Beamforming Apertures with Wideband Low-Cost Front-Ends

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***Abstract*—Low cost beamforming for 5G communication systems is of strong interest. A goal is to reduce complexity and the number of components for the beamforming network. In this paper, we present a novel hardware-reduced radio frequency (RF) front-end of beamforming at 5G bands. To reduce the large number of RF chains in such millimeter-wave (mm-wave) massive arrays, we introduce a frequency independent beamforming concept based on element-to-element mixing (BEEM). BEEM avoids conventional phase shifters and further reduces components by grouping several antenna elements into subarrays. Doing so, more than 96% in hardware and size reduction is achieved. Simulations were conducted to validate our system's performance using 16-quadrature amplitude modulation (16-QAM) schemes. Results show that a near theoretical signal-to-noise ratio (SNR) gain is achieved using our topology.**

Keywords— millimeter-wave, 5G, beamforming, self-mixing array

I. Introduction

It is well recognized that the sub-6GHz cellular spectrum suffers from congestion and limited bandwidth. Therefore, techniques are pursued to improve spectral efficiency. These include simultaneous transmit and receive (STAR) systems, higher order modulation schemes, and other advanced spectrum access techniques. However, such methods are often associated with increased hardware complexity and cost. Alternatively, the newly approved mm-wave bands for cellular links have provided avenues for a new class of wideband transceivers. Nevertheless, mm-wave technologies suffer from high pathloss and atmospheric absorption, implying reduced communication range.

To compensate for pathloss at mm-wave bands, high gain beamforming antenna arrays are required. But traditional analog and digital beamformers are narrowband, power-hungry, and SWaP (size, weight, and power) inefficient. In particular, analog beamforming employs inexpensive phase shifters [1], [2] to compensate for time delays, at the expense of lack of flexibility. This is because shifters are fixed, frequency dependent, and restricted to a single angle of arrival (AoA). On the other hand, digital beamforming provides more flexibility by utilizing adaptive algorithms for signal tracking, reception enhancement, and interference mitigation [2]. Still, digital techniques suffer from complexity, high cost, and massive size, especially when integrated with systems operating at mm-waves. In this paper, we proposed a new hybrid beamforming concept that combines both analog and digital techniques. Notably, the hybrid process offers more reduction in the number of analog-to-digital converters (ADCs) and maintains flexibility and adaptive behavior [2], [3]. The hybrid beamformer is also optimized to reduce power, cost, and complexity.

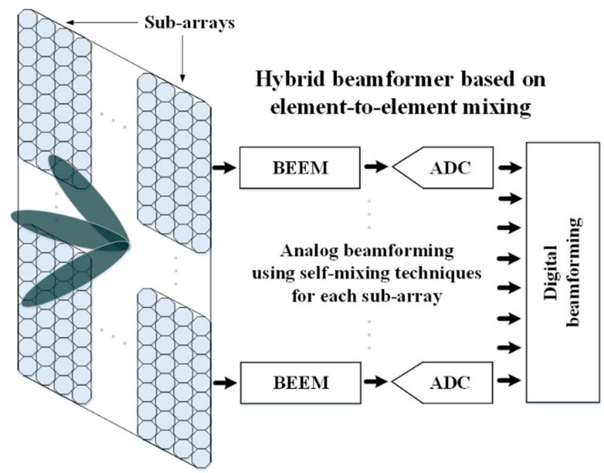

Fig. 1 - Novel hybrid beamforming topology with element-to-element mixing (BEEM) concept for phase delay cancellation

The proposed novel hardware-reduced RF front-end supporting a hybrid beamformer is depicted in Fig. 1. The architecture promises >96% reduction in SWaP for applications requiring massive arrays (>10^4 elements). Central to its realization is the introduction of a beamformer based on element-to-element mixing concept to avoid use of conventional bulky analog phase shifters. This implies substantial reduction in size, power, and cost as compared to other beamformers. A detailed analysis of our BEEM topology is presented. We show that our system is able to achieve near theoretical SNR gain in presence of additive white Gaussian noise (AWGN) channel.

II. System Description

As shown in Fig. 1, the hybrid beamformer consists of an analog stage that employs element-to-element mixing (BEEM) and a digital stage. At the analog stage, a massive array with a large number of elements is divided into smaller sub-arrays. Each sub-array is connected to a BEEM network and a single RF chain. As a result, the hybrid system promises >96% reduction in hardware and size (see Table 1), as compared to conventional beamformers. For instance, in the case of a 1000 elements array, using a 10×10 BEEM topology, we achieve a 99% reduction in total hardware and size.

The architecture of the BEEM concept is depicted in Fig. 2. For simplicity, we only consider a uniform linear array. However, this concept can be extended to multi-dimensional arrays. The design exploits the process of mixing two opposite elements in reference of a center element with one another, but without using local oscillator (LO) sources, as illustrated in Fig. 2. Instead, each antenna element is fed to a

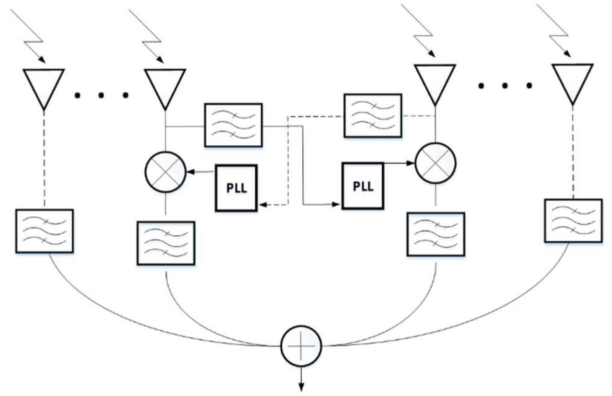

Fig. 2 – Proposed beamforming concept based on element-to-element mixing (BEEM) architecture

Table 1 – Size reduction using the proposed hybrid frequency independent beamforming concept

Array size	Subarray Size	Number of RF Chains	Percent Reduction in Size
1000	5x5	40	96
1000	10x10	10	99

phase-locked loop (PLL) circuit. The latter locks the phase of the signal to the phase delay of the input and feeds it to the mixer of the oppositely spaced antenna element. Doing so, the phase lag at one element cancels out the phase lead at the corresponding opposite element. Therefore, the process yields delay-free signals and a compensation of the phase delays.

The concept in Fig.2 is a departure from using traditional RF mixers where an external source is required to generate the LO signal. Instead, our system generates its LO from the received signal, implying more reduction in RF components. More importantly, the element-to-element mixing process allows for coherent signal combining without using phase shifters as in traditional analog beamformers. Notably, our design establishes an unprecedented flexibility in the analog domain. In addition, the design is agnostic to all incoming signals regardless of their AoA. By contrast, conventional beamformers are fixed to a certain angle and require a hardware modification for each AoA. More importantly, using our BEEM, we do not lose the AoA information as with the other architectures [4], [5]. As such, the presented design can be assembled as a subarray and integrated in hybrid beamforming structures. Notably, our BEEM can capture desired signals and reject all interferers. To our knowledge, this is the first self-mixing subarray (SMS) structure for beamforming applications.

III. Simulation Results

Studies were conducted to validate the operation of BEEM topology using 16-QAM signal in presence of AWGN channel. For simplicity, we only considered symbols with the same phase, ϕ_d, but different amplitudes. The constellation is depicted in Fig. 3. Our goal is to show that BEEM achieves coherent combining, and hence SNR gain, without altering the amplitude and phase modulation. Results showed that for 2, 4, and 8 elements array, a gain of 3, 6, and 9dB was achieved respectively (see Fig. 4).

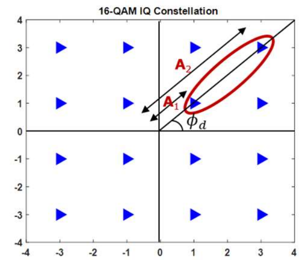

Fig. 3 - 16-QAM IQ constellation

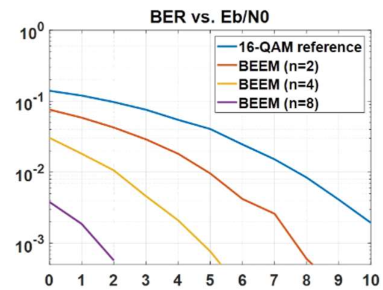

Fig. 4 – Bit-error rate curves for 16-QAM signals in an AWGN channel using 2, 4, and 8 elements array

IV. Conclusion

We presented a novel beamforming architecture based on sub-arraying and element-to-element mixing. Key to the proposed approach is the use of subarrays. These subarrays employ a self-mixing concept that relies on a PLL to preserve the phase of the incoming signals from each antenna elements. The signal is then passed into a single ADC to significantly reduce power requirements. It was demonstrated that the use of 5x5 subarrays achieves an impressive 96% reduction in size and power. For 10x10 subarrays, the reduction reaches 99%.

Acknowledgment

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