Multibeam Digital Array Receiver Using a 16-Point Multiplierless DFT Approximation

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***Abstract*— An N-element array with receivers subject to an N-point spatial fast Fourier transform (FFT) leads to N directionally orthogonal radio frequency (RF) beams. FFTs are fast algorithms for computing the N-point discrete Fourier transform (DFT) at reduced complexity. The brute-force computation of a DFT requires $\mathcal{O}(N^2)$ multiplications while an FFT provides the same computation at $\mathcal{O}(N \log N)$ multiplications. The digital chip area and power consumption of the DFT computation are still dominated by the multipliers required by the FFT used. In this paper, an approximation to the 16-point DFT is proposed which maintains mathematical properties close to the ideal 16-point DFT to obtain 16 RF beams by computing an approximate spatial DFT in every clock cycle at significantly lower area and power in the digital realization. The proposed approximation can be implemented using FFT-like fast algorithms that are multiplierless, thereby further reducing the digital chip area and power consumption associated with multiplication in a conventional FFT approach to zero. A 16-beam beamformer employing a 16-element linear array of patch antennas, direct-conversion receivers, and a Xilinx Virtex-6 field-programmable gate array-based real-time digital back-end clocked at 240 MHz are described as an example realization of 16 complex-valued (IQ) receive-mode RF beams, centered at 2.4 GHz with 120 MHz of bandwidth per beam.**

***Index Terms*— Beamforming, low-complexity algorithms, multibeam, spatial DFT.**

I. Introduction

MULTIBEAM beamforming is a key requirement for a host of applications in wireless communications [1], imaging [2], radar [3], and radio astronomy [4]. With the recent advancements of the fifth generation (5G) wireless communication systems at millimeter-wave (mmW) frequencies, multibeam antenna technologies have been highly demanded. In mmW frequencies, atmospheric attenuation is high and to mitigate higher path loss in these frequencies high gain antenna arrays with multiple sharp beams [5], [6] are desired.

The Federal Communication Commission has made several mmW bands available for flexible terrestrial wireless mobile radio services [7]. Out of these bands, the low atmospheric absorption in the 28 GHz band is attractive for commercial 5G deployments. Commercial organizations have started testing 5G systems at 28 GHz [8] and initial implementations target a 100 MHz channel bandwidth [9].

For 5G systems with such specifications, digital beamforming becomes a viable solution as the radio frequency (RF) signal of interest can be brought down to baseband and sampled to achieve beamforming in the digital domain. Thus, digital beamforming is a promising approach for larger beamforming arrays as they offer a great deal of flexibility while providing control of both the transmitted and received signals at each antenna element. A digital beamforming architecture can exploit all degrees of freedom of the array and the numbers of simultaneous beams that can be formed from such system would be directly related to the number of antennas. Enhanced calibration capabilities with the potential for low sidelobes and wideband equalization make digital beamforming an attractive option [10] for wireless communication applications. Examples of digital arrays can be found in [11]–[13].

The proposed digital beamforming architecture provides low size-weight-and-power (SWaP) digital circuit solution for achieving 16-parallel beams while maintaining the 5G 28 GHz band channel bandwidth requirement of 100 MHz per beam. A 2.4 GHz array receiver setup is build to demonstrate and verify the functionality of the proposed low-complexity digital solution which is capable of handling 120 MHz of bandwidth per beam, which exceeds the minimum requirements of the latest 5G standard [9].

The paper [14] provides an overview of multibeam technologies including passive multibeam techniques that are based on quasi-optical components and beamforming circuits, multibeam phased-array enabled by analog phase shifters as well as modern digital technologies having several different system architectures. Consider an N-element uniform linear array with Δx interelement spacing. The underline function

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