support N-input-N-output MIMOs. Moreover, it only forms 2-element spatial notch with limited spatial selectivity and ability to process multiple spatial signals/blockers.

We present a wideband 27-41GHz RX array for N-input-N-output MIMO systems (Fig.1), which employs scalable cascadable array-based high-order Autonomous Spatial Filters (ASFs) as a “smart” spatial filter bank for instinctual multi-blocker/signal management to assist digital beamforming. Mm-Wave wideband LNAs and passive mixers provide broadband frontend spectral filtering. The ASFs operate at IF, and each ASF employs an array-based phase-domain negative feedback for auto-beam-tracking and a feedforward path for spatial filtering. Identical ASF stages are cascaded to sequentially suppress multiple unknown spatially blockers or equalize multiple signals. An example 4-element broadband mm-Wave

RX array frontend includes passive mixer spectral filter and three cascaded IF ASFs (Fig. 1).

## II. VARIOUS OPERATION MODES OF THE RX ARRAY

Each IF ASF comprises phase shifters (PS), an array-based closed-loop autonomous BF, and feedforward signal combining/subtraction. The autonomous BF contains a power-aware phase detector (PD) for feedback PS control voltage generation. When multiple co-channel tones are received, the power-aware PD selects the strongest one, detects its adjacent-channel phase difference, and generates feedback PS control voltages, e.g.,  $-3 \times V_{ctrl}$ ,  $-1 \times V_{ctrl}$ ,  $+1 \times V_{ctrl}$ , and  $+3 \times V_{ctrl}$  for a uniform  $1 \times 4$  array, so that PSs align the RX array to this tone [7]-[9] (Fig. 2). Then, an auxiliary (Aux) path adds together N phase-aligned channels as a BF to accurately extract this strongest tone, which is then feedforward subtracted from the N-channel Main paths for spatial notching. The ASF equivalently rotates the array towards the strongest tone and spatially notches it by feedforward subtraction, so the array size and full-FoV are preserved. The ASF also acts only on RF power and needs no prior AoA/frequency/modulation knowledge or external BF controls. For the extracted tone in each ASF, although a one-step demodulation should verify whether it is signal or blocker, this consumes negligible time/resource than backend AoA computation in conventional arrays, ensuring rapid spatial filtering. Larger array sizes result in high-order ASF spatial filtering with sharpened selectivity (Fig. 2), while multiple cascaded ASFs can sequentially process

more unknown co-channel signals/blockers. For instance, cascading 3 ASFs can create three independent spatial notches to suppress three similar-power blockers (case 1), suppress one strong blocker twice and reject one other medium-power blocker (case 2), or reject two blockers and beamform on one desired signal (case 3). The notch depth is also tunable by the Main/Aux-path gains if multiple co-channel signals require “power equalization”.

### III. MEASUREMENT RESULTS

A proof-of-concept mm-Wave 4-input-4-output MIMO RX array with 3-stage ASFs in 45nm CMOS SOI is implemented (Fig. 7). All autonomous spatial notching or beamforming measurements are achieved only by on-chip ASFs with no external beamforming controls. The autonomous performance of one-stage ASF is first tested (Fig. 3), showing a 40-51dB spatial blocker notching or a flat normalized array factor  $> -0.2$ dB for desired signal beamforming over full-FoV. When two spatial co-channel tones are concurrently received, the power-aware PD can accurately discriminate the stronger one and achieve  $\geq 28$ dB suppression, if the two tones have  $\geq 1$ dB power difference. Response time of one ASF stage is  $1.47\sim 1.75\mu\text{s}$  over full-FoV, enabling fast beamforming for low-latency MIMOs.

Figure 3 shows the RX with cascaded 3-stage ASFs tested for different receiving cases. When three similar-power blockers are concurrently received (case 1), the three ASF

stages will sequentially suppress them by three independent spatial notches with maximum 51dB cancellation. If one blocker is excessively strong (case 2), the first two ASFs will both track it and suppress it twice with a total 62dB deep spatial notch, and the 3rd ASF can reject one other blocker with a 46dB notch. When two blockers and one desired signal are simultaneously received (case 3), the two similar-power blockers are sequentially suppressed by two independent spatial notches with max 50dB rejection over full FoV. Compared to the fixed 2-element spatial filters in [5][6], the ASFs achieve 4-element spatial filters with sharpened selectivity that can be further improved for larger array sizes [10].

The RX achieves 27-41GHz wideband operation, 36dB conversion gain (CG) with 15dB controls, and 4.3-6.3dB NF with 3-stage ASFs on to support 5G multi-band MIMOs (Fig. 4). When the 1st ASF stage is on, the measured in-band blocker-Pin1dB achieves 15/17dB enhancement for 35/25dB CG. The measured in-band OIP3 of a desired signal achieves 18/24dB improvement for in-notch incidence at 35/25dB CG. Moreover, the RX array realizes “power equalization.” When receiving three independent 64QAM 100MSym/s signals (max/min=15dB) over 900MHz instantaneous bandwidth at different incidences, the RX array spatially equalizes and demodulates them with  $>26.2$ dB SNR, successfully relaxing the DR of downstream ADCs by 15dB.

The RX is also tested with concurrent multiple wideband modulated co-channel blockers (-35~-40dBm) and one desired signal (-43dBm) with at least 50% frequency overlap (case 3)

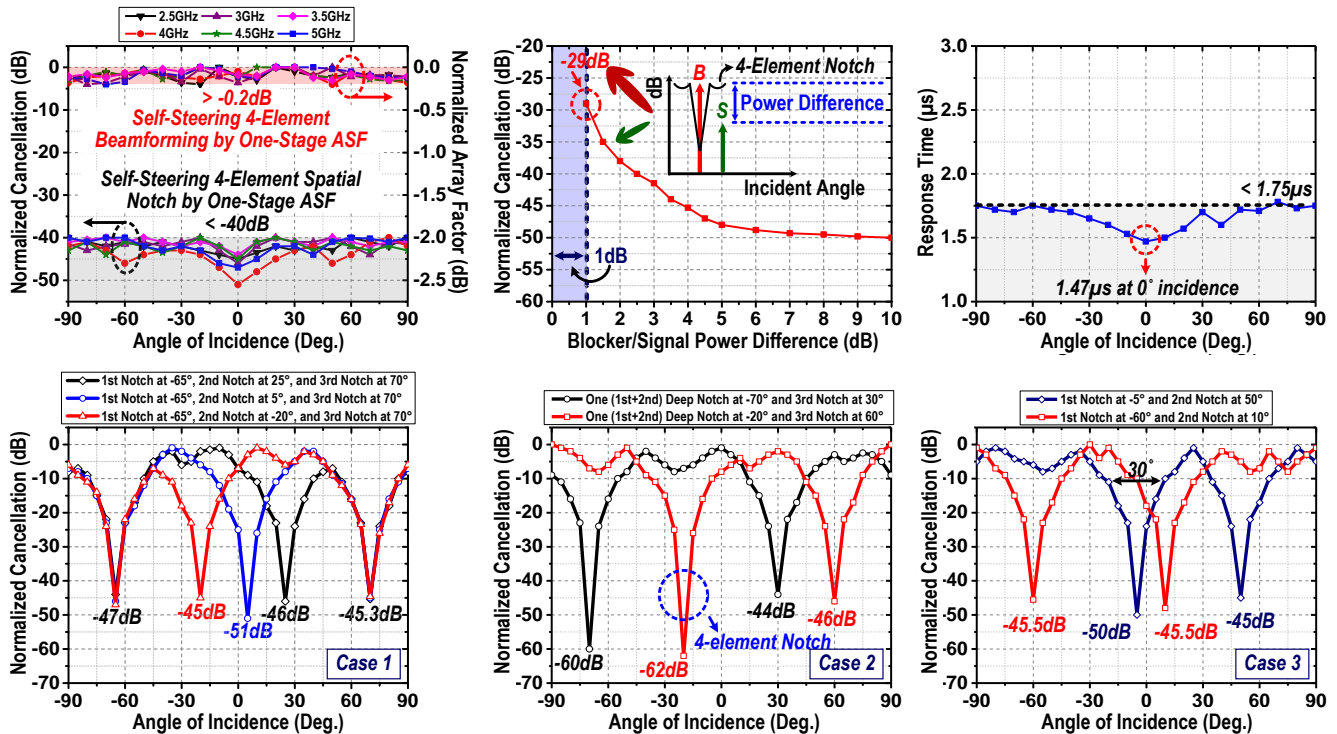


Fig. 3. Measured single stage ASF performance over full FoV, including autonomous blocker rejection and desired signal beamforming, ASF autonomous discrimination of concurrently received multi-tones (blocker/signal incidence difference =  $60^\circ$ ), and instintual ASF response time, as well as 3-stage ASF performance in different receiving cases shown in Fig. 2.

(Fig. 5). All the blockers/signals are independently modulated, and the blockers have various power levels (3-8dBc) to mimic practical MIMO scenarios. With the 3-stage ASFs, multiple wideband modulated blockers are autonomously rejected, and the desired signal is successfully demodulated for 3Gbit/s 64QAM with -28.64dB EVM and 0.8Gbit/s 256QAM with -32.7dB EVM. The desired signal is then swept for its incident angle. With a 4-element array, a clear spatial signal selection by the array-based ASFs is shown.

#### IV. CONCLUSION

In summary (Fig. 6), this is the first N-Input-N-Output MIMO RX array with array-based high-order scalable cascadable ASFs for autonomous suppression of multiple unknown blockers and desired signals beamforming supporting Gbit/s complex modulations and  $\mu$ s low-latency.

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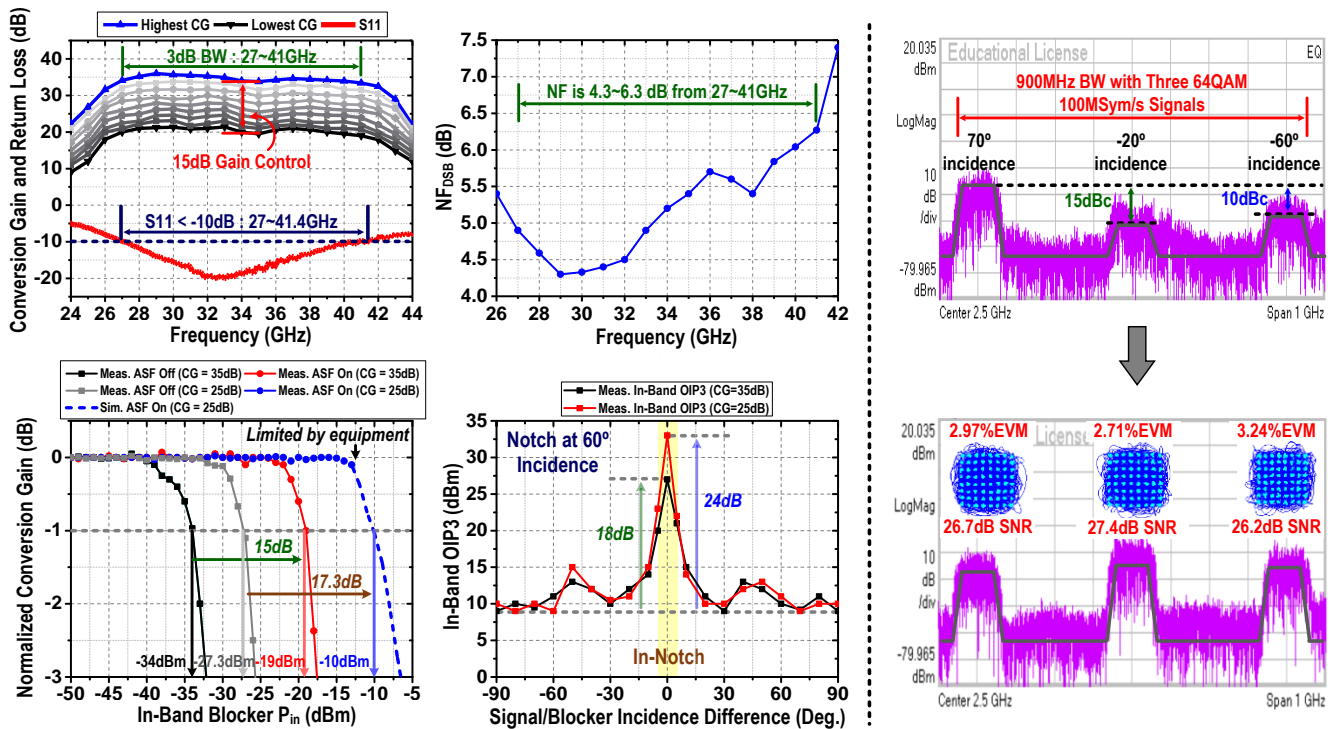


Fig. 4. Measured wideband RX CG, S11, NF, and in-band blocker Pin1dB with the 1st-stage ASF on/off, and in-band OIP3 versus signal/blocker incidence difference, as well as measured power equalization for three 64QAM 100MSym/s desired signals.

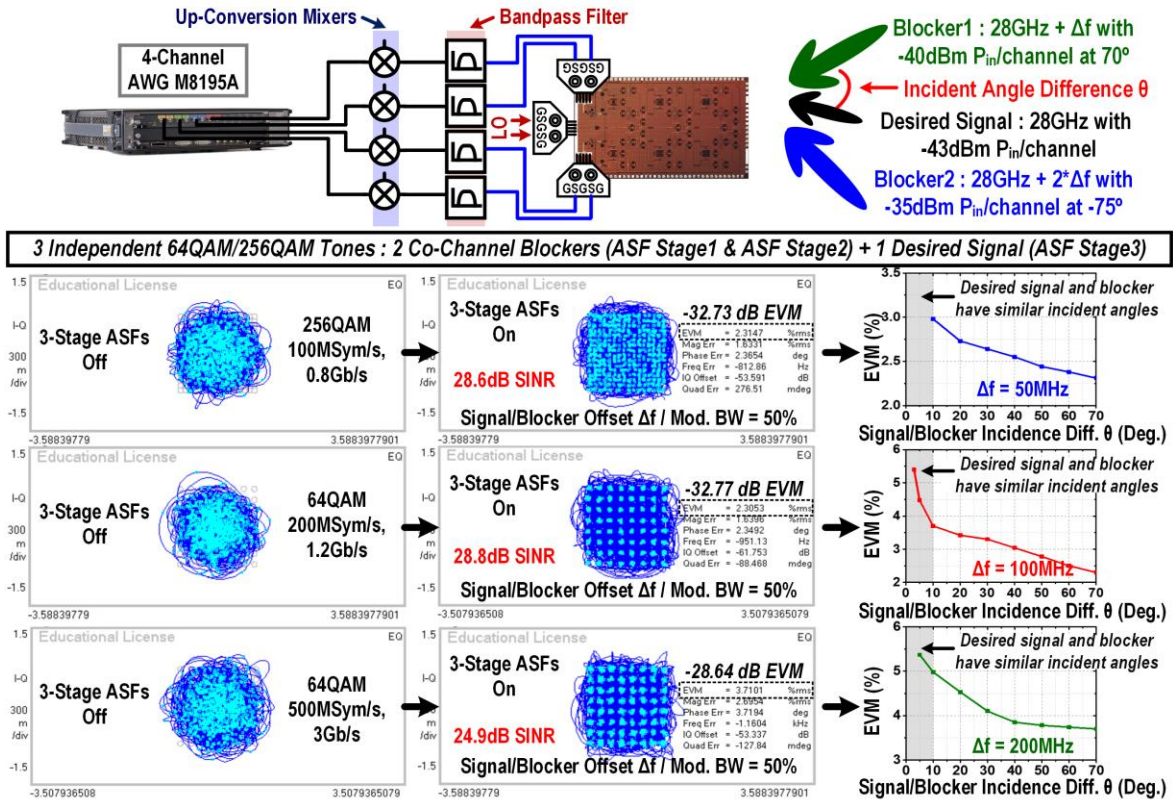


Fig. 5. The RX with 3-stage array-based ASFs demonstrate autonomous rejection of multiple (2-3) blockers and desired signal beamforming (as case 3 in Fig. 2), when the blockers and desired signal have the same broadband modulation scheme and data-rate, showing successful demodulation of the desired signal after autonomous spatial suppression of multi-blockers by the 3-stage ASFs.

	Mm-Wave 5G Beamforming RX Array					Spatial Notch RX Array
	This Work	W. Roh Commun. Mag.'14	B. Sadhu JSSCC'17	J. Dunworth ISSCC'18	M. Huang ISSCC'18	L. Zhang JSSCC'17
Functionality	MIMO Array-based ASF	MIMO	MISO	MISO	MIMO SSA	MIMO ASF
Technology	45nm CMOS SOI	NR	130nm SiGe BiCMOS	28nm LPRF CMOS	130nm SiGe BiCMOS	65nm CMOS
Frequency (GHz)	27 – 41	28	28	25 – 30.5	22 – 30	0.1 – 3.1
# of Inputs / Outputs	4 / 4	32 / NR	32 / 1	12 / 1	8 / 2	4 / 4
Conversion Gain	36dB / element	NR	34dB / element	34dB / 4 element	33dB / element	43dB / element
NF <sub>dB,eq</sub> (dB)	4.3 – 6.3	NR	6	4.4 – 4.8	4.2 – 6.3	3.4 – 5.8
Beamforming	4-Element High-Order Array-based Closed Loop ASFs	Open Loop + Backend DSP	Open Loop + Backend DSP	Open Loop + Backend DSP	2-Element Closed Loop with SSA Front-End BFs	Open Loop + Backend DSP
Blocker Rejection	4-Element High-Order Array-based Closed Loop ASFs	No	No	No	2-Element Closed Loop with SSA Front-End BFs	Open Loop + Backend DSP
Spatial Order of Notch	4-element (Scalable)	No	No	No	2-element (Fixed)	4-element (Scalable)
Spatial Suppression 1- / 2- / 3 Notches (dB)	62 / 50 / 51	No	No	No	54 / 41 / No	56 / 48.6 / 41.8
>10dB Cancellation						
Spatial Notch Width (Deg.)	27° – 32°	No	No	No	48° – 58°	~30°
Spatial Selectivity						
Blocker Modulation Scheme	3Gb/s 64-QAM and 0.8Gb/s 256-QAM	No	No	No	3Gb/s 64-QAM and 0.8Gb/s 256-QAM	CW
Blocker/Signal Frequency Offset (Δf) / Modulation BW	< 50%	No	No	No	< 100%	>400%
# of Modulated Blockers Concurrently Received	1 or 2 or 3 (Scalable)	No	No	No	1 (Fixed)	2
Desired Signal Modulation Scheme	3Gb/s 64-QAM and 0.8Gb/s 256-QAM	2.1Gb/s 16QAM	NR	2.4Gb/s 64QAM	3Gb/s 64-QAM and 0.8Gb/s 256-QAM	2Mb/s QPSK
Signal EVM after Blocker Suppression	1.2Gb/s 64-QAM : 2.3% <sup>1</sup> 3Gb/s 64-QAM : 3.7% <sup>1</sup> 0.8Gb/s 256-QAM : 2.3% <sup>1</sup>	No	No	No	0.6Gb/s 64-QAM : 3.2% <sup>2</sup> 3Gb/s 64-QAM : 4.7% <sup>2</sup> 0.8Gb/s 256-QAM : 2.7% <sup>2</sup>	2Mb/s QPSK: 20.5% <sup>3</sup>
Response Time	1.47 μs	45 ms	NR	NR	< 1 μs	NR
Power Consumption / RX Element (mW)	70-85 : LNA/Mixer + 3 ASFs 55-65 : LNA/Mixer + 2 ASFs	NR	206	42.5	70	28.5 – 36.75
Area (mm <sup>2</sup> )	23.4	NR	165.9 <sup>4</sup>	29 <sup>4</sup>	21.6	2.25

NR: Not reported.

The modulation test is based on

<sup>1</sup> 2 independent blockers + 1 desired signal and Δf / Modulation BW = 50%,

<sup>2</sup> 1 blocker + 1 desired signal and Δf / Modulation BW = 50%,

<sup>3</sup> 2 independent blockers + 1 desired signal and Δf / Modulation BW = 400%.

<sup>4</sup> The area includes its transmitter design.

Fig. 6. Comparison with the state-of-the-art RX array for mm-Wave 5G beamforming or spatial notching

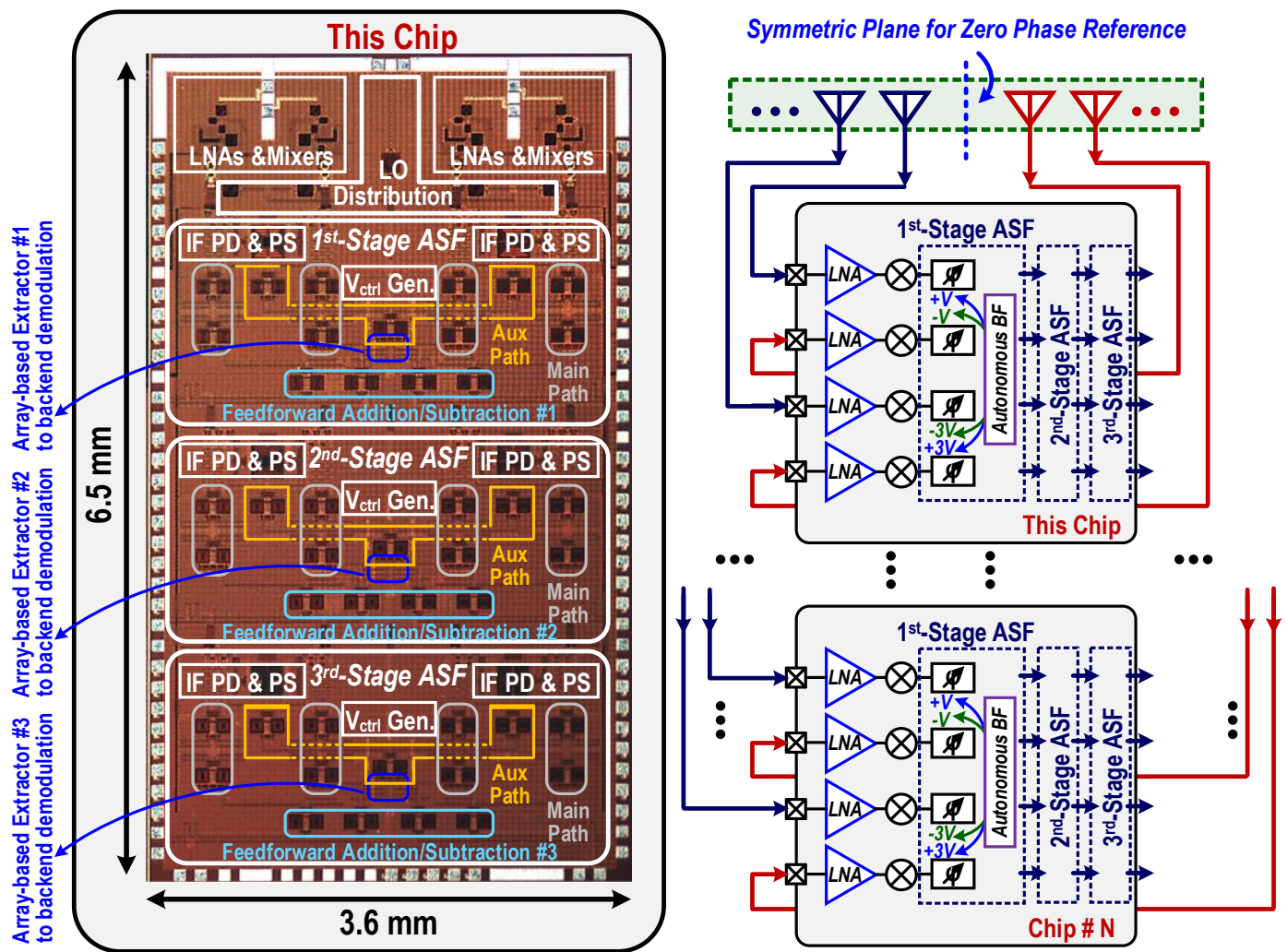


Fig. 7. Chip micrograph and its use in a large-scale MIMO system.