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Low Cost Massive MIMO: A Key Technology for 5G

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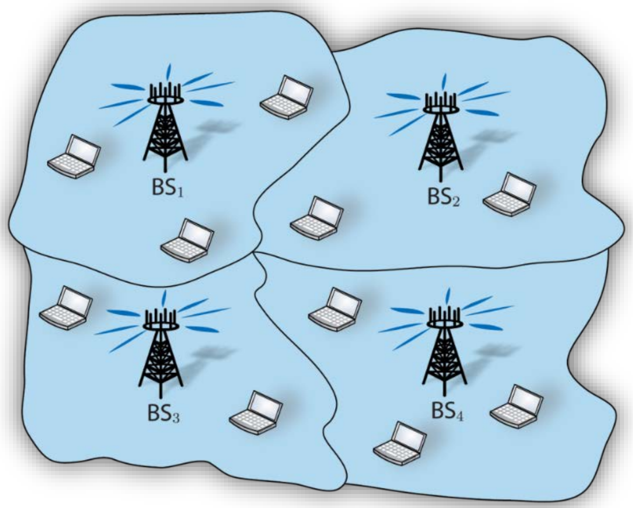
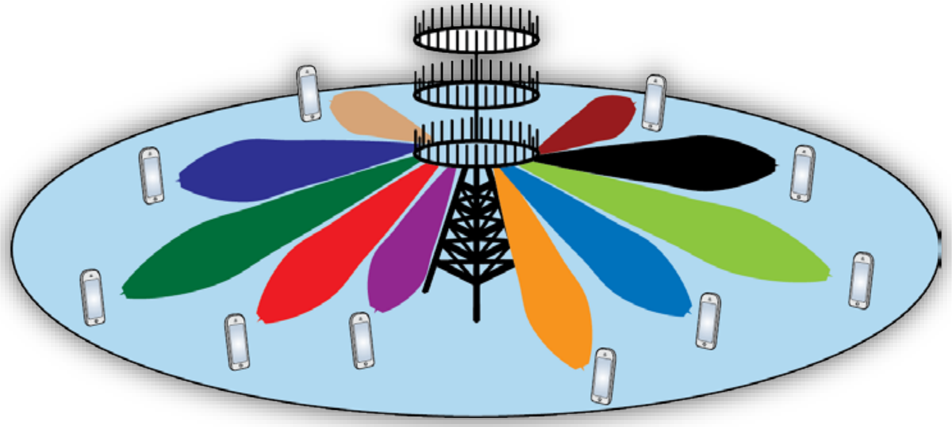
Basics of massive MIMO

- Multi-Cell Multiple-Input Multiple-Output (MIMO)
  - Cellular system with L cells
  - Base stations (BSs) with N antennas
  - K single-antenna users per cell
  - Share a flat-fading subcarrier
  - Beamforming: Spatially directed transmission/reception





Massive MIMO

Large arrays: e.g., $N = 200$

Often: $N \gg K$ (not necessary!)

Very narrow beamforming

Little interference leakage

Low-cost massive MIMO: A technological shift

- Excessive degrees of freedom: in case one antenna unit fails, the system performance will not be greatly affected!
- Hardware accuracy constraints can be **relaxed**, thus allowing the deployment of lower-quality (inexpensive) components in massive MIMO, compared to today's examples.

Low-cost massive MIMO: A technological shift

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Research challenge

Lower quality components ⇒
More prone to hardware imperfections

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Research challenge

Lower quality components ⇒
More prone to hardware imperfections

Systematic modeling of hardware imperfections is missing from the literature

Low-cost massive MIMO: A technological shift

- Many Antenna Elements?
  - We already have many antennas!
  - LTE-A: $N = 3 \cdot 4 \cdot 20 = 240$
  - But only 12-24 antenna ports!
- MIMO with Many Antenna Ports
  - Duplicate # of hardware components

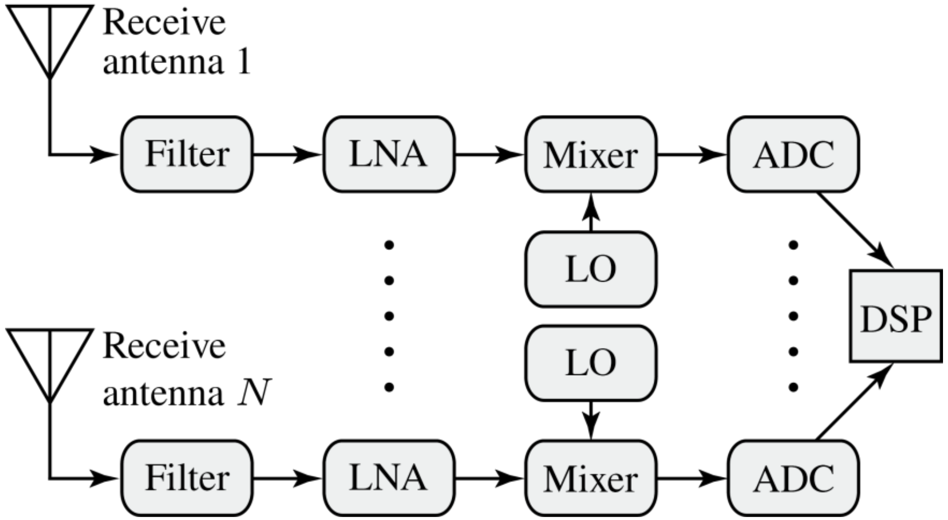
On Each Uplink Receiver Chain

Different Filters

Low-Noise Amplifier (LNA)

Mixer, Local Oscillator (LO)

Analog-to-Digital Converter (ADC)



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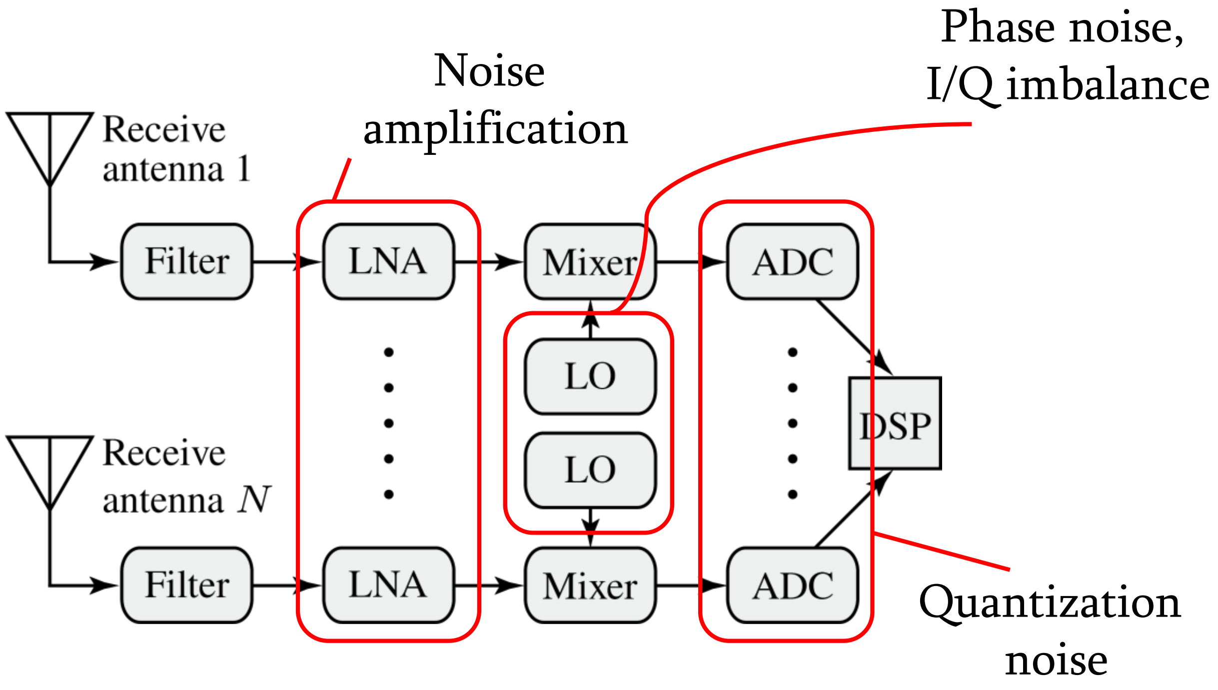
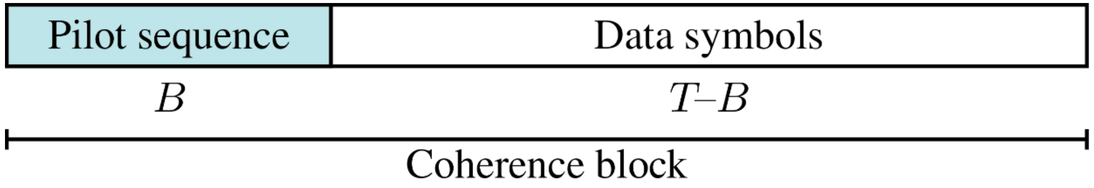


Research highlights: New generalized error model and hardware scaling laws

- Channel Assumptions
  - Channels from cell l to cell j: $\mathbf{H}_{jl} = [\mathbf{h}_{jl1} \ \ldots \ \mathbf{h}_{jlK}] \in \mathbb{C}^{N \times K}$
  - Rayleigh fading: $\mathbf{h}_{jlk} = [h_{jlk}^{(1)} \ \ldots \ h_{jlk}^{(N)}]^{\mathrm{T}} \sim \mathcal{CN}(\mathbf{0}, \lambda_{jlk}\mathbf{I}_N)$
- Block Fading
  - Fixed realizations for T channel uses (coherence block)



- Uplink Signals
  - From UE k, cell l: $x_{lk}(t)$ with power $\mathbb{E}\{|x_{lk}(t)|^2\} \leq p_{lk}$
  - Used for both pilot and data
  - Signals from cell l: $\mathbf{x}_l(t) = [x_{l1}(t) \ \ldots \ x_{lK}(t)]^{\mathrm{T}} \in \mathbb{C}^K$

Research highlights: New generalized error model and hardware scaling laws

- Received in Cell j: $$\mathbf{y}_j(t) = \sum_{l=1}^{L} \mathbf{H}_{jl} \mathbf{x}_l(t) + \mathbf{n}_j(t)$$

Channels from UEs in cell l

Signal from UEs in cell l

Thermal noise (variance σ^2)

Receiver Noise

$$\boldsymbol{\eta}_j(t) = \sqrt{\xi}\,\mathbf{n}_j(t) \sim \mathcal{CN}(\mathbf{0}, \sigma^2 \xi \mathbf{I}_N)$$

- New Generalized Model: $$\mathbf{y}_j(t) = \mathbf{D}_{\boldsymbol{\phi}_j(t)} \sum_{l=1}^{L} \mathbf{H}_{jl} \mathbf{x}_l(t) + \boldsymbol{\upsilon}_j(t) + \boldsymbol{\eta}_j(t)$$

Phase Drift

$$\mathbf{D}_{\boldsymbol{\phi}_j(t)} \triangleq \mathrm{diag}\left(e^{\imath \phi_{j1}(t)}, \ldots, e^{\imath \phi_{jN}(t)}\right)$$

Rotates phases by Wiener process:

$$\phi_{jn}(t) \sim \mathcal{N}(\phi_{jn}(t-1), \delta)$$

Distortion Noise

$$\boldsymbol{\upsilon}_j(t) \sim \mathcal{CN}(\mathbf{0}, \boldsymbol{\Upsilon}_j(t))$$

Proportional to received signal:

$$\boldsymbol{\Upsilon}_j(t) \triangleq \kappa^2 \sum_{l,k} \mathbb{E}\{|x_{lk}(t)|^2\} \mathrm{diag}\left(|h_{jlk}^{(1)}|^2, \ldots, |h_{jlk}^{(N)}|^2\right)$$

Research highlights: New generalized error model and hardware scaling laws

- Model has 3 Parameters: δ, κ, ξ
  - Ideal hardware: $\delta = \kappa = \xi = 0$
- Phase Drifts
  - $\delta =$ Variance of innovations
  - Source: Phase noise in oscillator
- Distortion Noise
  - $\kappa =$ Error vector magnitude (EVM) $= \dfrac{\text{Distortion magnitude}}{\text{Signal magntitude}}$
  - Ratio between distortion and signal magnitudes
  - Source: Quantization noise (with automatic gain control)
- Receiver Noise
  - $\xi =$ Noise amplification factor
  - Source: Amplification of thermal noise

Main Question

How do δ, κ, ξ
affect the performance in
massive MIMO?

Research highlights: New generalized error model and hardware scaling laws

- Hardware can be Gradually Degraded as $N \to \infty$
  - May use hardware components of lower quality!

Additive distortions
- Increase Distortion/Receiver Noise Variances (κ^2, ξ) as $\sqrt{N}$
- Example: $0.25 \cdot \log_2(N)$ fewer quantization bits (in ADC)
  $5 \log_{10}(N)$ higher noise figure (in LNA)

Multiplicative distortions
- Increase Phase Drift Variance as $\frac{1}{\delta_0(T-B)} \log_e(N)$
- Example: Increase phase noise variance δ or handle larger T

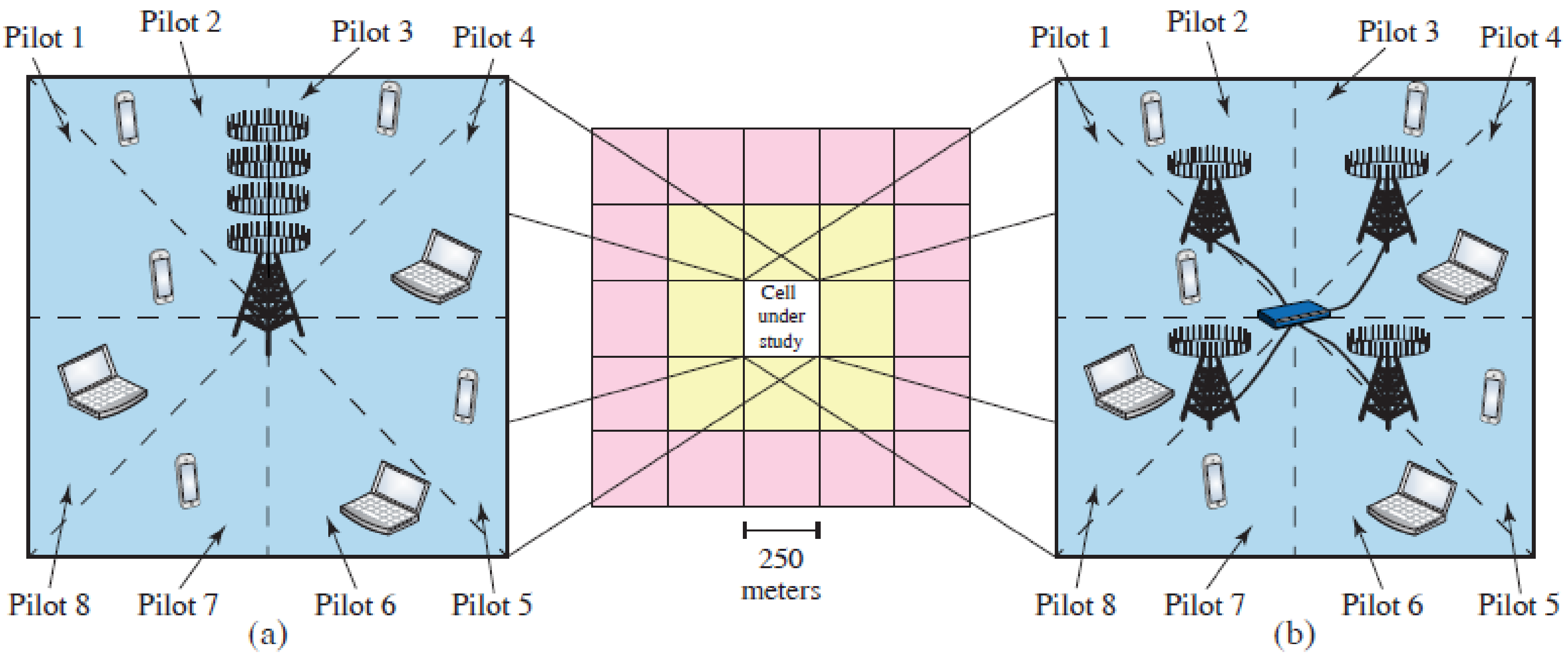
Corollary 2 (Scaling Law on Hardware Imperfections)

Substitute $\kappa^2 \mapsto \kappa_0^2 N^{\tau_1}$, $\xi \mapsto \xi_0 N^{\tau_2}$, and $\delta \mapsto \delta_0(1 + \log_e(N^{\tau_3}))$.

If exponents τ_1, τ_2, τ_3 are selected as $\max(\tau_1, \tau_2) + \frac{\delta_0(t-B)}{2}\tau_3 \leq \frac{1}{2}$

then the SINRs stay non-zero as $N \to \infty$

Numerical results



- $K = 8$, uniform UE distribution in 8 virtual sectors
- Typical 3GPP pathloss model
- 24 interferering cells

Assumptions

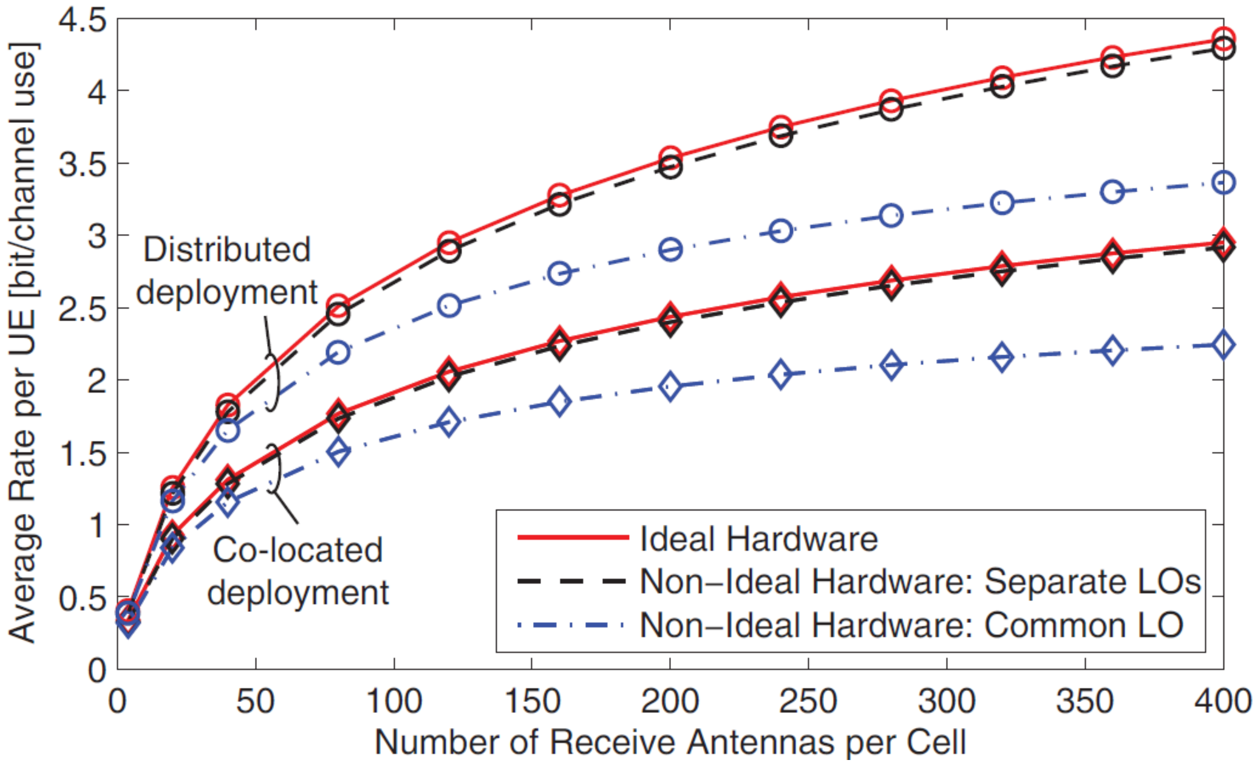
Pilot sequences: $B = 8$, DFT matrices

Coherence block: $T = 500$

Number of antennas:

$0 \leq N \leq 500$

Numerical results



Fixed hardware imperfections with $(\kappa,\xi,\delta)=(0.0156,1.58\sigma^2,1.58\text{x}10^{-4})$.

- Hardware imperfections cause small rate losses when the number of antennas, *N*, is small
- Large-*N* behaviour depends strongly on the oscillators: the rate loss is small for SLOs at any *N*, while it can be very large if a CLO is used when *N* is large (e.g., 25% rate loss at $N = 400$).
- Distributed massive MIMO deployment achieves 20–50% higher rates than co-located massive MIMO (exploit both proximity gains, achieved by small cells, as well as array gains and spatial resolution over many antennas.

Research highlights: Low-resolution ADCs for massive MIMO

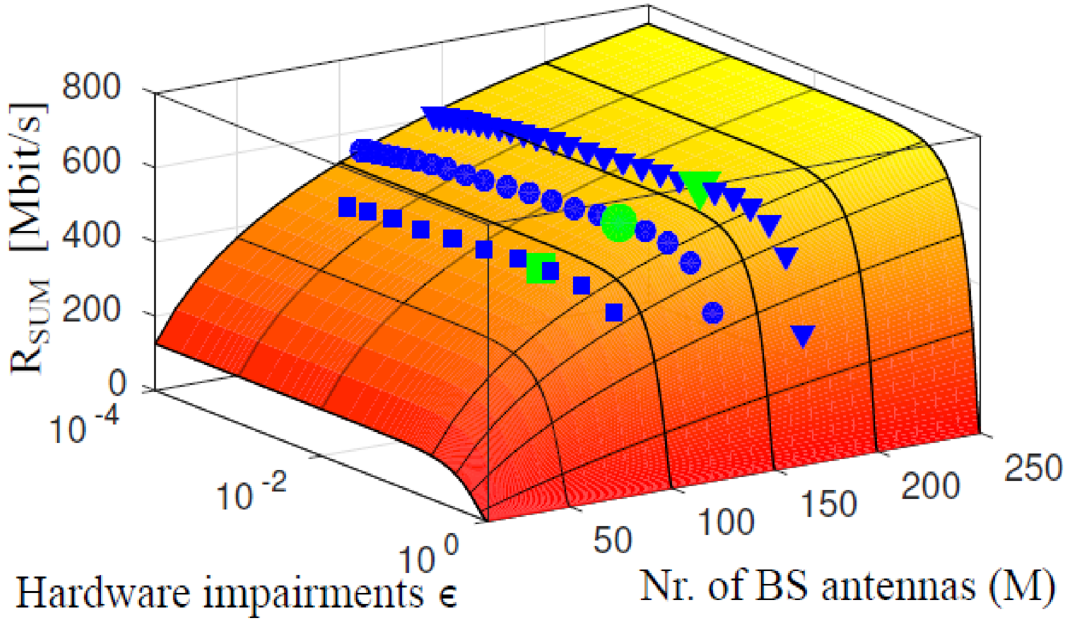


Figure 2. Sum data rate [Mbit/s] as a function of M and ϵ for $K = 10$ and $\rho = 0.3162\sigma^2$ (SNR= -5dB). The blue squared, circle and triangle points represent the curves where $P(\epsilon, M) = \gamma$ for $\gamma = \{22, 26, 30\}$ [W] respectively, and the green points are the corresponding maximum data rates.

The sum rate is an increasing function of *M* and decreasing function of ε.

For a maximum power of γ = {22,26,30}W the maximum rate is obtained for *M* = {87,126,164} and ε = {0.055,0.056,0.056) which corresponds to 4 or 5 quantization bits.

Research highlights: Low-resolution ADCs for massive MIMO

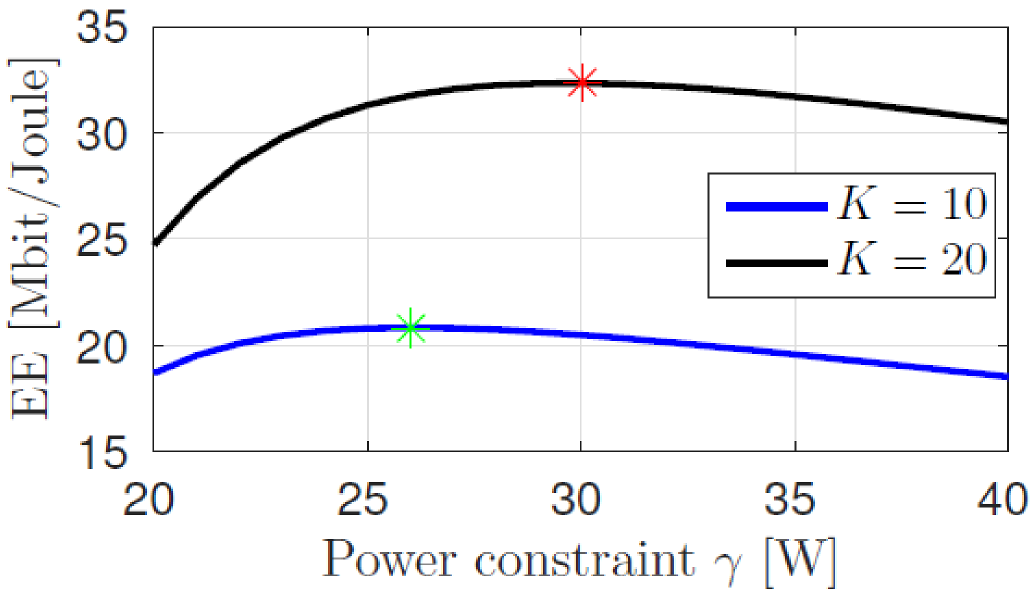


Figure 3. EE [Mbit/Joule] as a function of γ for $K = \{10, 20\}$ and $\rho = 0.3162\sigma^2$ (SNR = −5dB). The star represents the maximum EE located at $\gamma^* = \{26, 30\}$ [W], which corresponds to $M^* = \{126, 132\}$ and $\epsilon^* = \{0.056, 0.0795\}$ respectively.

Notice that the EE has a unique maximum point, which means that we should appropriately select the level of hardware impairments ε to maximize the EE.

Research highlights: I/Q imbalance in massive MIMO

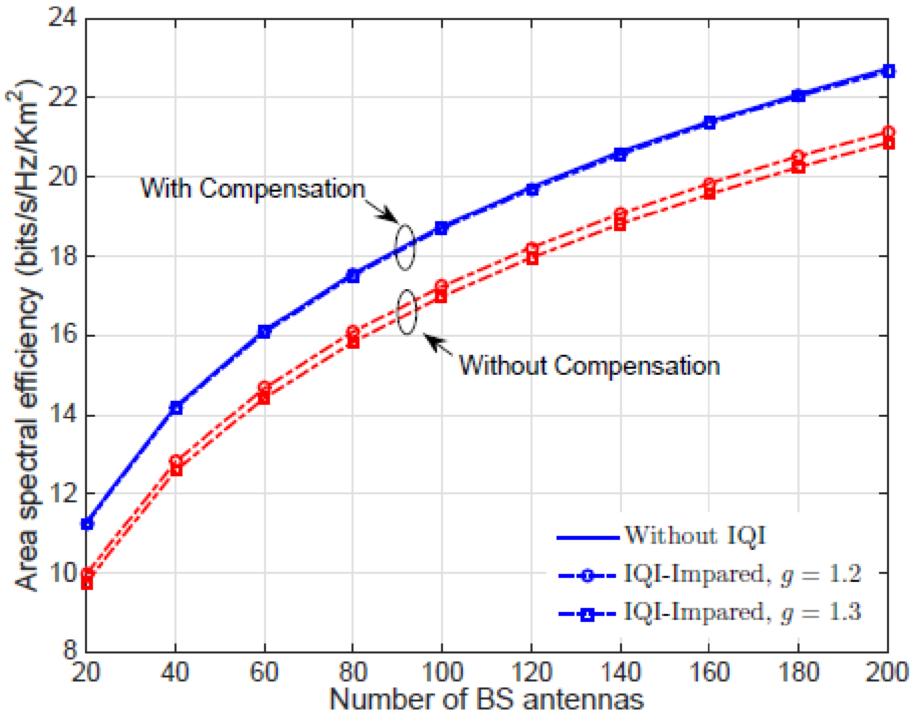
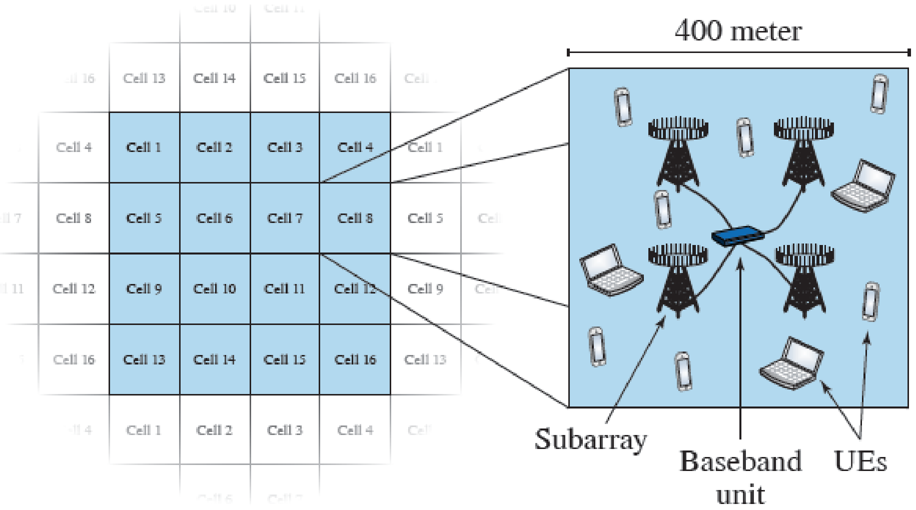


Fig. 4. Area spectral efficiency of MRC receivers with different estimation error of the IQI coefficients. In this example, $K = 10$, $\rho_u = 16$dB and the propagation channel parameters are $\sigma = 10$dB and pathloss $\alpha = 3.8$.

The proposed compensation scheme is based on the zero-forcing principle. Without I/Q compensation, the performance degradation is at least 10%. Yet, massive MIMO shows resilience to the effects of I/Q imbalance.

Research highlights: Phase noise in massive MIMO



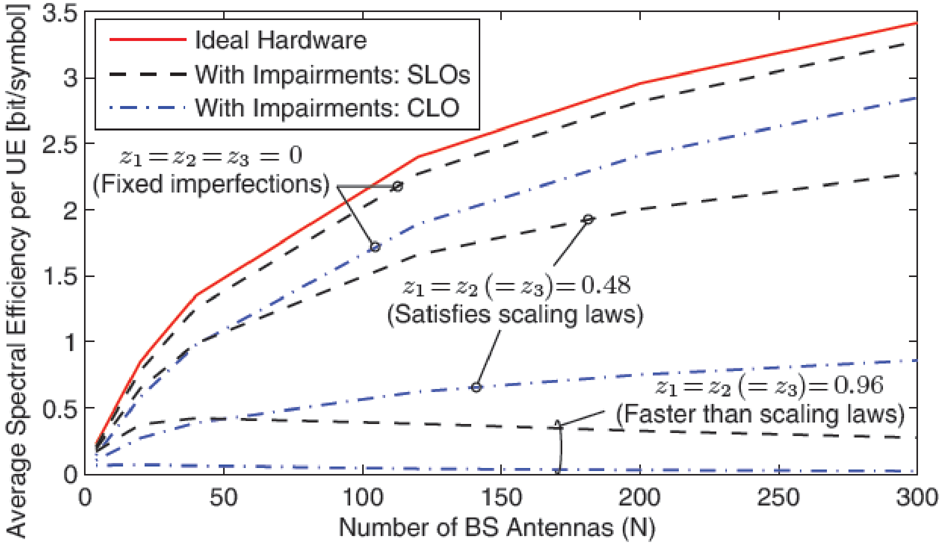


Fig. 3. Average DL spectral efficiency for distributed massive MIMO with fixed or increasing hardware impairments.

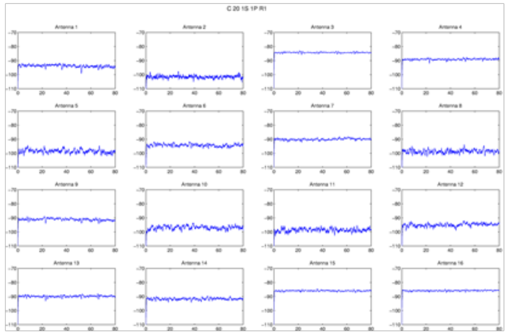
By gradually degrading the hardware with N, there is a performance loss at every N, but the curves are still increasing with N. The performance loss is small for SLOs, but very large for a CLO.

What's inside that building?

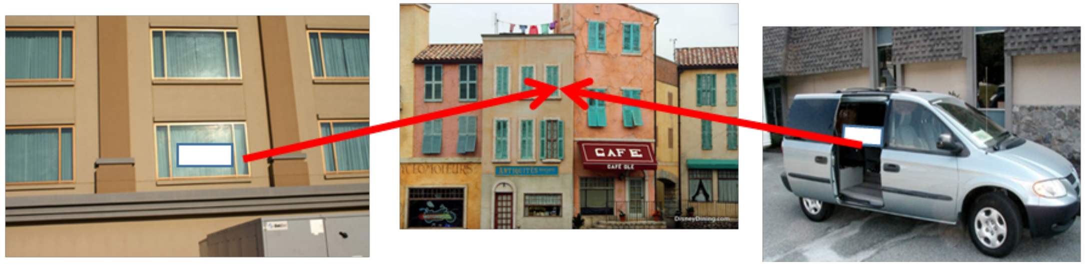
Key idea: Massive MIMO offers a large number of degrees of freedom that can be exploited to determine:

- the actual occupancy of a building, since the movement of people causes variations in the channel response;
- degree of activity inside the building by examining the temporal variation in the number of noise sources detected.

Prototype 2.48 GHz ULA and sample output

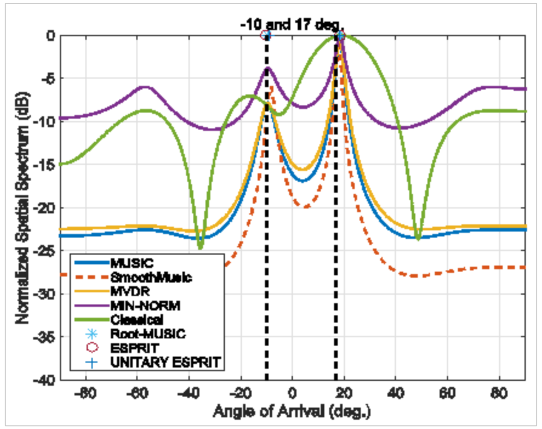


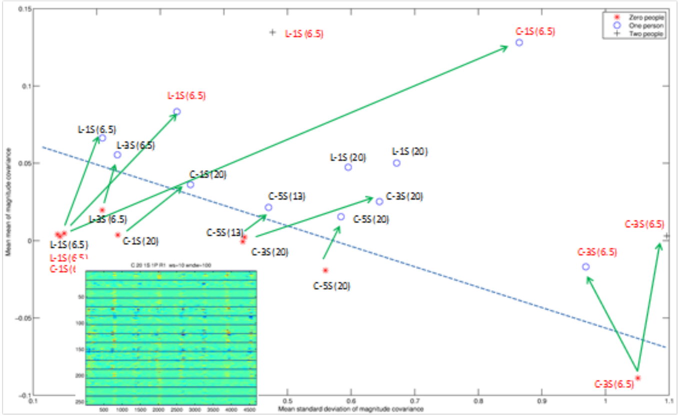
Low-cost massive MIMO sensing system that can be easily deployed in any combat scenario to remotely detect pedestrian activity in populated buildings in real-time



Project contributions

- Implementation of array processing algorithms to determine the actual position of noise sources inside a building
- Extensive real-time measurements in a variety of cluttered environments using different array configurations (ULA, UCA) and at different frequencies (868MHz, 2.48GHz)
- Second-order characterisation of channel variations using only magnitude-information.





Left graph: Performance of different DoA algorithms with two noise sources located at -10 and 17deg.

Right graph: Mean standard deviation of pair-wise covariance versus mean of means for the linear array. The unoccupied cases are indicated by a red star (*) and the one person cases by a blue circle (O). Any matching "unoccupied-occupied" cases are joined by a green arrow. The cases with two pedestrians are shown as +.

Conclusions

- Massive MIMO has been identified as a core technology for 5G networks. The main challenge pertaining to its successful roll-out is to maintain the implementation cost to affordable levels by reducing the cost per RF chain!
- Low-cost massive MIMO seems as the most viable candidate to realize this goal by deploying low-cost, low-power hardware.
- We investigated the fundamental tradeoff between having many BS antennas and high-quality hardware.
- We have developed new error models to account for phase noise, ADC quantization noise and I/Q imbalance
- We have also developed hardware scaling laws for circuit-aware design, compensation schemes and have determined the optimal operating points
- We built a passive massive MIMO receiver to detect the human occupancy inside buildings from a stand-off distance of 32m.

Main collaborators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Relevant research outputs

- C. D. Ho, H. Q. Ngo, **M. Matthaiou**, and T. Q. Duong, "On the performance of zero-forcing processing in multi-way massive MIMO relay networks," *IEEE Communications Letters*, vol. 21, no. 4, pp. 849-852, April 2017.
- W. Tan, **M. Matthaiou**, S. Jin, and X. Li, "Spectral efficiency of DFT-based processing hybrid architectures in massive MIMO," *IEEE Wireless Communications Letters*, 2017.
- N. Kolomvakis, **M. Matthaiou**, and M. Coldrey, "IQ imbalance in multiuser systems: Channel estimation and compensation," *IEEE Transactions on Communications*, vol. 64, no. 7, pp. 3039–3051, July 2016.
- X. Zhang, **M. Matthaiou**, E. Björnson, and M. Coldrey, "Impact of residual transmit RF impairments on training-based MIMO systems," *IEEE Transactions on Communications*, vol. 63, no. 8, pp. 2899-2911, August 2015.
- E. Björnson, **M. Matthaiou**, and M. Debbah, "Massive MIMO with non-ideal arbitrary arrays: Hardware scaling laws and circuit-aware design," *IEEE Transactions on Wireless Communications*, vol. 14, no. 8, pp. 4353-4368, August 2015.
- D. Verenzuela, E. Björnson, and **M. Matthaiou**, "Per-antenna hardware optimization and mixed resolution ADCs in uplink massive MIMO," in *Proc. IEEE Asilomar Conference on Signals, Systems, and Computers*, November 2017 **(Invited paper)**.
- D. Verenzuela, E. Björnson, and **M. Matthaiou**, "Hardware design and optimal ADC resolution for massive MIMO systems," in *Proc. IEEE Sensor Array and Multichannel Signal Processing Workshop (SAM),* July 2016 **(Invited paper)**.
- L. Fan, D. Qiao, S. Jin, C.-K.Wen and **M. Matthaiou**, "Optimal pilot length for uplink massive MIMO systems with low-resolutions ADCs," in *Proc. IEEE Sensor Array and Multichannel Signal Processing Workshop (SAM),* July 2016 **(Invited paper)**.

Open research challenges

- Low-ADC resolution for frequency-selective and mm-wave channels
- Mixed-ADC receivers for massive MIMO systems
- Phase noise mitigation in massive MIMO: Pilot orthogonality is broken!
- Optimal operating points in the SE-EE curve with hardware-constrained massive MIMO base stations
- Hybrid processing in massive MIMO systems: How much processing can we throw into the analog domain before the performance is substantially degraded?
- Lens arrays vs ULAs: Which one is the best and cheapest?

Thank You!

Any questions?