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

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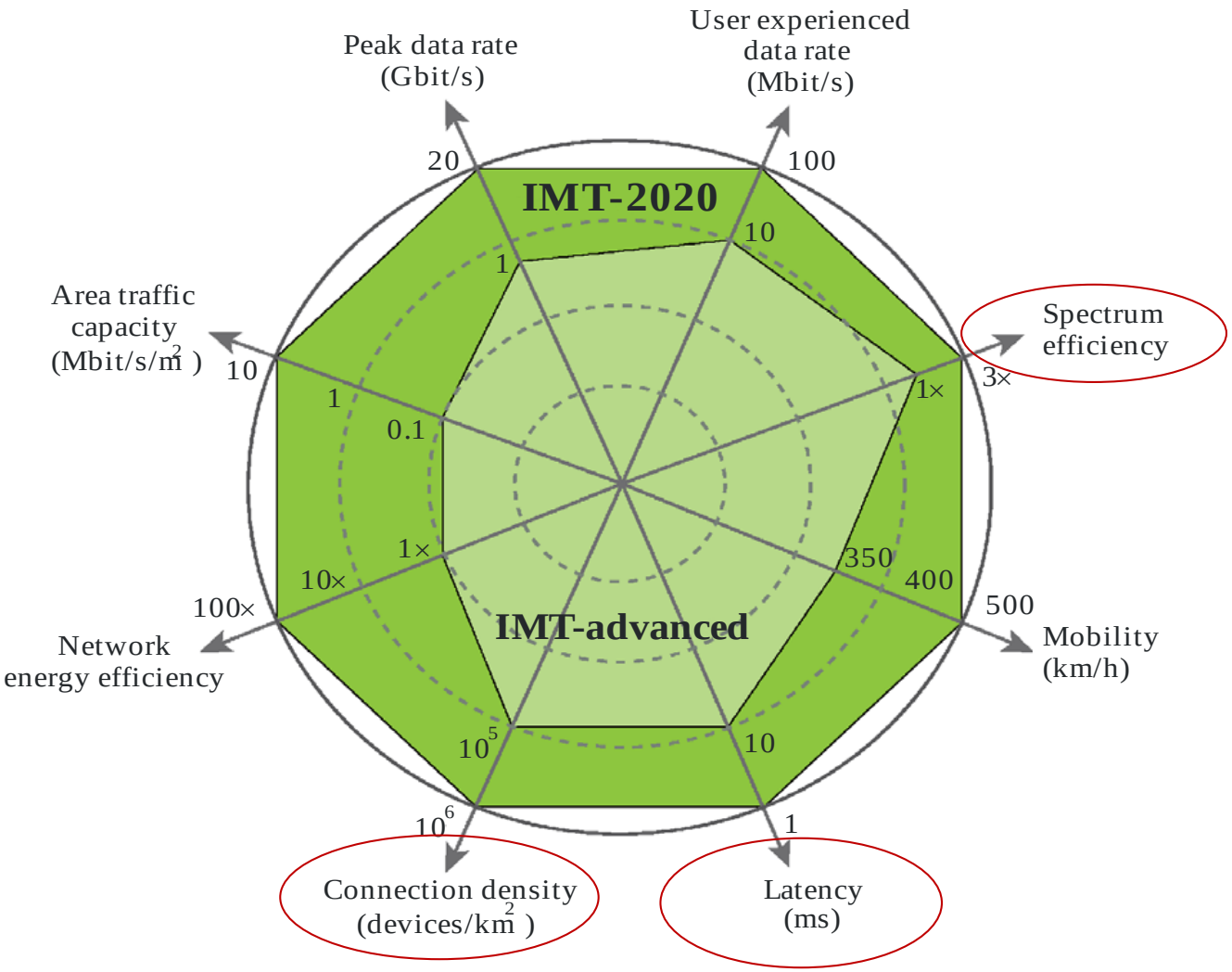
Outline

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

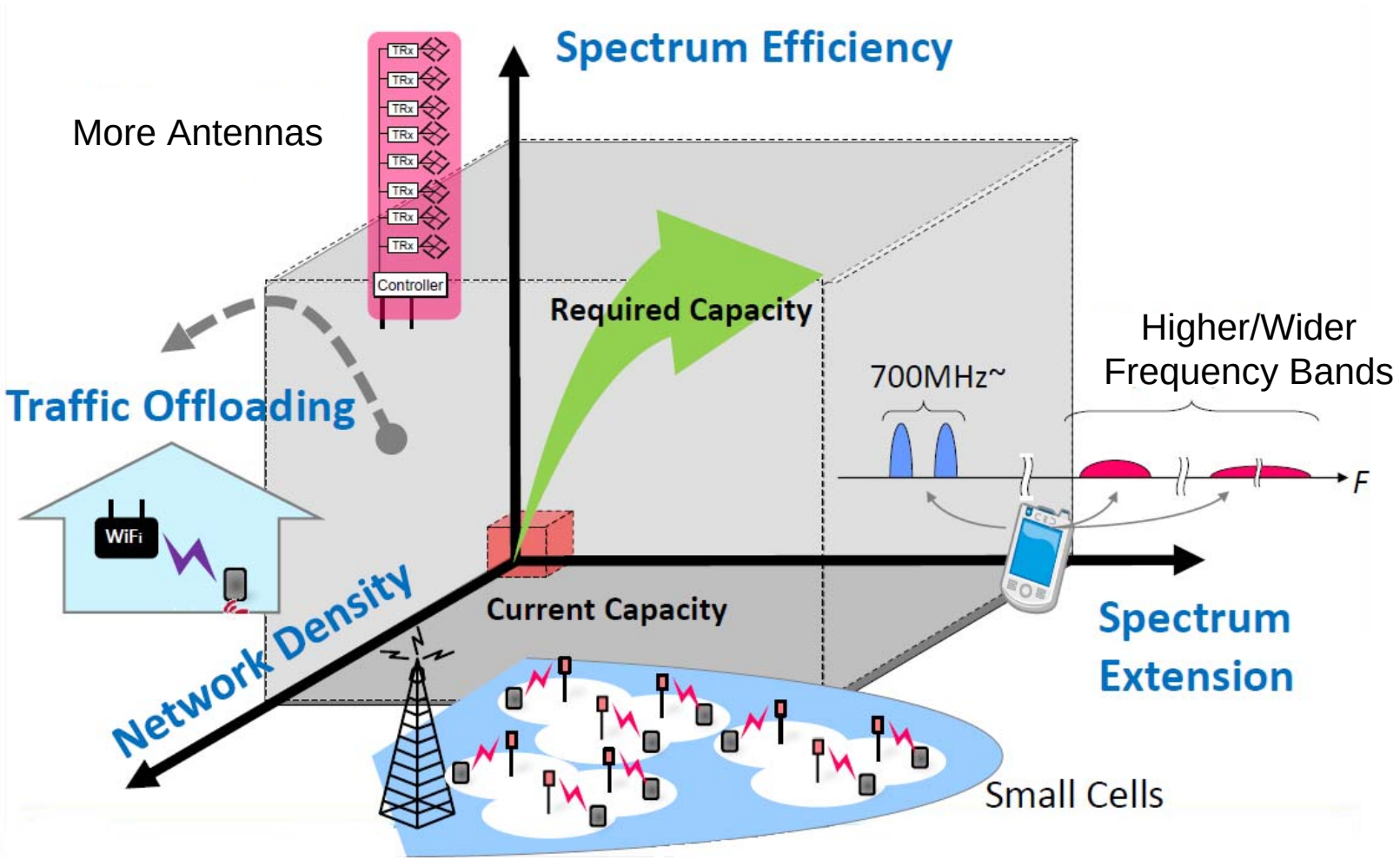
Technical Background

- 5G key performance indicators (KPIs) defined by ITU



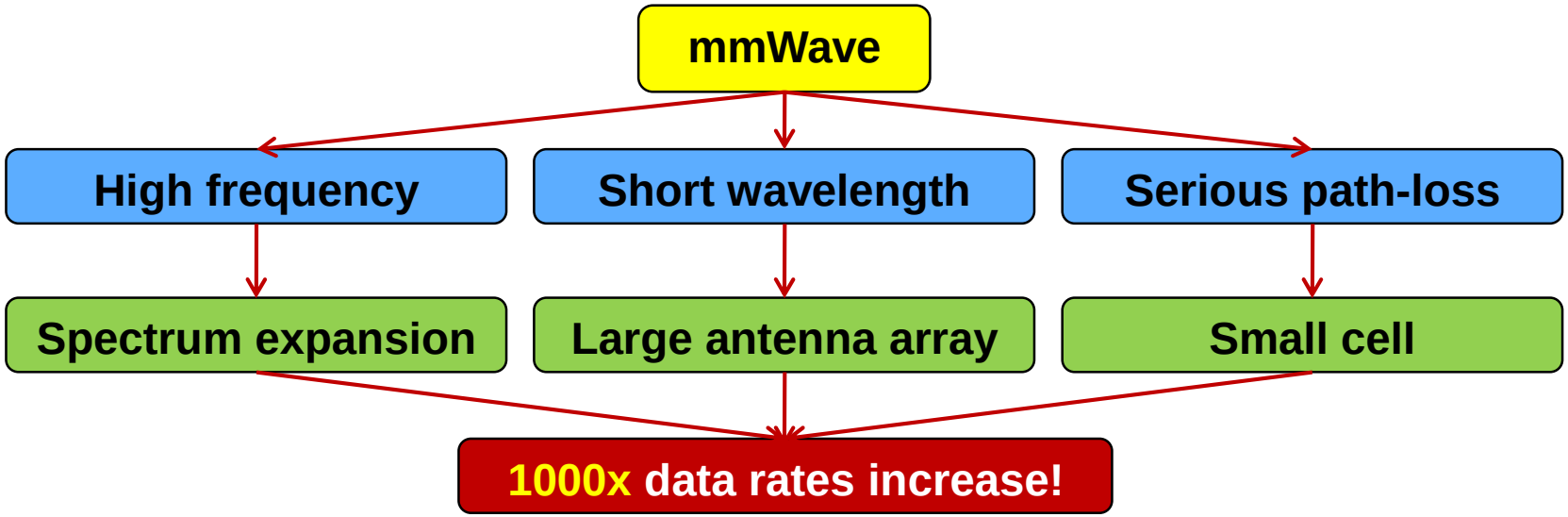
Technical Background

- Three technical directions for 5G



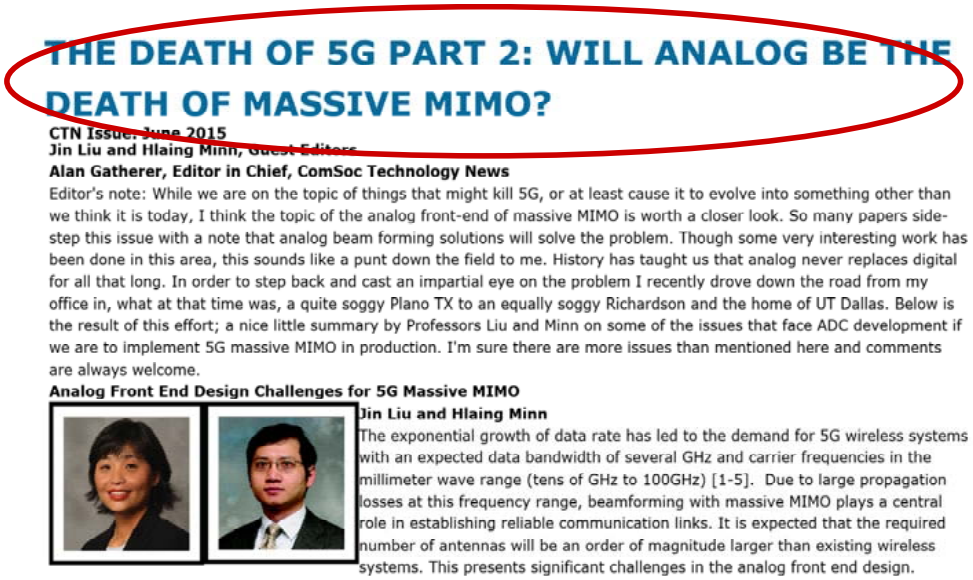
Technical Background

- 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?

CTN Issue: June 2015
Jin Liu and Hlaing Minn, Guest Editors
Alan Gatherer, Editor in Chief, ComSoc 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 we think it is today, I think the topic of the analog front-end of massive MIMO is worth a closer look. So many papers side-step 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 Plano 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'm sure there are more issues than mentioned here and comments are always welcome.

Analog Front End Design Challenges for 5G Massive MIMO

Jin Liu and Hlaing Minn

The exponential growth of data rate has led to the demand for 5G wireless systems with an expected data bandwidth of several GHz and carrier frequencies in the millimeter wave range (tens of GHz to 100GHz) [1-5]. Due to large propagation losses at this frequency range, beamforming with massive MIMO plays a central role in establishing 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?

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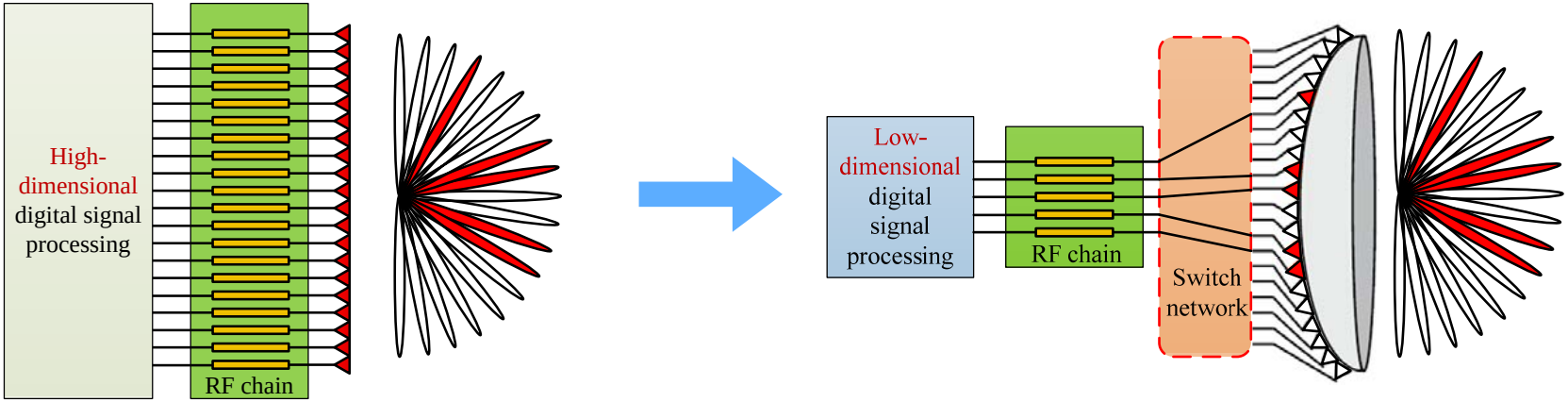
System Model of Beamspace MIMO

- 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



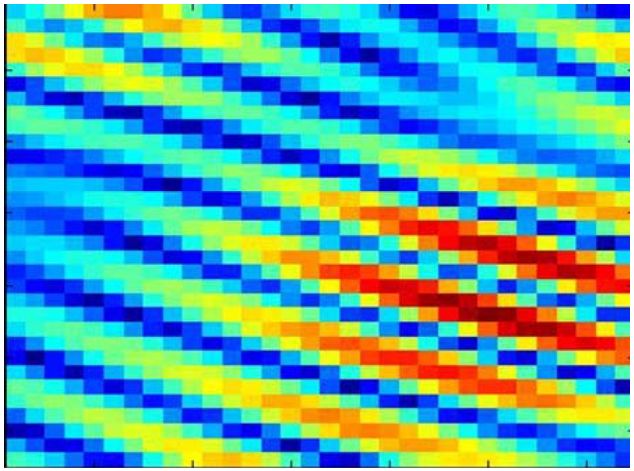
Conventional MIMO

Beamspace MIMO

System Model of Beamspace MIMO

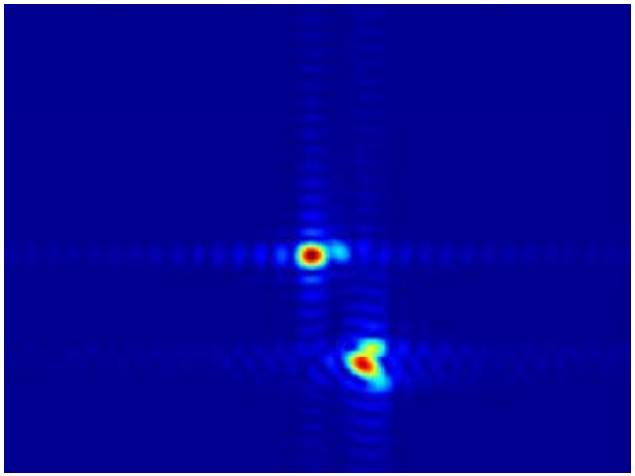
- Sparsity
  - $\tilde{\mathbf{H}} = \left[\tilde{\mathbf{h}}_1, \tilde{\mathbf{h}}_2, \cdots, \tilde{\mathbf{h}}_K\right] = \mathbf{UH} = [\mathbf{Uh}_1, \mathbf{Uh}_2, \cdots, \mathbf{Uh}_K]$
  - $\tilde{\mathbf{h}}_k$ with a small number of dominant elements
  - Approximately sparse
- Beam selection
  - Select a small number of dominant beams
  - Only a small number of RF chains

Spatial channel



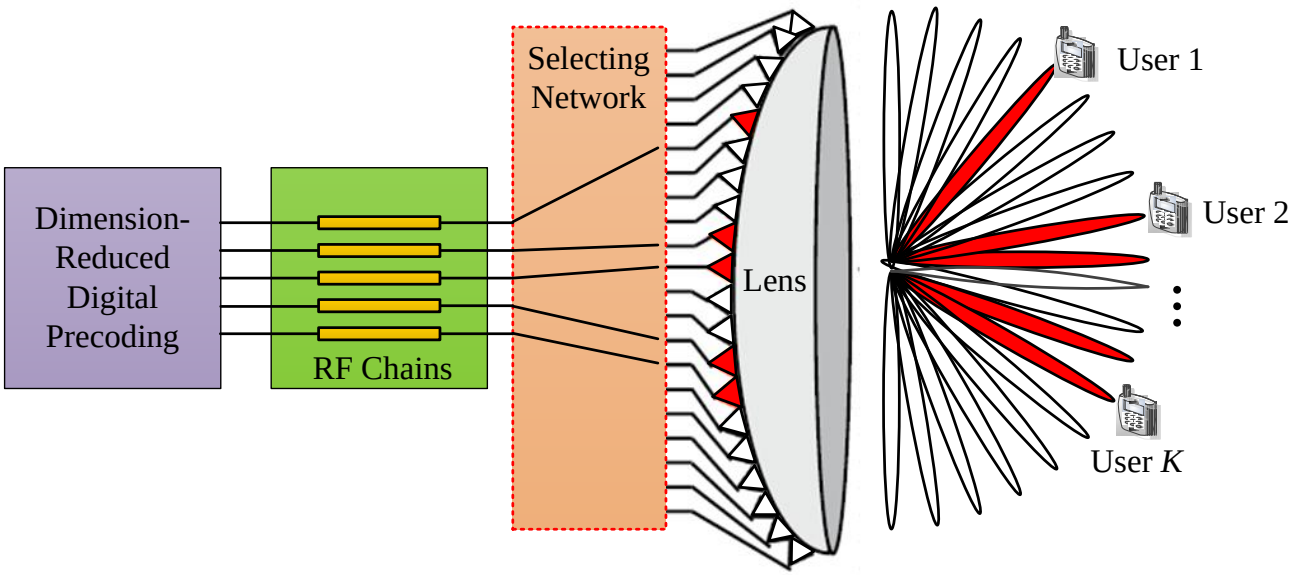
$\tilde{\mathbf{H}} = \mathbf{UH}$

Beamspace channel



System Model of Beamspace MIMO

- 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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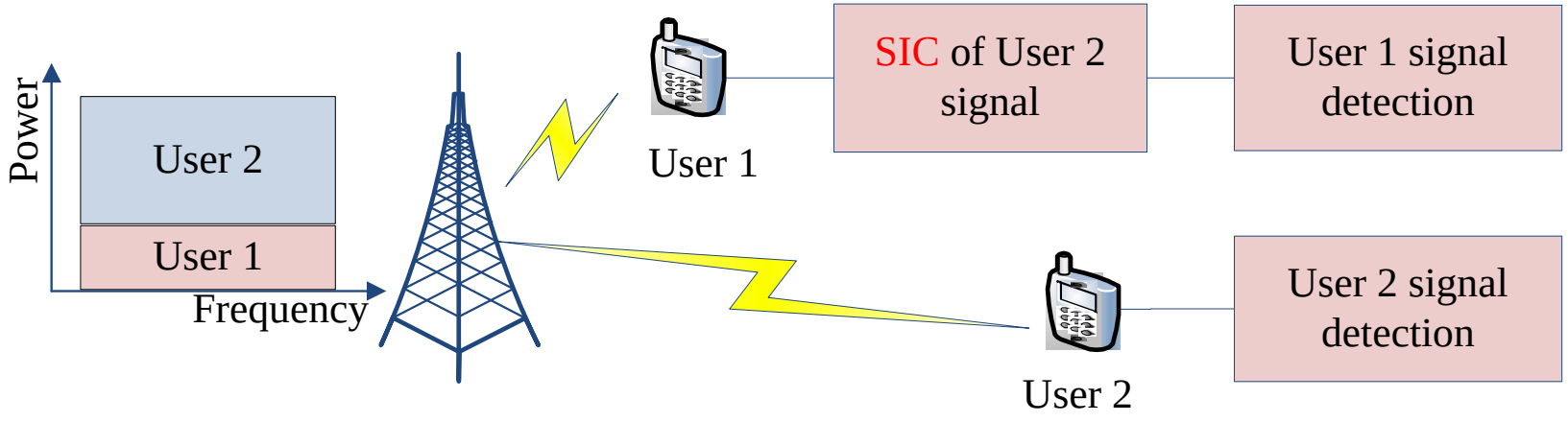
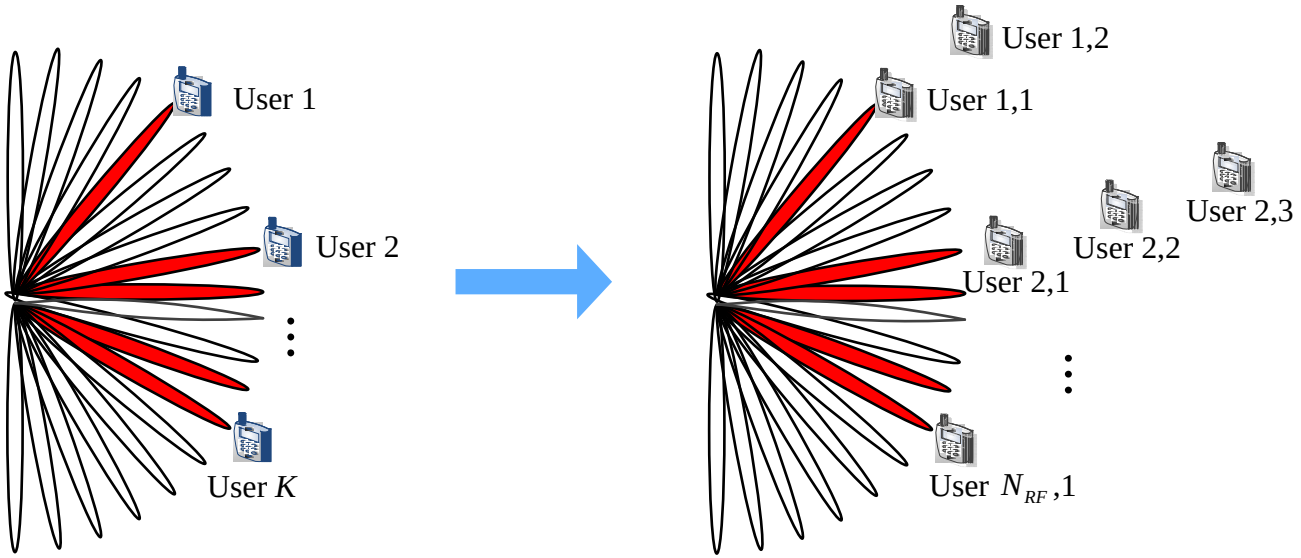
Proposed Beamspace MIMO-NOMA

- 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 nth beam is S_n ($S_i \cap S_j = \Phi$)
  - Beamspace channel vector between the BS and the mth user in the nth beam is denoted by $\mathbf{h}_{m,n}$
  - Uniform precoding vector for users in the nth beam is $\mathbf{w}_n$
  - We assume that $\left\|\mathbf{h}_{1,n}^H \mathbf{w}_n\right\|_2 \geq \left\|\mathbf{h}_{2,n}^H \mathbf{w}_n\right\|_2 \geq \cdots \geq \left\|\mathbf{h}_{|S_n|,n}^H \mathbf{w}_n\right\|_2$
  - After intra-beam SIC, the remaining signal received at the mth user in the nth beam beam can be written as

$$\hat{y}_{m,n} = \underbrace{\mathbf{h}_{m,n}^H \mathbf{w}_n \sqrt{p_{m,n}} s_{m,n}}_{\text{desired signal}} + \underbrace{\mathbf{h}_{m,n}^H \mathbf{w}_n \sum_{i=1}^{m-1} \sqrt{p_{i,n}} s_{i,n}}_{\text{intra-beam interferences}}$$

$$+ \underbrace{\mathbf{h}_{m,n}^H \sum_{j \neq n} \sum_{i=1}^{|S_j|} \mathbf{w}_j \sqrt{p_{i,j}} s_{i,j}}_{\text{inter-beam interferences}} + \underbrace{v_{m,n}}_{\text{noise}}$$

Proposed Beamspace MIMO-NOMA

- System model
  - The SINR the mth user in the nth beam can be represented as

$$\gamma_{m,n} = \frac{\left\|\mathbf{h}_{m,n}^H \mathbf{w}_n\right\|_2^2 p_{m,n}}{\xi_{m,n}}$$

where $\xi_{m,n} = \left\|\mathbf{h}_{m,n}^H \mathbf{w}_n\right\|_2^2 \sum_{i=1}^{m-1} p_{i,n} + \sum_{j \neq n} \left\|\mathbf{h}_{m,n}^H \mathbf{w}_j\right\|_2^2 \sum_{i=1}^{|S_j|} p_{i,j} + \sigma^2$

  - The achievable rate of the mth user in the nth beam

$$R_{m,n} = \log_2 \left(1 + \gamma_{m,n}\right)$$

  - Achievable sum rate

$$R_{\text{sum}} = \sum_{n=1}^{N_{\text{RF}}} \sum_{m=1}^{|S_n|} R_{m,n}$$

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

$$\tilde{\mathbf{H}} = [\mathbf{h}_{1,1}, \mathbf{h}_{1,2}, \cdots, \mathbf{h}_{1,N_{\mathrm{RF}}}]$$

Proposed Beamspace MIMO-NOMA

- Precoding
  - Precoding matrix:

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

  - After normalizing the precoding vectors, the precoding vector for the nth beam can be written as

$$\mathbf{w}_n = \frac{\tilde{\mathbf{w}}_n}{\|\tilde{\mathbf{w}}_n\|_2}$$

Proposed Beamspace MIMO-NOMA

- Power allocation
  - Problem formalization:

$$
\begin{aligned}
\max_{\{p_{m,n}\}} & \sum_{n=1}^{N_{\mathrm{RF}}} \sum_{m=1}^{|S_n|} R_{m,n} \\
\text{s.t. } C_1 : & \; p_{m,n} \geq 0, \quad \forall n, m, \\
C_2 : & \sum_{n=1}^{N_{\mathrm{RF}}} \sum_{m=1}^{|S_n|} p_{m,n} \leq P \\
C_3 : & \; R_{m,n} \geq R_{\min}, \quad \forall n, m
\end{aligned}
$$

  - 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 $e_{m,n} = \mathrm{E}\left\{ \left| s_{m,n} - c_{m,n} \hat{y}_{m,n} \right|^2 \right\}$

  - The optimization problem can be reformulated as

$$\max_{\{p_{m,n}\}} \sum_{n=1}^{N_{\mathrm{RF}}} \sum_{m=1}^{|S_n|} \max_{c_{m,n}} \max_{a_{m,n}>0} \left(-\frac{a_{m,n} e_{m,n}}{\ln 2} + \log_2 a_{m,n} + \frac{1}{\ln 2} \right)$$

$$\text{s.t. } C_1, \ C_2, \ C_3$$

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

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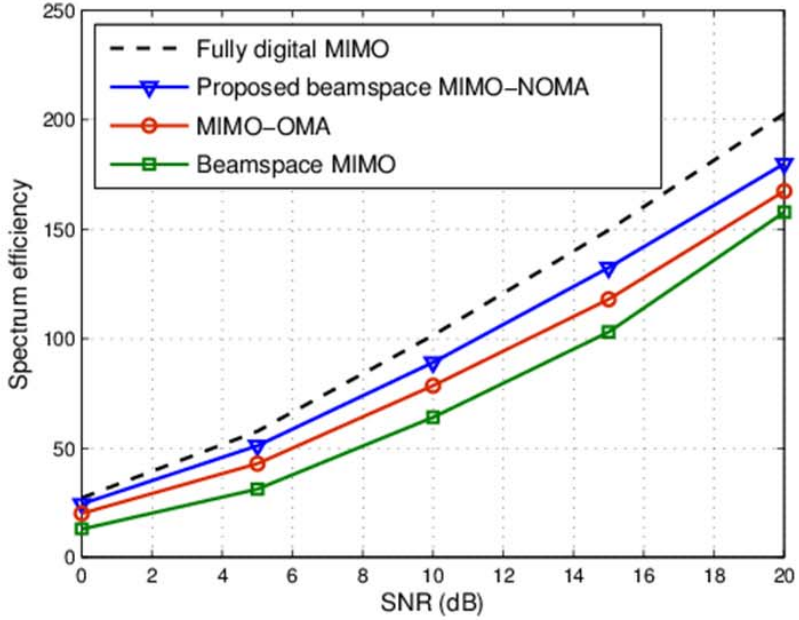
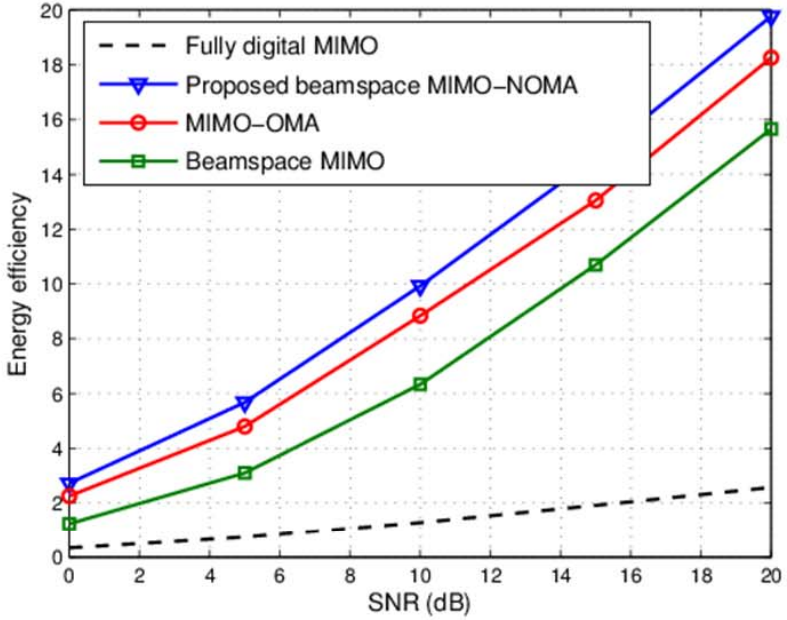
Simulation Results

- 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


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