N-port LNAs for mmW Array Processors using 2-D Spatio-Temporal $\Delta - \Sigma$ Noise-Shaping

Yingying Wang*, Suranga Handagala†, Arjuna Madanayake†, Leonid Belostotski‡, Soumyajit Mandal*

*Electrical Engineering and Computer Science Department, Case Western Reserve University, Cleveland, Ohio 44106

†Electrical and Computer Engineering Department, University of Akron, Akron, Ohio 44325

‡Electrical and Computer Engineering Department, University of Calgary, Calgary, AB, Canada

Email: yxw788@case.edu, {smh205, arjuna}@uakron.edu, lbelosto@ucalgary.ca, sxm833@case.edu

***Abstract*—A novel delta-sigma ($\Delta - \Sigma$) modulation method is proposed for extending noise-shaping to two dimensions: space and time. The goal is to improve the noise figure (NF) and linearity of low noise amplifiers (LNAs) for use in microwave and mm-wave antenna arrays. We show that a spatially-oversampled antenna array coupled to an N-port noise-shaped LNA can diminish in-band additive noise and distortion by shaping the multi-dimensional spectrum of these unwanted components towards higher spatial frequencies that are outside the space-time region of support (ROS) of all possible propagating electromagnetic waves. The shaped noise is then removed by spatial filtering with a linear beamformer. This paper analyzes the concept and presents simulation results for a 33, 65, and 129-port noise-shaped LNAs in 65nm CMOS operating at 4GHz.**

I. Introduction

Milimeter-wave (mmW) communications promises unprecedented advantages for the wireless industry, while also generating many unanswered scientific questions and engineering challenges. The use of antenna arrays to form multiple sharp and steerable beams is essential for taking advantage of real-world mmW channels. State-of-the-art transceivers for N-element arrays replicate N high sensitivity receivers (or modular transmitters) at each element in the array in order to create an N-element aperture. This approach is not optimal because it does not consider the relationships between signals, noise, interference, and non-linear distortion across the array [1]. In particular, Special Relativity defines a region of causality (the light cone) outside which no propagating waves can exist. This fact has the potential to significantly improve the performance of array processors. In particular, spatially-oversampled arrays can be used to spectrally shape both the noise and non-linear distortion of amplifiers, mixers, and data converters such that they do not overlap with the light cone of the input signals, i.e., the region of support (ROS) of propagating electromagnetic (EM) waves [2]. This novel approach is known as spatio-temporal noise shaping. It is conceptually similar to $\Delta - \Sigma$ modulation, but operates in the 2-D spatio-temporal domain. The shaped noise/distortion can be later directionally low-pass filtered out by using a linear beamformer (see Fig. 1). This approach enables i) lower thermal noise and higher linearity in amplifiers, and ii) higher resolution in data converters. This paper focuses on applications to LNAs [3]. At a conceptual level, spatio-temporal noise shaping replaces the N independent LNAs of a conventional array with a multi-dimensional (N-port) amplifier that has improved NF and linearity. The resulting mmW array processors are shown in Fig. 2. They consist of spatially-oversampled antenna arrays, noise-shaped N-port front-ends, analog multi-beam sub-arrays, low-complexity digital beamformers, and efficient medium access algorithms.

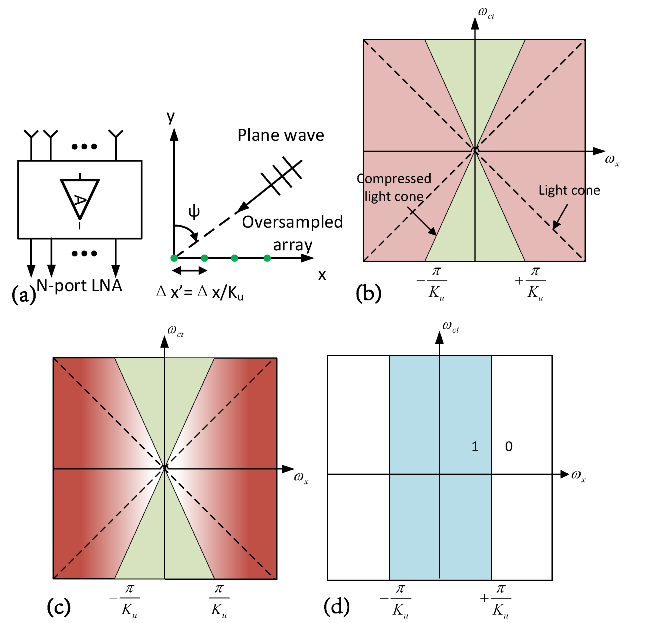


Fig. 1. (a) A K_u-times spatially-oversampled antenna array, i.e., with an antenna spacing of $\lambda/(2K_u)$ where λ is the EM wavelength; (b) the ROS of waves received by the array (green), which consists of a narrow light cone that overlaps with receiver noise and distortion (red); (c) spatial Δ-Σ noise-shaping ensures that noise lies outside the ROS of the received signals; (d) a space–time low-pass filter removes shaped noise from the outputs.

II. N-port LNA Design

A. Noise shaping concept

$\Delta - \Sigma$ modulation is a well-known signal processing method in which desirable signals are oversampled in order to spectrally separate them from unwanted signals, such as noise and distortion [4]–[6]; this process is known as noise shaping. We apply this concept to shape the noise and nonlinear distortion of LNAs to lie outside the ROS of array signals [2]. The resulting N-port LNAs amplify antenna signals in

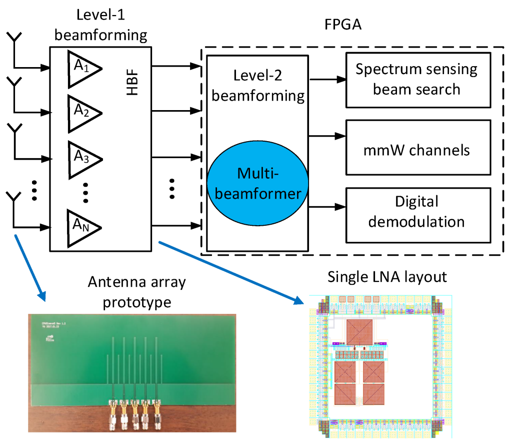


Fig. 2. Overview of the proposed multi-beam mmW array receivers based on noise-shaped N-port LNAs. The spatially-oversampled antenna array ($K_u = 4$) shown uses planar monopoles and has been recently fabricated and tested.

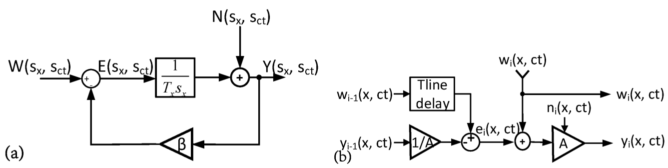


Fig. 3. (a) Continuous frequency-domain representation of the proposed 2-D first-order $\Delta - \Sigma$ modulator; (b) the spatial integration and amplification module (SIAM) used to implement it.

a multi-dimensional spatio-temporal operation in which the internal noise and distortion are shaped to be non-overlapping in the 2-D (space, time) frequency domain. These unwanted components can then be removed by spatial low-pass filtering (beamforming), so relatively low-performance building blocks (high NF, low linearity) may be used to realize N-port LNAs with low NF and high linearity.

Spatially oversampled arrays use an inter-element spacing of $\Delta x = \lambda_{min}/(2K_u)$, where λ_{min} is the minimum EM wavelength of interest and $K_u \geq 1$ is the oversampling ratio. Plane waves incident at an angle ψ on such an array have a normalized spatial frequency $\omega_x = \pi \sin(\psi)/K_u$. Thus, the allowable range of spatial frequencies $\pm\pi/K_u$ decreases as K_u increases (see Fig. 1(c)). The basis of the proposed approach is to process such spectrally-compressed signals using 2-D spatio-temporal $\Delta - \Sigma$ modulators. A first-order version in the continuous Laplace domain is shown in Fig. 3(a). Let $w(x, ct) \leftrightarrow W(s_x, s_{ct})$ be the input signal and $n(x, ct) \leftrightarrow N(s_x, s_{ct})$ be the LNA noise, which will together produce the corresponding 2-D spatio-temporal output signal $y(x, ct) \leftrightarrow Y(s_x, s_{ct})$. The parameter $\beta = 1/A$ where A is the voltage gain of a single LNA channel. The amplified and noisy output signal $Y(s_x, s_{ct})$ is attenuated and subtracted from the input signal to produce the error signal $e(x, ct) \leftrightarrow E(s_x, s_{ct})$, which will then be integrated by the spatial integrator $I_x(s_x)$, where T_x is the "spatial time constant" of the network.

Mathematically, the error signals can be expressed in the Laplace domain by analyzing the signal flow graph (SFG) shown in Fig. 3(a), resulting in $E(s_x, s_{ct}) = W(s_x, s_{ct}) - \beta Y(s_x, s_{ct})$. The output of the modulator with added noise is

$$Y(s_x, s_{ct}) = E(s_x, s_{ct}) I_x(s_x) + N(s_x, s_{ct}), \qquad (1)$$

which can be expressed as

$$Y(s_x, s_{ct}) = \frac{W(s_x, s_{ct})}{\beta + T_x s_x} + N(s_x, s_{ct}) \frac{T_x s_x}{\beta + T_x s_x}. \qquad (2)$$

Hence the signal is low-pass filtered while the noise is high-pass filtered, thus reducing the overlap between them. However, the system described in (2) is unrealizable because in practice antenna elements have to be placed in a spatially discrete manner, i.e., with spacing Δx. This necessitates transformations that allow spatial discretization of the array. The bilinear transform operator $s_x = \left(1 - z_x^{-1}\right)/\left(1 + z_x^{-1}\right)$ when used in spatial integration results in a delay-free loop which makes the algorithm uncomputable. Alternatively, it can be shown that a modified lossless discrete integrator (LDI) [3] with the transformation $T_x s_x = \beta\left(1 - z_x^{-1}\right)/z_x^{-1}$ can overcome delay-free loops, which makes it a viable candidate for spatially-discrete realizations [3]. The resulting spatially-discretized system is given by

$$Y(z_x, s_{ct}) = \frac{1}{\beta} z_x^{-1} W(z_x, s_{ct}) + (1 - z_x^{-1}) N(z_x, s_{ct}). \qquad (3)$$

The input signal is amplified by $A = 1/\beta$ and also undergoes a spatial shift, while the noise gets shaped by the first-order spatial high-pass filter $\left(1 - z_x^{-1}\right)$. Practical N-port LNA array architectures can be realized with this topology.

B. N-port LNA Array Structure

The transfer functions given in (3) can be represented in terms of a building block that we term the spatial integration and amplification module (SIAM). The proposed SIAM (see Fig. 3(b)) has been modified from that proposed in [3] to enable implementation with passive elements, which is critical for minimizing noise and nonlinearity. It consists of an LNA with gain A and a passive spatial integration network at its input. The latter subtracts an attenuated version of the output of the previous LNA (denoted by y_{i-1}/A) from the signal generated by the previous antenna (denoted by w_{i-1}) to create the error signal e_i. The group delay of the LNA is compensated by delaying w_{i-1} prior to subtraction. As a result, $e_i = w_{i-1} - y_{i-1}/A \approx -n_{i-1}/A$, where n_{i-1} denotes the noise and distortion generated by the previous LNA. It is then added to the signal generated by the local antenna (denoted by w_i) and fed into the LNA, resulting in the following output:

$$y_i \approx A w_i + (n_i - n_{i-1}). \qquad (4)$$

Thus, the input signal is amplified while the LNA noise is spatially high-pass filtered, as desired. Feedforward interconnection of the proposed SIAMs results a N-input, N-output system, as shown in Fig. 4(a). This structure achieves 2-D $\Delta - \Sigma$ noise shaping while being amenable to integrated circuit realizations at microwave or mm-wave frequencies. Its

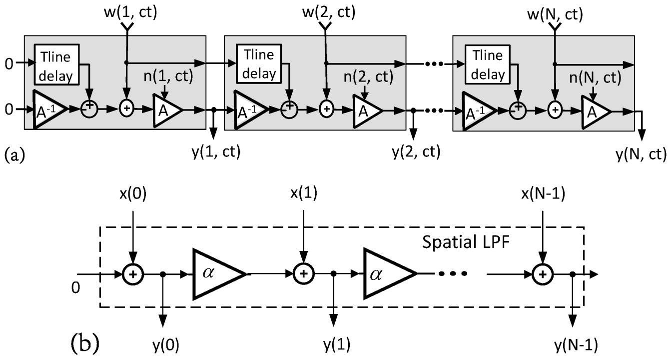
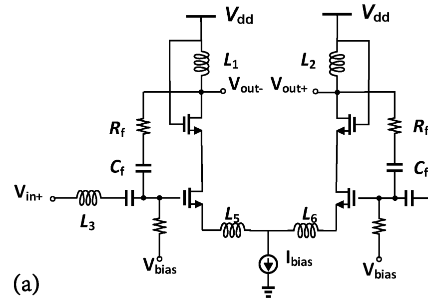


Fig. 4. (a) N-port LNA architecture based on spatially-interconnected SIAMs; (b) Block diagram of a first-order spatial low-pass filter.



Parameter	Value
V_{dd}	1.8 V
I_{bias}	2.5 mA
$L_{1,2}$	8.5 nH
$L_{3,4}$	8.9 nH
$L_{5,6}$	0.2 nH
R_f	1.8 KΩ
C_f	0.5 pF

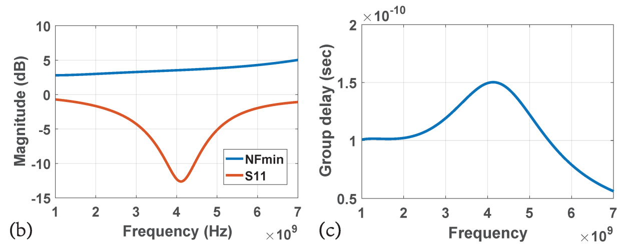
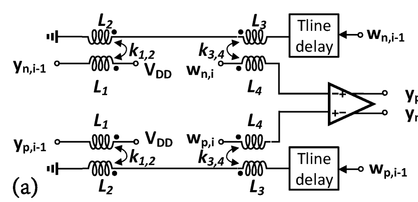


Fig. 5. (a) Fully-differential LNA and its simulated performance: (b) return loss ($|S_{11}|$) and minimum noise figure (NF$_{min}$); (c) group delay.



Parameter	Value
L_1	4 nH
L_2	0.38 nH
L_3	1.35 nH
L_4	2 nH
$k_{1,2}$, $k_{3,4}$	0.9
Q	12.5

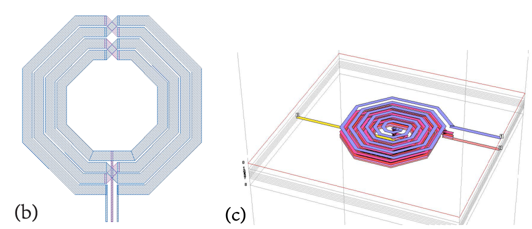


Fig. 6. (a) Schematic of the SIAM for the proposed N-port LNA. (b) Custom octagonal center-tapped inductor (2-D view). (c) Custom transformer based on stacking inductors similar to that in (b) (3-D view).

outputs are ultimately spatially low-pass filtered to remove the shaped noise and distortion. Fig. 4(b) shows a suitable first-order spatial low-pass filter. It uses signal averaging, defined by $y(n_x) = x(n_x) + \alpha y(n_x - 1)$ where $|\alpha| < 1$, to realize the low-pass transfer function $Y(z_x)/X(z_x) = 1/\left(1 - \alpha z_x^{-1}\right)$.

It is important to note that improvements in the NF and linearity of N-port LNA require the spatial integrator, i.e., the attenuator, time delay, and summing junctions within each SIAM (see Fig. 3(b)), to be realized using noiseless and linear components. As a result, we propose a completely passive network that uses on-chip transformers and an LC delay line to realize the spatial integrator (described in the next section). Losses in this network (e.g. due to finite Q of the transformer windings) add noise that is not filtered by the $\Delta - \Sigma$ operation and thus degrade the NF. Hence the finite Q of on-chip passives will limit the lowest achievable system NF.

III. Simulation Results

A prototype microwave LNA has been designed in the UMC 65nm RF-CMOS process to serve as the amplifier within each SIAM (see Fig. 5(a)). An inductively-degenerated design with resistive shunt feedback is adopted to achieve wide bandwidth, good input impedance matching (to 50Ω), and good noise performance. It is also fully-differential to minimize even-order distortion and improve common-mode and power supply rejections, and the gain stages are cascoded to improve gain and isolation [7]–[9]. The design was realized using RF macromodels provided by the foundry (which include layout parasitics) and simulated with the Cadence design suite. Simulation results (see Fig. 5(b)) show gain and NF of 9.5dB and 3.5dB, respectively at the designed center frequency of 4GHz, while the peak group delay is 150ps (see Fig. 5(c)). The power consumption was 3.2mW.

The schematic of the SIAM used to realize the N-port LNA is shown in Fig. 6(a). It uses two custom on-chip transformers: The first realizes the passive voltage divider while the second acts as the signal combiner for spatial integration. An ideal time delay of 150ps is used for now to eliminate the finite group delay effects of each LNA block; in the final design, it will be implemented using lumped on-chip LC sections. The resulting circuit was simulated by combining the foundry-provided transistor, capacitor, and resistor macromodels with custom inductor models derived from finite-element EM simulations. Specifically, an automated closed-loop method was used to design custom on-chip inductors and transformers with specified properties and performance constraints [10]. Synthesis results are shown in Figs. 6(b) and (c).

SIAMs were interconnected as shown in Fig. 4 to realize N-port LNA prototypes with $N = 33$, 65, and 129 channels. The circuits were simulated using Cadence and the outputs post-processed to analyze the resulting improvements in NF and linearity. Transient noise simulations with no inputs applied were first used to evaluate noise shaping performance. Fig. 7(a) shows the simulated noise-only output spatial spectrum of the 129-port interconnected LNA array (labeled as "SE") and

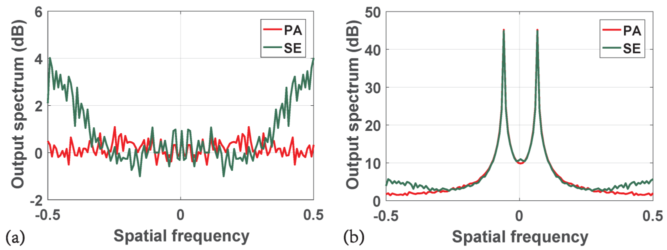


Fig. 7. Simulated spatial output spectra of the prototype 129-port LNA with and without noise shaping (denoted by "SE" and "PA", respectively). (a) No input signals were applied (i.e., noise only). (b) A broadband input signal corresponding to a plane wave incident at 30° was applied to both circuits.

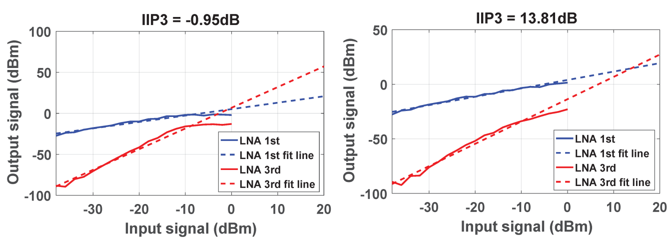


Fig. 8. Simulated IIP3 of (a) a single LNA and (b) an 16-port LNA.

a 129-port non-interconnected LNA array (labeled as "PA"). Wideband input signals were then fed into the circuit to evaluate the output signal-to-noise ratio (SNR); the time delays between them were set to simulate plane waves incident on the array at various angles. Fig. 7(b) shows the spatial output spectrum for $\psi = 30°$, which clearly shows the effects of noise shaping in the ω_x domain compared to the results from the non-noise-shaped (parallel) structure with the same number of channels. The $SNR_{\Delta\Sigma}$ is 30.43 dB while the $SNR_{\|}$ is 30.01 dB, corresponding to a NF improvement of 0.42 dB for $K_u = 4$. Thus, the N-port LNA has an effective noise figure of 3.0dB, which is lower than that of the individual LNA.

Simulated NF improvements for different array sizes and oversampling factors are summarized in Table I. The table shows results for $N = 33$, 65 and 129 antenna elements, and spatial oversampling factors $K_u = 2$ and 4. The simulation results suggest that a larger value of N has a trade-off influence on NF improvements since it requires a larger number of noisy spatial integration modules.

The proposed N-port LNA can also be used for suppressing non-linear distortion generated by the individual amplifiers. This results in increased linearity that improves both blocker- and interference- rejection in wireless communication systems. Simulations show that the proposed N-port LNA has ~15dB higher IIP3 than the individual amplifier (see Fig. 8(a), (b)). In other words, by creating a N-port noise-shaped LNA, we can make highly non-linear LNA units collectively behave as a high linear LNA, while each of the individual LNA block has much worse linearity that the N-port LNA as a whole. Such performance gain would be impossible without the proposed approach, which shapes unwanted distortion out of the ROS of signals of interest. Hence the new degrees of freedom introduced by multi-dimensional processing allow us to use spatial filtering to remove distortion.

TABLE I
NF IMPROVEMENTS FOR VARIOUS COMBINATIONS OF N AND K_u

K_u \ N	33	65	129
2	0.86	0.52	0.80
4	0.60	0.33	0.42

IV. Conclusion

We have described an array processing method derived from $\Delta - \Sigma$ data converters that significantly reduces the additive noise and distortion of LNAs present within the frequency-domain ROS of propagating EM waves. This improved performance comes at the cost of a spatially-oversampled and highly-dense antenna array that generates a redundant set of signals that can be processed using the proposed 2-D noise-shaping method. The resultant noise and distortion spectra are shaped towards higher out-of-band spatial frequencies, resulting in improved SNR and signal-to-distortion ratio (SDR) at the output. Circuit simulations in a 65nm CMOS process with various array sizes and oversampling factors show significant improvement in both noise figure and linearity. In future work, the proposed LNAs will be tested together with oversampled arrays of planar monopole antennas.

Acknowledgment

This project is partly sponsored by the National Science Foundation under grants CCF-1525162 and CNS-1629903.

References

[1] N. Liyanage, L. Bruton, and P. Agathoklis, "On the attenuation of interference and mutual coupling in antenna arrays using 3D space-time filters," in *2009 IEEE Pacific Rim Conference on Communications, Computers and Signal Processing*, Aug 2009, pp. 146–151.
[2] S. M. Handagala, "Special relativistic array multi-port circuits with spacetime noise-shaping," Master's thesis, University of Akron, 2016.
[3] S. Handagala, A. Madanayake, L. Belostotski, and L. T. Bruton, "δ-σ noise shaping in 2D space-time for uniform linear aperture array receivers," in *IEEE Moratuwa Engineering Research Conference*, 2016.
[4] B. E. Boser and B. A. Wooley, "The design of sigma-delta modulation analog-to-digital converters," *IEEE Journal of Solid-State Circuits*, vol. 23, no. 6, pp. 1298–1308, Dec 1988.
[5] P. M. Aziz, H. V. Sorensen, and J. vn der Spiegel, "An overview of sigma-delta converters," *IEEE Signal Processing Magazine*, vol. 13, no. 1, pp. 61–84, Jan 1996.
[6] R. Corey and A. Singer, "Spatial sigma-delta signal acquisition for wideband beamforming arrays," in *20th International ITG Workshop on Smart Antennas (WSA)*, March 2016.
[7] C. Garuda, X. Cui, P. Lin, S. Doo, P. Zhang, and M. Ismail, "A 3-5 GHz fully differential CMOS LNA with dual-gain mode for wireless UWB applications," in *Midwest Symp. on Circuits & Systems*, August 2005.
[8] C.-F. Liao and S.-I. Liu, "A broadband noise-canceling CMOS LNA for 3.1-10.6 GHz UWB receivers," *IEEE Journal of Solid-State Circuits*, vol. 42, no. 2, pp. 329–339, 2007.
[9] B. Razavi, "Design of millimeter-wave CMOS radios: A tutorial," *IEEE Transactions on Circuits and Systems I: Regular Papers*, vol. 56, no. 1, pp. 4–16, Jan 2009.
[10] Y. Wang and S. Mandal, "Automated design and optimization of integrated inductors and transformers," in *National Aerospace & Electronics Conference & Ohio Innovation Summit (NAECON-OIS)*, July 2016.