Massive MIMO Communications with One-Bit Quantization
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Massive MIMO Communications with One-Bit Quantization

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The Spectral Crunch

- More active mobile wireless devices than people on the planet
- Ubiquitous wireless access is now a commodity
  - emergency services
  - e-Health
  - environmental monitoring
  - smart grid
  - vehicular communications
- And private uses: communications, internet, HDTV on demand, gaming
- To meet growing needs, we need 1000x more throughput!
- Current systems don’t have any more bandwidth available ....
What if we knew that in 5 years, we would need to handle 1000x more traffic?
The Road to Gigabit Wireless (5G and Beyond)

- How do we get to Gb/s wireless links?

- Three symbiotic trends emerging:
  - Deployment of pico- and femto-cells (OoM decrease in cell size)
    *Build more roads, closer together*
  - Millimeter wave frequencies (OoM increase in bandwidth)
    *Build wider roads*
  - Massive MIMO (OoM increase in antennas)
    *Stack the roads on top of each other!*
(1) “Pico” and “Femto” Cells
(2) Millimeter Wave Frequencies (30-300 Ghz)
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(3) Massive Multi-Input Multi-Output (MIMO) Antenna Arrays

Lund University

Rice University

Nokia/Mitsubishi
A Symbiotic Relationship

- Millimeter wave frequencies
  - short wavelengths
  - larger propagation losses, shorter range operation
  - little multipath, line-of-sight (LOS) or near-LOS
  - low SNR
  - larger Doppler shifts, more sensitive to mobility

- Massive antenna arrays
  - large array gain
  - size proportional to wavelength
  - narrow, focused beamforming

- Small cells
  - short range
  - lower power
  - low mobility
  - interference-limited
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Research Group: Exploiting Antenna Arrays for Next-Generation Wireless Systems
“Smart” Antenna Systems

- interference reduction

Interference 1

Interference 2

User 1

User 2
“Smart” Antenna Systems

- interference reduction
- multiplexing users in space
- at high SNR, $M$ antennas can yield $M$-fold gain in rate w/out bandwidth expansion
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- in general, to increase rate by $R$ and null $J$ jammers, need $M=R+J$ antennas

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- user 1 and user 2 can be different antennas for the same user: MIMO

Interference 1

user 1

user 2

Interference 2
Massive Antenna Arrays for Wireless

The advantages of multiple antennas in wireless communications is by now well known:

- improved coverage
- improved diversity
- increased spectral efficiency
- reduced interference

MIMO is an important component of current WiFi and 4G-LTE standards
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At millimeter wave frequencies, on- or near-chip antennas produce a small Footprint for large arrays; e.g., a 12x12 array @ 30 GHz is less than 6”x6”
Standard Receiver Implementation

- Full precision ADC requires linear, low-noise amplifiers and AGC
- ADC power consumption grows exponentially with resolution
- A commercial TI 1 Gs/s 12-bit ADC requires as much as 2-4W
- Not practical for ideal massive MIMO
A One-Bit Receiver

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- A commercial TI 1 Gs/s 12-bit ADC requires as much as 2-4W
- Not practical for ideal massive MIMO
- One-bit ADC ⇒ simple RF, no AGC or high cost LNA
- Operates at a fraction of the power (mW)
- Compensate for quantization error with signal processing
Single Antenna Theoretical Analysis

**AWGN Channel Capacity**

\[ B \log_2(1 + \text{SNR}) \]

**1-Bit AWGN Capacity**

\[ 2B \left( 1 - H_b(\Phi(\sqrt{\text{SNR}})) \right) \]

*loss in power efficiency < 2dB when SE < 1.4 bpcu*

*trade-off between power and energy efficiency is less apparent for 1-bit systems*
Consider a Gaussian signal that passes through a non-linear operator:

\[ r = Q(x) \]

Bussgang (Bell Labs, 1952) showed that a statistically “equivalent” (up to second order) linear model exists for the non-linearity

\[ r = Q(x) = Ax + q \]

that results in the error \( q \) (here the quantization noise) and the signal \( x \) being uncorrelated, namely

\[ A = \mathcal{E}\{xr^T\}\mathcal{E}\{xx^T\}^{-1} \]

This is also the choice that minimizes the quantization noise:

\[ A = \arg \min_A \|r - Ax\|^2 \]
Recent Research Activities

- How many more antennas are needed with one-bit quantization?
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Answer: \( \frac{\pi^2}{4} \approx 2.5 \)
Recent Research Activities

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  \[ \frac{\pi^2}{4} \approx 2.5 \]

- How to estimate the wireless channel with one-bit quantization?
  
  Answer: Bussgang LMMSE
Example: Channel Estimation Error Bounds

This is why dithering is beneficial!
Example: Channel Estimation

- $M = 128$
- $K = 8$
- $\tau = K$
- Rayleigh fading
Recent Research Activities

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- How to maximize spectral/energy efficiency?
  
  Answer: Convex optimization for energy-per-bit
Example: Optimizing Energy per Bit

- $K = 8$ users
- unoptimized
  $\rho_d = \rho_p$
- coherence interval $T = 200$
- sum spec. eff.
  \[ S = \frac{T - K}{T} K R \]
Recent Research Activities

- How many more antennas are needed with one-bit quantization?
  
  Answer: $\frac{\pi^2}{4} \approx 2.5$

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  Answer: Bussgang LMMSE

- How to maximize spectral/energy efficiency?
  
  Answer: Convex optimization for energy-per-bit

- How to precode the signals to account for one-bit DAC?
  
  Answer: Perturbed quantized linear precoding
Example: Performance of Perturbed Quantized ZF Precoder

- $M = 128$
- $K = 8$ users
- Rayleigh fading
- Perfect CSI

![Graph showing the performance of different precoding schemes with respect to SNR at user terminals. The graph plots Symbol Error Rate (y-axis) against SNR at user terminals (x-axis). Different lines represent various precoding schemes including Q-MRC, Q-ZF, Q-MMSE, MRC, ZF, and MMSE. The perturbed Q-ZF scheme is indicated.]
Conclusion

Can we get a 1000x improvement in throughput with only one-bit transceivers?
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Can we get a 1000x improvement in throughput with only one-bit transceivers?

YES!

(with a GHz of bandwidth and the right processing)