A FOURIER ANALYSIS OF DIGITAL BEAMFORMING WITH SEVERELY QUANTIZED MMWAVE ARRAYS

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Introduction

- ADCs are a key bottleneck in realizing all-digital mmWave massive MIMO at multi-GHz bandwidths ➔ Can we reduce power consumption and hardware complexity by drastically reducing ADC precision?
- Previous work in ComSenTer on all-digital massive multiuser MIMO systems with reduced ADC precision ➔ Bussgang linearization works well for design and performance prediction for a moderate number of users (so that per-antenna input looks Gaussian).
- This work: Can we go down to 1-bit ADCs even when the Bussgang linearization does not work? We consider a scenario motivated by fast-moving users in a small picocell: small number of users & sparse mmWave channels ➔ **Gaussian input approximation not valid & SNR per antenna too high (imperfect power control) for sufficient dithering from noise.**

Approach

Analysis of Quantized Input in the Beamspace Domain

- We start by analyzing the 1-bit quantized antenna input with one user. The corresponding system model is the following figure:

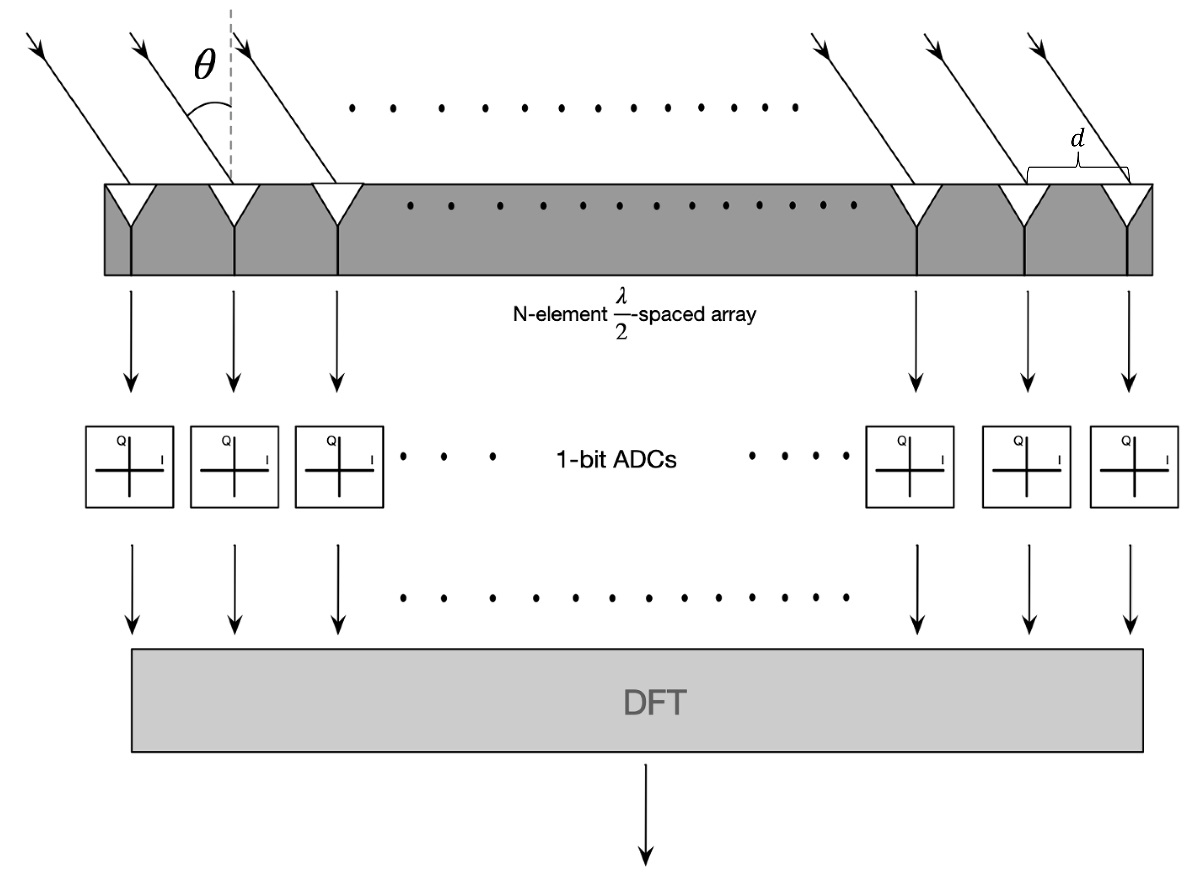
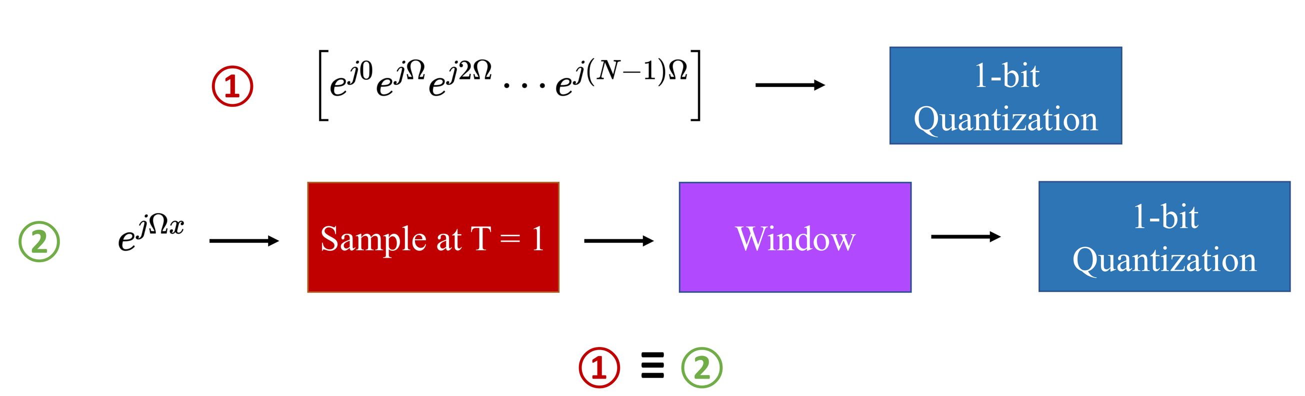
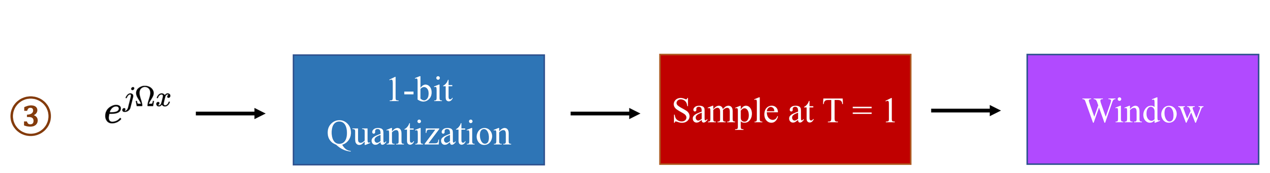


Figure: Uplink massive MIMO with 1-bit ADCs and a single user

- Angle of arrival: θ, spatial frequency: $\Omega = \frac{2\pi d sin\theta}{\lambda}$ and $v = \frac{d sin\theta}{\lambda}$, relative phases between antennas: $\boldsymbol{a}(\Omega) = \left[e^{j0}e^{j\Omega}e^{j2\Omega}\cdots e^{j(N-1)\Omega}\right]$.

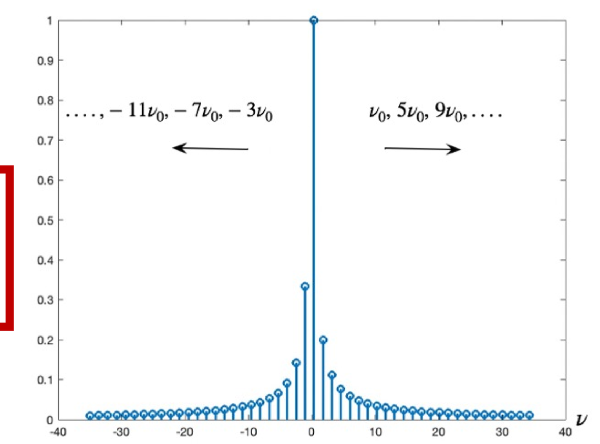


An important observation for the analysis: ② can be rearranged as in ③:



- The output of the quantizer in ③ is complex exponentials at $(-1)^n(2n+1)\Omega$, $n = 0, 1, 2, \ldots$
- The Fourier series of the 1-bit quantized complex exponential is given by

$$Q(e^{j(\Omega x+\phi)}) = \sum_{k=0}^{\infty} \frac{4(-1)^k}{\pi(2k+1)} e^{j(-1)^k((2k+1)2\pi\nu_0 x+(2k+1)\phi)}$$



- Sampling and windowing lead to aliasing and spreading of spatial harmonics, respectively.
- Fourier analysis of the quantized input and the DFT outputs of the input match:

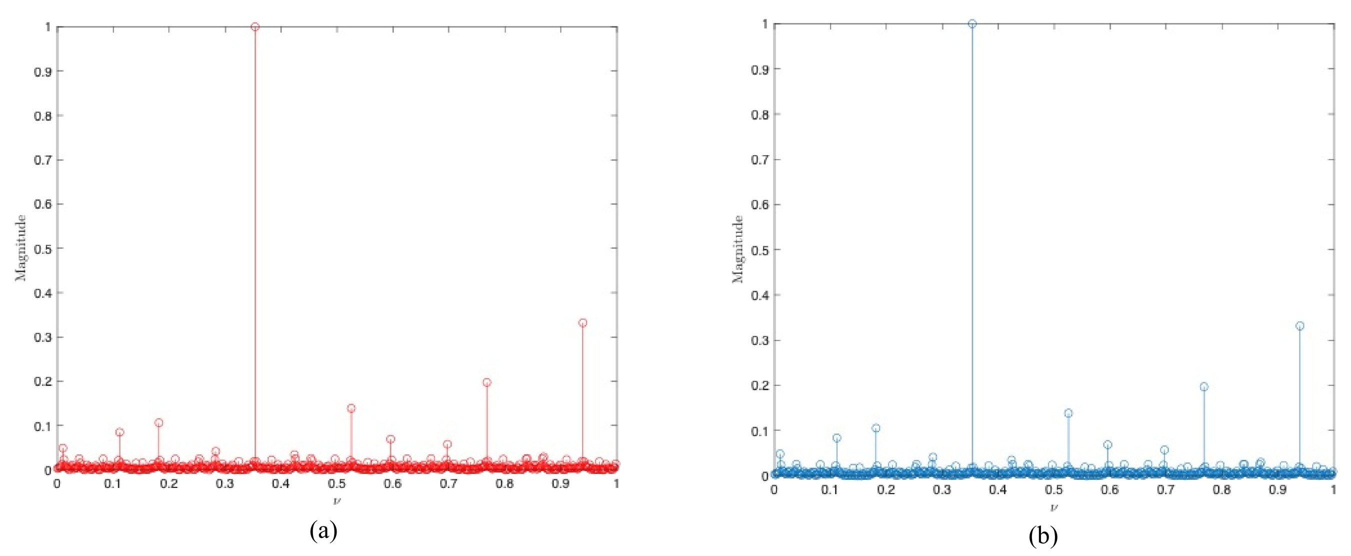


Figure: (a) 512-point DFT of the quantized input. (b) Result of the Fourier analysis.

High and Low SNR Regime Distinction

- When the SNR per antenna element is low, the dithering effect of noise is in play.

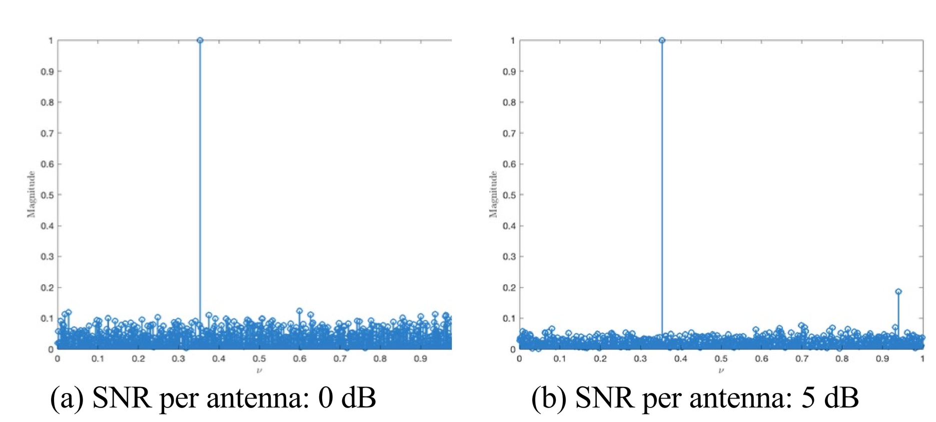
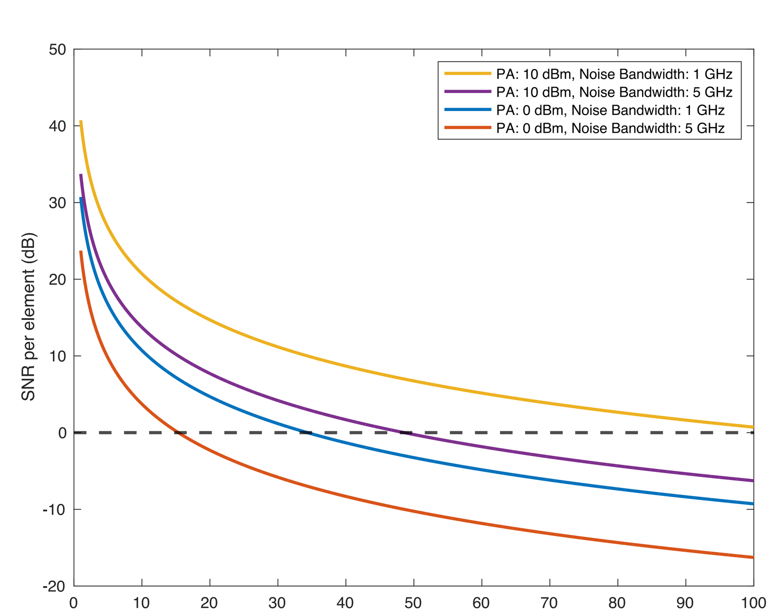


Figure: Magnitude versus spatial frequency of 512-point FFT outputs. N = 512 and $\theta = \frac{\pi}{4}$ for each case.

- Link budget analysis shows that high SNR regime appears at reasonably high distances:



Parameters for the link budget analysis:
- number of transmit antenna elements is 16,
- gain of each individual transmit and receive element is 2 dBi,
- receiver noise figure is 6 dB,
- carrier frequency is 140 GHz,
- thermal noise is calculated for 1 and 5 GHz noise bandwidth,
- transmit powers of each Power Amplifier (PA) are 0 and 10 dBm.

Figure: Link-budget analysis for the given parameters.

Isolating the Right FFT Bin for Each User

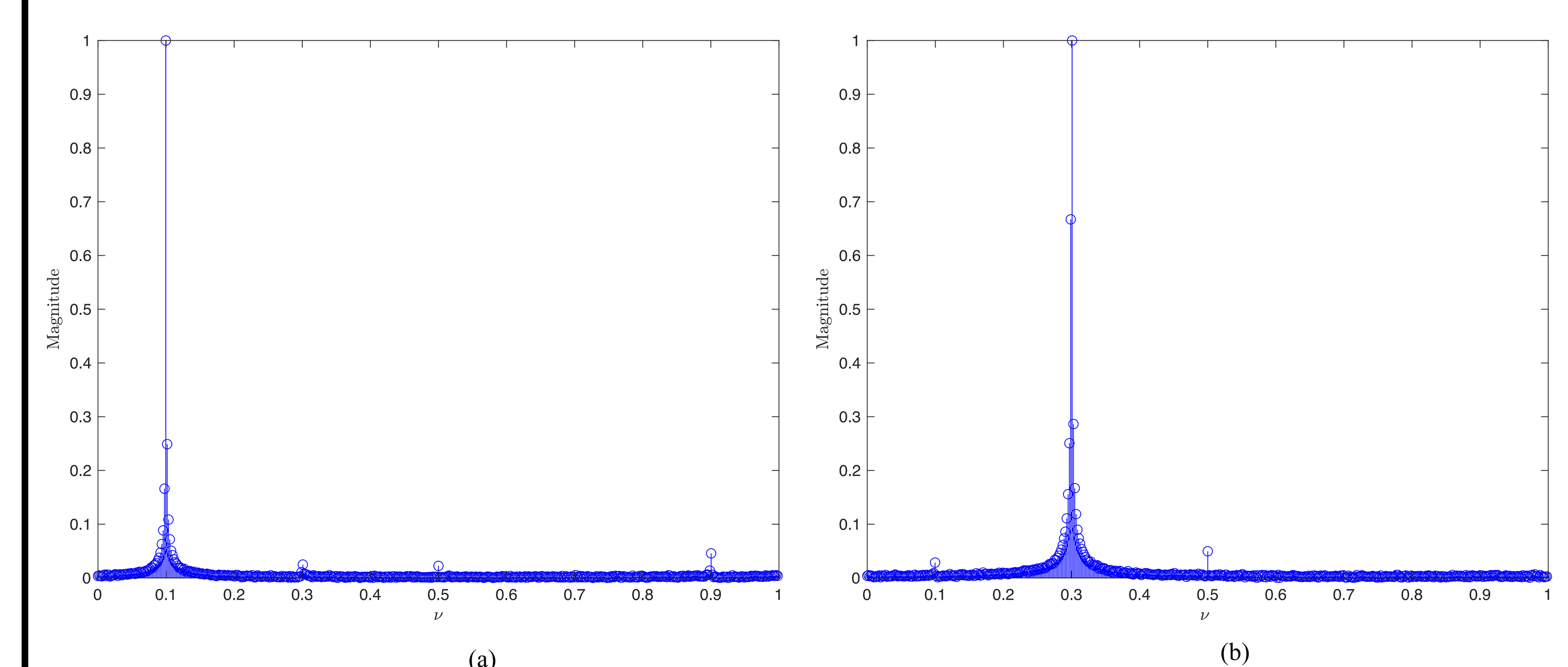
- The analysis provides a basis for a training sequence design to suppress higher-order harmonics.
- Correlating the $(2n+1)$th harmonic ($n = 0, 1, 2, \ldots$) against the phase of the mth symbol ($\phi[m]$) yields

$$e^{j((2n+1)\phi[m](-1)^n)}e^{-j\phi[m]} = \begin{cases} e^{j2n\phi[m]}, & \text{if } n \text{ is even} \\ e^{j(-2(n+1))\phi[m]}, & \text{if } n \text{ is odd} \end{cases}$$

- With QPSK signaling, correlation with a standard training sequence does not suppress higher-order harmonics.
- We introduce an additional phase ramp into the training sequence. For the mth training symbol, the phase is $\phi[m] = m\frac{\pi}{N_t} + \psi[m]$ where $\psi[m]$ is the phase due to the QPSK signaling, N_t is the number of training symbols. This makes the correlator output corresponding to higher-order harmonics sum to zero over the training symbols.

Results

- The plots below show the results of the correlations for two users where training sequences with the ramped phase are used.
- Fundamental spatial frequencies: 0.1 and 0.3, and SNR/element is 6 dB per antenna for both users (high SNR regime).



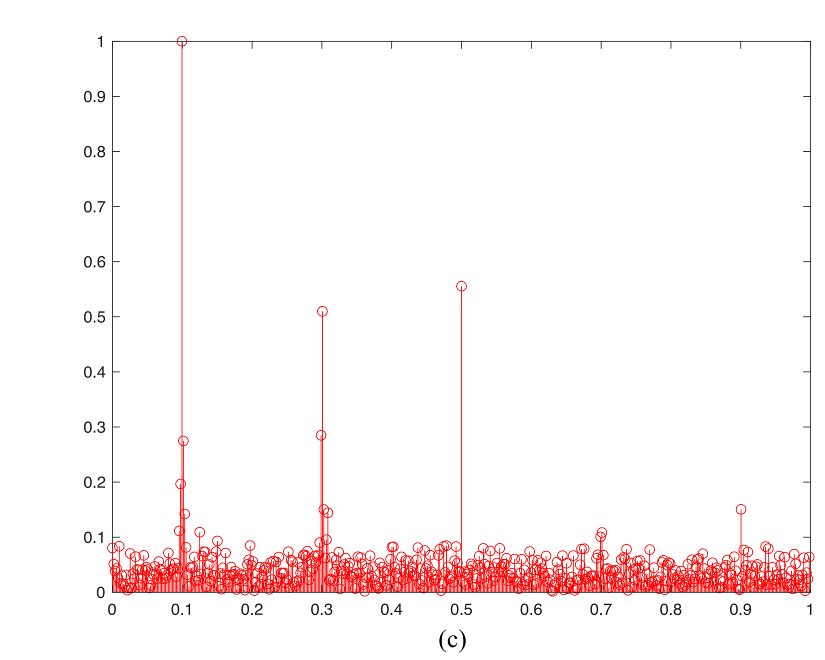


Figure (a) – (b) Correlation results for user 1 and user 2.
(c) Magnitude spectrum of N = 512-point DFT of the quantized input with two users.

Next Steps

- Design guidelines for larger constellations in the high SNR per antenna element regime.
- Evaluation of the performance with smaller antenna arrays, where the spreading of the harmonics is more prominent.

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