Sigma-Delta Arrays for Rejecting Amplifier Noise, Distortion, and Quantization Noise

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Introduction

Multiple narrow beams formed by large-scale antenna arrays are fundamental for 5G wireless networks if they are to achieve exponentially larger capacities and data rates than the current state-of-the-art. We investigate fundamentally new circuits based on multi-dimensional signal processing for simultaneously forming many steerable mm-wave (mmW) beams, each with several GHz of bandwidth. The proposed system replaces the N independent LNAs and ADCs of a conventional array with a spatially-oversampled array interfaced to a single energy-efficient multi-dimensional (N-port) LNA and ADC. A hybrid approach based on a combination of analog sub-arrays and low complexity digital systems is then developed to simultaneously form multiple narrow mmW beams [1, 2].

Concept

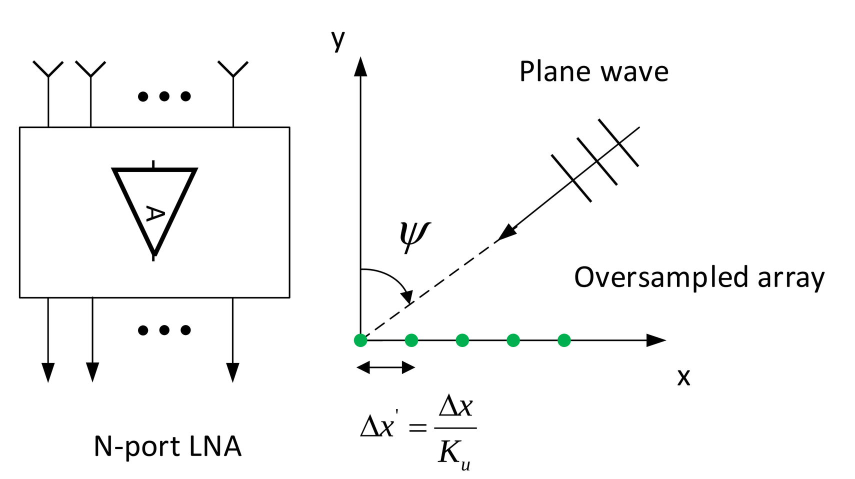
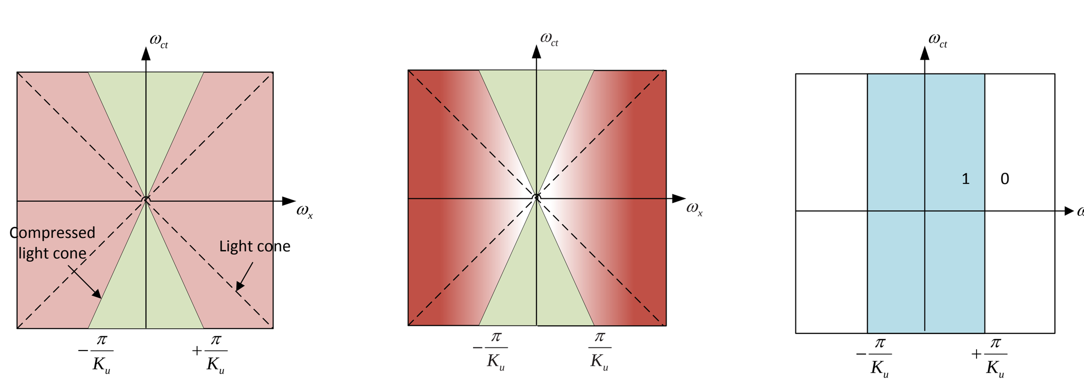
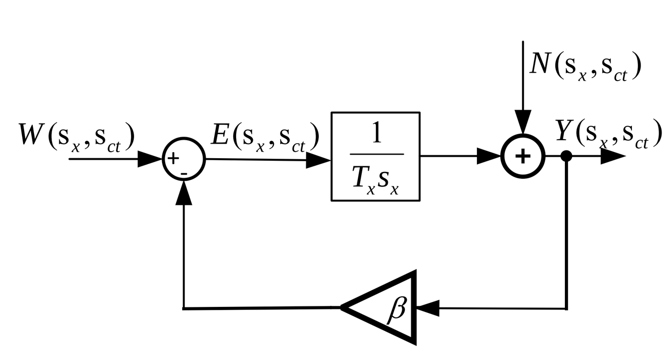


Figure 1: (a) A K_u-times spatially-oversampled array with an antenna spacing of $\lambda/(2K_u)$; (b) the ROS of received waves (green) is a compressed light cone that overlaps receiver noise and distortion (red); (c) spatial Δ-Σ noise-shaping removes noise from the ROS; (d) a space–time low-pass filter removes shaped noise from the outputs.





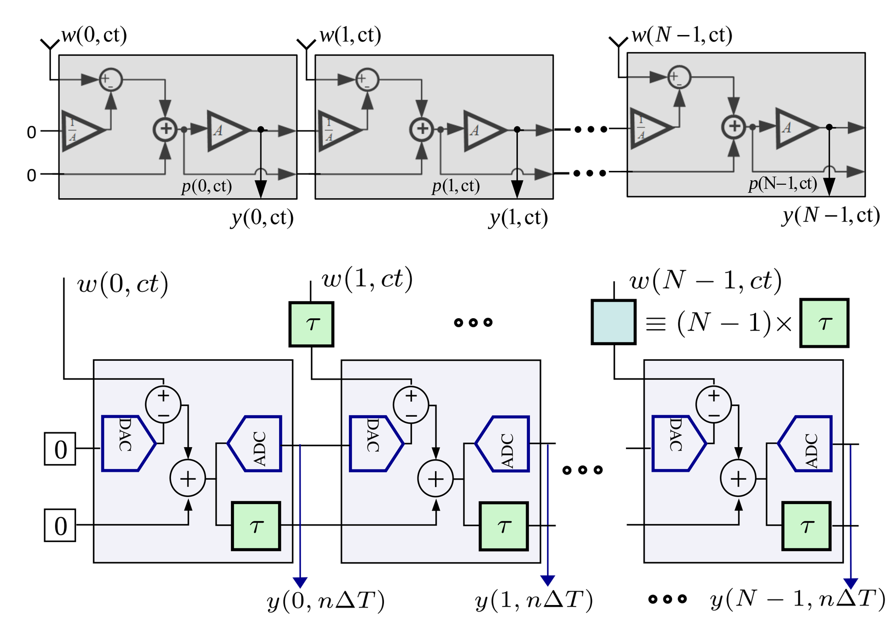
$$Y(s_x,s_{ct}) = \frac{W(s_x,s_{ct})}{\beta+T_x s_x} + N(s_x,s_{ct})\frac{T_x s_x}{\beta+T_x s_x}.$$

Figure 2: Continuous frequency domain representation of a 2-D $\Delta - \Sigma$ modulator.

N-Port LNAs and ADCs

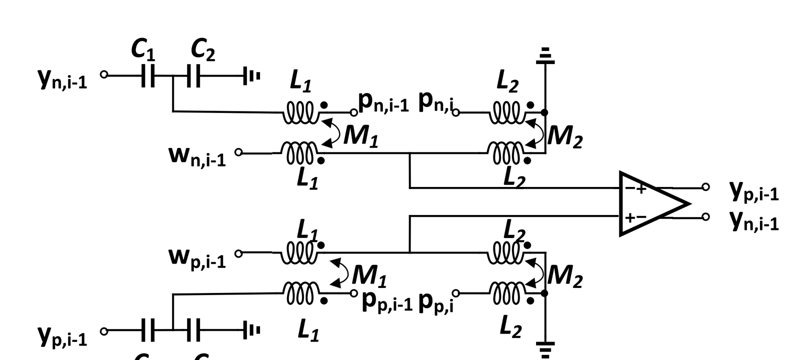
State-of-the-art receivers for N-element antenna arrays simply replicate N high-sensitivity receivers at each element to create an N-element aperture. This approach is not optimal because it ignores the relationships that must exist between signals, noise, interference, and non-linear distortion across the elements of the array. In particular, Special Relativity defines a region of causality (the light cone) outside which no propagating waves can exist. We use this fact to improve the performance of array processors. Specifically, we develop spatially-oversampled arrays to spectrally shape the noise and distortion of LNAs and ADCs such that they do not overlap with the light cone of the input signals, i.e., electromagnetic waves. We call this approach spatio-temporal noise shaping.

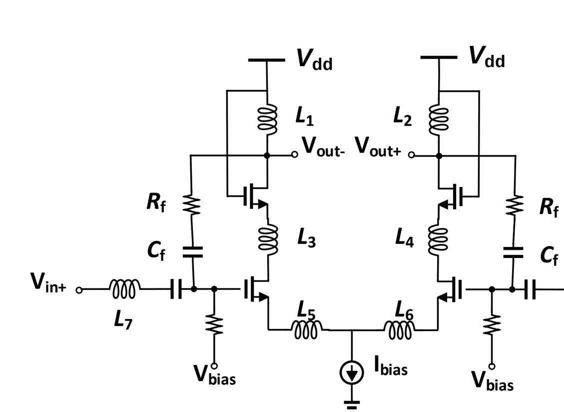
Circuit Implementation



$$Y(z_x,s_{ct}) = \frac{z_x^{-1}}{\beta}W(z_x,s_{ct}) + (1-z_x^{-1})N(z_x,s_{ct}).$$

Figure 3: N-port LNA (top) and ADC (bottom) architectures with spatially-interconnected spatial integration and amplification modules (SIAMs).

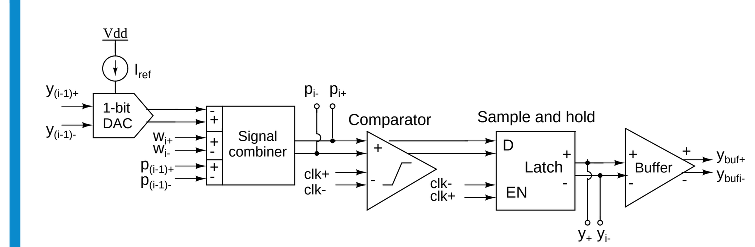




Parameter	Value
V_{dd}	1.8 V
I_{bias}	0.9 mA
$L_{1,2}$	4.1 nH
$L_{3,4}$	0.15 nH
$L_{5,6}$	0.2 nH
$L_{7,8}$	0.2 nH
R_f	1.45 KΩ
C_f	2 pF

Figure 4: (a) SIAM used in the proposed N-port LNA. (b) Fully-differential amplifier used to realize each channel of the LNA in 65nm CMOS.

Circuit Implementation



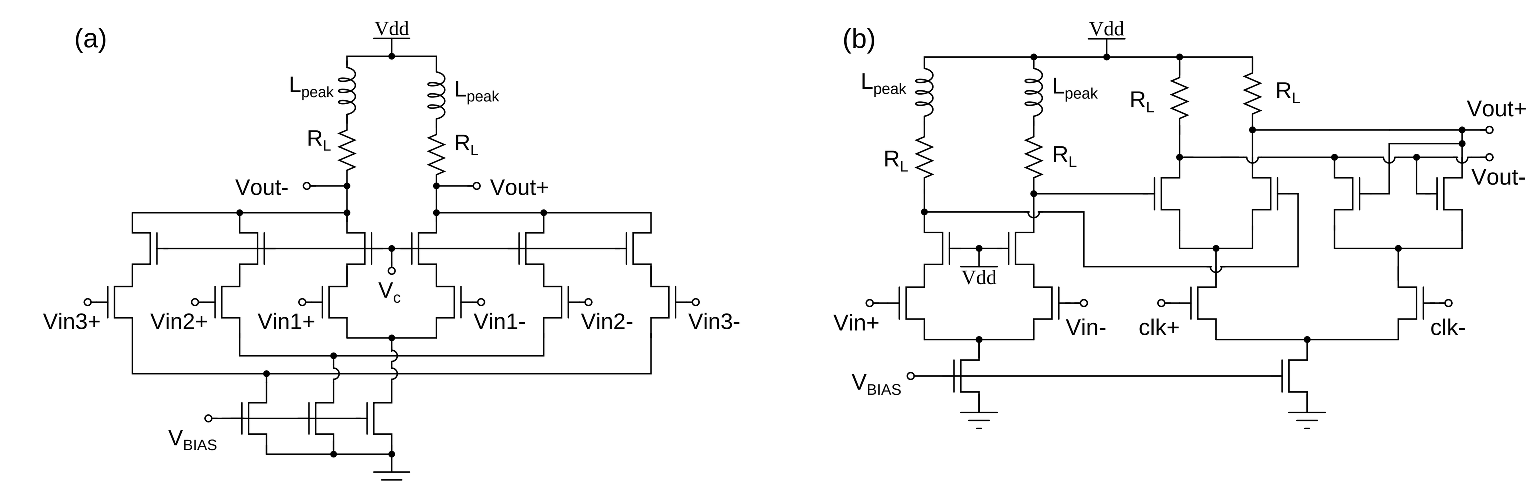


Figure 5: SIAM used in the N-port ADC. Right: schematic of the (a) signal combiner and (b) comparator used in the SIAM.

Results

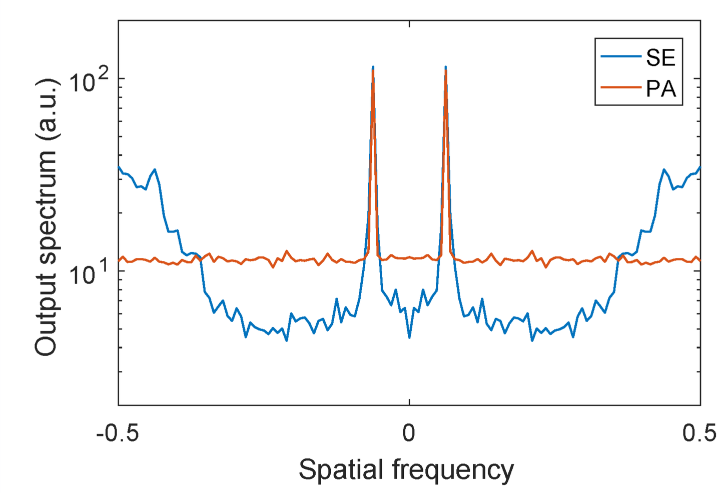


Figure 6: Spatial output spectra with ("SE") and without ("PA") noise shaping. Input: a broadband plane wave incident at 30°.

Table 1: NF improvement (dB) for various oversampling factors and array sizes. The individual amplifier has $NF = 5.5$dB.

N \ K_u	2	4	8
65	0.73	3.16	3.19
129	0.70	3.46	3.38

Process: UMC 65nm RF-CMOS

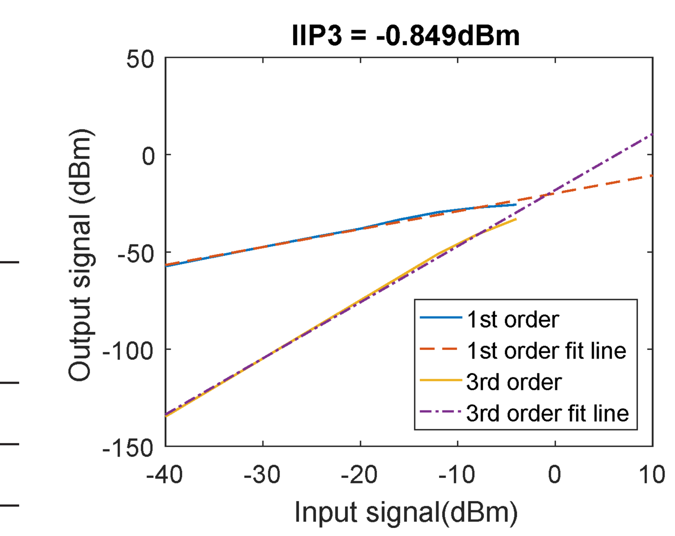


Figure 7: Simulated IIP3 of a 16-port LNA; it is 3.7dB higher than without noise-shaping.

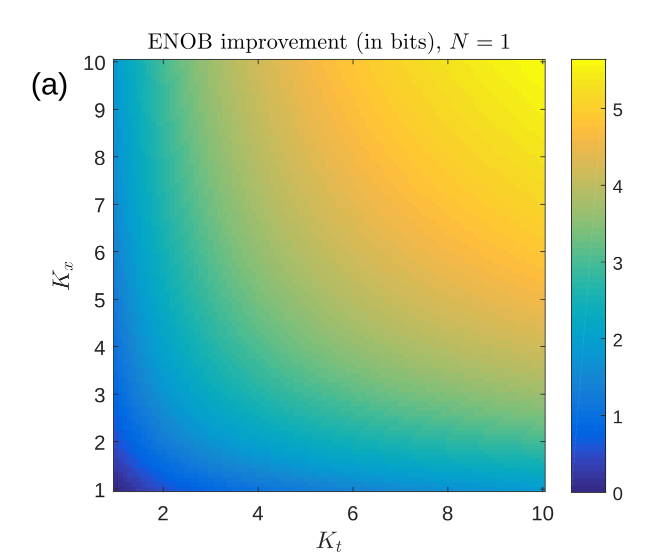


Figure 8: Normalized quantization noise improvement (in bits) due to time-space over-sampling.

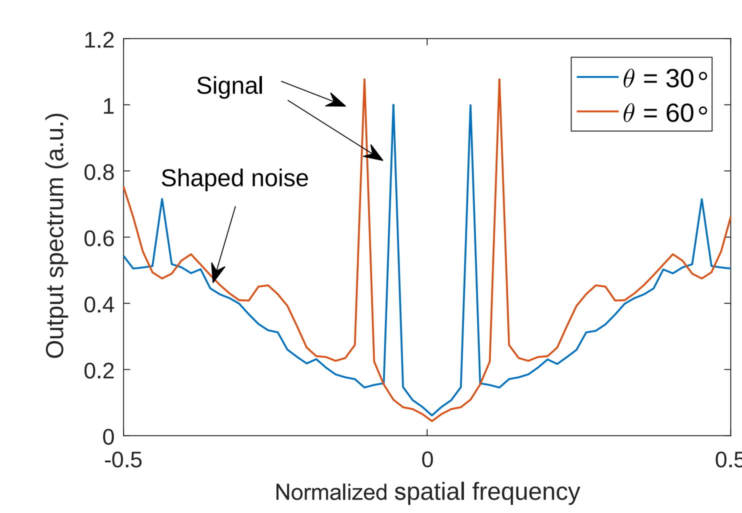


Figure 9: Spatial output spectra of a noise-shaped 64-port ADC for 10% full-scale inputs at two different arrival angles.

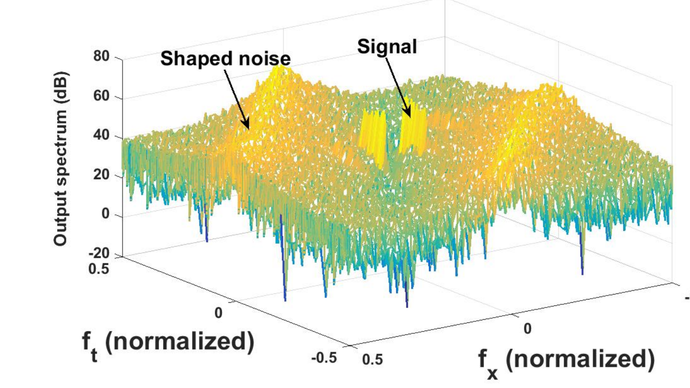


Figure 10: Noise-shaped 2-D output spectrum of a 64-port ADC for $K_x = 4$, $K_t = 10$, and an arrival angle of 30°.

Conclusion

We have introduced two-dimensional Δ-Σ noise-shaping methods for N-port LNAs and ADCs. These methods use spatial integration and oversampled antenna arrays to enable improvements in the noise figure, linearity, and resolution of mmW beamforming receivers. Theoretical results have been verified with transistor-level simulations in 65nm CMOS.

References

[1] A. Nikoofard, A. Madanayake, S. Handagala, L. Belostotski, and S. Mandal. Low-complexity N-port ADCs using 2-D Δ-Σ Noise-Shaping in N-Element Array Receivers. In *submitted to ISCAS*, 2017.

[2] Y. Wang, A. Madanayake, S. Handagala, L. Belostotski, and S. Mandal. Antenna Array N-port LNAs using 2-D Spatio-Temporal Δ-Σ Noise-Shaping. In *submitted to ISCAS*, 2017.

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