Working with a huge number of antennas - A Look Beyond massive MIMO

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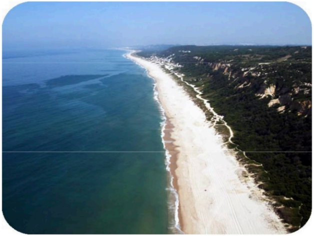
Costa de Caparica



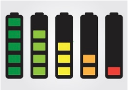
Costa de Caparica

Outline

Digital Communications

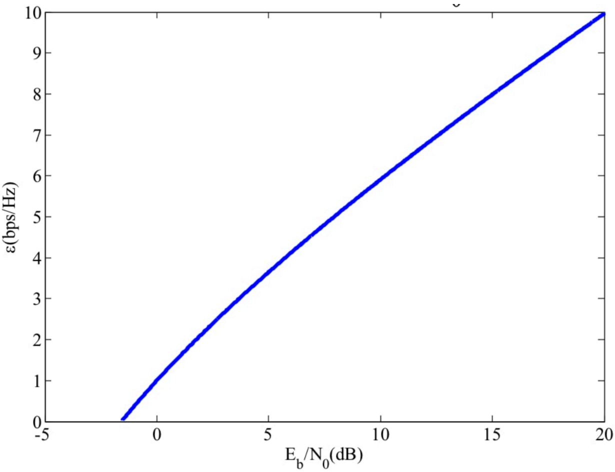
- Low error rates
- Higher and higher bit rates
- Spectral efficiency [bps/Hz]

- Power savings



Channel Capacity

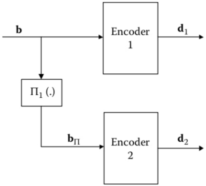
$$C = B\log_2(1+SNR) \iff \frac{E_b}{N_0} = \frac{2^\epsilon - 1}{\epsilon}$$



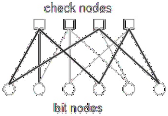
Approaching Channel Capacity

Channel codes

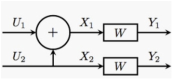
- Turbo codes



- LDPC codes

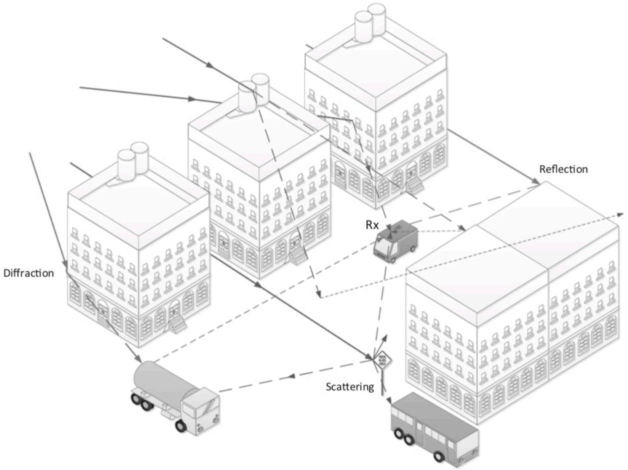


- Polar codes



Performance a fraction of dB from the channel capacity

Multipath propagation effects

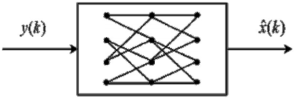


$\Rightarrow$ Frequency Selective Channels

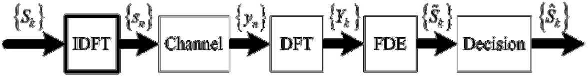
Frequency Selective Channels

Equalization techniques

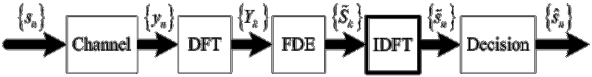
- MLSE (Maximum Likelihood Sequence Estimation)



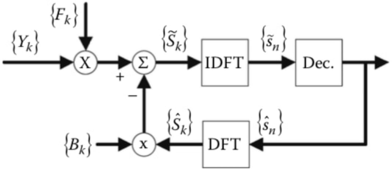
- OFDM

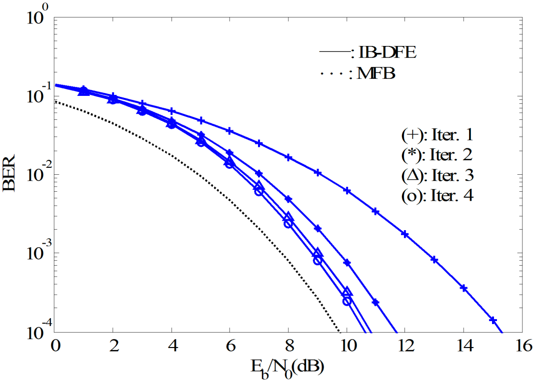


- SC-FDE



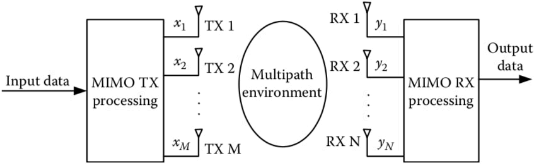
Iterative Block Decision Feedback Equalizer





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

MIMO Channel



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

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

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

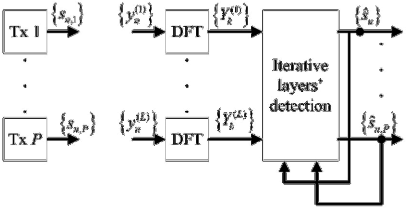
- No channel knowledge at the transmitter

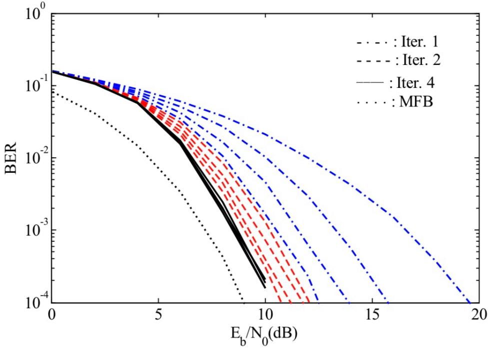
$$C = \log_2 \left(\det \left(\mathbf{I} + \frac{SNR}{N_{Tx}} \mathbf{H}\mathbf{H}^H \right) \right)$$

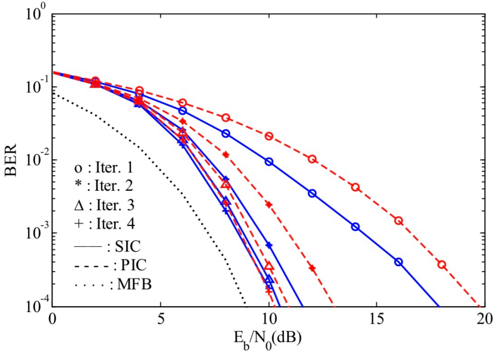
MIMO Channel

- 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

Massive MIMO

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

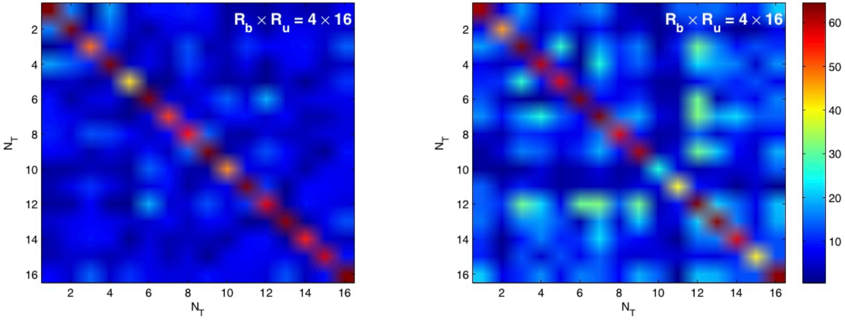
Massive MIMO

- 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

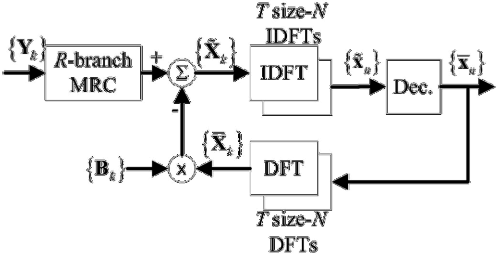
$\rho = 0.1$ $\rho = 0.9$

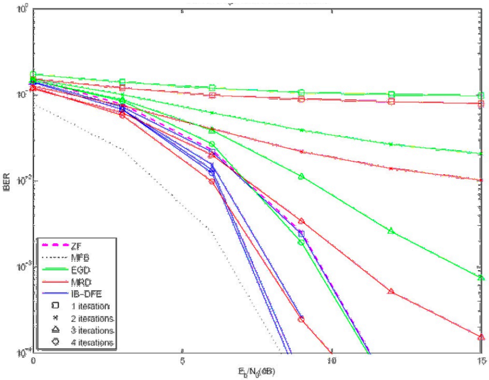


- MRC/EGC schemes do not need matrix inversions
- Require $N_{Rx} >> N_{Tx}$

Massive MIMO - Low Complexity Equalization

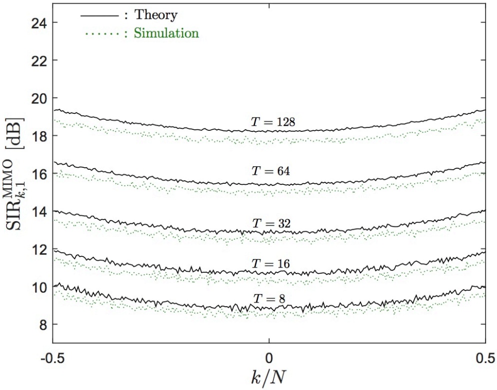
- MRC/EGC combined with IB-DFE
- Excellent performance



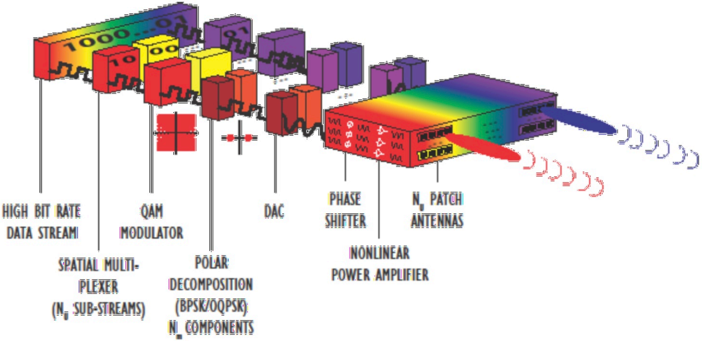


Massive MIMO - Low Resolution DACs

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

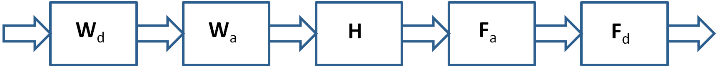


Massive MIMO - Multi-Layer Architectures



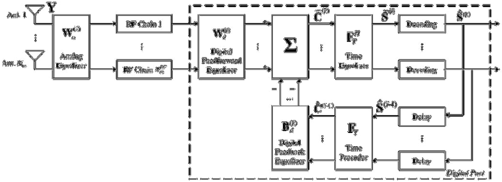
- Layer 1: Efficient power amplification (LINC schemes, multi-amplifiers)
- Layer 2; Beamforming
- Layer 3: Spacial multiplexing (conventional MIMO)

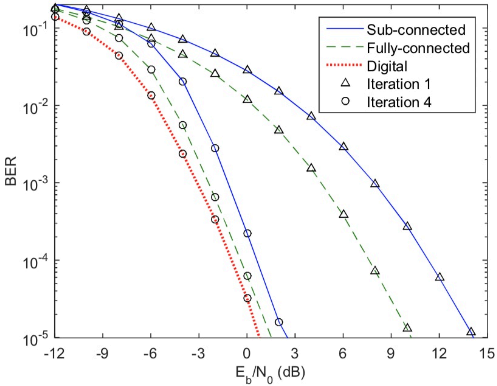
Massive MIMO - Hybrid Analog/Digital Architectures



- 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

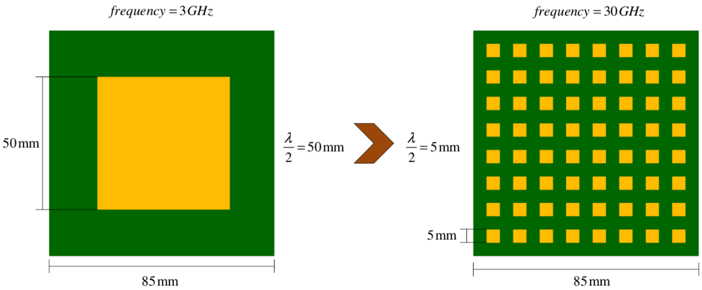
Massive MIMO - Hybrid Analog/Digital Architectures





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

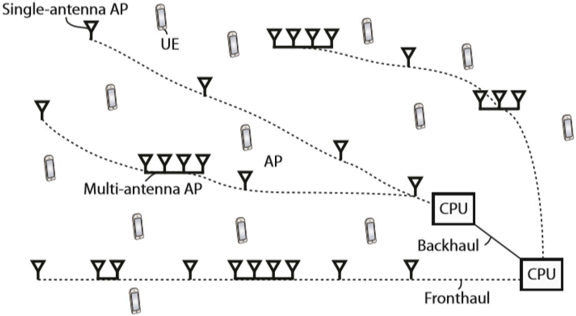
Increased Antenna Density



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

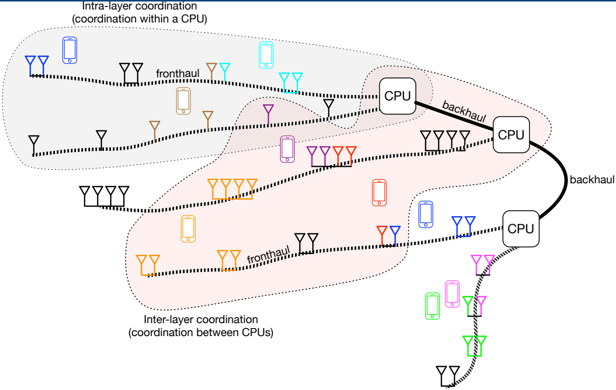
Beyond Massive MIMO: Cell Free

Cell-Free



- Ubiquitous service experience to the user's equipment (UE) regardless of their location in the cell.
- Concept of cell boundary disappears - no cells
- APs geographically spread out over a cellular network.

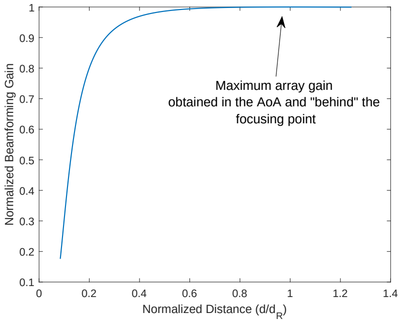
Cell-Free



- Sets of antennas grouped in access points (APs)
- AP behave as a distributed massive MIMO system
- User associated to several APs
- User separation at CPU and/or AP level

Far Field Beamforming

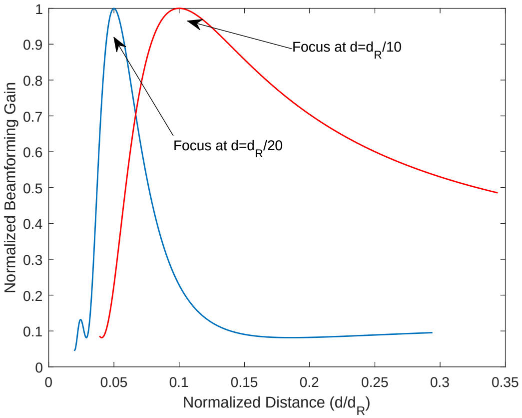
- Fraunhofer distance: $d_R = \frac{D^2}{\lambda}$ (D is the largest array dimension)
- $d > d_R$
- Plane wave assumption
- Infinite depth beamforming
- Beamforming gain a function of the AoA



Optimum normalized beamforming gain

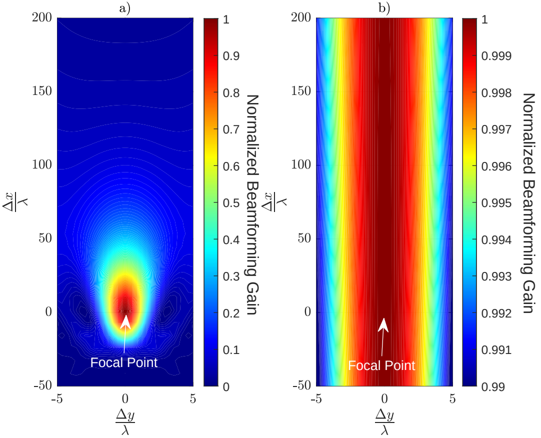
Near field Beamforming

- Large antenna arrays and/or very high carrier frequencies.
- Communication likely occurs in the near-field propagation region



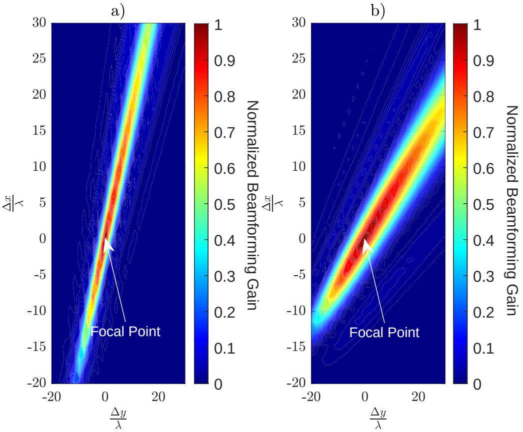
Optimum normalized beamforming gain for $d = d_R/20$ and $d = d_R/10$.

Near field vs Far Field Beamforming



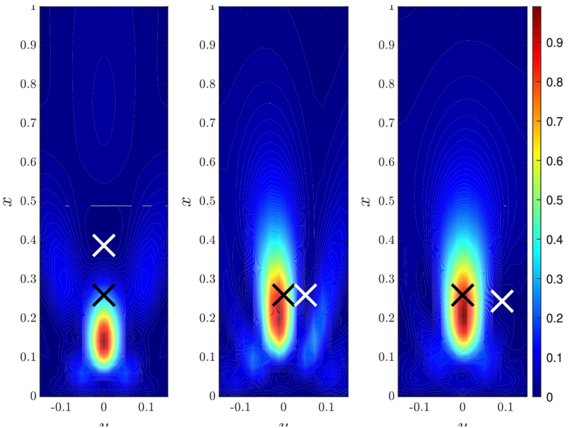
Normalized beamforming gain in the broadside direction for $d = d_R/30$ (a) and $d = d_R$ (b).

Near-field Beamforming



Normalized beamforming gain for $d = d_R/30$ considering different beamforming directions.

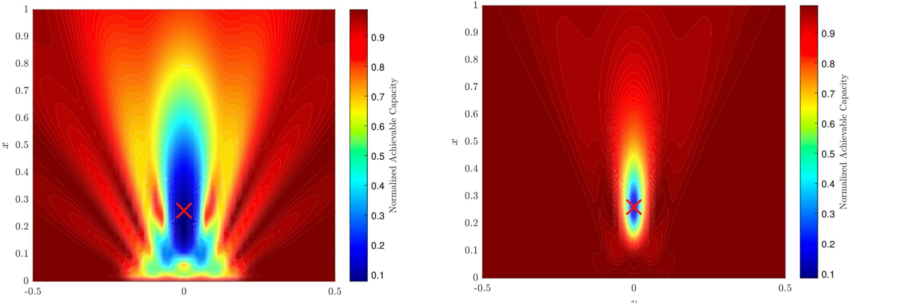
Near Field Communication



Receiver power with anti-jamming LIS

- Accurate focusing
- Interference rejection

Near Field Communication

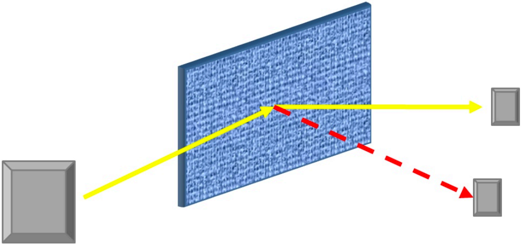


Capacity without LIS without or with knowledge of jammer position

- Strong anti-jammer capabilities
- Increased capacity over a wide area

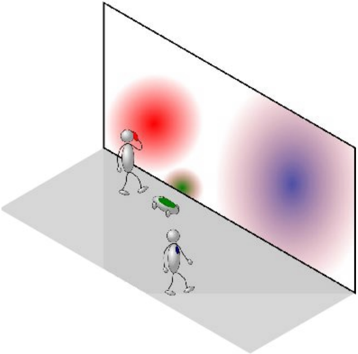
Enabling Technologies

RIS - Reflective Intelligent Surfaces



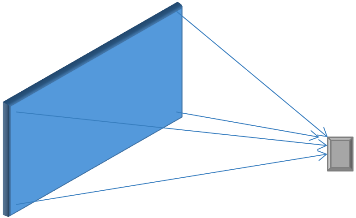
- Metasurfaces composed of sub-λ-sized "meta-atom" elements with controllable delay/phase, polarization
- Energy focusing and nulling
- Improved coverage and interference management
- Relatively low complexity
- Require channel knowledge
- Difficult to obtain with passive elements

LIS - Large Intelligent Surfaces



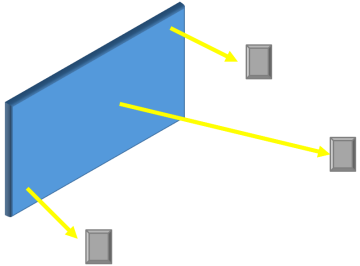
- Active elements
- Short range
- Near field communication
- LoS communication
- Antennas switched on and off according to user position/requirements
- Resource allocation at the space domain

LIS for Positioning



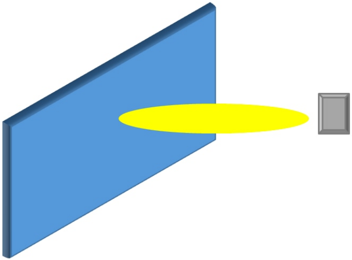
- Antennas with different RSS and/or AoA/AoD
- Accurate positioning

LIS for Communication



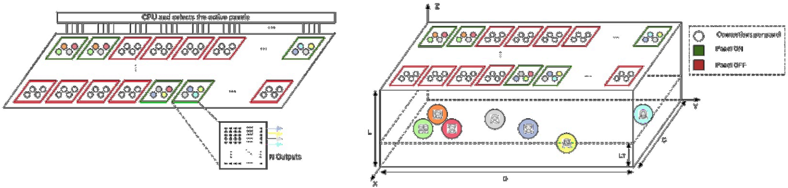
- Communication aided by positioning information
- Low complexity transmission and detection schemes
- Huge capacity and coverage gains
- Robustness to interference and imperfections

LIS for Energy Harvesting



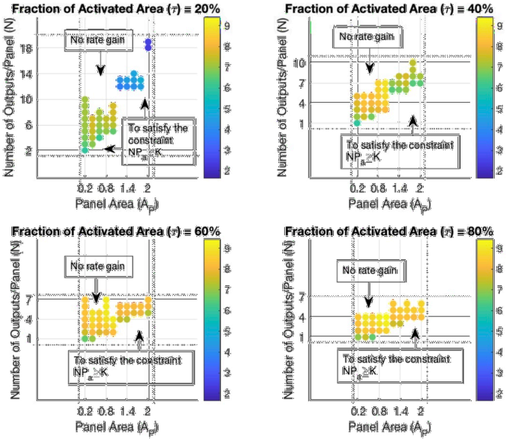
- Beamforming to compensate losses in energy harvesting
- Better range and/or energy harvesting efficiency than traditional techniques
- Ranges of 1m or more

Panel-based LIS



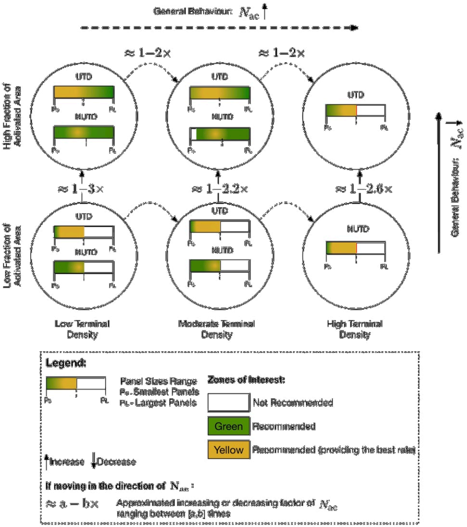
- Space-domain resource allocation
- Aided by position information
- LIS split in panels
  - Many antennas per panel
  - Small number of outputs per panel
  - A user can be associated to several panels

Panel-based LIS



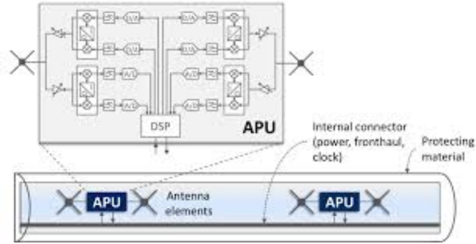
- Ideal panel area A_p and number of panel outputs
- Only a fraction of the LIS needs to be activated

Panel-based LIS



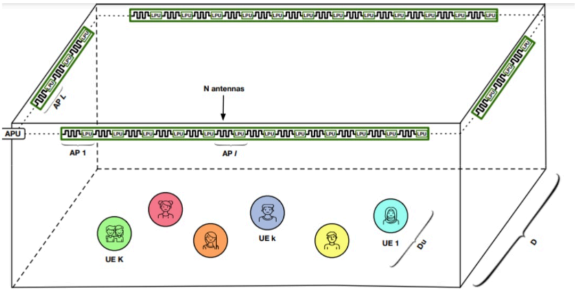
- Larger panels for non-uniform users
- More panel outputs N_{ac} with more users or larger panels

Radio Stripes



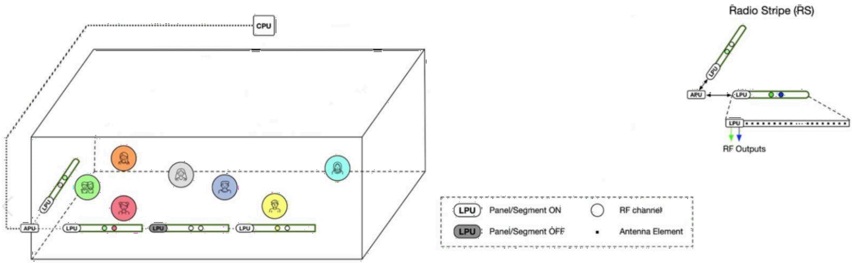
- APs sequentially located inside the same cable, providing synchronization, data transfer and power supply via a shared link.
- The need for dedicated fronthaul links between each AP and the corresponding CPU is avoided
- Low cost and easy to deploy

Radio Stripes



- RSs not associated with the coverage tier of a network, but rather dedicated to increase the capacity in specific small-to-moderate areas where it is hard to deploy conventional base stations
- Suitable to areas with many APs and UEs per km^2

Radio Stripes



- RS split in segments (as LIS with panels)
- Only a fraction of the segments is activated
- Users can be served by several RS segments

Challenges

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)

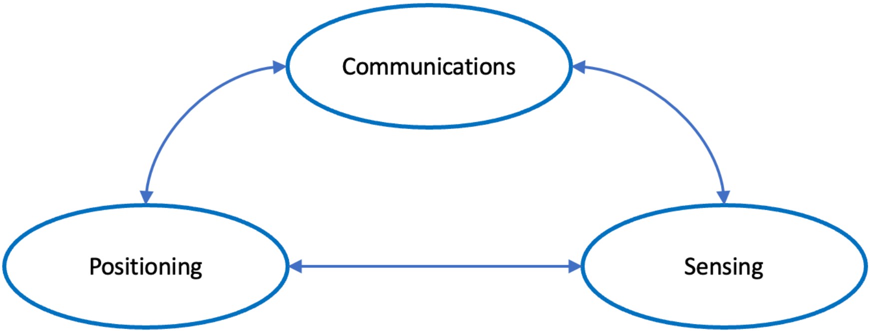
Channel Estimation

- 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

- Spacial resource allocation (plus conventional time/frequency allocation)
- Activation of LIS panels/RS segments and UE association to them
- Complex optimization problem
  - Non-convex
  - Multi-objective (sum rate, minimum-rate, power)
- Need for machine learning and/or meta-heuristic approaches

Joint communications, positioning and sensing



- Full cooperation between communications positioning and sensing
- Reduced complexity and signaling requirements
- Improved performance

Conclusions

- Path from SISO to massive MIMO
- Beyond massive MIMO
  - Enabling technologies (RIS, LIS, Radio Stripes)
  - Cell free systems
  - Near field communications
- Challenges
  - Low complexity hardware implementation
  - Channel estimation
  - Resource allocation
- Need for joint communications, positioning and sensing

Thank you!