On Throughput of Millimeterwave MIMO Systems with Low Resolution ADCs

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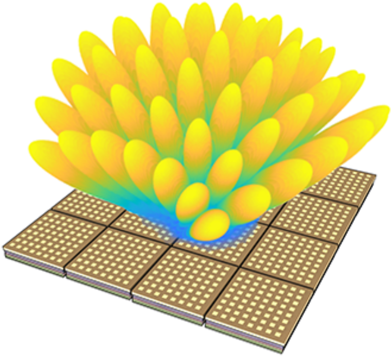
ICASSP 2020

Motivation

- MmWave and Massive MIMO
  - Large antenna arrays $\begin{cases} \text{Spatial multiplexing} \\ \text{Beamforming} \end{cases}$



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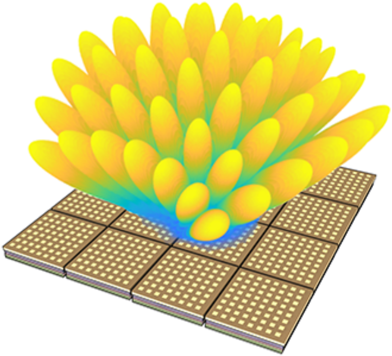

Low Resolution Analog to Digital Converter (ADC)

Conventional receivers

- One RF chain per antenna.
  - Fully digital receiver.
- High resolution ADCs.

⇒ High power consumption ($\propto 2^{bits}$)

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1. What performance can we achieve in practical mmWave systems?
2. How much loss do we have using small number of one-bit ADCs?
3. How much loss do we have due to channel estimation?

Preview of the Results

- MmWave downlink
- Data rate with small number of one-bit ADCs is close to that of the fully digital receiver with high resolution ADCs.
- Channel estimation with one-bit ADCs does not degrade the data rate much.

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  - *Blockwise analog receiver*
  - *Adaptive threshold receiver*
  - Optimal high SNR rate

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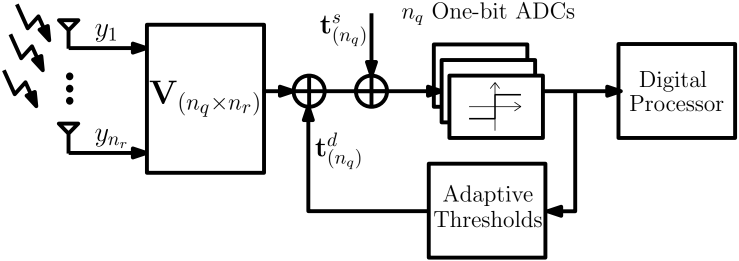
  - Optimal high SNR rate
- This work:
  - Considers the adaptive threshold receiver.
  - Investigates the performance in practical mmWave systems.

Adaptive Threshold Receiver



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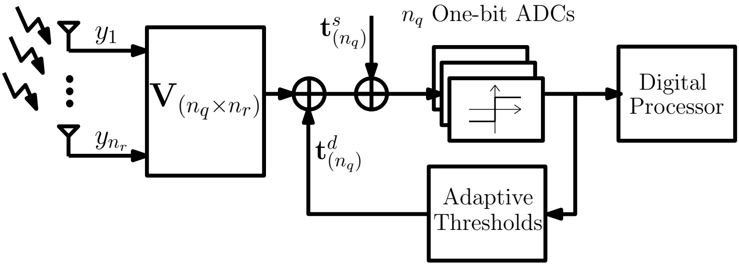

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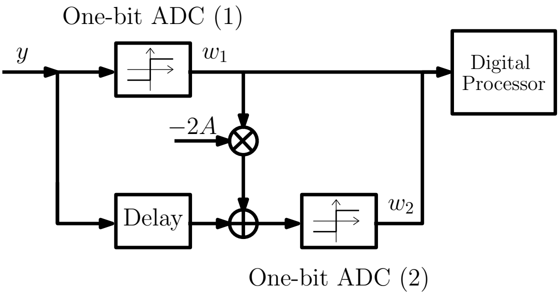
- Derived closed-form expressions of the achievable rates for all SNRs for point to point, broadcast, and multiple access channels.

Example: Adaptive Threshold Receiver

For $Y(1) =$ -A and $Y(2) = +$A we have



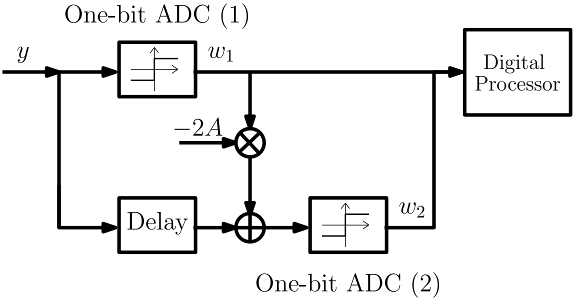
Symbols

3A	+1 +1
A	+1 -1
-A	-1 +1
-3A	-1 -1

ADCs Outputs

Channel use	W_1	W_2
1	-1	_
2	+1	+1
3	_	-1

Observations



- Constructed a two-bit ADC with **two** one-bit ADCs.
- In general it can construct a b-bit ADC with b one-bit ADCs.

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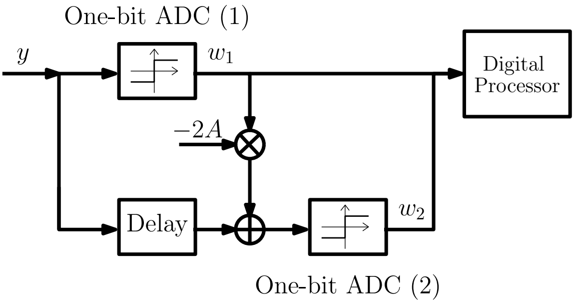

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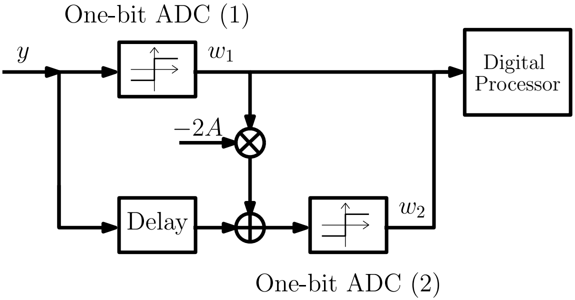

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- Similar effect using successive approximate register ADC.

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- For a subchannel which is allocated b one-bit ADCs
  - User process each received signal through n time slots by effectively performing nb-bit quantization.
  - The user is actively decoding through all time slots.
  - Base station uses 2^{nb}-PAM modulation for transmission which maximizes the rate.

Achievable Rate

Theorem: [Khalili et. al. '19] For n user downlink system with perfect CSI, rate tuple $(R_1, R_2, \cdots R_n)$ is achievable if

$$R_j \leq \frac{1}{n} \max \sum_{k=1}^{s_j} I(\widetilde{X}_{j,k}; \widetilde{Y}_{j,k})$$

- $\widetilde{X}_{j,k} = a_{j,k}\left(2\widehat{X}_{j,k} - 1 - 2^{nn_{q,j,k}}\right)$
- $\widetilde{Y}_{j,k} = \sigma_{j,k}\widetilde{X}_{j,k} + N_{j,k}$
- $\widehat{X}_{j,k} \sim unif(\{1, 2, \cdots, 2^{nn_{q,j,k}}\})$
- $a_{j,k} = \sqrt{\frac{3P_k}{2^{2nn_{q,j,k}}-1}}$
- $\sum_{i\in[s_j]} n_{q,j,i} = n_{q,j}$
- $\sum_{i\in[s_j]} P_{j,i} = P$
- s_j : Number of non-zero singular values of $\mathbf{H}_j$

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  - **UP-UA (Uniform Power/Uniform ADCs)**: Both the transmit power at the transmitter and ADCs at the receiver are distributed uniformly among the subchannels.

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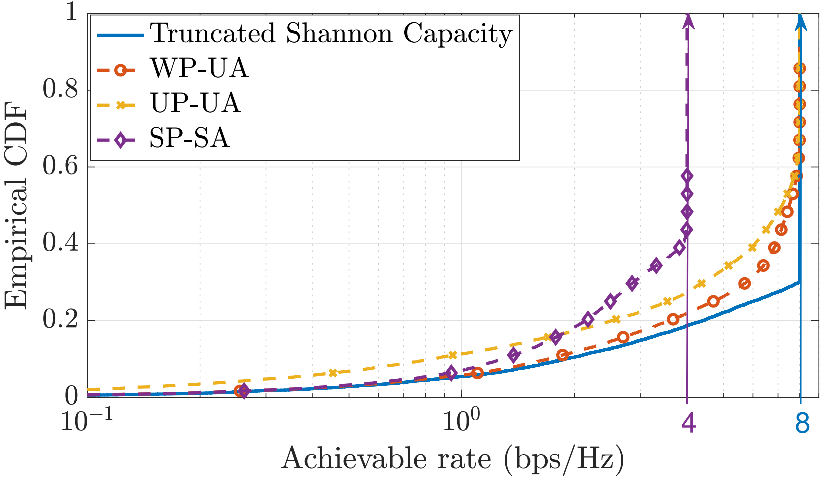
  - **UP-UA (Uniform Power/Uniform ADCs)**: Both the transmit power at the transmitter and ADCs at the receiver are distributed uniformly among the subchannels.
  - **SP-SA (Selection Diversity)**: Allocates all power and ADCs to the strongest subchannel.

Simulation Assumptions

- Downlink in a mmWave single-cell system
- Clustered mmWave channel model [Akdeniz et. al. '14]
- Up to 256 QAM modulation (16 PAM per dimension)
- Uniform input distribution
- Perfect channel code
- Perfect channel state information
- Other system parameters:

Parameter	Value
Cell radius	10 to 50 m
Carrier frequency	28 GHz
Bandwidth	1 GHz
Noise spectral density	−174 dBm/Hz
Noise figure	6 dB
BS antenna	8x8 uniform planar array
User antenna	4x4 uniform planar array
BS transmit power	30 dBm
Path loss (LOS) in dB	$61.4 + 20\log_{10}(d \text{ in m}) + \mathcal{N}(0, 5.8^2)$
Path loss (NLOS) in dB	$72 + 29.2\log_{10}(d \text{ in m}) + \mathcal{N}(0, 8.7^2)$
Probability of LOS	$\exp(-0.0149d \text{ in m})$



Empirical CDF of the achievable rate of the single link system with perfect channel state information when the receiver is equipped with $n_q = 8$ one-bit ADCs.

Observations

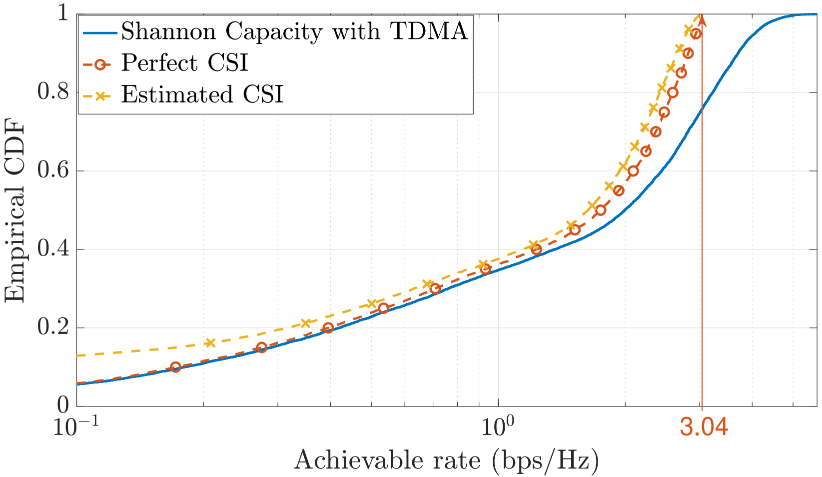
- WP-UA has better performance compared to the other approaches while in the power-limited regime (low rates) SP-SA approach achieves better rate-complexity trade-off.
- WP-UA performs close to the truncated Shannon upperbound implying that using complex optimization for joint power and ADC allocation would only lead to incremental improvements in achievable rates.

Impact of Channel Estimation

Assumptions

- The BS transmits a pilot sequence of length $n_p = 512$ and the coherence time is $n_c = 10240$.
- During pilot transmission users use three one-bit ADCs per dimension (real and imaginary).
- Users perform channel estimation using **EM-GAMP** algorithm [Mo et. al. '18].
- After estimating the channel, the base station and users configure their transmit power and ADCs using the WP-UA algorithm.

Multi-user Performance with Channel Estimation



Empirical CDF of the achievable rates of the users for downlink transmission when there are a total of $n = 10$ users and the users are equipped with $n_q = 8$ one-bit ADCs for data communication.

Observations

- Although we use three one-bit ADCs per dimension ($16 \times 2 \times 3 = 96$ in total) during channel estimation, we do not need that many ADCs to achieve near-optimal performance during data transmission.
- The performance loss is small for intermediate and high SNRs, it is larger in the low SNR regime. This is due to the fact that in low SNRs the channel estimation error is high.

Conclusion

- Downlink mmWave with adaptive threshold receiver.
- Using small number of one-bit ADCs and a low-complexity algorithm for power and ADC allocation, achieves data rate close to that of the fully digital receiver with high resolution ADCs.
- Channel estimation with one-bit ADCs does not degrade the data rate much.