Non-Orthogonal Multiple Access for 5G and Beyond
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Outline

1 Overview and Motivation: OMA vs NOMA

2 Power-Domain NOMA Basics

3 Sustainability of NOMA Networks

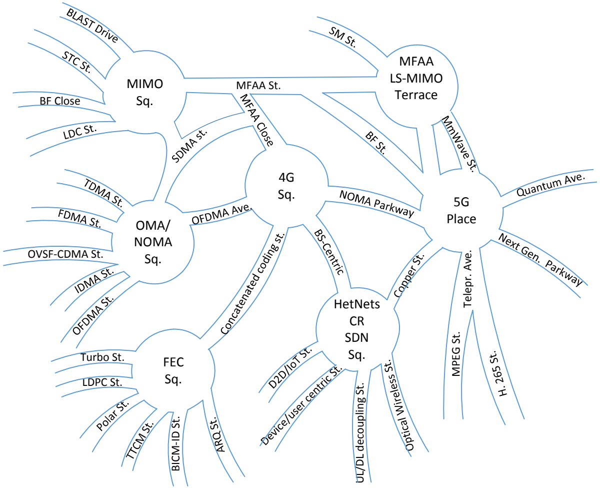
4 Compatibility of NOMA in 5G Networks

5 Security Issues in NOMA Networks

6 Other Research Contributions on NOMA

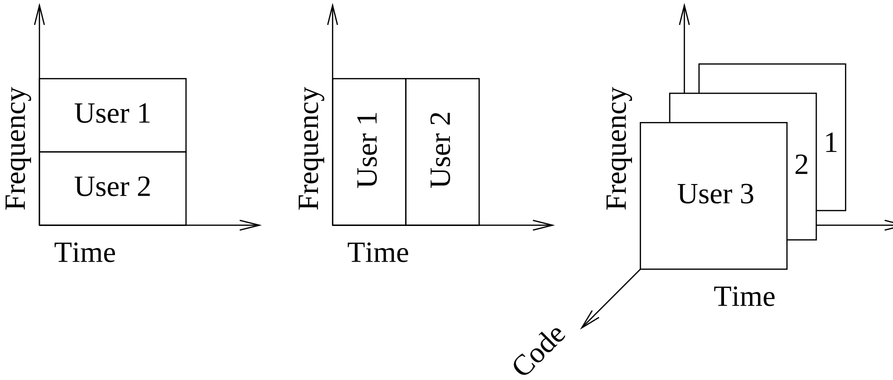
7 Research Opportunities and Challenges for NOMA

Brief History of Wireless Standardization

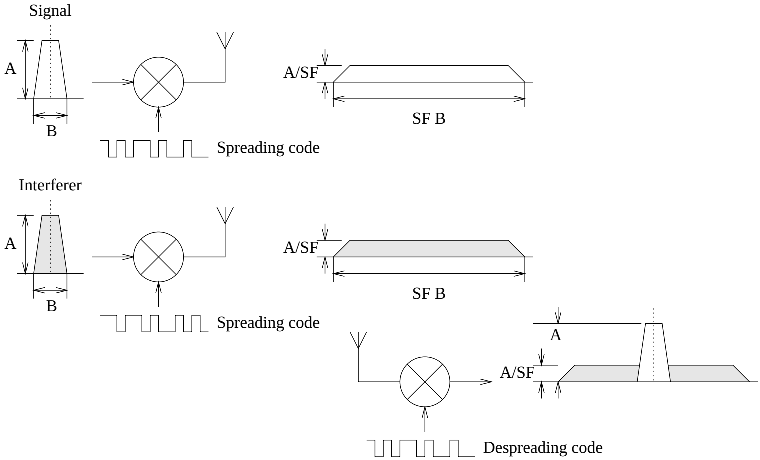


[1] Y. Liu, Z. Qin, M. Elkashlan, Z. Ding, A. Nallanathan, and L. Hanzo, "Non-Orthogonal Multiple Access for 5G", ***Proceedings of the IEEE***; Dec 2017.

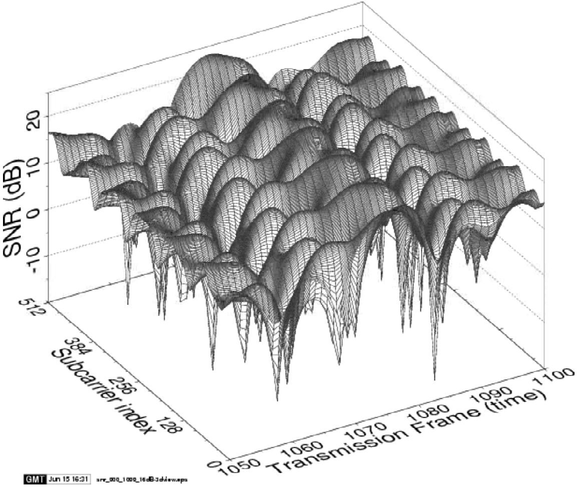
Orthogonal multiple access: FDMA, TDMA and CDMA



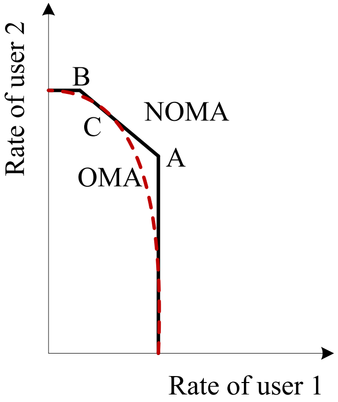
Intentional DS-CDMA Spreading



Unintentional Spreading in the FD



Capacity of OMA vs. NOMA in AWGN channel: (a) Uplink; (b) Downlink.



(a) (b)

Diverse NOMA contributions

- R. Zhang and L. Hanzo, “A unified treatment of superposition coding aided communications: Theory and practice,” *IEEE Commun. Surveys Tutorials*, vol. 13, no. 3, pp. 503–520, Mar. 2011.
- P. Botsinis, D. Alanis, Z. Babar, H. Nguyen, D. Chandra, S. X. Ng, and L. Hanzo, “Quantum-aided multi-user transmission in non-orthogonal multiple access systems,” *IEEE Access*, vol. PP, no. 99, pp. 1–1, 2016.
- A. Wolfgang, S. Chen, and L. Hanzo, “Parallel interference cancellation based turbo space-time equalization in the SDMA uplink,” *IEEE TWC*, vol. 6, no. 2, pp. 609–616, Feb. 2007.
- L. Wang, L. Xu, S. Chen, and L. Hanzo, “Three-stage irregular convolutional coded iterative center-shifting K-best sphere detection for soft-decision SDMA-OFDM,” *IEEE TVT*, vol. 58, no. 4, pp. 2103–2109, May 2009.
- S. Chen, L. Hanzo, and A. Livingstone, “MBER space-time decision feedback equalization assisted multiuser detection for multiple antenna aided SDMA systems,” *IEEE TSP*, vol. 54, no. 8, pp. 3090–3098, Aug. 2006.
- L. Hanzo, S. Chen, J. Zhang, and X. Mu, “Evolutionary algorithm assisted joint channel estimation and turbo multi-user detection/decoding for OFDM/SDMA,” *IEEE TVT*, vol. 63, no. 3, pp. 1204–1222, Mar. 2014.
- S. Chen, A. Wolfgang, C. J. Harris, and L. Hanzo, “Symmetric RBF classifier for nonlinear detection in multiple-antenna-aided systems,” *IEEE TNN*, vol. 19, no. 5, pp. 737–745, May 2008.

Diverse NOMA contributions

- S. Chen, A. Livingstone, H. Q. Du, and L. Hanzo, “Adaptive minimum symbol error rate beamforming assisted detection for quadrature amplitude modulation,” *IEEE Trans. Wireless Commun.*, vol. 7, no. 4, pp. 1140–1145, Apr. 2008.
- J. Zhang, S. Chen, X. Mu, and L. Hanzo, “Turbo multi-user detection for OFDM/SDMA systems relying on differential evolution aided iterative channel estimation,” *IEEE Trans. Commun.*, vol. 60, no. 6, pp. 1621–1633, Jun. 2012.
- J. Zhang, S. Chen, X. Mu, and L. Hanzo, “Joint channel estimation and multi-user detection for SDMA/OFDM based on dual repeated weighted boosting search,” *IEEE Trans. Veh. Technol.*, vol. 60, no. 7, pp. 3265–3275, Jun. 2011.
- C.-Y. Wei, J. Akhtman, S.-X. Ng, and L. Hanzo, “Iterative near-maximum-likelihood detection in rank-deficient downlink SDMA systems,” *IEEE Trans. Veh. Technol.*, vol. 57, no. 1, pp. 653–657, Jan. 2008.
  A. Wolfgang, J. Akhtman, S. Chen, and L. Hanzo, “Iterative MIMO detection for rank-deficient systems,” *IEEE Signal Process. Lett.*, vol. 13, no. 11, pp. 699–702, Nov. 2006.
- L. Xu, S. Chen, and L. Hanzo, “EXIT chart analysis aided turbo MUD designs for the rank-deficient multiple antenna assisted OFDM uplink,” *IEEE Trans. Wireless Commun.*, vol. 7, no. 6, pp. 2039–2044, Jun. 2008.

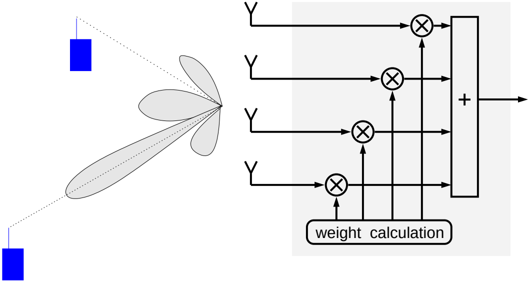
Diverse NOMA contributions

- A. Wolfgang, J. Akhtman, S. Chen, and L. Hanzo, "Reduced-complexity near-maximum-likelihood detection for decision feedback assisted space-time equalization," *IEEE Trans. Wireless Commun.*, vol. 6, no. 7, pp. 2407–2411, Jul. 2007.
- J. Akhtman, A. Wolfgang, S. Chen, and L. Hanzo, "An optimized-hierarchy-aided approximate Log-MAP detector for MIMO systems," *IEEE TWC*, vol. 6, no. 5, pp. 1900–1909, May 2007.

NOMA Beamforming Example

Uplink/Downlink Beamforming

- Why?
  Increase of capacity
- How?
  Spatially separated interfering signals are suppressed



$$y = \mathbf{w}^H \mathbf{x}$$

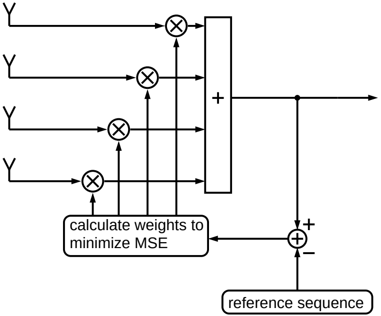
MMSE Based Beamforming

- Weights are calculated in order to minimize:

$$\epsilon(t)^2 = \left(\mathbf{w}^H\mathbf{x}(t) - r(t)\right)^2$$

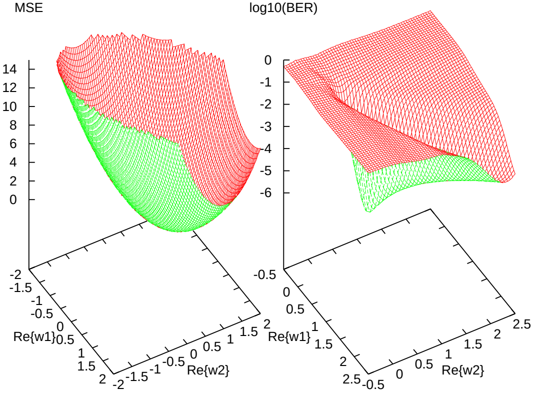
$\mathbf{w}$: Beamformer weights
$\mathbf{x}(t)$: Channel output
$r(t)$: Reference symbol

- For AWGN channels MMSE weights can be calculated using a closed form expression
- Realizations: LMS, RLS, SMI



MSE and BER Surfaces at the Output of a [5 x 2] NOMA Beamformer

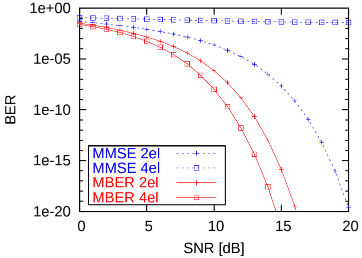
Error surfaces at the receiver's output calculated for five BPSK modulated sources having equal received power and communicating over AWGN channels at SNR=10 dB.



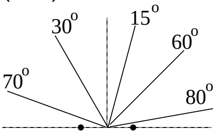
The imaginary part of both weights of the 2-element array was fixed.

MMSE vs MBER NOMA Beamforming

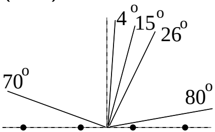
- Test case: BPSK modulated sources having equal received power and communicating over AWGN channels
- MMSE solution calculated analytically
- MBER solution obtained with the aid of conjugate gradient algorithm



Scenario S (2el.)

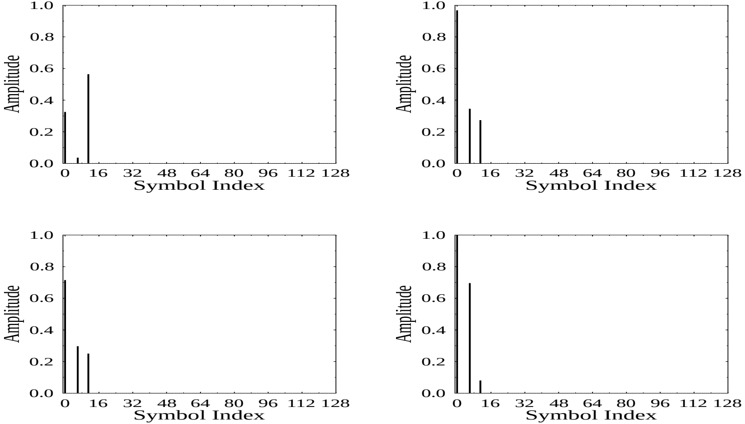


Scenario U (4el.)



NOMA SDMA Example

Evolution from CDMA-NOMA to SDMA-NOMA



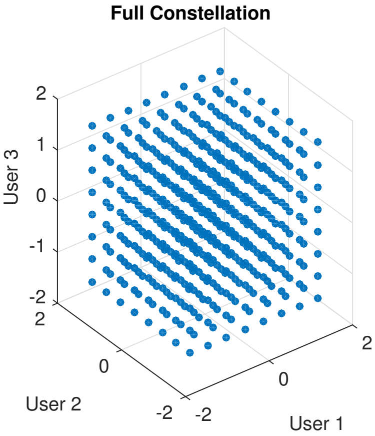
Quantum-Search Aided MUD in NOMA

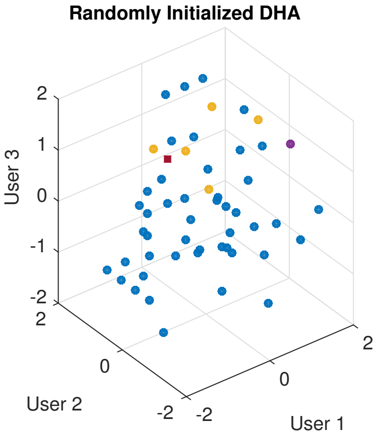
Multiple Access	SDMA-OFDM
Number of Users	$U = 3$
Number of AEs at the BS	$P = 1$
Normalized User-Load	$U_L = U_q/P = 3$
Modulation	8-PAM $M = 8$
E_b/N_0	0 dB
Channel Code	Turbo Convolutional Code, 8 trellis states, $R = 1/2$
Channel Model	Extended Typical Urban (ETU)
Mobile Velocity	$v = 130$ km/h
Carrier Frequency	$f_c = 2.5$ GHz
Sampling Frequency	$f_s = 15.36$ GHz (77 delay taps)
Doppler Frequency	$f_d = 70$ Hz
Number of Subcarriers	$\mathcal{Q} = 1024$
Cyclic Prefix	CP $= 128$
Interleaver Length	10 240 bits per user
Channel Estimation	Perfect

Quantum-Search Aided MUD in NOMA

- There are $8^3 = 512$ symbols in the full constellation, while 53 and 46 symbols are obtained by the randomly-initialized and ZF-initialized DHA, respectively.
- The purple circle denotes the random initial input, or the ZF detector's output, which may be used as an initial input. The ZF is as bad as the random one in this rank-deficient scenario.
- By using the DHA, we find symbols better than the previously found symbols, which are denoted by the yellow circles in the 3D figure.
- But we also find symbols that are "worse" than the previously found symbols, as represented by the blue circles in the 3D figure.
- The red square is the optimal symbol which is eventually found.

Dürr-Høyer MUD for CDMA/SDMA NOMA - Userload=2



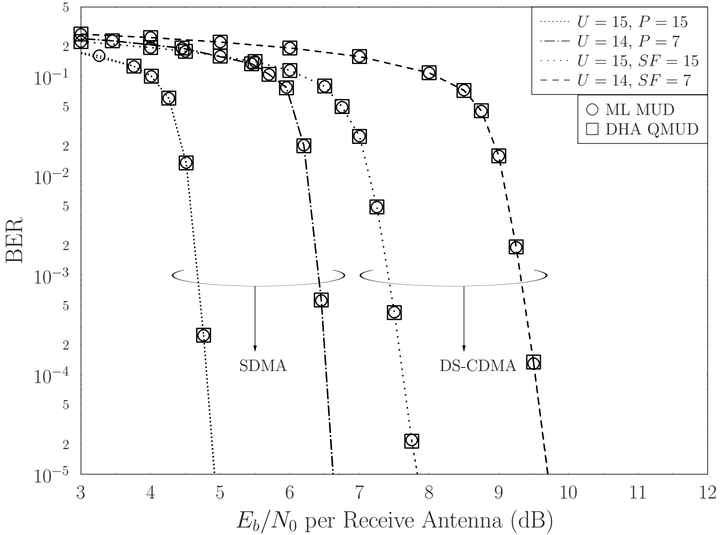


NOMA CDMA vs SDMA

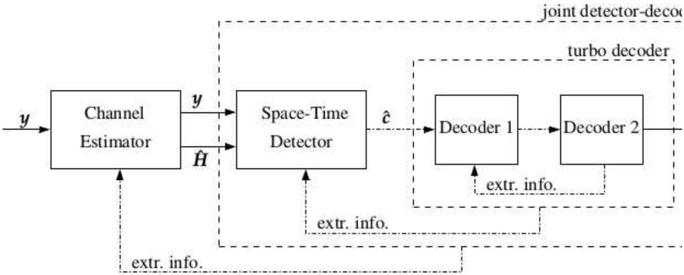
DS-CDMA vs SDMA NOMA Systems

	System 1	System 2	System 3	System 4
Number of Users	$U = 14$	$U = 14$	$U = 15$	$U = 15$
Multiple Access Scheme	DS-CDMA	SDMA	DS-CDMA	SDMA
Number of AEs at the BS	$P = 1$	$P = 7$	$P = 1$	$P = 15$
Spreading Factor	$SF = 7$	N/A	$SF = 15$	N/A
Spreading Codes	m-sequences	N/A	Gold Codes	N/A
Normalized User Load	$U_L = 2$	$U_L = 2$	$U_L = 1$	$U_L = 1$
Bit-based Interleaver Length	42 000	42 000	40 000	40 000
Number of AEs per User	$N_{T_x} = 1$			
Modulation	BPSK $M = 2$			
Channel Code	Turbo Code, $R = 1/2$, 8 Trellis states $I_{inner} = 4$ iterations			
Channel	Uncorrelated Rayleigh Channel			
Channel Estimation	Perfect			

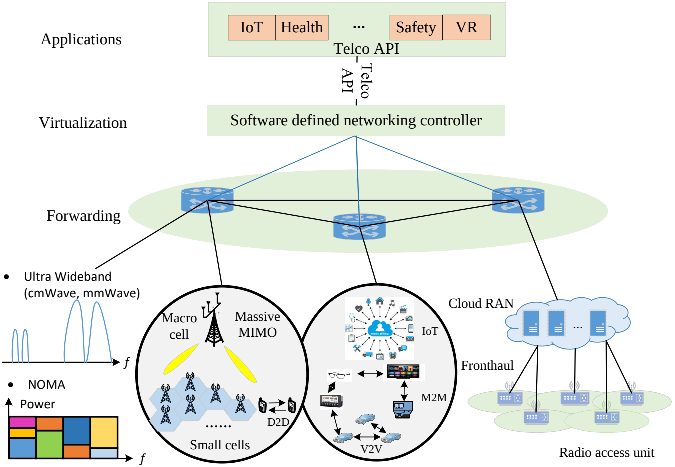
Dürr-Høyer CDMA/SDMA NOMA AT Userload=2



Iterative Joint Channel & Data Estimation Turbo-Receivers for NOMA



Future 5G network architecture.



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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).

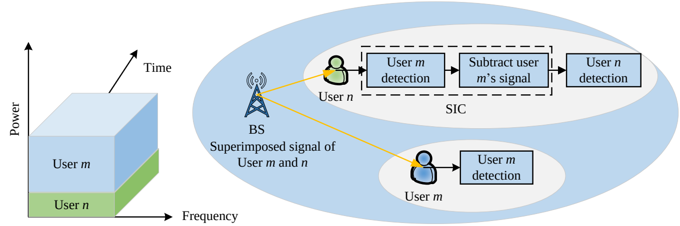
Introduction to NOMA Systems

- The non-orthogonal nature of a multiple access system may manifest itself in the time-, frequency-, code- or spatial-domains as well as in their arbitrary combinations;
- Even if originally an OMA scheme is used, the deleterious effects of the wireless channel may erode the orthogonality. For example, the channel-induced dispersion may 'smear' the originally orthogonal time-slots of a TDMA system into each other, because the transmitted signal is convolved with the dispersive channel's impulse response (CIR).
- Similarly, the Orthogonal Variable Spreading Factor (OVSF) codes of the 3G systems rely on orthogonal Walsh-Hadamard codes, but upon transmission over the dispersive channel their orthogonality is destroyed.

Introduction to NOMA Systems

- This realization has then led to the concept of NOMA based on the Spatial Division Multiple Access (SDMA) philosophy, where the unique, user-specific non-orthogonal channel impulse responses are used for distinguishing the uplink transmissions of the users - provided that their CIR is estimated sufficiently accurately.
- In simple tangible terms this implies that a NOMA system is capable of supporting more users than the number of distinct time-, frequency-, code-domain resources, provided that their channels can be sufficiently accurately estimated even under these challenging interference-contaminated conditions.
- Naturally, this challenging channel estimation and user-separation process typically imposes an increased signal processing complexity.
- Many of these NOMA-user-separation techniques are surveyed in this paper, with a special emphasis on the power-domain

Power-Domain NOMA Basics



1. Supports multiple access within a given resource block (time/frequecy/code), using **different power levels** for distinguishing/separating them [1].
2. Apply successive interference cancellation (SIC) at the receiver for separating the NOMA users [2].
3. If their power is similar, PIC is a better alternative.

[1] Y. Liu, Z. Qin, M. Elkashlan, Z. Ding, A. Nallanathan, and L. Hanzo, "Non-Orthogonal Multiple Access for 5G", ***Proceedings of the IEEE***; Dec 2017.

[2] Z. Ding, Y. Liu, J. Choi, Q. Sun, M. Elkashlan, Chih-Lin I, and H. V. Poor (2017), "Application of Non-orthogonal Multiple Access in LTE and 5G Networks", ***IEEE Communication Magazine***;(**Web of Science Hot**

NOMA Basics

1. **Question**: Why NOMA is a popular proposition for 5G?
2. Consider the following two scenarios.
   - If a user has poor channel conditions
     - The bandwidth allocated to this user via OMA cannot be used at a high rate.
     - NOMA - **improves the bandwidth-efficiency.**
   - If a user only needs a low data rate, e.g., IoT networks.
     - The use of OMA gives the IoT node more capacity than it needs.
     - NOMA - **heterogeneous QoS and massive connectivity.**

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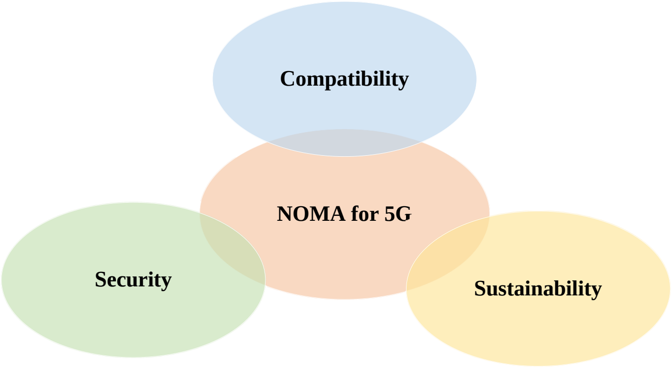
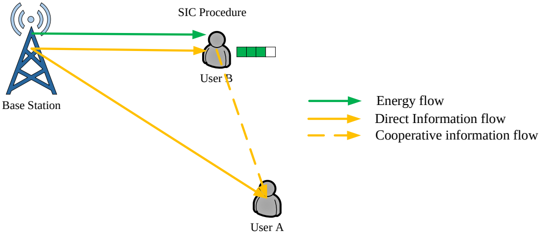
Research Contributions in NOMA



Sustainability of NOMA Networks

1. **Transmission reliability** - cooperative NOMA.
2. **Energy consumption** - radio signal energy harvesting.



3. Propose a wireless powered cooperative NOMA protocol [1].
4. The first contribution on wirelessly powered NOMA networks.

[1] Y. Liu, Z. Ding, M. Elkashlan, and H. V. Poor (2016), "Cooperative Non-orthogonal Multiple Access with Simultaneous Wireless Information and Power Transfer", ***IEEE Journal on Selected Areas in Communications (JSAC)***. (**Web of Science Hot Paper**, **Top 15 Most Popular Article on JSAC**)

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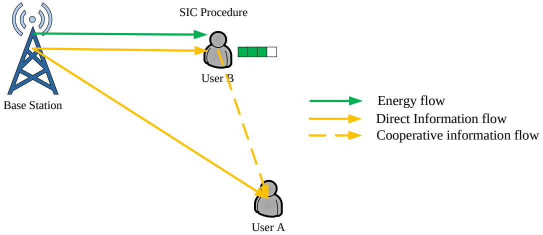

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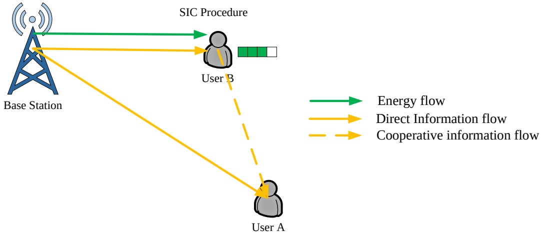

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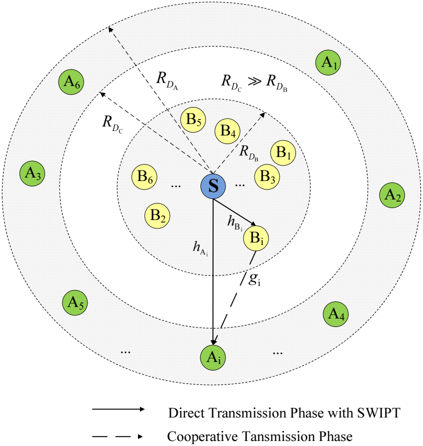
Network Model



- Illustration of a downlink SWIPT NOMA system with a base station S (blue circle). The spatial distributions of the near users (yellow circles) and the far users (green circles) obey a homogeneous Poisson Point Process (PPP).

Network Model

- The locations of the near and far users are modeled as homogeneous PPPs Φ_κ $(\kappa \in \{\mathrm{A}, \mathrm{B}\})$ with densities λ_{Φ_κ}.
- The near users are uniformly distributed within the disc and the far users are uniformly distributed within the ring.
- The users in $\{\mathrm{B_i}\}$ are energy harvesting relays that harvest energy from the BS and forward the information to $\{\mathrm{A_i}\}$ using the harvested energy as their transmit powers.
- The DF strategy is applied at $\{\mathrm{B_i}\}$ and the cooperative NOMA system consists of two phases.
- It is assumed that the two phases have the same transmission periods.

Non-Orthogonal Multiple Access with User Selection

- A natural question arises: which specific near NOMA user should help which particular far NOMA user?
- To investigate the performance of a specific pair of selected NOMA users, three opportunistic user selection schemes may be considered, based on the particular locations of users to perform NOMA as follows:
  - random near user and random far user (RNRF) selection, where both the near and far users are randomly selected from the two groups.
  - nearest near user and nearest far user (NNNF) selection, where a near user and a far user closest to the BS are selected from the two groups.
  - nearest near user and farthest far user (NNFF) selection, where a near user which is closest to the BS is selected and a far user which is farthest from the BS is selected.

Outage Probability of the Near Users of RNRF

- An outage of $\mathrm{B_i}$ can occur for two reasons.
  1. $\mathrm{B_i}$ cannot detect x_{i1}.
  2. $\mathrm{B_i}$ can detect x_{i1} but cannot detect x_{i2}.
- Based on this, the outage probability of $\mathrm{B_i}$ can be expressed as follows:

$$P_{\mathrm{B_i}} = \Pr\left(\frac{\rho|h_{\mathrm{B_i}}|^2|p_{i1}|^2}{\rho|h_{\mathrm{B_i}}|^2|p_{i2}|^2+1+d_{\mathrm{B_i}}^{\alpha}} < \tau_1\right) + \Pr\left(\frac{\rho|h_{\mathrm{B_i}}|^2|p_{i1}|^2}{\rho|h_{\mathrm{B_i}}|^2|p_{i2}|^2+1+d_{\mathrm{B_i}}^{\alpha}} > \tau_1, \gamma_{\mathrm{S,B_i}}^{x_{i2}} < \tau_2\right). \quad (1)$$

Outage Probability of the Far Users of RNRF

Outage experienced by $\mathrm{A_i}$ can occur in two situations.

1. $\mathrm{B_i}$ can detect x_{i1} but the overall received SNR at $\mathrm{A_i}$ cannot support the targeted rate.
2. Neither $\mathrm{A_i}$ nor $\mathrm{B_i}$ can detect x_{i1}.

Based on this, the outage probability can be expressed as follows:

$$P_{\mathrm{A_i}} = \Pr\left(\gamma_{\mathrm{A_i,MRC}}^{x_{i1}} < \tau_1,\, \gamma_{\mathrm{S,B_i}}^{x_{i1}}\Big|_{\beta_i=0} > \tau_1\right) + \Pr\left(\gamma_{\mathrm{S,A_i}}^{x_{i1}} < \tau_1,\, \gamma_{\mathrm{S,B_i}}^{x_{i1}}\Big|_{\beta_i=0} < \tau_1\right). \quad (2)$$

Diversity Analysis of RNRF—Near Users

- The diversity gain is defined as follows:

$$d = -\lim_{\rho\to\infty} \frac{\log P(\rho)}{\log \rho}. \tag{3}$$

- *Near users:* When $\varepsilon \to 0$, a high SNR approximation with $1 - e^{-x} \approx x$ is given by

$$F_{Y_i}(\varepsilon) \approx \frac{1}{2}\sum_{n=1}^{N} \omega_N \sqrt{1-{\phi_n}^2} c_n \varepsilon_{\mathrm{A}_i} (\phi_n + 1). \tag{4}$$

- Substituting (4) into (3), we obtain that the diversity gain for the near users is one, which means that using NOMA with energy harvesting will not decrease the diversity gain.

Diversity Analysis of RNRF—Far Users

Far users: For the far users, we obtain

$$d = -\lim_{\rho\to\infty} \frac{\log\left(-\frac{1}{\rho^2}\log\frac{1}{\rho}\right)}{\log\rho} = -\lim_{\rho\to\infty} \frac{\log\log\rho - \log\rho^2}{\log\rho} = 2. \quad (5)$$

Remarks:

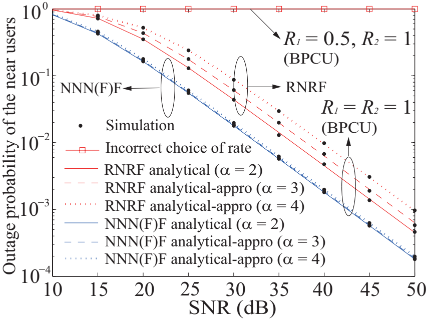
- This result indicates that using NOMA with an energy harvesting relay will not affect the diversity gain.
- At high SNRs, the dominant factor for the outage probability is $\frac{1}{\rho^2}\ln\rho$.
- The outage probability of using NOMA with SWIPT decays at a rate of $\frac{\ln SNR}{SNR^2}$. However, for a conventional cooperative system without energy harvesting, a faster decreasing rate of $\frac{1}{SNR^2}$ can be achieved.

NNNF Selection Scheme and NNFF Selection Scheme

- **Advantage of NNNF**: it can minimize the outage probability of both the near and far users.
- **Advantage of NNFF**: NOMA can offer a larger performance gain over conventional MA when user channel conditions are more distinct.

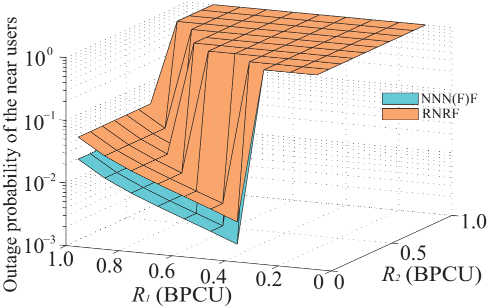
Following a procedure similar to that of RNRF, we can obtain the outage probability, diversity gain, and the throughput of NNNF and NNFF.

Numerical Results



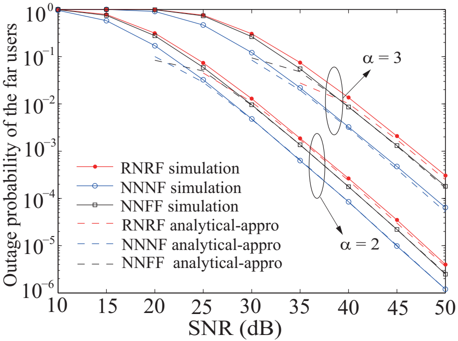
- Lower outage probability is achieved than with RNRF.
- All curves have the same slopes, which indicates the same diversity gains.
- The incorrect choice of rate results in an outage probability for the near users, which is always one.

Numerical Results



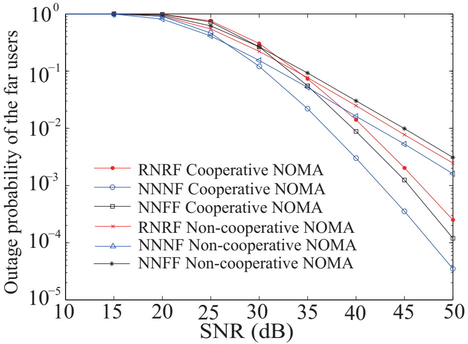
- The outage of the near users occurs more frequently as the rate of the far user, R_1, increases.
- For the choice of R_1, it should satisfy the condition $(|p_{i1}|^2 - |p_{i2}|^2\tau_1 > 0)$.
- For the choice of R_2, it should satisfy the condition that the split energy for detecting x_{i1} is also sufficient to detect x_{i2} $(\varepsilon_{\mathrm{A}_i} \geq \varepsilon_{\mathrm{B}_i})$.

Numerical Results



- NNNF achieves the lowest outage probability.
- NNFF achieves lower outage than RNRF, which indicates that the distance of the near users has more impact than that of the far users.
- All of the curves have the same slopes, which indicates that the diversity gains of the far users are the same.

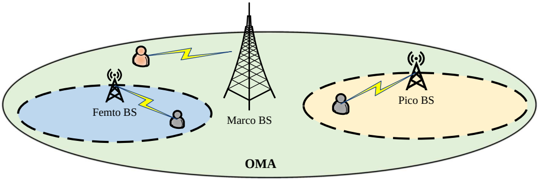
Numerical Results



- Cooperative NOMA has a steeper slope than that of non-cooperative NOMA.
- NNNF achieves the lowest outage probability.
- NNFF has higher outage probability than RNRF in non-cooperative NOMA, however, it achieves lower outage probability than RNRF in cooperative NOMA.

NOMA in 5G Networks—HetNets

1. **Heterogenous networks (HetNets)**: meet the requirements of high data traffic in 5G.
   - **Question**: How to support massive connectivity in HetNets?
   - **Question**: How to further improve the spectral efficiency of HetNets?



2. **New framework**: NOMA-enabled HetNets.
3. **Challenge**: Complex co-channel interference environment.

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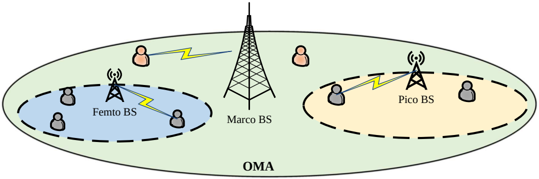

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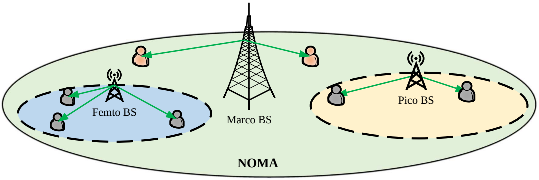

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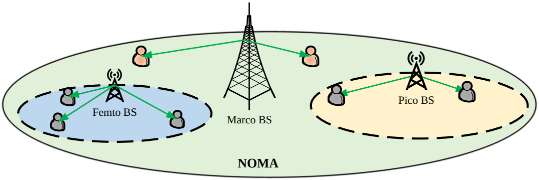

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NOMA in HetNets I — Resource Allocation

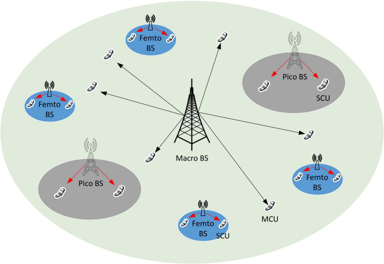


Fig.: System model.

- K-tier HetNets: One macro base station (MBS), B small base stations (SBSs)
- M macro cell users (MCUs), M RBs, K small cell users (SCUs) served by each SBS
- Each SBS serves K SCUs simultaneously on the same RB via NOMA

[1] J. Zhao, Y. Liu, K. K. Chai, A. Nallanathan, Y. Chen and Z. Han (2017),"Spectrum Allocation and Power Control for Non-Orthogonal Multiple Access in HetNets", ***IEEE Transactions on Wireless Communications***

Channel Model

- Received signal at the k-th SCU, i.e., $k \in \{1, ..., K\}$, served by the b-th SBS, i.e., $b \in \{1, ..., B\}$, on the m-th RB is given by

$$y_{b,k}^{n} = \underbrace{f_{b,k}^{m}\sqrt{p_b a_{b,k}}x_{b,k}^{m}}_{\textbf{desired signal}} + \underbrace{f_{b,k}^{m}\sum_{k'=k}^{K}\sqrt{p_b a_{b,k'}}x_{b,k'}^{m}}_{\textbf{interference from NOMA users}} + \underbrace{\zeta_{b,k}^{m}}_{\textbf{noise}}$$
$$+ \underbrace{\sum_{m=1}^{M}\lambda_{m,b}h_{m,b,k}\sqrt{p_m}x_m}_{\textbf{cross-tier interference}} + \underbrace{\sum_{b*\neq b}\lambda_{b*,b}g_{b*,b,k}^{m}\sqrt{p_{b^*}}x_{b*}^{m}}_{\textbf{co-tier interference}}. \quad (6)$$

- Received SINR:

$$\gamma_{b,k,k}^{m} = \frac{\left|f_{b,k}^{m}\right|^2 p_b a_{b,k}^{m}}{I_N^{k,k} + I_{co}^{k} + I_{cr}^{k} + \sigma^2}, \quad (7)$$

where $I_N^{k,k} = |f_{b,k}^{m}|^2 p_b \sum_{i=k+1}^{K} a_{b,i}^{m}$

Problem Formulation

$$\max_{\lambda,\mathbf{a}} \sum_{b=1}^{B} \sum_{m=1}^{M} U_\alpha \left(R_b^m \left(\lambda, \mathbf{a}\right)\right), \tag{8a}$$

$$\text{s.t.} \quad \sum_{b=1}^{B} \lambda_{m,b} p_b \left|t_{b,m}\right|^2 \leq I_m^{thr} \quad \forall m, \tag{8b}$$

$$\Delta(\lambda) \geq 0, \quad \forall m, b, \tag{8c}$$

$$\lambda_{m,b} \in \{0, 1\}, \quad \forall m, b, \tag{8d}$$

$$\sum_{m} \lambda_{m,b} \leq 1, \quad \forall b, \tag{8e}$$

$$\sum_{b} \lambda_{m,b} \leq q_{max}, \quad \forall m, \tag{8f}$$

$$a_{b,k} \geq 0, a_{b,j} \geq 0, \quad \forall b, \tag{8g}$$

$$a_{b,k} + a_{b,j} \leq 1, \quad \forall b. \tag{8h}$$

Matching Model

Solution:

- NP-hard $\Longrightarrow$ High complexity
- Solution: Many-to-one matching theory

Matching Model:

- Two-sided matching between SBSs and RBs
- $\succ$: "Preference" based on players' utility
- SBSs' utility: sum-rate of all the serving SCUs minus its cost for occupying RB m

$$U_b = \sum_{k=1}^{K} R_{b,k}^{m} - \beta p_b \left| g_{b,m} \right|^2, \tag{9}$$

- RBs' utility: sum-rate of the occupying SCUs

$$U_m = \sum_{b=1}^{B} \lambda_{m,b} \left(\sum_{k=1}^{K} R_{b,k}^{m} + \beta p_b \left| g_{b,m} \right|^2 \right), \tag{10}$$

Matching Algorithm

- Step 1: **Initialization**: GS algorithm to obtain initial matching state

- Step 2: **Swap operations**: keep finding swap-blocking pairs —- until no *swap-blocking* pair exists;

  Flag $\mathcal{SR}_{a,b}$ to record the time that SBS a and b swap their allocated RBs$\Longrightarrow$ prevent flip flop

- Step 3: **Final matching result**

Numerical Results

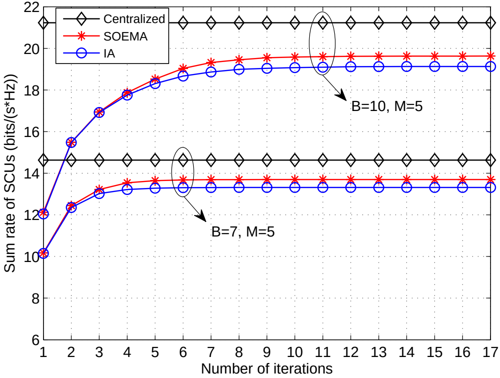


Fig.: Convergence of the proposed algorithms for different number of RBs and SBSs.

Numerical Results (cont')

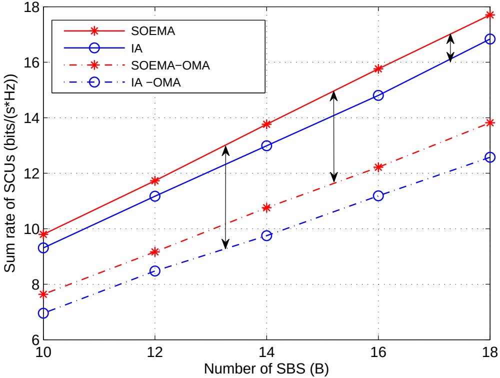


Fig.: Sum-rate of the SCUs for different number of small cells, with $M = 10$.

Summary

- NOMA-enabled HetNets
- Novel resource allocation algorithm based on **matching theory**
  - Complexity: $\mathcal{O}(B^2)$
  - Performance: near-optimal performance
- NOMA-enabled HetNets **outperform** OMA-based one

NOMA in HetNets II — Large-Scale Analysis

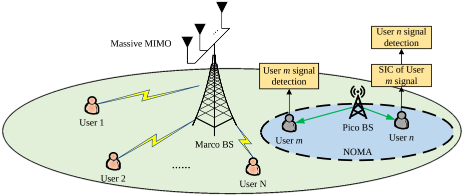


Fig.: System model.

- **High spectrum efficiency**
- **Low complexity**: The complex precoding/cluster design for MIMO-NOMA systems can be avoided.
- **Fairness/throughput tradeoff**: allocating more power to weak users.

[1] Y. Liu, Z. Qin, M. Elkashlan, A. Nallanathan, JA McCann (2017),"Non-orthogonal Multiple Access in Large-Scale Heterogeneous Networks", ***IEEE Journal on Selected Areas in Communications (JSAC)***.

Network Model

- **K-tier HetNets model**: the first tier represents the macro cells and the other tiers represent the small cells such as pico cells and femto cells.
- **Stochastic Geometry**: the positions of macro BSs and all the k-th tier BSs are modeled as homogeneous poisson point processes (HPPPs).
- **Hybrid access**: massive MIMO transmissions in macro cells and NOMA transmissions in small cells.
- **Flexible User association**: based on the maximum average received power.

Information Signal Model

- The signal-to-interference-plus-noise ratio (SINR) that a typical user experiences at a macro BS is

$$\frac{P_1/N h_{o,1} L\left(d_{o,1}\right)}{I_{M,1} + I_{S,1} + \sigma^2}. \tag{11}$$

- The SINR that user n experiences at the k-th tier small cell is

$$\gamma_{k_n} = \frac{a_{n,k} P_k g_{o,k} L\left(d_{o,k_n}\right)}{I_{M,k} + I_{S,k} + \sigma^2}. \tag{12}$$

- The SINR experienced by user m in the k-th tier small cell is

$$\gamma_{k_{m^*}} = \frac{a_{m,k} P_k g_{o,k} L\left(R_k\right)}{I_{k,n} + I_{M,k} + I_{S,k} + \sigma^2}. \tag{13}$$

User Association Probability

- The user association probability of a typical user connecting to the NOMA-enhanced small cell BSs in the k-th tier and to the macro BSs can be calculated as:

$$\tilde{A}_k = \frac{\lambda_k}{\sum_{i=2}^{K} \lambda_i \left(\tilde{P}_{ik} \tilde{B}_{ik} \right)^{\delta} + \lambda_1 \left(\frac{\tilde{P}_{1k} G_M}{N a_{n,k} B_k} \right)^{\delta}}, \tag{14}$$

and

$$\tilde{A}_1 = \frac{\lambda_1}{\sum_{i=2}^{K} \lambda_i \left(\frac{a_{n,i} \tilde{P}_{i1} B_i N}{G_M} \right)^{\delta} + \lambda_1}, \tag{15}$$

Remark 4.1

By increasing the number of antennas at the macro cell BSs, the user association probability of the macro cells increases and the user association probability of the small cells decreases.

Coverage Probability

A typical user can successfully transmit at a target data rate of R_t.

1. **Near User Case**: successful decoding when the following conditions hold.
   - The typical user can decode the message of the connected user served by the same BS.
   - After the SIC process, the typical user can decode its own message.

$$P_{cov,k}\left(\tau_c, \tau_t, x_0\right)\Big|_{x_0 \le r_k} = \Pr\left\{\gamma_{k_{n \to m*}} > \tau_c, \gamma_{k_n} > \tau_t\right\}, \quad (16)$$

2. **Far User Case**: successful decoding when the following condition holds

$$P_{cov,k}\left(\tau_t, x_0\right)\Big|_{x_0 > r_k} = \Pr\left\{g_{o,k_m} > \frac{\varepsilon_t^f x_0^{\alpha_i}\left(I_k + \sigma^2\right)}{P_k \eta}\right\}. \quad (17)$$

Spectrum Efficiency

- The spectral efficiency of the proposed hybrid Hetnet is

$$\tau_{\mathrm{SE,L}} = A_1 N \tau_{1,L} + \sum_{k=2}^{K} A_k \tau_k, \tag{18}$$

where $N\tau_1$ and τ_k are the lower bound spectrum efficiency of macro cells and the exact spectral efficiency of the k-th tier small cells.

Energy Efficiency

- The energy efficiency is defined as

$$\Theta_{\mathrm{EE}} = \frac{\text{Total data rate}}{\text{Total energy consumption}}. \tag{19}$$

- The energy efficiency of the proposed hybrid Hetnets is as follows:

$$\Theta_{\mathrm{EE}}^{\mathrm{Hetnets}} = A_1 \Theta_{\mathrm{EE}}^{1} + \sum_{k=2}^{K} A_k \Theta_{\mathrm{EE}}^{k}, \tag{20}$$

- Here, A_k and A_1 are the user association probability of the k-th tier small cells and macro cell, respectively. $\Theta_{\mathrm{EE}}^{k} = \frac{\tau_k}{P_{k,total}}$ and $\Theta_{\mathrm{EE}}^{1} = \frac{N\tau_{1,L}}{P_{1,total}}$ are the energy efficiency of k-th tier small cells and macro cell, respectively.

Numerical Results—User Association Probability

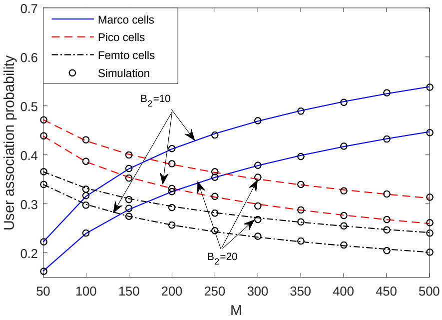


Fig.: User association probability versus antenna number with different bias factor.

- As the number of antennas at each macro BS increases, more users are likely to associate to macro cells — larger array gain.
- Increasing the bias factor can encourage more users to connect to the small cells — an efficient way to extend the coverage of small cells or control the load balance among each tier of HetNets.

Numerical Results — Coverage Probability

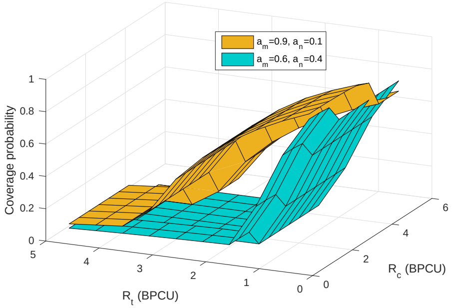


Fig.: Successful probability of typical user versus targeted rates of R_t and R_c.

- Observe the cross-over of these two surfaces — optimal power sharing for the target-rate considered.
- For inappropriate power and target-rate selection, the coverage probability is always zero.

Numerical Results — Spectrum Efficiency

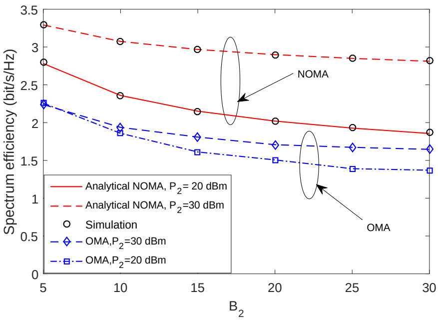


Fig.: Spectrum efficiency comparison of NOMA and OMA based small cells.

- NOMA-based small cells outperform the conventional OMA based small cells.
- The spectral efficiency of small cells is reduced as the bias factor is increased — larger bias factor results in associating more macro users having a low SINR to small cells.

Numerical Results — Energy Efficiency

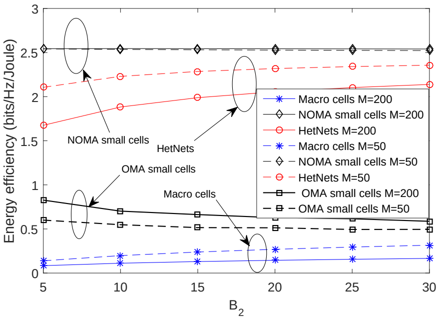
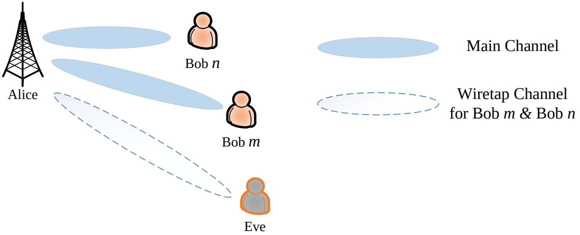


Fig.: Energy efficiency of the proposed framework.

- The energy efficiency of the macro cells is reduced as the number of antennas is increased owing to the power consumption of the baseband signal processing of massive MIMO.
- NOMA-assisted small cells may achieve higher energy efficiency than the massive MIMO aided macro cells as a benefit of densely deploying the BSs in NOMA-aided small cells.

Security in NOMA Networks

1. **Question**: Is NOMA still secure when there are eavesdroppers in the networks?



2. Propose to use **Artificial Noise** to enhance the security of NOMA [1].
3. The first work of considering the security in NOMA.

[1] Y. Liu, Z. Qin, M. Elkashlan, Y. Gao, and L. Hanzo(2017), "Enhancing the Physical Layer Security of Non-orthogonal Multiple Access in Large-scale Networks", ***IEEE Transactions on Wireless Communications (TWC)***. (**Web of Science Highly Cited Paper**, Top 2 Most Popular Article on TWC)

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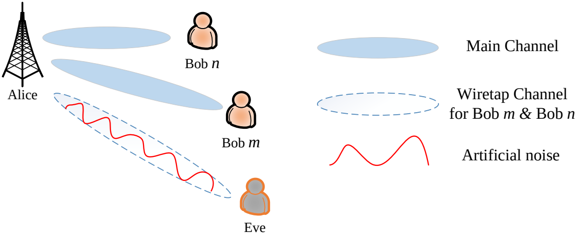

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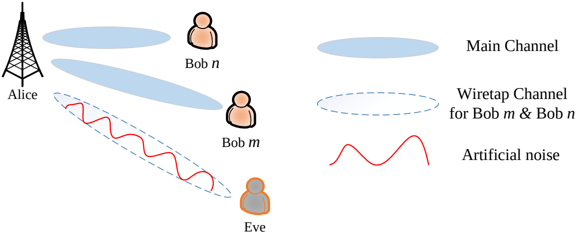

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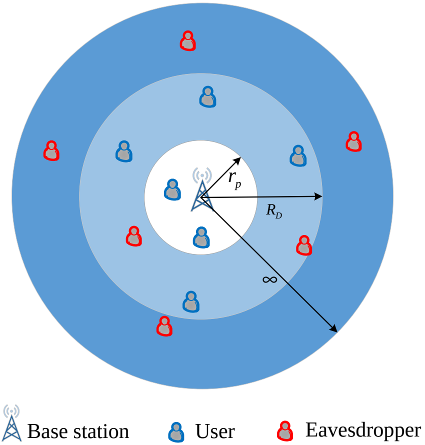
Network Model



- Network model for the NOMA transmission protocol under malicious attempt of eavesdroppers in large-scale networks, where r_p, R_D, and ∞ are the radius of the protected zone, NOMA user zone, and an infinite two dimensional plane for eavesdroppers, respectively.

Network Model—SINR for NOMA users

Based on the aforementioned assumptions, the instantaneous signal-to-interference-plus-noise ratio (SINR) for the m-th user and signal-to-plus-noise ratio (SNR) for the n-th user can be given by

$$\gamma_{B_m} = \frac{a_m |h_m|^2}{a_n |h_m|^2 + \frac{1}{\rho_b}}, \tag{21}$$

and

$$\gamma_{B_n} = \rho_b a_n |h_n|^2, \tag{22}$$

respectively. We denote $\rho_b = \frac{P_A}{\sigma_b^2}$ as the transmit SNR, where P_A is the transmit power at Alice and σ_b^2 is the variance of additive white Gaussian noise (AWGN) at Bobs.

Network Model—SNR for the Eavesdroppers

The instantaneous SNR for detecting the information of the m-th user and the n-th user at the most detrimental Eve can be expressed as follows:

$$\gamma_{E_\kappa} = \rho_e a_\kappa \max_{e \in \Phi_e, d_e \geq r_p} \left\{ |g_e|^2 L(d_e) \right\}. \tag{23}$$

It is assumed that $\kappa \in \{m, n\}$, $\rho_e = \frac{P_A}{\sigma_e^2}$ is the transmit SNR with σ_e^2 is the variance of AWGN at Eves.

- In this paper, we assume that Eves can be detected if they are close enough to Alice. Therefore, a protect zone with radius r_p is introduced to keep Eves away from Alice.

Secrecy Outage Probability

The secrecy rate of the *m*-th user and the *n*-th user can be expressed as

$$I_m = [\log_2(1 + \gamma_{B_m}) - \log_2(1 + \gamma_{E_m})]^+, \qquad (24)$$

and

$$I_n = [\log_2(1 + \gamma_{B_n}) - \log_2(1 + \gamma_{E_n})]^+, \qquad (25)$$

respectively, where $[x]^+ = \max\{x, 0\}$.

Exact Secrecy Outage Probability

Given the expected secrecy rate R_m and R_n for the m-th and n-th users, a secrecy outage is declared when the instantaneous secrecy rate drops below R_m and R_n, respectively. Based on (24), the secrecy outage probability for the m-th and n-th user is given by

$$\begin{aligned} P_m(R_m) &= \Pr\{I_m < R_m\} \\ &= \int_0^{\infty} f_{\gamma_{E_m}}(x) F_{\gamma_{B_m}}\left(2^{R_m}(1+x)-1\right) dx. \end{aligned} \tag{26}$$

and

$$\begin{aligned} P_n(R_n) &= \Pr\{I_n < R_n\} \\ &= \int_0^{\infty} f_{\gamma_{E_n}}(x) F_{\gamma_{B_n}}\left(2^{R_n}(1+x)-1\right) dx, \end{aligned} \tag{27}$$

respectively.

Secrecy Diversity Analysis

The secrecy diversity order can be given by

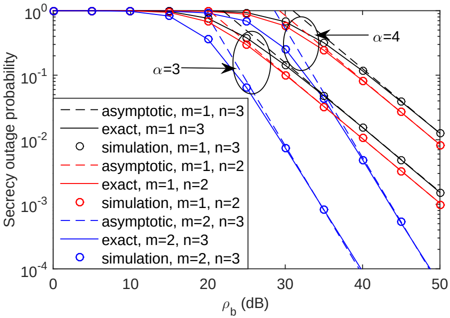
$$d_s = -\lim_{\rho_b \to \infty} \frac{\log\left(P_m^{\infty} + P_n^{\infty} - P_m^{\infty} P_n^{\infty}\right)}{\log \rho_b} = m, \tag{28}$$

The asymptotic secrecy outage probability for the user pair can be expressed as

$$P_{mn}^{\infty} = P_m^{\infty} + P_n^{\infty} - P_m^{\infty} P_n^{\infty} \approx P_m^{\infty} G_m(\rho_b)^{-D_m}. \tag{29}$$

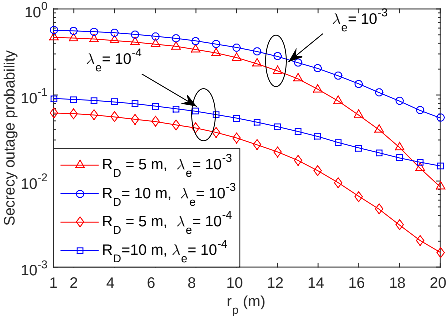
Remarks: It indicates that the secrecy diversity order and the asymptotic secrecy outage probability for the user pair are determined by the m-th user.

Numerical Results



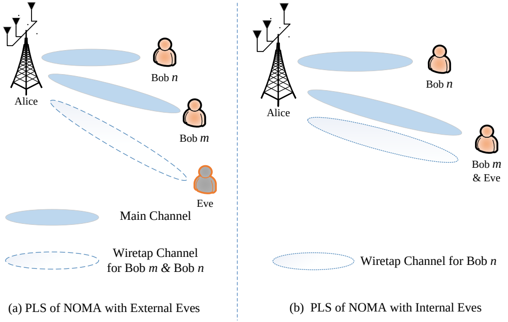
- The red curves and the black curves have the same slopes. While the blue curves can achieve a larger secrecy outage slope.
- It is due to the fact that the secrecy diversity order of the user pair is determined by the poor one m.
- This phenomenon also consists with the obtained insights in **Remark 1**.

Numerical Results



- The secrecy outage probability decreases as the radius of the protected zone increases, which demonstrates the benefits of the protected zone.
- Smaller density λ_e of Eves can achieve better secrecy performance, because smaller λ_e leads to less number of Eves, which lower the multiuser diversity gain when the most detrimental Eve is selected.

Multi-antenna Aided Security Provisioning for NOMA



1. Artificial Noise for enhancing the security [1].
2. Multi-antenna to create channel differences [2].

[1] Y. Liu, Z. Qin, M. Elkashlan, Y. Gao, and L. Hanzo(2017), "Enhancing the Physical Layer Security of Non-orthogonal Multiple Access in Large-scale Networks", ***IEEE Transactions on Wireless Communications (TWC)***.

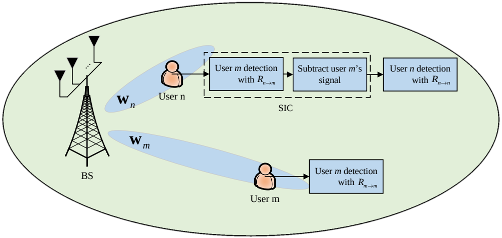
[2] Z. Ding, Z. Zhao, M. Peng, and H. V. Poor (2017), "On the Spectral Efficiency and Security Enhancements of NOMA Assisted Multicast-Unicast Streaming", ***IEEE Transactions on Communications (TCOM)***.

Other Research Contributions on NOMA

1. MIMO-NOMA design.
2. NOMA in mmWave Networks.
3. Interplay between NOMA and cognitive radio networks.
4. Cross layer design for NOMA — a QoE perspective.
5. NOMA in UAV networks.
6. Full-duplex design for NOMA.
7. Relay-selection for NOMA.
8. A Unified NOMA Network.

MIMO-NOMA Design - Beamformer Based Structure

1. **Centralized Beamforming**.
2. Coordinated Beamforming.



[1] Y. Liu, H. Xing, C. Pan, A. Nallanathan, M. Elkashlan, and L. Hanzo, "Multiple Antenna Assisted Non-Orthogonal Multiple Access", ***IEEE Wireless Communications***.

MIMO-NOMA Design - Beamformer Based Structure

1. Centralized Beamforming.
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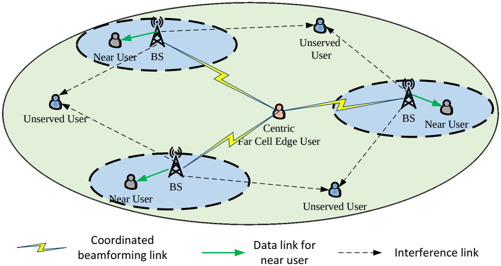
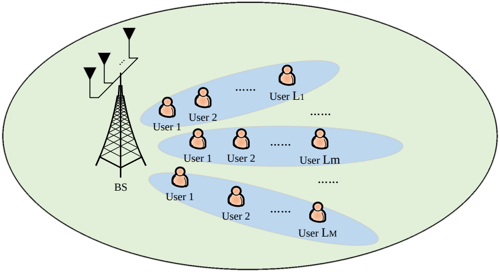


[1] Y. Liu, H. Xing, C. Pan, A. Nallanathan, M. Elkashlan, and L. Hanzo, "Multiple Antenna Assisted Non-Orthogonal Multiple Access", ***IEEE Wireless Communications***.

MIMO-NOMA Design - Cluster Based Structure

1. Inter-Cluster Interference Free Design.
2. Inter-Cluster Interference Contaminated Design.



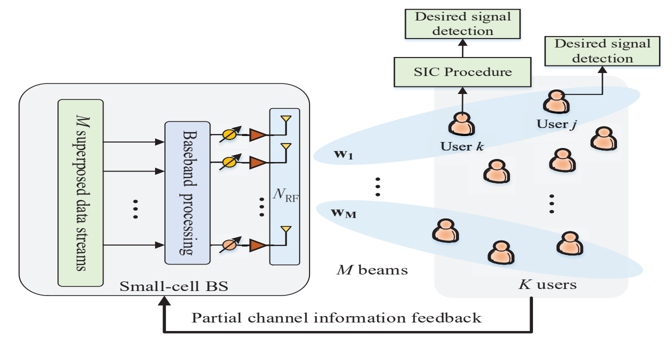
[1] Y. Liu, H. Xing, C. Pan, A. Nallanathan, M. Elkashlan, and L. Hanzo, "Multiple Antenna Assisted Non-Orthogonal Multiple Access", ***IEEE Wireless Communications***.

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.

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

[1] 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.*,vol. 17, no. 3, pp. 1502-1517, Mar. 2018.

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

$$\mathrm{SINR}_{j\to k}^{m} = \frac{g_k^m \beta_j^m}{g_k^m \sum_{\pi(i)>\pi(j)} \beta_i^m + \sum_{n\neq m} g_k^n \beta^n + \sigma^2} \quad (30)$$

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:

$$\max_{c,\beta} \quad \sum_{m=1}^{M} \sum_{j=1}^{q_m} R_{j\to j}^{m} \tag{31a}$$

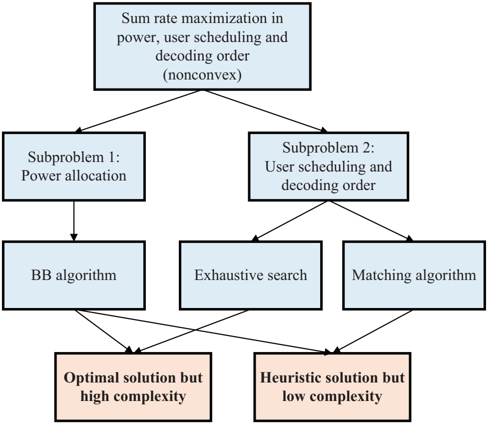
$$\text{s.t.} \quad R_{j\to k}^{m} \geq R_{j\to j}^{m}, \ \sum_{m=1}^{M} \sum_{j\in\mathcal{C}_m} \beta_j^m \leq P_{tot}, \tag{31b}$$

$$\sum_{k=1}^{K} c_k^m = q_m, \ \sum_{m=1}^{M} c_k^m \leq 1, \ R_{j\to j}^{m} \geq \bar{R}_j, \tag{31c}$$

$$\pi_m \in \Pi, \ \pi(k) > \pi(j), \ j,k \in \mathcal{C}_m, \ m \in \mathcal{M}. \tag{31d}$$

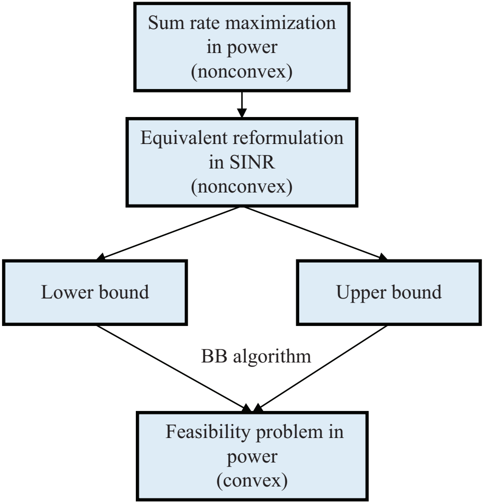
- c denotes the index set, where term c_k^m indicates the indicators for user k on beam m, $c_k^m \in \{0, 1\}$.
- Π denotes the set of all possible SIC decoding orders.

Overview of Proposed Solutions



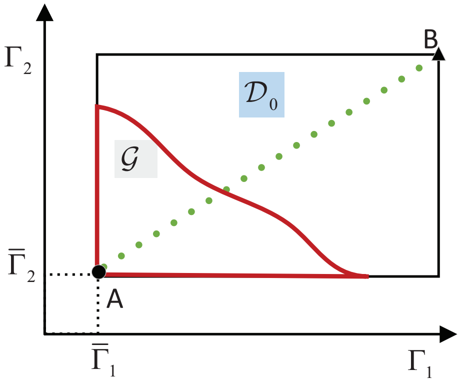
1. *Difficulties:*
   - Intra-beam and inter-beam interference are jointly considered.
   - The decoding order of NOMA is affected by the inter-beam power allocation.
   - Joint user scheduling and power allocation is NP-hard.
2. *Solutions:* Divide the complicated problem into some ease of subproblems.

Overview for Power Allocation Algorithm



- Intra-beam and inter-beam interference is jointly considered.
- The decoding order of NOMA is affected by the inter-beam power allocation.
- Joint user scheduling and power allocation is NP-hard.

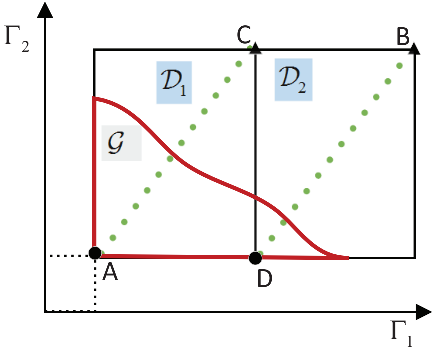
An example for Branch and Bound (BB) Algorithms



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 $f(\mathrm{B})$.

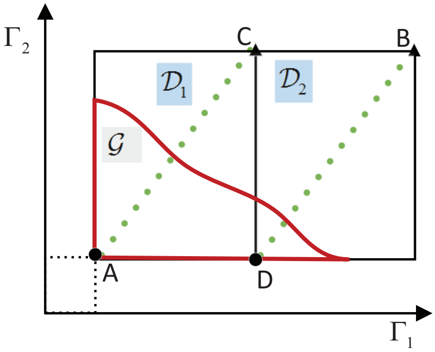
An Example for Branch and Bound (BB) Algorithms



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.

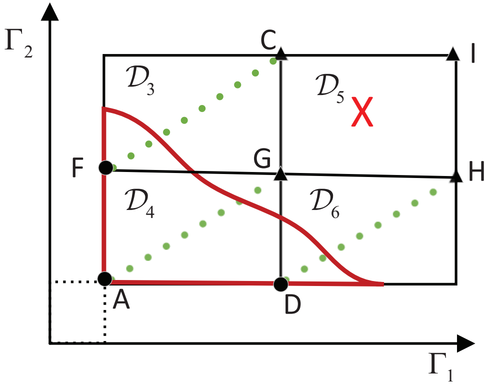
An Example for Branch and Bound (BB) Algorithms



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.

$$\min_{\tilde{\beta},\Gamma} - \sum_{m=1}^{M} \sum_{j_m=1}^{q_m} \log_2\left(1 + \Gamma_{j_m \to j_m}^{m}\right) \tag{32a}$$

$$\text{s.t.}\Gamma_{j_m \to j_m}^{m} \leq \frac{g_{j_m}^{m} \beta_{j_m}^{m}}{g_{j_m}^{m} \sum_{i_m=j_m+1}^{q_m} \beta_{i_m}^{m} + \sum_{n \neq m} g_{j_m}^{n} \beta^{n} + \sigma^2}, \tag{32b}$$

$$\sum_{m=1}^{M} \sum_{j_m=1}^{q_m} \beta_{j_m}^{m} \leq P_{tot}, \;\; R_{j_m \to j_m}^{m} \geq \bar{R}_{j_m}, \tag{32c}$$

$$\sum_{n \neq m} \left(g_{k_m}^{m} g_{j_m}^{n} - g_{j_m}^{m} g_{k_m}^{n} \right) \beta^{n} + \left(g_{k_m}^{m} - g_{j_m}^{m} \right) \sigma^2 \geq 0, \tag{32d}$$

$$k_m > j_m, \;\; j_m, k_m \in \mathcal{C}_m, \;\; m \in \mathcal{M}. \tag{32e}$$

Key Steps for Branch and Bound (BB) Algorithms

1 **Construct box constraint sets:**

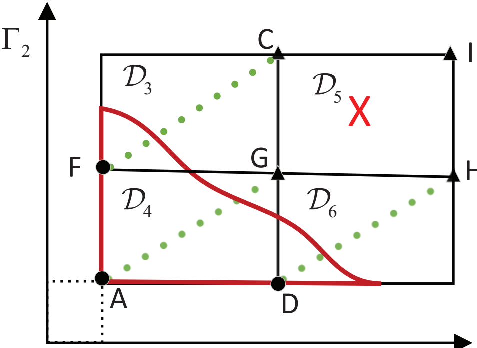
- The objective function and the feasible set of (32) can be rewritten as

$$\mathcal{U}(\Gamma) = -\sum_{m=1}^{M} \sum_{j_m=1}^{q_m} \log_2 \left(1 + \Gamma_{j_m \to j_m}^{m}\right), \mathcal{G} = \left\{\Gamma | (32b) - (32e)\right\}.$$

- The equivalent reformulation of power allocation problem is given by

$$\min_{\Gamma} \quad \mathcal{U}(\Gamma) \qquad \text{s.t.} \quad \Gamma \in \mathcal{G}. \tag{33}$$

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:

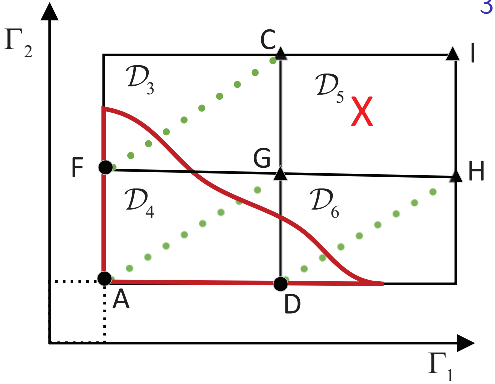
$$\overline{g}(\Gamma) = \begin{cases} \mathcal{U}(\underline{\Gamma}), & \underline{\Gamma} \in \mathcal{G} \\ 0, & \text{o.w.}. \end{cases}$$

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:

$$\begin{aligned} \text{Find} \quad & \text{PA coefficients} \\ \text{s.t.} \quad & \underline{\Gamma} \in \mathcal{G}. \end{aligned} \tag{34}$$

Observations:

- Problem (34) 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

$$
\begin{aligned}
\max_{\mathbf{c}} \quad & \mathcal{H} = \sum_{m=1}^{M} \sum_{j=1}^{q_m} R_{j\to j}^{m} \\
\text{s.t.} \quad & \sum_{k=1}^{K} c_k^m = q_m, \;\; \sum_{m=1}^{M} c_k^m \leq 1, \\
& \pi_m \in \Pi, \;\; \pi(k) > \pi(j), \;\; j,k \in \mathcal{C}_m, \;\; m \in \mathcal{M}.
\end{aligned}
\tag{35}
$$

- Problem (35) 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:

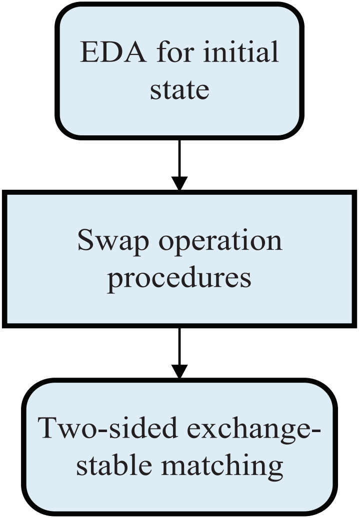
$$\mathcal{H}_k^m = \log_2\left(1 + \Gamma_k^m\right). \tag{36}$$

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

$$\mathcal{H}^m = \sum_{k \in \varphi(m)} \log_2\left(1 + \Gamma_k^m\right). \tag{37}$$

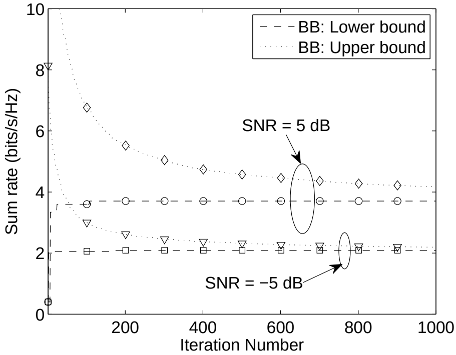
   - The inter-beam interference and the intra-beam interference exist for each user's rate.
   - Users and beams compose a **many-to-one matching with externalities**.

Overview for Matching Algorithms



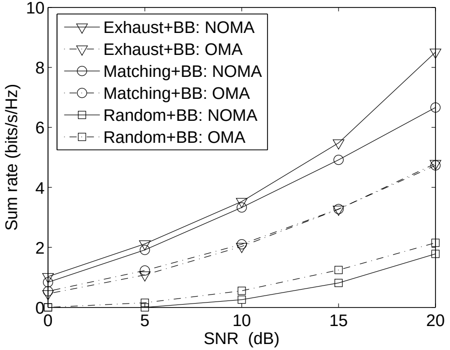
- EDA denotes the extend deferred acceptance.
- The users first propose to the BSs based on its preference list. Then each BS accepts the users with prior preferences.
- The goal of swap operation procedure is to further enhance the system sum rate.
- Two-sided exchange-stable matching provides the stop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

Exploiting Multiple Access in Clustered Millimeter Wave Networks: NOMA or OMA?

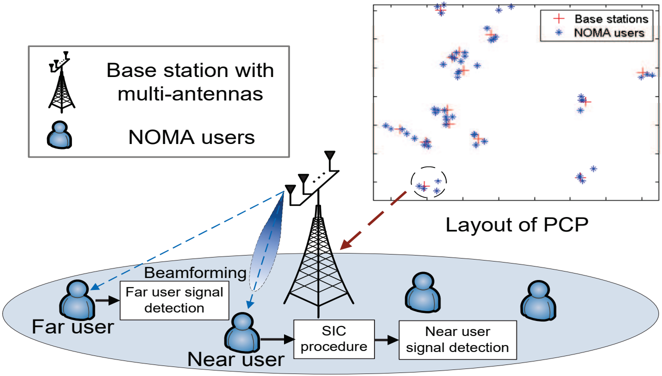
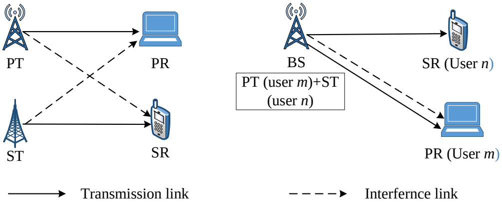


Fig.: Illustration of the clustered NOMA networks with mmWave communications. The spatial distributions of the NOMA users follow the Poisson Cluster Processes.

Interplay between NOMA and cognitive radio networks



(a) Conventional CR (b) CR Inspired NOMA

1. Cognitive radio inspired NOMA [1].
2. NOMA in cognitive radio networks [2].

[1] Z. Ding, P. Fan, and H. V. Poor (2016), "Impact of User Pairing on 5G Nonorthogonal Multiple-Access Downlink Transmissions", ***IEEE Trans. Veh. Technol. (TVT)***.
[2] Y. Liu, Z. Ding, M. Elkashlan, and J. Yuan, "Non-orthogonal Multiple Access in Large-Scale Underlay Cognitive Radio Networks", *IEEE Trans. Veh. Technol.* ***IEEE Trans. Veh. Technol. (TVT)***.

D2D Enabled NOMA

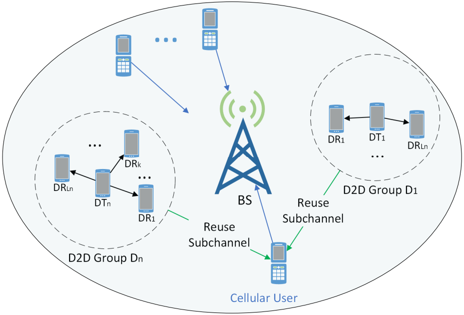


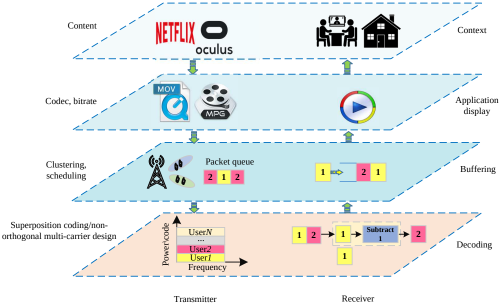
Fig.: System model.

- Single-cell uplink scenario
- Set of traditional cellular users: $\mathcal{C} = \{C_1, ..., C_M\}$
- Set of D2D groups: $\mathcal{D} = \{D_1, \ldots, D_n, \ldots, D_N\}$

[1] J. Zhao, Y. Liu, K. K. Chai, Y. Chen, and M. Elkashlan (2017),"Joint Subchannel and Power Allocation for NOMA Enhanced D2D Communications", ***IEEE Transactions on Communications (TCOM), 2017***.

Cross layer design for NOMA — a QoE perspective

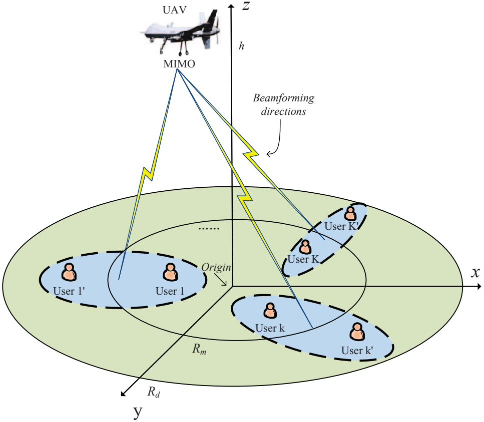
1. QoE-Aware NOMA Framework [1].
2. Multi-cell Multi-carrier QoE aware resource allocation [2].



[1] W. Wang, Y. Liu, L. Zhiqing, T. Jiang, Q. Zhang and A. Nallanathan, "Toward Cross-Layer Design for Non-Orthogonal Multiple Access: A Quality-of-Experience Perspective", ***IEEE Wireless Communications***.

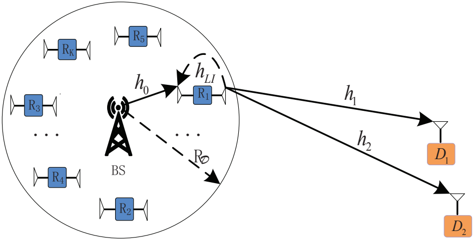
[2] J. Cui, Y. Liu, Z. Ding, P. Fan, and A. Nallanathan, "QoE-based Resource Allocation for Multi-cell NOMA Networks", ***IEEE Transactions on Wireless Communications (TWC)***.

Multiple antenna aided NOMA for UAV networks



[1] T. Hou, Y. Liu, Z. Song, X. Sun, Y. Chen, "Multiple Antenna Aided NOMA in UAV Networks: A Stochastic Geometry Approach", ***IEEE Transactions on Communications, arXiv available***.

HD/FD Relay Selection for NOMA



1. Network model for the NOMA transmission consisting of one base station (BS), K **relays** and **two users (i.e., the nearby user** D_1 **and distant user** D_2**)**.
2. Assuming that the BS is located at the origin of a disc and the location of the relays are modeled as homogeneous poisson point processes **(HPPPs)**.

[1] X. Yue, Y. Liu, S. Kao, A. Nallanathan, and Z. Ding,, "Spatially Random Relay Selection for Full/Half-Duplex Cooperative NOMA Networks", ***IEEE Transactions on Communications***.

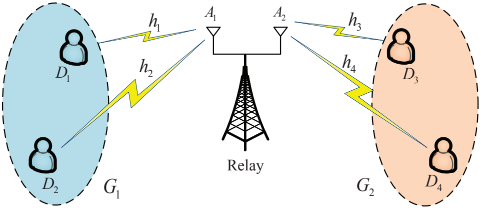
Two-Way Relay NOMA

1. **Two way relay (TWR) technique** is capable of boosting spectral efficiency, where the information is exchanged between two nodes with the help of a relay.

2. The existing treaties on cooperative NOMA are all based on **one-way relay scheme**, where the messages are delivered in only one direction, (i.e., from the BS to the relay or user destinations). Hence **the application of TWR to NOMA** is a possible approach to further improve the spectral efficiency of systems.

3. **A two-way relay non-orthogonal multiple access (TWR-NOMA) system** is investigated, where two groups of NOMA users exchange messages with the aid of one half-duplex (HD) decode-and-forward (DF) relay.

Two-Way Relay NOMA



1. System model for TWR-NOMA communication scenario consisting of one relay R, **two pairs of NOMA users** $G_1 = \{D_1, D_2\}$ and $G_2 = \{D_3, D_4\}$.
2. The exchange of information between user groups G_1 and G_2 is facilitated via the assistance of a **(DF)** relay with two antennas, namely A_1 and A_2.
3. Assume that the direct links between two pairs of users are **inexistent** due to the effect of strong shadowing.

[1] X. Yue, Y. Liu, S. Kao, A. Nallanathan, and Y. Chen (2018),"Modeling and Analysis of Two-Way Relay Non-Orthogonal Multiple Access Systems", ***IEEE Transactions on Communications***;

SINRs for NOMA signals

- During the first slot, the pair of NOMA users in G_1 transmit the signals to R just as uplink NOMA. Applying the NOMA protocol, R first decodes D_l's information x_l by the virtue of treating x_t as IS. Hence the received signal-to-interference-plus-noise ratio (SINR) at R to detect x_l is given by

$$\gamma_{R\to x_l} = \frac{\rho|h_l|^2 a_l}{\rho|h_t|^2 a_t + \rho\varpi_1(|h_k|^2 a_k + |h_r|^2 a_r) + 1}, \tag{38}$$

where $\rho = \frac{P_u}{N_0}$ denotes the transmit SNR. $\varpi_1 \in [0,1]$ denotes the impact levels of interference signal (IS) at R. $(l,k) \in \{(1,3),(3,1)\}$, $(t,r) \in \{(2,4),(4,2)\}$.

SINRs for NOMA signals

- After SIC is carried out at R for detecting x_I, the received SINR at R to detect x_t is given by

$$\gamma_{R\rightarrow x_t} = \frac{\rho|h_t|^2 a_t}{\varepsilon\rho|g|^2 + \rho\varpi_1(|h_k|^2 a_k + |h_r|^2 a_r) + 1}, \tag{39}$$

where $\varepsilon = 0$ and $\varepsilon = 1$ denote the pSIC and ipSIC employed at R, respectively. The residual IS is modeled as Rayleigh fading channels denoted as g with zero mean and variance Ω_I. In the second slot, the information is exchanged between G_1 and G_2 by the virtue of R.

SINRs for NOMA signals

- According to NOMA protocol, SIC is employed and the received SINR at D_k to detect x_t is given by

$$\gamma_{D_k \to x_t} = \frac{\rho |h_k|^2 b_t}{\rho |h_k|^2 b_l + \rho \varpi_2 |h_k|^2 + 1}, \tag{40}$$

where $\varpi_2 \in [0, 1]$ denotes the impact level of IS at the user nodes. Then D_k detects x_l and gives the corresponding SINR as follows:

$$\gamma_{D_k \to x_l} = \frac{\rho |h_k|^2 b_l}{\varepsilon \rho |g|^2 + \rho \varpi_2 |h_k|^2 + 1}. \tag{41}$$

Furthermore, the received SINR at D_t to detect x_r is given by

$$\gamma_{D_r \to x_t} = \frac{\rho |h_r|^2 b_t}{\rho |h_r|^2 b_l + \rho \varpi_2 |h_r|^2 + 1}. \tag{42}$$

Outage probability

- **Outage Probability of x_l**

In TWR-NOMA, the outage events of x_l are explained as follow: i) R cannot decode x_l correctly; ii) The information x_t cannot be detected by D_k; and iii) D_k cannot detect x_l, while D_k can first decode x_t successfully. The complementary events of x_1 are employed to express its outage probability and is given by

$$\begin{aligned} P_{x_l}^{ipSIC} =& 1 - \Pr\left(\gamma_{R\to x_l} > \gamma_{th_l}\right) \\ & \times \Pr\left(\gamma_{D_k\to x_t} > \gamma_{th_t}, \gamma_{D_k\to x_l} > \gamma_{th_l}\right), \end{aligned} \tag{43}$$

where $\varepsilon = 1$. $\gamma_{th_l} = 2^{2R_l} - 1$ with R_l being the target rate at D_k to detect x_l and $\gamma_{th_t} = 2^{2R_t} - 1$ with R_t being the target rate at D_k to detect x_t.

Outage probability

- **Outage probability of x_t**

Based on NOMA principle, the complementary events of outage for x_t have the following cases. One of the cases is that R can first decode the information x_l and then detect x_t. Another case is that either of D_k and D_r can detect x_t successfully. Hence the outage probability of x_t can be expressed as

$$\begin{aligned} P_{x_t}^{ipSIC} =& 1 - \Pr\left(\gamma_{R\to x_t} > \gamma_{th_t}, \gamma_{R\to x_l} > \gamma_{th_l}\right) \\ & \times \Pr\left(\gamma_{D_k\to x_t} > \gamma_{th_t}\right) \Pr\left(\gamma_{D_r\to x_t} > \gamma_{th_t}\right), \end{aligned} \tag{44}$$

where $\varepsilon = 1$.

Diversity analysis

To gain more insights for TWR-NOMA in the high SNR region, the diversity order analysis is provided according to the derived outage probabilities. The diversity order is defined as

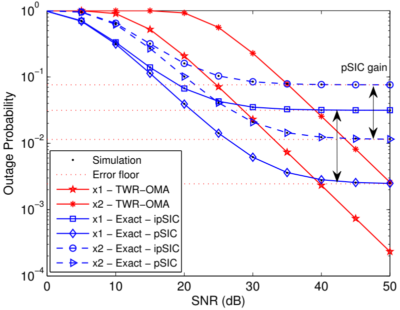
$$d = -\lim_{\rho\to\infty} \frac{\log\left(P_{x_i}^{\infty}(\rho)\right)}{\log \rho}, \tag{45}$$

where $P_{x_i}^{\infty}$ denotes the asymptotic outage probability of x_i.

Remarks:

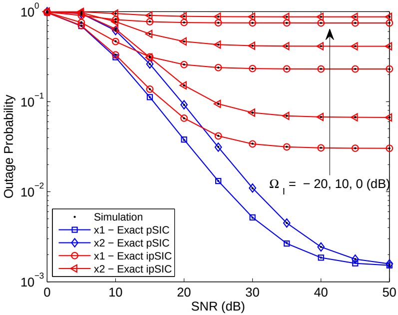
1. Due to impact of residual interference, the diversity order of x_l with the use of ipSIC is **zero**.
2. The communication process of the first slot similar to uplink NOMA, even though under the condition of pSIC, diversity order is equal to **zero** as well for x_l.
3. The diversity orders of x_t with ipSIC/pSIC are also equal to **zero**. This is because residual interference is existent in the total communication process.

Numerical Results



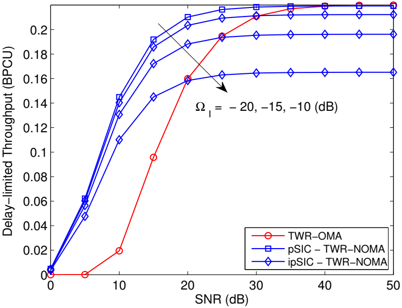
- As can be observed from the figure, the outage behaviors of x_1 and x_2 for TWR-NOMA are superior to TWR-OMA in the low SNR regime. This is due to the fact that the influence of IS is not the dominant factor at low SNR.
- It can be seen that the outage behaviors of x_1 and x_2 converge to the error floors in the high SNR regime. The reason can be explained that due to the impact of residual interference by the use of ipSIC, x_1 and x_2 result in zero diversity orders, which verifies the conclusion in **Remark 3**.

Numerical Results



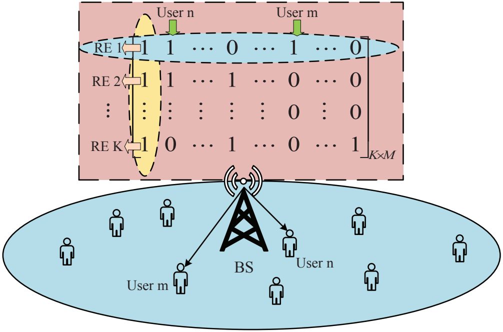
- It can be seen that the different values of residual IS affects the performance of ipSIC seriously.
- As the values of residual IS increases, the preponderance of ipSIC is inexistent. The outage behaviors of users' signals for TWR-NOMA become more worse.
- When $\Omega_I = 0$ dB, the outage probability of x_1 and x_2 will be in close proximity to one.

Numerical Results



- One can observe that TWR-NOMA is capable of achieving a higher throughput compared to TWR-OMA in the low SNR regime, since it has a lower outage probability.
- It is worth noting that ipSIC considered for TWR-NOMA will further degrade throughput with the values of residual IS becomes larger in high SNR regimes.

A Unified NOMA Framework



[1] Z. Qin, X. Yue, Y. Liu, Z. Ding, and A. Nallanathan (2017),"User Association and Resource Allocation in Unified Non-Orthogonal Multiple Access Enabled Heterogeneous Ultra Dense Networks", ***IEEE Communication Magazine***;

Research Opportunities and challenges for NOMA

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

Thank you!

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