Beamspace MIMO-NOMA for Millimeter-Wave Communications Using Lens Antenna Arrays

Bichai Wang†, Linglong Dai†, Xiqi Gao#, and Lajos Hanzo*

†Tsinghua University, Beijing, China
#Southeast University, Nanjing, China
*University of Southampton, Southampton, U.K.

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Technical Background
System Model of Beamspace MIMO
Proposed Beamspace MIMO-NOMA
Simulation Results
Conclusions
5G key performance indicators (KPIs) defined by ITU

- User experienced data rate (Mbit/s)
- Spectrum efficiency
- Mobility (km/h)
- Latency (ms)
- Connection density (devices/km²)
- Area traffic capacity (Mbit/s/m²)
- Network energy efficiency
- Peak data rate (Gbit/s)
- User experienced data rate (Mbit/s)

IMT-2020

IMT-advanced

0.1
1
10
100
100×
10×
1×
3×
400
350
400
100
10
1
10²
10³
10⁴
10⁵
10⁶
10⁷
10⁸
10⁹
Three technical directions for 5G

- Higher/Wider Frequency Bands
- More Antennas
- Traffic Offloading
- Network Density
- Spectrum Efficiency
- Required Capacity
- Current Capacity
- Spectrum Extension
- Small Cells
- Higher/Wider Frequency Bands
- WiFi
- Controller
- 700MHz~
- MmWave massive MIMO can combine the roadmaps of 5G in an unified form
Technical Background

Challenges of mmWave massive MIMO

- Traditional MIMO: One dedicated RF chain for one antenna
- Enormous number of RF chains due to large antenna array
- Unaffordable energy consumption (250 mW per RF chain at 60 GHz)

THE DEATH OF 5G PART 2: WILL ANALOG BE THE DEATH OF MASSIVE MIMO?

CTW Issue June 2015
Jin Liu and Hsiang Minn, Guest Editors
Alan Katherer, Editor in Chief, Tomorrow Technology News

Editor's note: While we are on the topic of things that might kill 5G, or at least cause it to evolve into something other than what it is today. I think the topic of the analog front-end of massive MIMO is worth a closer look. So many papers sidestep this issue with a note that analog beam forming solutions will solve the problem. Though some very interesting work has been done in this area, this sounds like a punt down the field to me. History has taught us that analog never replaces digital for all that long. In order to step back and cast an impartial eye on the problem I recently drove down the road from my office in what at that time was, a quite soggy Piano TX to an equally soggy Richardson and the home of UT Dallas. Below is the result of this effort, a nice little summary by Professors Liu and Minn on some of the issues that face ADC development if we are to implement 5G massive MIMO in production. I am sure there are more issues than mentioned here and comments are always welcome.

Analog Front End Design Challenges for 5G Massive MIMO

The exponential growth of data rate has led to the demand for 5G wireless systems with an expected data bandwidth of several GHz and higher frequencies in the millimeter wave range (tens of GHz to 100GHz) [1–3]. Due to large propagation losses at this frequency range, beamforming with massive MIMO plays a central role in maintaining reliable communication links. It is expected that the required number of antennas will be an order of magnitude larger than existing wireless systems. This presents significant challenges in the analog front end design.

How to reduce the number of required RF chains?
Outline

- Technical Background
- **System Model of Beamspace MIMO**
- Proposed Beamspace MIMO-NOMA
- Simulation Results
- Conclusions
Basic idea

- **Concentrate** the signals from different directions (beams) on different antennas by lens antenna array
- Transform conventional spatial channel into **beamspace** channel
- **Limited** scattering at mmWave $\rightarrow$ beamspace channel is **sparse**
- Select **dominant beams** to reduce the dimension of MIMO system
- Negligible performance loss $\rightarrow$ **significantly reduced** number of RF chains
System Model of Beamspace MIMO

- **Sparsity**
  - \( \tilde{H} = [\tilde{h}_1, \tilde{h}_2, \cdots, \tilde{h}_K] = UH = [Uh_1, Uh_2, \cdots, Uh_K] \)
  - \( \tilde{h}_k \) with a **small** number of **dominant** elements
  - Approximately **sparse**

- **Beam selection**
  - Select a small number of dominant beams
  - Only a **small** number of RF chains

\[ \tilde{H} = UH \]
Fundamental limit of beamspace MIMO
- A single beam can only support a single user in existing beamspace MIMO systems
- The maximum number of users that can be supported cannot exceed the number of RF chains
- Massive users cannot be supported with limited number of RF chains
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**Proposed Beamspace MIMO-NOMA**

- **Non-Orthogonal Multiple Access (NOMA)**
  - Superposition coding at the transmitter
  - Successive interference cancellation (SIC) at the receiver
  - Multiple users can be supported at the same time-frequency resources
Proposed Beamspace MIMO-NOMA

- **Basic principle**
  - Selecting one beam for each user using *beam selection* algorithms, such as the maximum magnitude (MM) selection and SINR maximization based selection
  - Interfering users can be *simultaneously served* within the same beam
  - The number of supported users can be *larger than* the number of RF chains
  - Spectrum efficiency and connectivity density can be improved
Proposed Beamspace MIMO-NOMA

- **System model**
  - $N_{RF}$ beams, $K$ users
  - The set of users in the $n$th beam is $S_n$ ($S_i \cap S_j = \emptyset$)
  - Beamspace channel vector between the BS and the $m$th user in the $n$th beam is denoted by $h_{m,n}$
  - Uniform precoding vector for users in the $n$th beam is $w_n$
  - We assume that $\|h_{1,n}^H w_n\|_2 \geq \|h_{2,n}^H w_n\|_2 \geq \cdots \geq \|h_{|S_n|,n}^H w_n\|_2$
  - After intra-beam SIC, the remaining signal received at the $m$th user in the $n$th beam beam can be written as

$$
\hat{y}_{m,n} = h_{m,n}^H w_n \sqrt{p_{m,n}} s_{m,n} + h_{m,n}^H w_n \sum_{i=1}^{m-1} \sqrt{p_{i,n}} s_{i,n} + h_{m,n}^H \sum_{j \neq n} |S_j| \sum_{i=1}^{\left|S_j\right|} w_j \sqrt{p_{i,j}} s_{i,j} + v_{m,n}
$$

- **desired signal**
- **intra-beam interferences**
- **inter-beam interferences**
- **noise**
Proposed Beamspace MIMO-NOMA

- **System model**
  - The SINR the $m$th user in the $n$th beam can be represented as
    \[
    \gamma_{m,n} = \frac{\left\| h_{m,n}^H w_n \right\|_2^2 p_{m,n}}{\xi_{m,n}}
    \]
    where \( \xi_{m,n} = \left\| h_{m,n}^H w_n \right\|_2 \sum_{i=1}^{m-1} p_{i,n} + \sum_{j \neq n} \left\| h_{m,n}^H w_j \right\|_2 \sum_{i=1}^{m-1} p_{i,j} + \sigma^2 \)
  - The achievable rate of the $m$th user in the $n$th beam
    \[
    R_{m,n} = \log_2 (1 + \gamma_{m,n})
    \]
  - Achievable sum rate
    \[
    R_{\text{sum}} = \sum_{n=1}^{N_{RF}} \sum_{m=1}^{|S_n|} R_{m,n}
    \]
Proposed Beamspace MIMO-NOMA

- **Precoding**
  - **Challenge:**
    * The number of users is higher than the number of beams, which means that this system is underdetermined
    * Conventional linear precoding cannot be directly used
  - **Solution:**
    * An equivalent channel can be determined for each beam to generate the precoding vector
    * The beamspace channel vectors of different users in the same beam are highly correlated
    * We use the beamspace channel vector of the first user in each beam as the equivalent channel vector

\[ \tilde{H} = [h_{1,1}, h_{1,2}, \cdots, h_{1,N_{RF}}] \]
Precoding

- Precoding matrix:

\[
\tilde{\mathbf{W}} = [\tilde{\mathbf{w}}_1, \tilde{\mathbf{w}}_2, \cdots, \tilde{\mathbf{w}}_{N_{RF}}] = (\tilde{\mathbf{H}})^\dagger = \tilde{\mathbf{H}} (\tilde{\mathbf{H}}^H \tilde{\mathbf{H}})^{-1}
\]

- After normalizing the precoding vectors, the precoding vector for the \( n \)th beam can be written as

\[
\mathbf{w}_n = \frac{\tilde{\mathbf{w}}_n}{\|\tilde{\mathbf{w}}_n\|_2}
\]
• Power allocation
  - Problem formalization:

  \[
  \max_{\{p_{m,n}\}} \sum_{n=1}^{N_{RF}} \sum_{m=1}^{|S_n|} R_{m,n}
  \]

  s.t. \( C_1 : p_{m,n} \geq 0, \ \forall n, m, \)

  \[
  \sum_{n=1}^{N_{RF}} \sum_{m=1}^{|S_n|} p_{m,n} \leq P
  \]

  \( C_3 : R_{m,n} \geq R_{\text{min}}, \ \forall n, m \)

  - The objective function is non-convex
Proposed Beamspace MIMO-NOMA

- Power allocation

  - **Theorem 1:**

  
  \[ R_{m,n} = \max_{c_{m,n}} \max_{a_{m,n} > 0} \left( -\frac{a_{m,n}e_{m,n}}{\ln 2} + \log_2 a_{m,n} + \frac{1}{\ln 2} \right) \]

  where \( e_{m,n} = \mathbb{E}\left\{ |s_{m,n} - c_{m,n}\hat{y}_{m,n}|^2 \right\} \)

  - The optimization problem can be reformulated as

    \[
    \max \sum_{n=1}^{N_{RF}} \sum_{m=1}^{\left\lvert S_n \right\rvert} \max_{c_{m,n}} \max_{a_{m,n} > 0} \left( -\frac{a_{m,n}e_{m,n}}{\ln 2} + \log_2 a_{m,n} + \frac{1}{\ln 2} \right)
    \]

    \[
    \text{s.t. } C_1, \ C_2, \ C_3
    \]

  - **Iteratively optimize** \( \{c_{m,n}\}, \ {a_{m,n}\}, \ {p_{m,n}\} \) (All of the three optimization problems are convex)
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Simulation Results

- Simulation parameters
  - $N = 256$, $K = 32$
  - Channel: Saleh-Valenzuela multipath channel (1 LoS + 2 NLoS)
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Conclusions

- Propose the beamspace MIMO-NOMA to break the fundamental limit of beamspace MIMO
- The equivalent channel vector was determined for each beam for ZF-based precoding
- Propose to jointly optimize the power allocation of all users by maximizing the achievable sum rate
- An iterative optimization algorithm was developed for power allocation
- The proposed beamspace MIMO-NOMA achieves better performance than beamspace MIMO in terms of spectrum and energy efficiency
Thanks