A Radix-2 Algorithm For Forming N True-Time-Delay
RF Beams at Complexity $O(N \log N)$

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Introduction

- Multi-beam beamforming is essential to modern telecommunications technologies like 5G that operate in millimeter-waves.
- The current algorithms to perform multi-beam beamforming is computationally intensive.
- We propose multi-beam architectures that operate in baseband to achieve low-complexity simultaneous beams.
- Our FFT beamformers are based on a fast ADFT algorithm which approximates the DFT.
- We also introduce a new Radix-2 algorithm for true time delay beamformers.

Approximate DFT

- Approximate DFT matrix consists only ±1, ±i, ±2, ±2i which leads to multiplicationless digital implementation.
- Approximate matrix can be implemented directly or using the factorization. Factorized version makes it attractive for higher values of N.
- The complexity of the factorized implementation decreases as N increases.

Experimental Setup

- Receiver backend
  - LNA
  - BPF
  - Mixer
  - IF Amp
  - ADC

- Hardware Specification
  - LNA has a gain of 15 dB
  - Amplifier has a gain of 30 dB
  - Digital hardware is implemented using Xilinx Virtex-6 platform
  - The FPGA used is a Xilinx Virtex-6 6S475
  - ADC support up to 10GHz sampling rate

DVM Factorization

- Direct implementation of DVM $A_2$ requires 60 TTD elements.
- Low-complexity factorization requires only 24 delay elements.
- Ideal linear phase delay $e^{-j\omega_0 t}$ can be approximated by AIDs that can be realized on-chip at low-SWAP using CMOS technology.
- $e^{-j\omega_0 t} = \sum_{n=0}^{N-1} e^{-j2\pi \omega_0 n/N} e^{j2\pi \alpha n/N}$ $\approx (\sigma_{max} - \sigma_{min})/2$, $N \in 2^k$, therefore the ideal unit delay can be approximately realized in an analog RC-active topology using a cascade of M second-order all-pass filters.
- Typically, $M = 3$ is sufficient for approximation of $e^{-j\omega_0 t}$.

ADC

- $\psi_j(x), \psi_k(x)$ can be realized by cascading LM identical AIDs.

CMOS All-Pass Filter

- True time delays were realized using CMOS analog all-pass filters.
- Group delay of the APF was calculated as 57 ps.
- Antenna spacing $\lambda_{f} \frac{\sin(\theta)}{\sin(\phi)} N$, for $N=3$, $\lambda_{f}=68\text{mm}$.
- The array factors have been simulated for 2.4, 2.0 and 1.6 GHz frequencies.

Hardware resource utilisation

- Measured beam patterns corresponding to ADFT, fixed-point FFT digital core, and the simulated beam patterns. A-DFT Beamformers of each output

Reference

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Simulated 5-Beams using Measured APF Data

- Squint-Free Wideband IF Multi-Beamformer
  - Low-complexity 9 beam IF beamformer using a 4-element array can be realized using the same factorization technique.
  - For a given TTD beamformer that forms a beam in the direction $\hat{n}$ measured from the array broadside where $-90^\circ \leq \phi \leq 0^\circ$; we can reverse the order of the antenna outputs that is fed to a TTD beamformer to achieve a beam at $-\hat{n}$ direction.
  - We use this concept to achieve 9 beams pointing at non-uniformly spaced directions.
  - For operation in IF, DVM needs to be modified such that $\alpha = 3$ for $\hat{n}$ and $\alpha = 0$ for $-\hat{n}$.