Frequency Independent Millimeter-Wave Beamformer via Cross-Mixing

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***Abstract*— The need for high data rate communications has led to the exploration of the millimeter-wave (mm-wave) spectrum. But, significant losses at these frequencies imply high gain phased array antennas. Concurrently, low cost fabrication and beamforming across wide bandwidths is a foundational challenge. In this paper, we present a novel hybrid beamforming design using the concept of element-to-element mixing for the signal delay compensation. Notably, our novel architecture eliminates bulky phase shifters and local oscillators. Further, our system is combined with a baseband on-site coding technique for further hardware and cost reduction. Studies show that our design offers unparalleled flexibility in signal reception and promises 95% reduction in cost and power consumption.**

Keywords— millimeter-wave, beamforming, self-mixing array, on-site code division multiplexing

I. INTRODUCTION

Future communications, navigation, and networking require much higher data rates, multiple beams, and higher transmit/receive gain. These capabilities will address multi-functionality and security for terrestrial, satellite, and shipboard communications. The enabling infrastructures are radio frequency (RF) front-ends that are wideband, adaptable, very small in size, light-weight, require low power and are of low cost (SWAP-C). As such, there is a growing interest for reduced size apertures and platforms to enable mobility, portability, and inconspicuous integration on small platforms.

Wideband antenna arrays enable continuous operations across large bandwidths of the RF spectrum. As such, multiple radios can be integrated into a single multifunctional platform. Nevertheless, the sub-6GHz spectrum suffers from congestion and limitations on available bandwidth. This provides an impetus for a more aggressive exploration of the relatively unused bandwidth available in the millimeter-wave (mm-wave) regime (30–300 GHz). To compensate for the high losses at these frequencies, high gain beamforming antenna array systems are required. However, traditional analog and digital beamformers are narrowband, power-hungry, and SWAP-inefficient [1-3].

To overcome these issues, in this paper, a frequency independent beamforming architecture for mm-wave arrays is presented. Notably, our front-end architecture eliminates bulky phase shifters and local oscillators (LO) from the architecture [4]. This is achieved by employing a novel cross-element mixing technique where the signal from each antenna is mixed with another element in a systematic manner to achieve maximum diversity. Further hardware and power reduction in the backend is achieved using a well-established

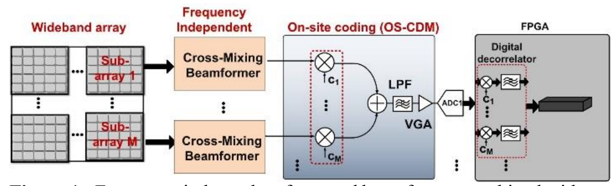

Figure 1 - Frequency independent front-end beamformer combined with on-site code division multiplexing technique.

on-site code division multiplexing (OS-CDM) technique [5]. The latter has been demonstrated to substantially reduce the costly and power-hungry analog-to-digital converters (ADCs) needed for digital beamforming by > 80% as compared to traditional digital beamforming. More importantly, the implementation of OS-CDM with frequency independent beamformer promises >95% reduction in hardware and power requirements, a much-needed capability for small mm-wave platforms.

II. FREQUENCY INDEPENDENT CROSS-MIXING BEAMFORMING

Our novel hybrid beamforming architecture is shown in Fig. 1. As depicted, cross-mixing is done between oppositely spaced antenna elements at the front-end of the array. Subsequently, these pairs are combined via OS-CDM for further hardware reduction. This combined approach provides even more reduction in hardware and power without impacting beamforming resolution. More important, our hybrid beamformer concept is simple and easy to implement. Concurrently, it applies to large and smaller antenna arrays.

Its operation is as follows: 1) the entire array is first segmented into sub-arrays of N-elements. The number of elements will be determined based on the design goals. 2) Using the concept of cross-element mixing beamformer (CMB) and symmetrical phase cancellation, the subarray elements are summed in congruence to produce the beam without using phase shifters and LOs at the front-end, as depicted in Fig. 2. Notably, a phase locked loop (PLL) is employed to extract an LO signal from the received modulated signal. Only mixers are used to cross-mix signals at oppositely spaced phased array elements to produce coherent signals.

Simulations were conducted to evaluate the signal-to-noise ratio (SNR) gain after signal combining. In Fig. 3, we plot the signal power before and after combining the cross-mixed signals. As expected, a 3dB gain is achieved for two elements. That is, this architecture accomplishes phase delay cancellation, coherent signal combining, and improvements in receiver sensitivity. After proper filtering, the crossed-mixed signals are all coherently combined and

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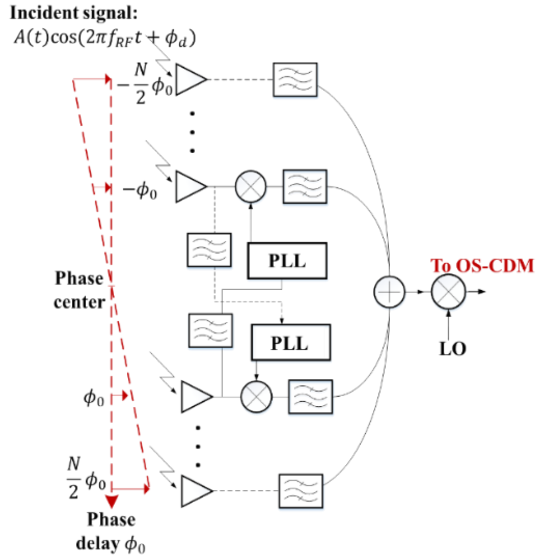

Figure 2 - CMB RF front-end with frequency independent and autonomous beamforming topology [4].

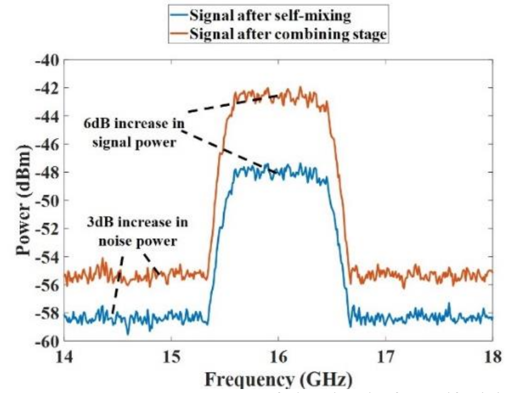

Figure 3 – Frequency spectrum of the signal after self-mixing and combining of signals from two elements.

down-converted using a single LO, as illustrated in Fig. 2. Notably, signals from any direction will be equally well received. As a result, higher gain is achieved in all directions. Next, the combined signals from all subarrays are fed to the OS-CDM baseband architecture (see Fig. 1).

III. On-Site Coding Division Multiplexing

Further hardware reduction at the analog baseband can be achieved by reducing the number of ADCs required for digital beamforming. Traditionally, beamformers employ an ADC for each antenna element, implying higher cost and power requirements. By contrast, our OS-CDM approach groups several signal paths through a single channel [5]. That is, each CMB output is coded and multiplexed in the analog domain. Then, several signals are grouped together without loss of identity and fed into a single ADC.

Notably, combining CMB with OS-CDM achieves about 95% reduction in cost and power as compared to traditional digital beamforming architectures. As indicated in Table 1, if the CMB sub-aperture has 100 elements, a total of 8 CMB front-ends are needed. Then, using an 8-signal path OS-CDM, only a single ADC is required. This is a significant reduction as compared to 800 ADCs required in conventional digital beamforming architectures. That is, the total cost and power will be reduced by ~97%. As such, the hybrid concept promises game-changing reductions in size, cost, and power.

IV. Conclusion

We presented a novel hybrid beamforming architecture based on elements cross-mixing and OS-CDM. Key to this concept is the use of mixing for beamforming and coding to reduce the number of ADCs in digital beamforming architectures.

In summary, our beamformer 1) is scalable to mm-wave bands, 2) can be integrated inconspicuously into small platforms, 3) allows for beam steering and beam shaping to realize smart antenna systems, 4) enables communications in severe environments using advanced digital beamforming and coding algorithms, and 5) promises significant reduction in size, cost and power as compared to traditional architectures.

Acknowledgment

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Table 1 - ADCs requirements for various array sizes showing reduction in cost and power using the CMB & OS-CDM concepts.

Array Size (elements)	Sub-array size (elements)	No. of ADCs (conventional)	No. of ADC CMB/OS-CDM	%Reduction in Power	%Reduction in Cost
800	100	800	1	97.51%	96.87%
200	25	200	1	90.05%	87.49%
64	8	64	1	96.11%	95.11%