5G and Multi-User MIMO

Petteri Kela
Senior Researcher

Petteri.kela@huawei.com / petteri.kela@aalto.fi
Lecture Topics

- 5G Key Technologies
- MIMO Basics
- Multi-user MIMO
- Massive MIMO
- Coordinator Multi-Point (CoMP)
- 5G Ultra-dense Networks

"Why you should work in wireless? You can always lay down more optical fiber, but you cannot lay down more spectrum.” – Thomas Marzetta
Key 5G Technologies
Introduction – 5G Targets

• The general consensus on the 5G requirements are:
  – 1000x increase in area capacity with respect to the LTE-A
  – 1 ms Round Trip Time (RTT) latency
  – 100x improvement in energy efficiency
  – 10-100x reduction in cost of deployment
  – Mobility support and always-on connectivity of users that have high throughput requirements like 100 Mbps

• Commercial launch around 2020?

• Several Technologies are needed for fulfilling the targets
5G Technologies

- **mmWave Systems**
  - Above 6 GHz spectrum utilization, huge bandwidths available
  - Solutions for serving mobile users not matured enough for the first phase of 5G

- **Advanced MIMO**
  - Multi-User MIMO and Massive MIMO
  - Coordinated Multi-Point (CoMP)

- **Network densification**
  - Ultra-Dense Networks (UDN)

- **Advanced D2D**
  - Helps to reduce latencies and support more simultaneous connections
5G Technologies

- **Multiple access and new waveforms**
  - Filtered-OFDM
    - Waveform technology for supporting different waveforms, multiple access chemes and frame structures based on the application and scenarios and service requirements
    - Co-existence of different waveforms and different OFDM parameters

- **Multi-RAT**
  - Integration of multiple technologies and carrier aggregation of licenced and unlicenced bands to increase available bandwidth

- **Full Duplex**
  - Full-duplex breaks the barrier of today’s communications by supporting bidirectional communications without time or frequency duples
5G Radio Access Virtualization

• Paradigm shift:
  – Cellular -> "Non-cellular" or "cell-less" network

• Elimination of cell boundaries
  – Traditionally link performance may degrade as device moves away from the cell center
  – In virtualized user-centric network, the network determines which access point(s) are to be associated with the user
MIMO Basics
Multiple Input Multiple Output
Multiple Antenna Systems (MIMO)

- Wireless communications are suffering from attenuation and interference
- With multi-antenna systems we can fight against
- Advanced MU-MIMO techniques are promising additional advantages over traditional MIMO solutions
MISO, SIMO and MIMO

- **SIMO**
  - A single transmit antenna and N receiver antennas
  - Receive spatial diversity
    - Requires CSI at receiver

- **MISO**
  - M transmit antennas and a single receive antenna
  - Transmit spatial diversity
    - Requires CSI at transmitter

- **MIMO**
  - M transmit antennas and N receive antennas
MIMO Spatial Multiplexing (SM)

- In theory MxN MIMO can multiply data rate by \( \min(M,N) \) if there is enough multipath
  - Best in urban high-multipath environment (and indoors)
  - Less effective in rural low-multipath environment

- High SINR for reliable decoding and rich scattering environment for high channel rank required
  - It can be seen that the rank of channel matrix \( H \) is precisely the number of non-zero singular values
  - Full rank MIMO channel provides \( \min(M,N) \) spatial degrees of freedom
MIMO Spatial Multiplexing (SM)

- MIMO uses multipath to advantage
  - Data rate can be multiplied by multiplexing data streams through separate paths

$$H = \begin{bmatrix} h_{1,1} & \cdots & h_{1,n} \\ \vdots & \ddots & \vdots \\ h_{m,1} & \cdots & h_{m,n} \end{bmatrix}$$

![Diagram of MIMO spatial multiplexing](image)
Closed-loop SM MIMO

- Requires CSI at transmitter and receiver
  - Transmitter uses CSI for precoding
  - Receiver needs information for stream separation
    - Precoder feedback signalling from user to
      - Codebooks used for limiting feedback signaling data

- Transmitter sends reference signals from each antenna port, which are measured by user

- User figures out optimal choice for precoder from codebook and signals that information to transmitter
Point-to-point MIMO summary

• Brilliant invention
  – Multiplies throughput by \( \min(M,N) \) in ideal high multi-path conditions
  – 2x2 MIMO systems currently available and 4x4/8x8 are also standardized by 3GPP and they are being brought into consumer devices

• Not scalable though
  – Training signaling resources (time/freq.) needs grow with system size
  – Not very good multiplexing gains at cell edge
    • E.g. With 8x4 configuration at -3 dB SNR:

<table>
<thead>
<tr>
<th>TX antennas</th>
<th>1</th>
<th>2</th>
<th>4</th>
<th>8</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bits/s/Hz</td>
<td>1.51</td>
<td>1.83</td>
<td>2.06</td>
<td>2.19</td>
</tr>
</tbody>
</table>
Multi-User MIMO
Space Division Multiple Access
Multi-User MIMO

- Splitting the multi-antenna user into autonomous single antenna users does not decrease the sum-throughput!
- Only simple single antenna user nodes required
- Propagation environment almost always favorable
  - At least when compared to point-to-point MIMO
Multi-User MIMO

- Multiple antennas at the transmitter side and multiple antennas at the receiver side as in all MIMO
  - In MU-MIMO receivers are separated spatially with beamforming

- MIMO channel matrix $H$ for $M$ transmit antennas and $N$ receivers

$$H = \begin{bmatrix} h_{1,1} & \cdots & h_{1,n} \\ \vdots & \ddots & \vdots \\ h_{m,1} & \cdots & h_{m,n} \end{bmatrix}$$
Multi-User Beamforming

- Matched Filter precoding with equal power allocation
  - Hermitian transpose of the channel matrix
  \[ W_{MF} = \sqrt{P_t} \frac{H^H}{\|H^H\|_F} \]

- Zero Forcing precoding with equal power allocation
  - Moore-Penrose pseudo-inverse of the channel matrix
  \[ W_{ZF} = \sqrt{P_t} \frac{H^+}{\|H^+\|_F} \]

- \( P_t \) is transmit power budget of the access node

- In case of equal power allocation Frobenius norm is used for precoder matrix normalization
  - Provides equal received power allocation regardless of channel condition differences between users
Multi-User MIMO performance evaluation

Signal to Interference plus Noise Ratio for $i$th user served by single MU-MIMO base station:

$$SINR_i = \frac{S}{I + N} = \frac{\|w_i h_i\|^2}{\sum_{j=1, j \neq i}^{N} \|w_j h_j\|^2 + \sigma_i^2}$$

- $w_i$ is precoding vector for $i$th user
- $h_i$ is the channel vector for $i$th user
- $\sigma_i^2$ is the variance of the complex-circular zero-mean white Gaussian noise at the $n$th user

Rather good compact lecture about Massive MIMO and MU-MIMO calculus:
https://www.youtube.com/watch?v=zhncADqR9rg
Massive MIMO
Spatial multiplexing pushed to extreme
Massive MIMO

- MU-MIMO with massive transmit antenna array
  - >100 antenna elements at the base station antenna array

- Using measured channels, beamforming gain grows linearly with number of antennas
  - Channels are measured from uplink training signals i.e. pilots

- Channel measurements basically constrain to TDD and usage of channel reciprocity due to huge number of antennas
  - Channel state information at transmitter (CSIT) needed
  - Receiver does not necessarily need CSI
  - Channel is measured with all transmit antenna elements from orthogonal pilots sent by users
Benefits of Macro Cellular Deployment

• In 4G way of thinking macro cells can handle mobility due to large cell sizes which reduces handovers
  – True, because handovers cause extra latency and network load in LTE

• Today’s deployed 4G networks are mostly based on LTE macro cells only

• In theory, macro cell capacity can boosted with Massive MIMO
  – Spatial multiplexing with massive arrays consisting of hundreds of antenna elements
  – Huge capacity increase potential when number of antenna elements is approaching infinity

• In theory, power consumption can be reduced significantly with M-MIMO
  – when number of antenna elements is approaching infinity, then required TX power approaches $\epsilon$, where $\epsilon$ is infinitely small value next to zero
Well Known M-MIMO Research Problems [2]

- Pilot contamination & channel aging
  - Large cell sizes will increase pilot contamination problems
  - It is easy to exhaust the available supply of orthogonal pilot sequences in a multicellular system in a 1ms coherence distance

- Cost of reciprocity calibration
  - TDD requires reciprocity calibration. What is the cost in time and frequency resources in large cells with high active user densities?

- Low cost hardware challenge
  - Building hundreds of RF chains, up/down converters, A/D and D/A converters and so forth

- Power consumption
  - In practice the total power consumption must be considered including baseband signal processing
5G Macro cells with M-MIMO in practice

• With realistic array sizes efficient spatial separation of users in urban environment with M-MIMO is challenging
  – With Zero Forcing (ZF) beamforming intra-cell interference can be eliminated, but it comes with the cost of power consumption [2]
  – Another considered precoding method Matched Filter (MF) precoding on the other hand is not able to separate beams well enough for providing significant capacity boost with M-MIMO [1]

• Channel aging is still a major show stopper for serving high densities of mobile users with M-MIMO [1]
  – Due to ultra short channel coherence distances, zero forcing performance collapses already with moderately moving mobile terminals [1]
M-MIMO has severe problems when serving mobile users in urban environment [1]

- Massive MIMO is (in theory) capable boosting macro cell capacity to new levels, but channel aging and power consumption restrains heavily performance gain in realistic urban environment.

- Further research and novel solutions are needed for boosting up macro cell performance when serving high densities of mobile users in urban environment.

![Graph showing Mean User Throughput (Mbps) with different beam configurations at various speeds.](image)
Coordinated Multipoint MIMO (CoMP)
Reducing inter-cell interference with coordination
Coordinated Scheduling (CoMP-CS)

- Allocate different time and frequency resources to cell edge users served by different cells

- E.g. in synchronized network, neighboring access nodes are using different resource blocks for serving cell edge users
Coordinated Beamforming (CoMP-CB)

- Allocate different spatial resources to users at cell edge, but time and frequency resources are reused.

- Beamforming weights can be calculated in a way that cell edge users served neighbors are nulled:
  - E.g. when calculating zero-forcing precoders, then also users served by neighbouring access node are taken into account, but zero power is allocated on those precoders.
  - Requires CSI from users to be nulled.
Joint Transmission (CoMP-JT)

• Central precoding needed for multiple access nodes (or remote radio heads)
  – Data transmitted simultaneously from multiple access nodes
  – High demand onto the backhaul since data has to be in several places
  – Tight synchronization of access nodes needed
    • Network needs to be time and phase synchronized
  – In theory can get rid of all inter-cell interference
    • ”Hyper cell Massive MIMO with distributed antennas”

• Practical implementation is challenging
  – How to phase synchronize access nodes
  – In large scale, sensitive to channel aging as M-MIMO
  – Interference from outside of coordination area can collapse the gain
CoMP Schemes

- CS/CB schemes share each access node scheduling information
  - Each access node needs to obtain CSI from shared users

- In JT scheme access nodes share their associated users’ information including CSI and users’ data
  - CSI collected in centralized manner for CoMP cluster
Ultra-Dense Networks (UDNs) with densely deployer multi-user MIMO access nodes
Continuous Ultra-Dense Network for 5G

- **Continuous coverage of small access nodes**
  - e.g. lamp posts can be utilized for deployment

- **Centrally controlled user centric mobility**
  - User is agnostic to cells, i.e. no handovers etc.

- **Borderless quality of experience**

- **Always-on connectivity**

- **Network oriented measurements**
UDN Gives High Line-of-Sight Probability

- **Pilot reuse in spatial domain**
  - Helps with pilot contamination problem of Massive MIMO

- **Line of sight propagation**
  - Helps beamforming and reception due to so dominant strongest LoS path

- **Accurate positioning with LoS channels**
  - Position based beamforming
Benefits of Short Distances

- Short Inter-Site Distance (ISD) gives freedom for designing frame structure
  - e.g. in case of OFDM, required cyclic prefix overhead is smaller
  - easier to have enough physical resources for pilots

- Low transmit powers can be used
  - e.g. 0-23 dBm power budgets at access nodes

- <1ms latency target can be achieved with high throughputs
  - Enabler for augmented reality, cloud gaming in vehicles etc.
Performance of 5G C-UDN [1]

- UDN can tolerate spatial CSI beacon reuse for MU-MIMO

- Channel aging is not affecting to performance so much when there is reasonable number of transmit antennas and high LoS probability
Thank you
References
