Working with a Huge Number of Antennas in 5G and Beyond: Challenges and Opportunities

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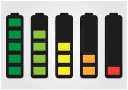
Outline

Digital Communications

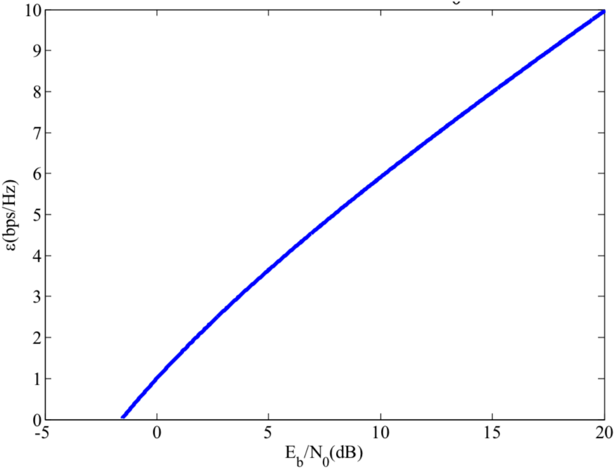
- Low error rates
- Higher and higher bit rates
- Spectral efficiency [bps/Hz]

- Power savings



Channel Capacity

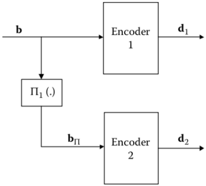
$$C = B\log_2(1+SNR) \iff \frac{E_b}{N_0} = \frac{2^\epsilon - 1}{\epsilon}$$



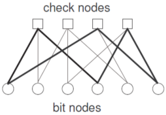
Approaching Channel Capacity

Channel codes

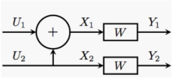
- Turbo codes



- LDPC codes

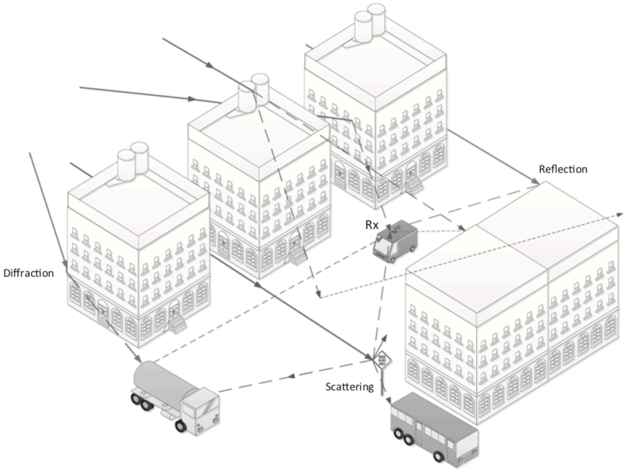


- Polar codes



Performance a fraction of dB from the channel capacity

Multipath propagation effects

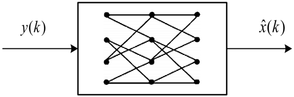


⇒ Frequency Selective Channels

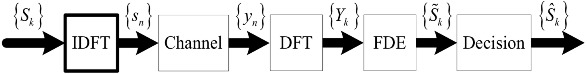
Frequency Selective Channels

Equalization techniques

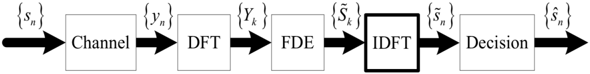
- MLSE (Maximum Likelihood Sequence Estimation)



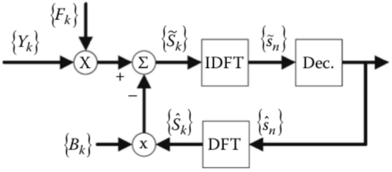
- OFDM

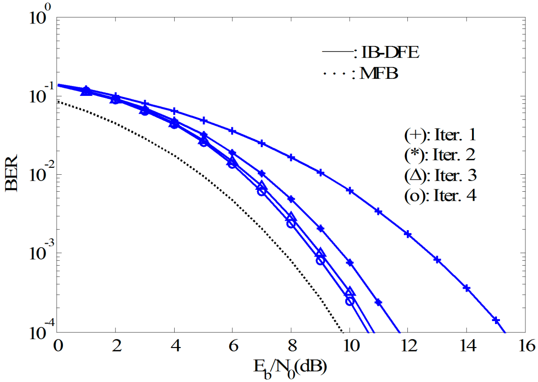


- SC-FDE



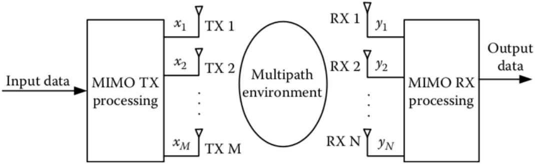
Iterative Block Decision Feedback Equalizer





- Iterative equalizer
- No error propagation effects
- Performance close to the MFB (Matched Filter Bound)

MIMO Channel



- Received signal: $\mathbf{y} = \mathbf{Hx} + \mathbf{n}$
- Channel knowledge at the transmitter

$$C = \max_{\mathbf{R}} \log_2 \left(\det \left(\mathbf{I} + SNR\mathbf{HRH}^H \right) \right)$$

$$C = \sum_p \log_2(1 + SNR|\lambda_p|^2)$$

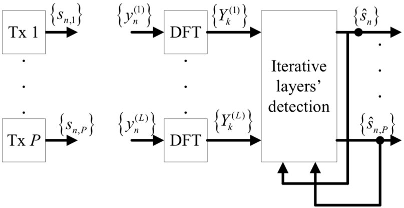
- No channel knowledge at the transmitter

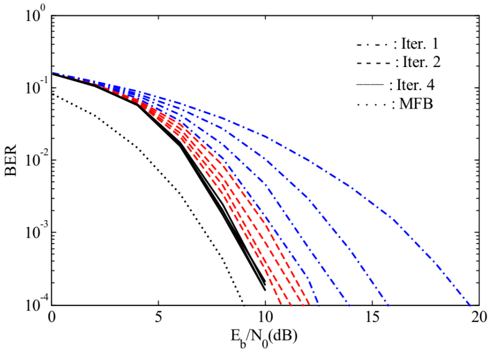
$$C = \log_2 \left(\det \left(\mathbf{I} + \frac{SNR}{N_{Tx}} \mathbf{HH}^H \right) \right)$$

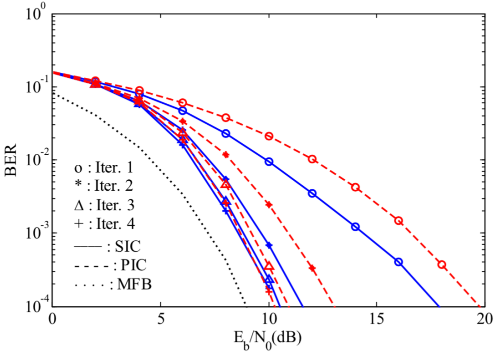
MIMO Channel

- Channel capacity grows with the number of antennas
- Gain relatively the SISO case upperbounded by $\min(N_{Tx}, N_{Rx})$
- Suitable for OFDM and SC-FDE schemes
- Optimum receiver too complex
- Practical receivers based on MMSE with excellent performance/complexity trade-offs

IB-DFE for MIMO







Massive MIMO

- Capacity gains increase with number of antennas
- Desire to have many antennas (say, 10 to 100)
- Massive MIMO

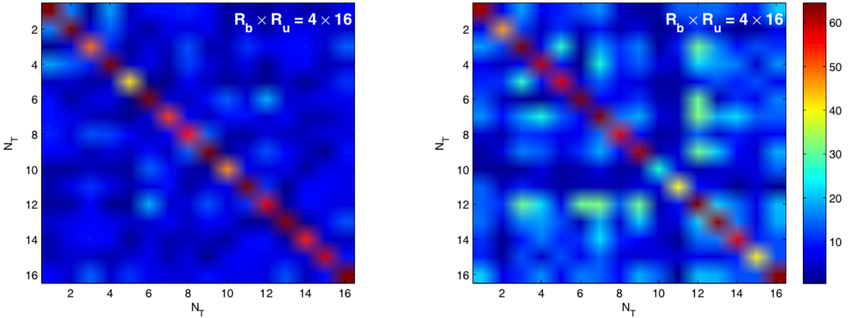
Massive MIMO

- Conventional MIMO schemes suitable for systems up to about 8×8
- Massive MIMO not a scaled version of MIMO!
- Need for low complexity implementations
- Common elements (RF chains, mixers, DAC/ADC, etc.)
- Low complexity implementations (low resolution DACs and ADCs, strongly nonlinear amplifiers, etc.)
- Channel estimation challenges (e.g., pilot contamination)

Massive MIMO - Low Complexity Equalization

- ZF/MMSE schemes require large matrix inversions
- Gram matrix of the channel

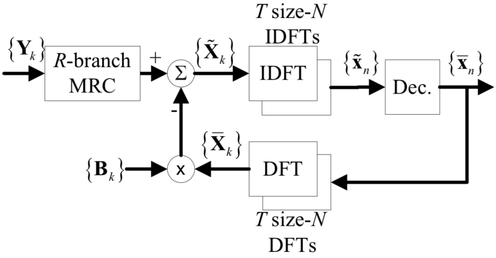
$\rho = 0.1$ $\rho = 0.9$

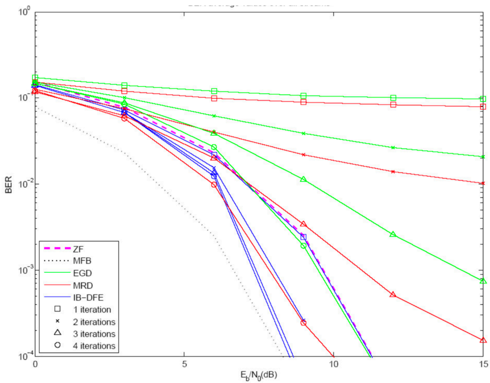


- MRC/EGC schemes do not need matrix inversions
- Require $N_{Rx} >> N_{Tx}$

Massive MIMO - Low Complexity Equalization

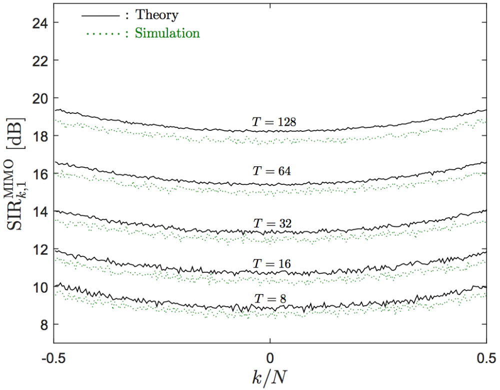
- MRC/EGC combined with IB-DFE
- Excellent performance



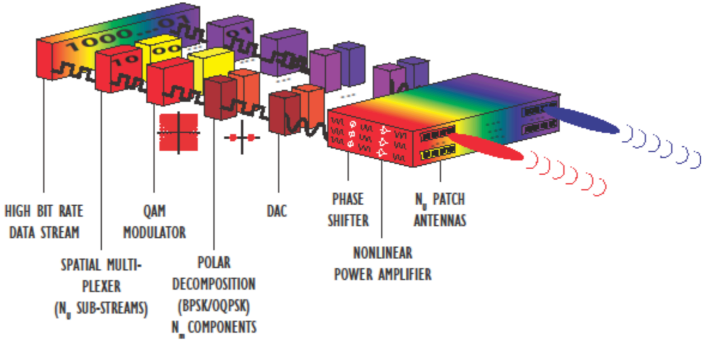


Massive MIMO - Low Resolution DACs

- Nonlinear distortion with small correlation for different DACs
- $SIR^{MIMO} \approx \frac{T}{R} SIR^{SISO}$
- Possible use of 1-bit DACs

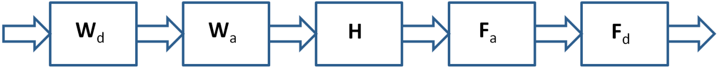


Massive MIMO - Multi-Layer Architectures

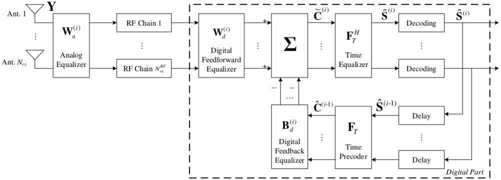


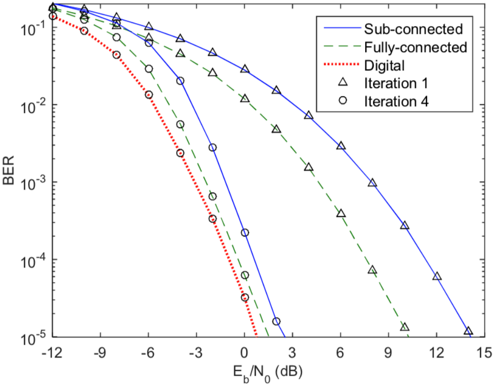
- Layer 1: Efficient power amplification (LINC schemes, multi-amplifiers)
- Layer 2; Beamforming
- Layer 3: Spacial multiplexing (conventional MIMO)

Massive MIMO - Hybrid Analog/Digital Architectures



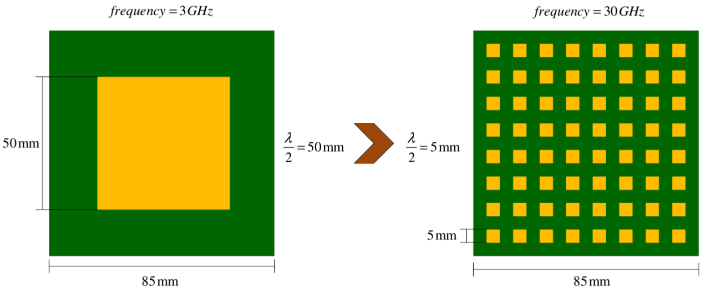
- MIMO processing split in digital and analog parts
- Analog part
  - Large matrices
  - Constant-modulus operations
  - Based on phased arrays
  - Common for all band
- Digital part
  - Small matrices
  - No (or little) constraints on the operations
  - Change with thes subcarrier
- Partially connected of fully connected approaches





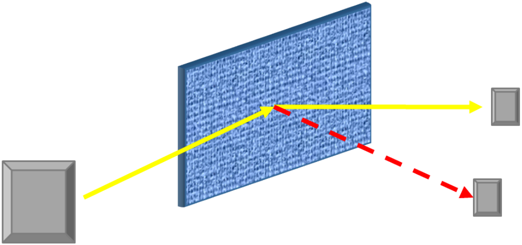
- Iterative receiver
- Low complexity
- Performance close to the fully digital approaches

Increased Antenna Density



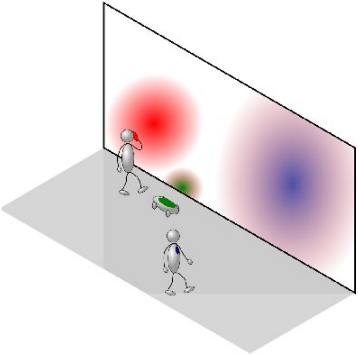
- Higher frequencies
- Smaller wavelengths
- Smaller antennas
- Large number of antennas per area
- Beyond massive MIMO

IRS - Intelligent Reflective Surfaces



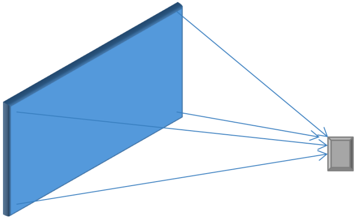
- Metasurfaces (Intelligent Reflecting Surfaces)
- Sub-λ-sized "Meta-atom" elements with controllable delay/phase, polarization
- Energy focusing
- Energy nulling
- Ideal positioning close to Tx or Rx
- Metasurface with built-in source: holographic beamforming
  $\Rightarrow$ No pathloss between Tx and metasurface

LIS - Large Intelligent Surfaces



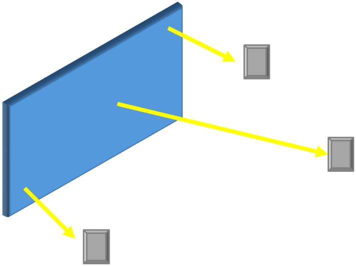
- Active elements
- Short range
- Near field communication
- LoS communication
- Antennas switched on and off according to user position/requirements
- Resource allocation at the space domain

LIS for Positioning



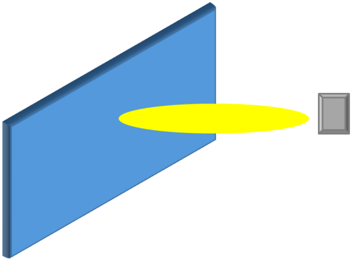
- Antennas with different RSS and/or AoA/AoD
- Accurate positioning

LIS for Communication



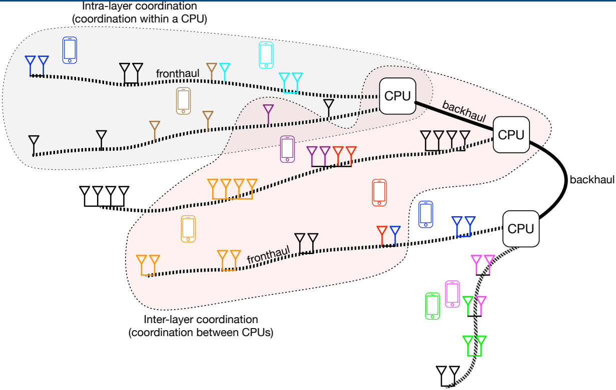
- Communication aided by positioning information
- Low complexity transmission and detection schemes
- Huge capacity and coverage gains
- Robustness to interference and imperfections

LIS for Energy Harvesting



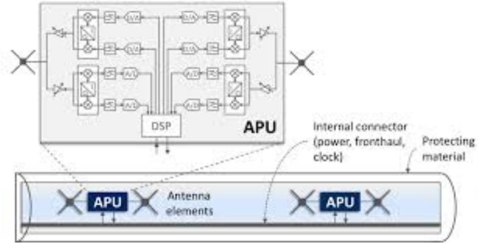
- Beamforming to compensate losses in energy harvesting
- Better range and/or energy harvesting efficiency than traditional techniques
- Ranges of 1m or more

Cell-Free Wireless Systems



- No cells
- AP behave as a distributed massive MIMOA system
- User associated to several APs
- User separation at CPU and/or AP level

Radio Stripes



- A stripe of APs
- Low cost
- Easy to deploy
- Almost invisible

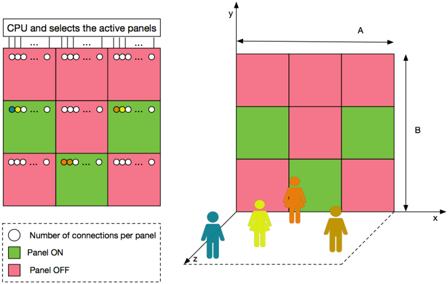
Transceiver Design

- Need for very low complexity transceivers
- On/off approaches
- Beamforming
- Skip equalizers?
- Interference cancellation
- Low resolution DAC/ADC (1 bit quantizers?)
- Low complexity amplifiers (saturated or even switched amplifiers)

Channel Estimation

- Too many channel to estimate
- Traditional channel estimation techniques not suitable
- Nonconventional approaches
  - Parameterized channel models
  - Position-aided channel estimation
  - Machine learning techniques
    - Deep learning
    - Reinforced learning
  - Channel tracking

Resource Allocation



- Space-domain resource allocation
- Aided by position information
- LIS split in panels
  - Many antennas per panel
  - Small number of outputs per panel
  - A user can be associated to several panels

Conclusions

- Path from SISO to beyond massive MIMO
- Several promising techniques
  - IRS
  - LIS
  - Radio stripes
- Challenges
  - Low complexity hardware implementation
  - Channel estimation
  - Resource allocation

Thank you!