A Compact Beamforming Concept Based on Element-to-Element Mixing For 5G Applications

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***Abstract*— Recent studies focus on exploring the untouched millimeter-wave spectrum as it offers more bandwidth and higher data rates. Nevertheless, the high losses, power consumption, and cost of RF components at such frequencies remain prohibitive. In this paper, we present a novel compact beamforming concept using self-mixing techniques in an effort to downsize the overall number of RF components required and achieve higher efficiency. To do so, we introduce a novel analog beamforming method based on element-to-element mixing (BEEM) with flexibility in signal reception for any angle of arrival (AoA). Preliminary evaluation of the proposed BEEM topology is presented here. More specifically, we have conducted simulations with 16-quadrature amplitude modulation (16-QAM) to evaluate our beamforming concept. Simulations show that phase delay cancellation as well as coherent summation can be achieved using our BEEM topology, implying a near-theoretical diversity gain.**

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

Introduction

There is growing interest in beamforming for 5G and millimeter-wave (mm-wave) communication systems. However, the frequency spectrum of such links suffers from high absorption and path loss. As such, we are restricted with denser networks to compensate for these losses. An obvious solution to enhance the range of transmission and improve the receiver's sensitivity is using multiple antenna systems with beamforming capabilities. Traditional beamforming architectures employ either phase shifters or true time delays at the analog front-ends. These components are associated with high losses, which drastically limit the system's dynamic range. In addition, for large number of antenna elements, the integration of these phase shifters with 5G systems is prohibitive and leads to much bulkier receivers.

To further downsize these systems, self-mixing techniques are introduced into the chain to avoid the use of phase shifters at the RF front-ends [1-3]. More importantly, no local oscillator (LO) sources are needed for such architecture. In other words, the LO signal is extracted from the received signal, either from the LO signal transmitted along with the RF signal [4-5], or from the information signal itself [6].

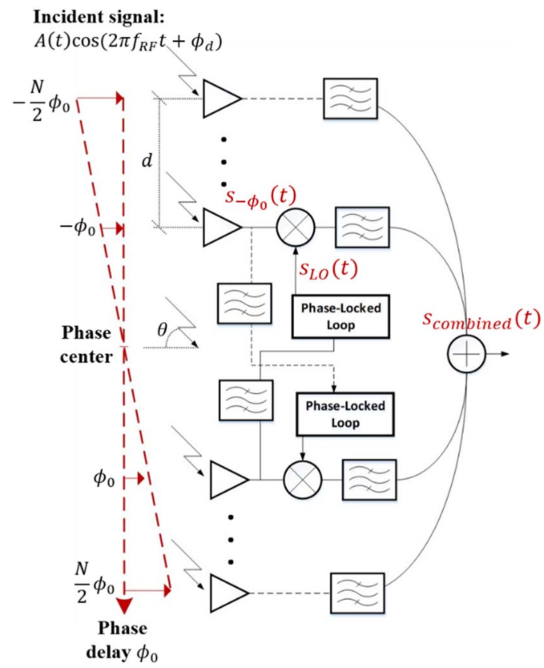

Fig. 1 - Beamforming based on element-to-element mixing architecture.

In this paper, we present a novel self-mixing array, previously introduced in [3]. We adopt a self-generated LO approach to implement a beamformer with element-to-element mixing (BEEM). We prove that our BEEM achieves phase delay cancellation and diversity gain comparable to conventional beamformers, with drastic reduction in size and power consumption.

System Description

Fig. 1 depicts the block diagram of our BEEM topology. In our work, we consider a uniform array with N-linearly spaced antenna elements. The oppositely spaced elements, in reference to the phase center, have an incremental shift of $\pm\phi_0$. The latter depends on the angle of arrival θ and the antenna elements spacing d. As such, the phase shift at the n^{th} antenna element is computed using,

$$n\phi_0 = n\frac{2\pi f_{RF} d}{c}\sin(\theta) \qquad (1)$$

where f_{RF} is the RF carrier frequency and c the speed of light.

For simplicity, we consider a two-elements array. The received signals at the two oppositely spaced antennas from the center reference can be expressed as follows,

$$s_{\pm\phi_0}(t) = A(t)\cos(2\pi f_{RF} t + \phi_d \pm \phi_0) \qquad (2)$$

where $A(t)$ and ϕ_d are the amplitude and phase modulation, respectively.

The goal is to combine all the antenna elements in phase to achieve maximum diversity gain. For instance, for N-antenna elements, the maximum diversity gain is $10\log_{10} N$ dB. To do so, the RF signal received at each element is first bandlimited and fed into a phase-locked loop (PLL). The latter is able to generate a clean LO for the mixing process. The synthesized LO signal has a fixed peak amplitude with a phase following the delay in reception of the feeding modulated signal. In other words, the synthesized LO is

$$s_{LO}(t) = A_L\cos(2\pi f_{RF} t \mp \Delta\phi) \qquad (3)$$

where A_L *and* $\Delta\phi$ are the LO amplitude and phase. Ideally, $A_L = 1$ and $\Delta\phi = \phi_0$. Fig. 2 (a) and (b) show the modulated signal and the corresponding self-generated LO signal frequency spectrum, respectively.

The next stage translates into mixing the resulting signal with the one received at the opposite antenna element in reference to the center, as depicted in Fig.1. As a result, oppositely spaced antenna elements are indirectly mixed the one with the other. Such technique promises an unprecedented flexibility in the analog domain, and achieves a diversity gain comparable to conventional beamformers.

The product signal resulting from the mixing stage is band-pass filtered out as follows

$$\begin{aligned} BPF[\, s_{\pm\phi_0}(t) \times s_{LO}(t)] = \\ A(t)\cos(2\pi f_{RF} t + \phi_d \pm \phi_0) \times \\ \cos(2\pi f_{RF} t \mp \phi_0)\,] \\ = A(t)\cos(2\pi(2f_{RF})t + \phi_d) \qquad (4) \end{aligned}$$

The converted signal is depicted in Fig. 2 (c).

Following the same mixing strategy with each array element, all antenna signals are converted and combined, yielding

$$s_{combined}(t) = 2.A(t)\cos(2\pi(2f_{RF})t + \phi_d) \qquad (5)$$

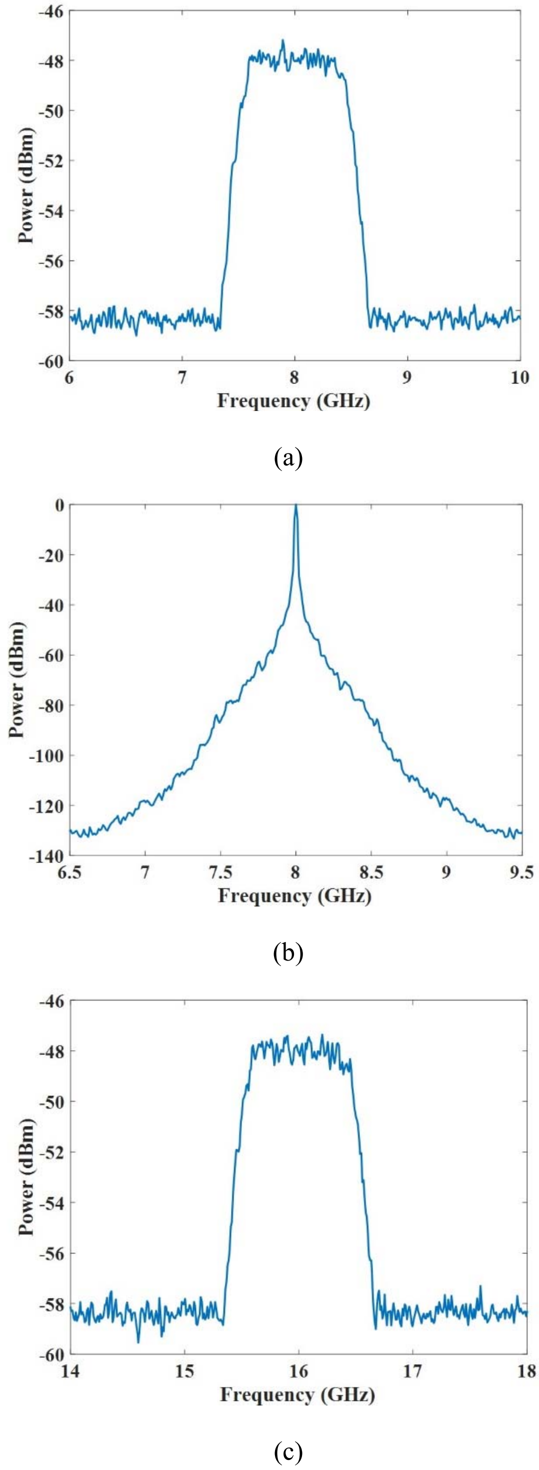

Fig. 2 – Frequency spectrum of (a) the modulated signal, (b) the synthesized LO signal, and (c) the outcome of self-mixing process.

Fig. 3 shows the frequency domain representation of the received and the combined signals. Clearly, a 3dB gain is achieved using two antenna elements.

Notably, the architecture accomplishes phase delays cancellation, coherent signal combining, and improvement in the receiver's sensitivity.

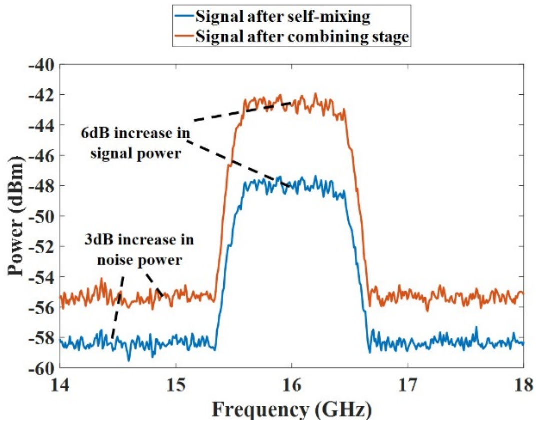

Fig. 3 – Frequency spectrum of the signal after the self-mixing and thee combining processes, having a two-antenna elements array.

CONCLUSION

BEEM presents a self-mixing array based on indirectly mixing every two oppositely spaced elements in reference to a center element to achieve coherent signal combining. BEEM introduces a novel topology exploiting the information signal to extract the LO data used to drive the mixers. This concept of phase delay cancellation is highly flexible and achieves drastic reduction in size and power consumption as compared to existing conventional beamformers. Finally, we showed that the deployment of our BEEM satisfies the foundational requirements of beamforming techniques and presents the requisites for establishing the expected diversity gain from such systems.

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