User Selection and Power Allocation for MmWave-NOMA Networks

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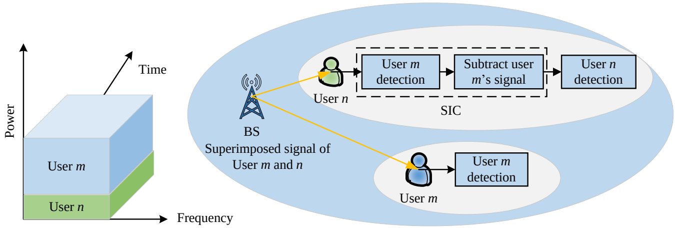
Outline

From OMA to NOMA

1. **Question**: What is multiple access?
2. **Orthogonal multiple access (OMA)**: e.g., FDMA, TDMA, CDMA, OFDMA.
3. New requirements in 5G
   - High spectrum efficiency.
   - Massive connectivity.
4. **Non-orthogonal multiple access (NOMA)**: to break orthogonality.
5. Standard and industry developments on NOMA
   - **Whitepapers for 5G**: DOCOMO, METIS, NGMN, ZTE, SK Telecom, etc.
   - **LTE Release 13**: a two-user downlink special case of NOMA.
   - **Next generation digital TV standard ATSC 3.0**: a variation of NOMA, termed Layer Division Multiplexing (LDM).

NOMA Basics



1. Realize the multiple access in the same resource block (time/frequecy/code), but with **different power levels** [1].
2. Apply successive interference cancellation (SIC) at the receiver.

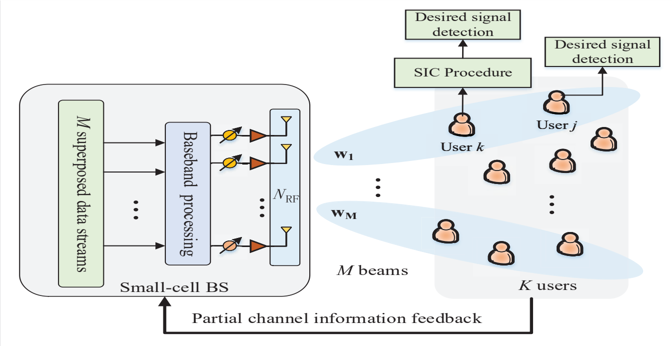
[1] **Y. Liu**, Z. Qin, M. Elkashlan, Z. Ding, A. Nallanathan and L. Hanzo, "Non-Orthogonal Multiple Access for 5G and Beyond", ***Proceedings of the IEEE***; vol. 105, no. 12, pp. 2347-2381, Dec. 2017.

Motivation for MmWave-NOMA Networks

1. **Motivation**
   - **Directional beams** in mmWave communication with large-scale arrays bring large antenna array gains and small inter-beam interference.
   - **Support massive connections** with high user-overload scenarios.
   - **Meet the diversified demands** of users while enhancing the spectral efficiency by using SIC techniques
2. **Challenges**
   - Accurate channel estimation and CSI feedback to the base station (BS) induce **heavy system overhead** particularly in multi-user mmWave downlink systems.
   - **The inter-beam and intra-beam interference** in mmWave NOMA systems affects the decoding order of NOMA.

[2] Z. Ding, P. Fan, and H. V. Poor, "Random beamforming in millimeterwave NOMA networks," *IEEE Access,* vol. PP, no. 99, pp. 1-1, 2017.

MmWave-NOMA System Model



1. Construct M **orthogonal beams** at BS in spatial domain.
2. Realize **NOMA transmission in each beam** and apply successive interference cancellation (SIC) at users.

[3] J. Cui, **Y. Liu**, Z. Ding, P. Fan, and A. Nallanathan, "Optimal User Scheduling and Power Allocation for Millimeter Wave NOMA Systems," *to appear in IEEE Trans. Wireless Commun.*

Received Signal Model

1. Based on the NOMA principle, the received **SINR** of user k to decode user j on beam m is given by

$$\mathrm{SINR}_{j\to k}^{m} = \frac{g_k^m \beta_j^m}{g_k^m \sum_{\pi(i)>\pi(j)} \beta_i^m + \sum_{n\neq m} g_k^n \beta^n + \sigma^2} \qquad (1)$$

2. Note that the achievable SINR for user j on beam m can be obtained with $k = j$.
3. The corresponding decoding rate is $R_{j\to k}^{m} = \log_2(1 + \mathrm{SINR}_{j\to k}^{m})$, for any $\pi(k) \geq \pi(j),\ j,k \in \mathcal{C}_m$.
4. **SIC condition of success**: $R_{j\to k}^{m} \geq R_{j\to j}^{m}$ for $\pi(k) \geq \pi(j)$, $j,k \in \mathcal{C}_m$.

Optimization Problem

1. The considered **sum rate maximization** problem:

$$\max_{c,\beta} \quad \sum_{m=1}^{M}\sum_{j=1}^{q_m} R_{j\to j}^{m} \tag{2a}$$

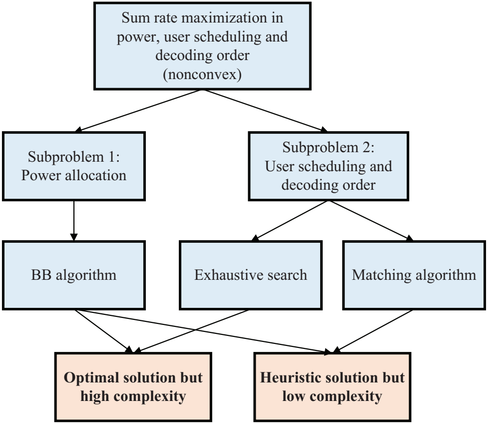
$$\text{s.t.} \quad R_{j\to k}^{m} \geq R_{j\to j}^{m}, \ \sum_{m=1}^{M}\sum_{j\in\mathcal{C}_m} \beta_j^m \leq P_{tot}, \tag{2b}$$

$$\sum_{k=1}^{K} c_k^m = q_m, \ \sum_{m=1}^{M} c_k^m \leq 1, \ R_{j\to j}^{m} \geq \bar{R}_j, \tag{2c}$$

$$\pi_m \in \Pi, \ \pi(k) > \pi(j), \ j,k \in \mathcal{C}_m, \ m \in \mathcal{M}. \tag{2d}$$

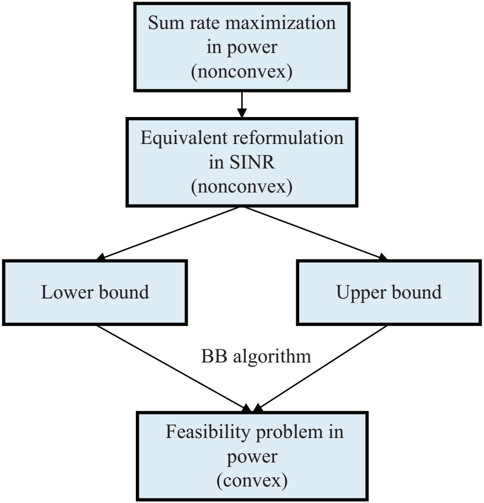
- c denotes the index set, where term c_k^m indicates the indicators for user k on beam m, $c_k^m \in \{0,1\}$.
- Π denotes the set of all possible SIC decoding orders.

Overview of Proposed Solutions



1. *Difficulties:*
   - Intra-beam and inter-beam interference are jointly considered.
   - The decoding order of NOMA is affected by the inter-beam power allocation.
   - Joint user scheduling and power allocation is NP-hard.
2. *Solutions:* Divide the complicated problem into some ease of subproblems.

Overview for Power Allocation Algorithm



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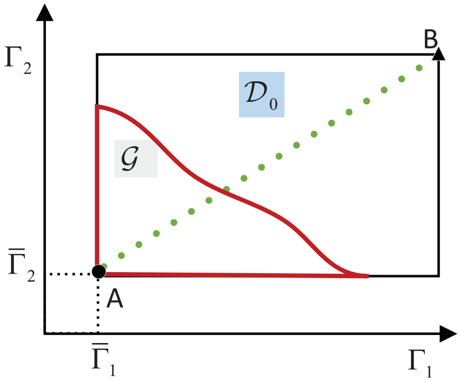
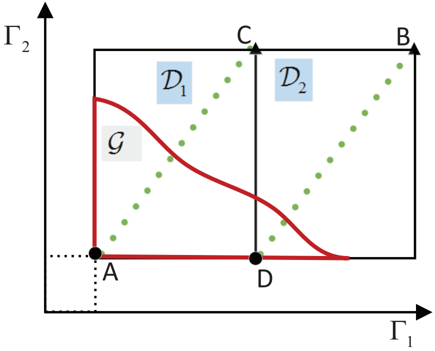
An example for Branch and Bound (BB) Algorithms



1. **Construct a box constraint:**
   - Consider a two-dimension space denoted by Γ_1 and Γ_2.
   - $\mathcal{G}$ is the feasible set. $\mathcal{D}_0$ is the constructed initial rectangle.
   - Point A and point B correspond to the minimum and maximum boundary point in $\mathcal{D}_0$, respectively.

- Let f be the objective function with monotonically decreasing. The optimal objective $f^\star$ belongs to the interval between $f(\mathrm{A})$ and $f(\mathrm{B})$.

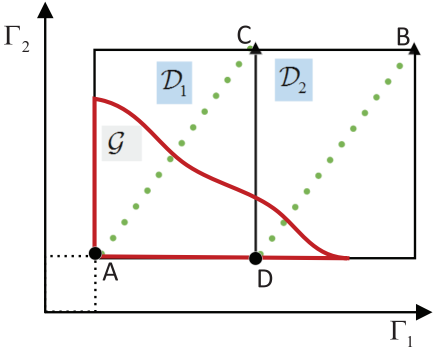
An Example for Branch and Bound (BB) Algorithms



2 **Branch operations:**

- Split $\mathcal{D}_0$ into $\mathcal{D}_1$ and $\mathcal{D}_2$ along the longest edge.
- (A,C) and (D,B) denote the boundary point of $\mathcal{D}_1$ and $\mathcal{D}_2$, respectively.
- Calculate the upper and lower bounds over $\mathcal{D}_1$ and $\mathcal{D}_2$, respectively.

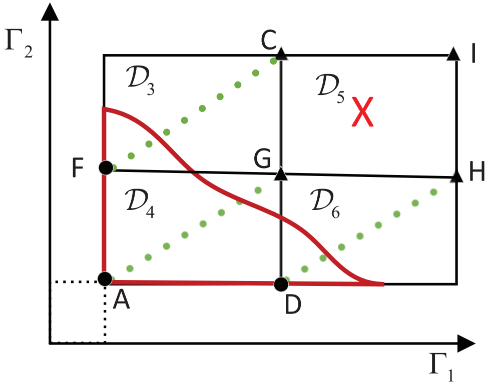
An Example for Branch and Bound (BB) Algorithms



3 **Bound operations:**

- The lower bound $L = \min\{f(\mathrm{A}), f(\mathrm{D})\}$.
- The upper bound $U = \min\{f(\mathrm{C}), f(\mathrm{B})\}$.
- Note that $U - L \leq f(\mathrm{A}) - f(\mathrm{B})$, the potential interval for $f^\star$ decreases.

An Example for Branch and Bound (BB) Algorithms



4 **Pruning operations:**

- Split $\mathcal{D}_1$ and $\mathcal{D}_2$ along its longest edge, respectively.
- Remove $\mathcal{D}_5$, which will not affect the optimality.

Subproblem 1: Power Allocation Problem

1. For given the **selected users** and the corresponding **decoding order**, the power allocation subproblem can be formulated as follows.

$$\min_{\tilde{\beta},\Gamma} -\sum_{m=1}^{M}\sum_{j_m=1}^{q_m} \log_2\left(1+\Gamma^m_{j_m\to j_m}\right) \tag{3a}$$

$$\text{s.t.}\Gamma^m_{j_m\to j_m} \leq \frac{g^m_{j_m}\beta^m_{j_m}}{g^m_{j_m}\sum_{i_m=j_m+1}^{q_m}\beta^m_{i_m}+\sum_{n\neq m} g^n_{j_m}\beta^n+\sigma^2}, \tag{3b}$$

$$\sum_{m=1}^{M}\sum_{j_m=1}^{q_m}\beta^m_{j_m} \leq P_{tot},\ \ R^m_{j_m\to j_m} \geq \bar{R}_{j_m}, \tag{3c}$$

$$\sum_{n\neq m}\left(g^m_{k_m}g^n_{j_m}-g^m_{j_m}g^n_{k_m}\right)\beta^n+\left(g^m_{k_m}-g^m_{j_m}\right)\sigma^2 \geq 0, \tag{3d}$$

$$k_m > j_m,\ \ j_m, k_m \in \mathcal{C}_m,\ \ m \in \mathcal{M}. \tag{3e}$$

Key Steps for Branch and Bound (BB) Algorithms

1 **Construct box constraint sets:**

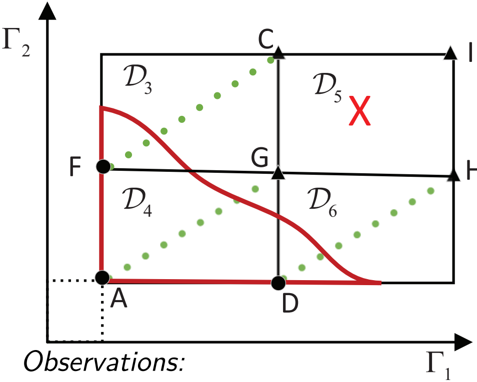
- The objective function and the feasible set of (3) can be rewritten as

$$\mathcal{U}(\Gamma) = -\sum_{m=1}^{M}\sum_{j_m=1}^{q_m} \log_2\left(1 + \Gamma_{j_m \to j_m}^{m}\right), \mathcal{G} = \{\Gamma | (3b) - (3e)\}.$$

- The equivalent reformulation of power allocation problem is given by

$$\min_{\Gamma} \quad \mathcal{U}(\Gamma) \qquad \text{s.t.} \quad \Gamma \in \mathcal{G}. \tag{4}$$

Key Steps for Branch and Bound (BB) Algorithms



2 **Construct bound functions:**

- The lower bound function:

$$\underline{g}(\Gamma) = \begin{cases} \mathcal{U}(\overline{\Gamma}), & \underline{\Gamma} \in \mathcal{G} \\ 0, & \text{o.w.}, \end{cases},$$

- The upper bound function:

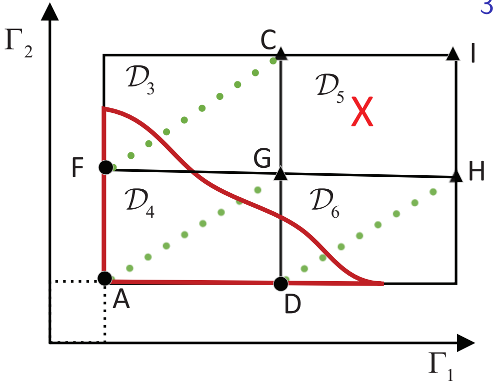
$$\overline{g}(\Gamma) = \begin{cases} \mathcal{U}(\underline{\Gamma}), & \underline{\Gamma} \in \mathcal{G} \\ 0, & \text{o.w.}. \end{cases}$$

Observations:

- $\underline{g}(C/G/H) = \mathcal{U}(C/G/H)$, and $\overline{g}(F/A/D) = \mathcal{U}(F/A/D)$, for $\mathcal{D}_3, \mathcal{D}_4, \mathcal{D}_6$, respectively.
- $\underline{g}(G) = 0$ and $\overline{g}(G) = 0$ for $\mathcal{D}_5$.

Key Steps for Branch and Bound (BB) Algorithms

Question: How to express the observations in mathematical problem?



3 **Check the feasibility:** Given a set of SINR values, testing if it is achievable is equivalent to solving the following feasibility problem:

$$\begin{aligned} \text{Find} \quad & \text{PA coefficients} \\ \text{s.t.} \quad & \underline{\Gamma} \in \mathcal{G}. \end{aligned} \tag{5}$$

Observations:

- Problem (5) is feasible for A, D and F.
- One cannot find a feasible PA coefficients for $\mathcal{D}_5$.

Subproblem 2: Matching Theory for User Selection

1. Given the user power allocation coefficients, the **user selection problem** can be transformed into

$$\begin{aligned} \max_{\mathbf{c}} \quad & \mathcal{H} = \sum_{m=1}^{M} \sum_{j=1}^{q_m} R_{j\to j}^{m} \\ \text{s.t.} \quad & \sum_{k=1}^{K} c_k^m = q_m, \ \sum_{m=1}^{M} c_k^m \le 1, \\ & \pi_m \in \Pi, \ \pi(k) > \pi(j), \ j, k \in \mathcal{C}_m, \ m \in \mathcal{M}. \end{aligned} \tag{6}$$

- Problem (6) is a combinational problem.
- Exhaustive search provides an optimal approach but it surfers a cumbersome computational complexity.
- There two objects: **users** and **beams**, which motivates us build a matching model.

Subproblem 2: Matching Theory for User Selection

1. **Preference lists:**
   - The preference value for the user k on beam m is the achievable rate of user k on beam m:

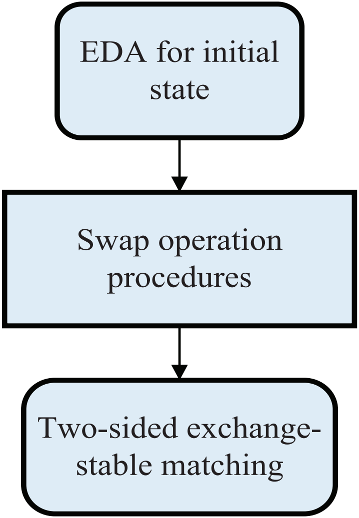
$$\mathcal{H}_k^m = \log_2\left(1 + \Gamma_k^m\right). \tag{7}$$

   - The preference value of beam m is the sum rate of all users on beam m:

$$\mathcal{H}^m = \sum_{k \in \varphi(m)} \log_2\left(1 + \Gamma_k^m\right). \tag{8}$$

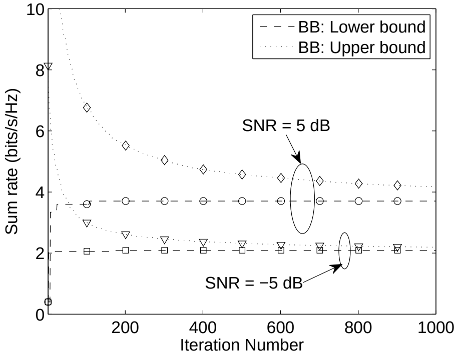
   - The inter-beam interference and the intra-beam interference exist for each user's rate.
   - Users and beams compose a **many-to-one matching with externalities**.

Overview for Matching Algorithms



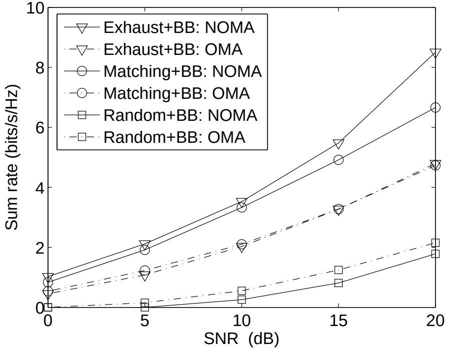
- EDA denotes the extend deferred acceptance.
- The users first propose to the BSs based on its preference list. Then each BS accepts the users with prior preferences.
- The goal of swap operation procedure is to further enhance the system sum rate.
- Two-sided exchange-stable matching provides the stop criteria.

Simulation Results



- The proposed BB algorithm is **converged** for different SNR.
- the convergence become **slow** when the SNR increases.

Simulation Results



- **Matching+BB** achieves a good balance between the performance and the computational complexity.
- The application of NOMA into mmWave can further improve the spectral efficiency by **appropriate power** and **user selection** policies.

Conclusions

- The problem to maximize the sum rate for the mmWave NOMA system by designing of user selection and power allocation algorithms has been considered.
- **BB technique** was applied for solving the power allocation problem optimally.
- For the integer optimization of the user selection, a low complexity algorithm based on **matching theory** was developed.

Research Opportunities and challenges for NOMA

1. MIMO-NOMA design.
2. Error Propagation in SIC.
3. Imperfect SIC and limited channel feedback.
4. Synchronization/asynchronization design for NOMA.
5. Different variants of NOMA.
6. Novel coding and modulation for NOMA.
7. Hybrid multiple access
8. Efficient resource management for NOMA
9. Security provisioning in NOMA
10. Grant free NOMA design for IoT

Y. Liu, Z. Qin, M. Elkashlan, Z. Ding, A. Nallanathan and L. Hanzo, "Non-Orthogonal Multiple Access for 5G and Beyond", ***Proceedings of the IEEE***; vol. 105, no. 12, pp. 2347-2381, Dec. 2017.

Questions?

Thanks for your attention.