The doubly massive MIMO regime in mmWave communications

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Millimeter Waves (mmWaves)

- One of the "key pillars" of 5G and B5G Wireless Systems
- Refers to above-6 GHz frequencies
- Regulators worldwide are releasing spectrum chunks at frequencies up to 100 GHz
- The main benefit is the availability of large bandwidths
- However... to overcome increased path-loss, MIMO processing is needed at both TX and RX
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- However... to overcome increased path-loss MIMO processing is needed at both TX and RX
The "doubly-massive" MIMO scenario at mmWaves is considered.

The main differences between mmWave and conventional cellular frequencies in Massive MIMO are discussed.

Results on the ASE and GEE of several beamforming structures in the doubly-massive regime are presented.

Our results show that, as far as GEE is concerned, fully digital beamforming may still be a good option.
In this talk...

- The "doubly-massive" MIMO scenario at mmWaves is considered
- The main differences between mmWave and conventional cellular frequencies in Massive MIMO are discussed
- Results on the ASE and GEE of several beamforming structures in the doubly-massive regime are presented

- Our results show that, as far as GEE is concerned, fully digital beamforming may still be a good option
mmWave vs microWave
Massive MIMO
mmWave vs microWave massive MIMO

- **mmWave may be doubly massive**
  - At *microWave frequencies* only the BS goes massive;
  - at *mmWave frequencies* the wavelength gets reduced, and, *at least in principle*, a large number of antennas can be mounted not only on the BS, but also on the user device;

At carrier frequency $f_c = 30$ GHz (i.e., $\lambda = 1$ cm), and with $\frac{\lambda}{2}$ antenna spacing, more than **180** antennas can be placed on an area as large as a standard credit card.

The number climbs up to **1300** at 80 GHz!!
mmWave vs microWave massive MIMO

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The rank of the channel

- At *microWave frequencies* the entries of the \((N_R \times N_T)\)-dimensional channel matrix are expressed as \([H]_{(n,m)} = h_{nm}\sqrt{\frac{\rho}{d^\alpha}},\) with \(h_{nm}\) i.i.d. complex standard normal variates.

The microWave channel has usually rank \(\min\{N_R, N_T\}\) w.p. 1.

- At *mmWave frequencies*, a "clustered" channel model is more representative of the physical propagation mechanism. We have thus:

\[
H = \gamma \sum_{i=1}^{N_{cl}} \sum_{l=1}^{N_{ray}} \alpha_{i,l} \sqrt{L(r_{i,l})} a_r(\phi_{i,l}, \theta_{i,l}) a_t^H(\phi_{i,l}, \theta_{i,l}) + H_{LOS}.
\]

The mmWave channel has at most rank \(N_{cl} N_{ray} + 1\), regardless of \(N_T\) and \(N_R\).

Increasing the number of antennas does not increase the multiplexing capabilities of the channel, at least not linearly.
The rank of the channel

- At *microwave frequencies* the entries of the \((N_R \times N_T)\)-dimensional channel matrix are expressed as \([H]_{(n,m)} = h_{nm} \sqrt{\frac{z}{d^\alpha}},\) with \(h_{nm}\) i.i.d. complex standard normal variates.

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Increasing the number of antennas does not increase the multiplexing capabilities of the channel, at least not linearly
Channel Estimation

- At *microWave frequencies*, channel estimation requires estimating $N_R N_T$ complex coefficients (too hard for doubly massive systems);

- at *mmWave frequencies*, instead, channel estimation is easier thanks to the parametric structure of the channel matrix.

$$H = \gamma \sum_{i=1}^{N_{cl}} \sum_{l=1}^{N_{ray}} \alpha_{i,l} \sqrt{L(r_{i,l})} a_r(\phi_{i,l}, \theta_{i,l}) a_t^H(\phi_{i,l}, \theta_{i,l}) + H_{LOS}.$$
Analog (beam-steering) beamforming may be optimal

According to the structure of the mmWave channel:

\[
H = \gamma \sum_{i=1}^{N_{\text{cl}}} \sum_{l=1}^{N_{\text{ray}}} \alpha_{i,l} \sqrt{L(r_{i,l})} a_r(\phi_{i,l}, \theta_{i,l}) a^H_t(\phi_{i,l}, \theta_{i,l}) + H_{\text{LOS}}
\]

For large \(N_T\) and \(N_R\), and distinct arrival and departure angles, the array response vectors \(a_r(\cdot, \cdot)\) and \(a_t(\cdot, \cdot)\) converge to the right and left singular vectors of the channel matrix.

Matrix Algebra

Recall indeed that \(H = UV^H = \sum_i \lambda_i u_i v_i^H\)
Antenna selection procedures

- At *microWave frequencies*, using the i.i.d. property of the channel coefficients, it is possible to use selection combining for diversity, so we can use the transmit and receive antennas with the best channel coefficients;

- at *mmWave frequencies*, instead, these procedures are less effective because the entries of the channel matrix are correlated.
ASE and GEE evaluation
We consider the following downlink scenario:
The considered performance measures

The performance measures considered here are:

- The **Achievable Spectral Efficiency** (ASE), assuming gaussian symbols measured in [bit/s/Hz];

- The **Global Energy Efficiency** (GEE) [1], it is obtained by dividing the ASE for the total power consumed in the transceiver circuitry and it is measured in [bit/Joule]:

  \[
  \text{GEE} = \frac{\text{WASE}}{\eta P_T + P_{TX,c} + K P_{RX,c}}.
  \]

**References**

Beamforming Structures

- **Channel Matched, fully digital (CM-FD)** beamforming using the singular-value decomposition of the channel matrix;

- **Partial Zero Forcing, fully digital (PZF-FD)** beamforming: in order to avoid a too severe noise enhancement, we require that the columns of the precoding matrix $Q_k$ are orthogonal to the $M$ right eigenvectors of the channels $H_\ell$ $\forall \ell \neq k$ corresponding to the largest eigenvalues;

- **Partial Zero Forcing, hybrid (PZF-HY)** beamforming: the desired beamformers are the PZF-FD matrices, and their approximation is realized by using the block coordinate descent for subspace decomposition algorithm [2];

**References**

Beamforming Structures

- **Fully Analog (AN)** beam-steering beamforming: focusing on the generic $k$-th user, the columns of the precoding matrix are chosen as the array responses corresponding to the departure angles associated to the $M$ dominant paths and a similar reasoning is made for the postcoding matrix;
- **Beamforming based on switches and fixed phase shifters (SW+PHSH)**, introduced in [3];
- **Switch-based (SW)** beamforming, introduced in [4].

References


Beamforming based on switches and fixed phase shifters (SW+PHSH):

Beamforming Structures: SW+PHSH
# Beamforming Structures: Power Consumption

**Table:** The amount of power consumed by the transmitter and receiver circuitry

<table>
<thead>
<tr>
<th>Structure</th>
<th>TX Circuitry</th>
<th>RX Circuitry</th>
</tr>
</thead>
<tbody>
<tr>
<td>CM-FD / PZF-FD</td>
<td>$P_{TX,c} = N_T (P_{RFC} + P_{DAC} + P_{PA}) + P_{BB}$</td>
<td>$P_{RX,c} = N_R (P_{RFC} + P_{ADC} + P_{LNA}) + P_{BB}$</td>
</tr>
<tr>
<td>PZF-HY</td>
<td>$P_{TX,c} = N_{RF}^T (P_{RFC} + P_{DAC} + N_T P_{PS}) + N_T P_{PA} + P_{BB}$</td>
<td>$P_{RX,c} = N_{RF}^R (P_{RFC} + P_{ADC} + N_R P_{PS}) + N_T P_{LNA} + P_{BB}$</td>
</tr>
<tr>
<td>AN</td>
<td>$P_{TX,c} = N_{RF}^T (P_{RFC} + N_T P_{element} + P_{DAC})$</td>
<td>$P_{RX,c} = N_{RF}^R (P_{RFC} + N_R P_{element} + P_{ADC})$</td>
</tr>
<tr>
<td>SW + PHSH</td>
<td>$P_{TX,c} = N_{RF}^T (P_{RFC} + P_{DAC} + N_Q P_{PS}^{fixed}) + N_T (N_{RF}^T P_{SW} + P_{PA}) + P_{BB}$</td>
<td>$P_{RX,c} = N_{RF}^R (P_{RFC} + P_{ADC} + N_Q P_{PS}^{fixed}) + N_R (N_{RF}^R P_{SW} + P_{LNA}) + P_{BB}$</td>
</tr>
<tr>
<td>SW</td>
<td>$P_{TX,c} = N_{RF}^T (P_{RFC} + P_{DAC} + P_{SW}) + N_T P_{PA} + P_{BB}$</td>
<td>$P_{RX,c} = N_{RF}^R (P_{RFC} + P_{ADC} + P_{SW}) + N_R P_{LNA} + P_{BB}$</td>
</tr>
</tbody>
</table>
Table: Power consumption of components

<table>
<thead>
<tr>
<th>Component</th>
<th>Power Consumption</th>
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<tbody>
<tr>
<td>$P_{RFC}$</td>
<td>40 mW</td>
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<tr>
<td>$P_{DAC}$</td>
<td>110 mW</td>
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<tr>
<td>$P_{ADC}$</td>
<td>200 mW</td>
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<tr>
<td>$P_{PA}$</td>
<td>16 mW</td>
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<tr>
<td>$P_{LNA}$</td>
<td>30 mW</td>
</tr>
<tr>
<td>$P_{BB}$</td>
<td>243 mW</td>
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<tr>
<td>$P_{PS}$</td>
<td>30 mW</td>
</tr>
<tr>
<td>$P_{element}$</td>
<td>27 mW</td>
</tr>
<tr>
<td>$P_{SW}$</td>
<td>5 mW</td>
</tr>
<tr>
<td>$P_{PS_{fixed}}$</td>
<td>1 mW</td>
</tr>
</tbody>
</table>
References


Numerical results for a single-user system
Figure: (a) ASE versus link length for several values of $N_R \times N_T$, $P_T = 0$ dBW, $M = 4$; (b) ASE versus transmit power for several values of $N_R \times N_T$, $d = 30$ m, $M = 4$. 
Figure: Impact of the number of clusters. $P_T = 0$ dBW, $N_R \times N_T = 50 \times 100$. 

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Numerical results for a MU-MIMO single-cell system
Performances with $N_T \to \infty$

**Figure:** Plot of ASE and GEE versus $N_T$ with $M = 1$, $N_R = 30$, $P_T = 0$ dBW and $K = 10$.

**Figure:** Plot of ASE and GEE versus $N_T$ with $M = 3$, $N_R = 30$, $P_T = 0$ dBW and $K = 10$. 
Performances with $N_R \to \infty$

Figure: Plot of ASE and GEE versus $N_R$ with $M = 1$, $N_T = 100$, $P_T = 0$ dBW and $K = 10$.

Figure: Plot of ASE and GEE versus $N_R$ with $M = 3$, $N_T = 100$, $P_T = 0$ dBW and $K = 10$. 
Performances with $N_T$ and $N_R \to \infty$

**Figure:** Plot of GEE versus $N_R$ and $N_T$ for several beamforming structures. $M = 3$, $P_T = 0$ dBW and $K = 10$. 

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Conclusions

- Considerations on the doubly massive MIMO regime at mmWaves have been given.
- Key differences with massive MIMO systems at microWaves have been highlighted.
- Several beamforming structures have been compared in terms of ASE and GEE.
- As hardware technology progresses, GEE results may change in the future.
- The clustered channel model needs validation in the doubly-massive MIMO regime.
- Low-complexity signal processing algorithms are required.
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This talk has been taken from papers [9] and [10].

References


THANK YOU FOR YOUR ATTENTION!

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