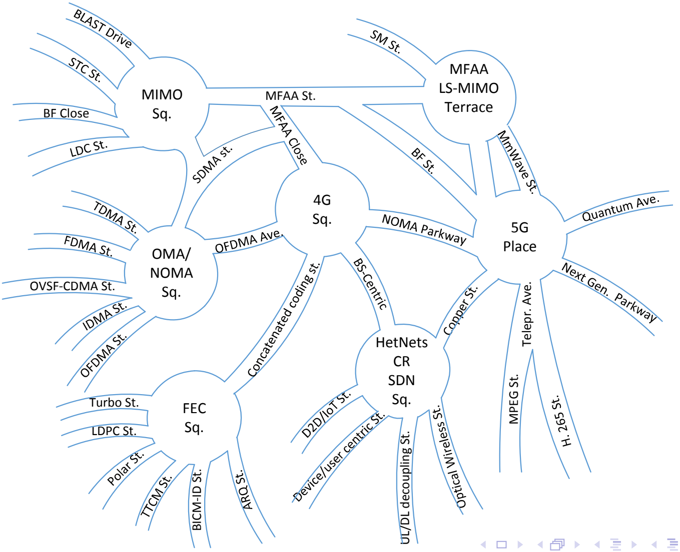
Non-Orthogonal Multiple Access for 5G and Beyond
Proceedings of the IEEE, Dec. 2017

Yuanwei Liu, Zhijin Qin, Maged Elkashlan, Zhiguo Ding, Arumugam Nallanathan and Lajos Hanzo

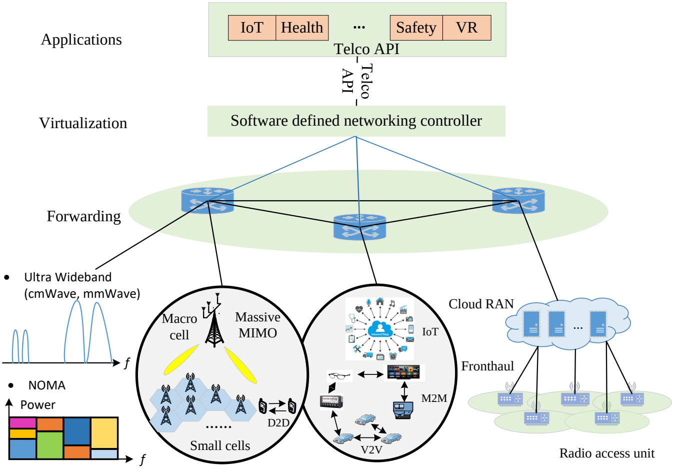
Dec. 2017

Outline

Brief History of Wireless Standardization



Future 5G network architecture.



[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.

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).

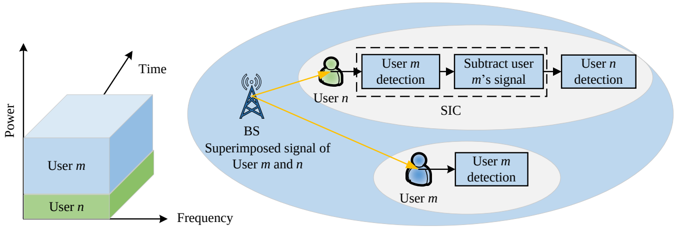
Introduction to NOMA Systems

- 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***.

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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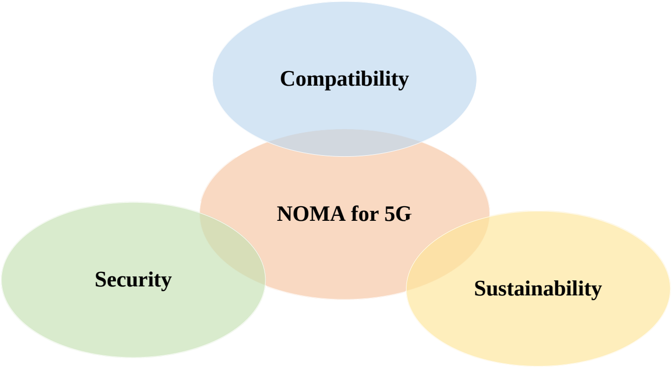
Research Contributions in NOMA



From NOMA to Cooperative NOMA

NOMA can pair a user having better channel conditions with another user having worse channel conditions and then detect them using SIC. For example, consider a downlink scenario in which there are two groups of users:

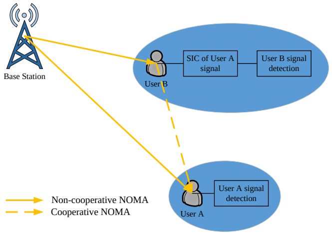
- **Cell-centre users:** close to the base station (BS) and have better channel conditions.
- **Cell-edge users:** close to the edge of the cell controlled by the BS and therefore have worse channel conditions.

While the bandwidth efficiency of NOMA is superior to OMA, the fact that the near users co-exist with the far users causes performance degradation to the far users. *This motivates us to invoke cooperative NOMA.*

- But again, the cell-edge user suffers from some performance erosion in NOMA
- The cell-centre user may infer the information sent to the cell-edge user.

What is Cooperative NOMA?

- Solution – Cooperative NOMA
- 3 time slots are needed for cooperative OMA, while cooperative NOMA only needs 2.
- **Cooperative NOMA**: cell-centre users act as relays to help the cell-edge users having poor channel conditions.

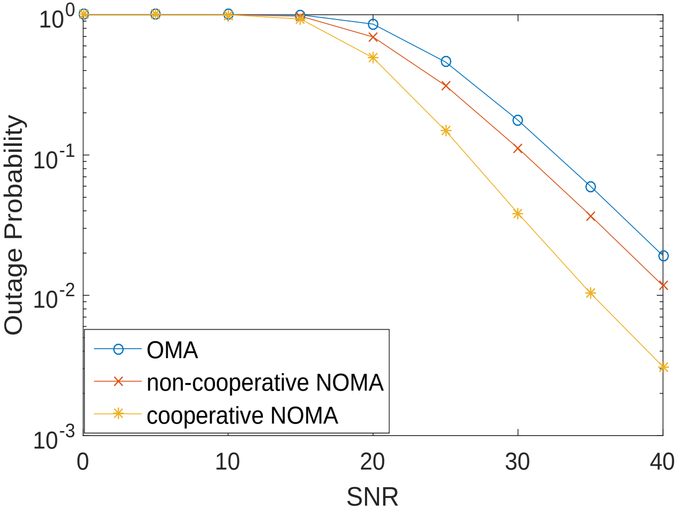


- **Advantages**: SIC is used and hence the information of the cell-edge users is known by the cell-centre users, which may act as DF relays.

A Simple Example (1/3)

- Consider a NOMA downlink with two users.
- Time slot I: BS sends the superimposed messages to both users
- Time slot II: The user with strong channel conditions is to help its partner by acting as a relay
- Simulation parameters are set as follows:
  - The BS is located at $(0, 0)$.
  - User 2 is located at $(5m, 0)$.
  - The x-y plane denotes the location of User 1.
  - A bounded path loss model is used to ensure all distances are greater than one. The path loss exponent is 3.
  - The transmit signal-to-noise ratio (SNR) is 30 dB.
  - The power allocation coefficient for User 2 and User 1 are $(a_A, a_B) = \left(\frac{4}{5}, \frac{1}{5}\right)$.
  - The targeted data rate is 0.5 bits per channel use (BPCU).

A Simple Example (2/3 – Overall Outage)



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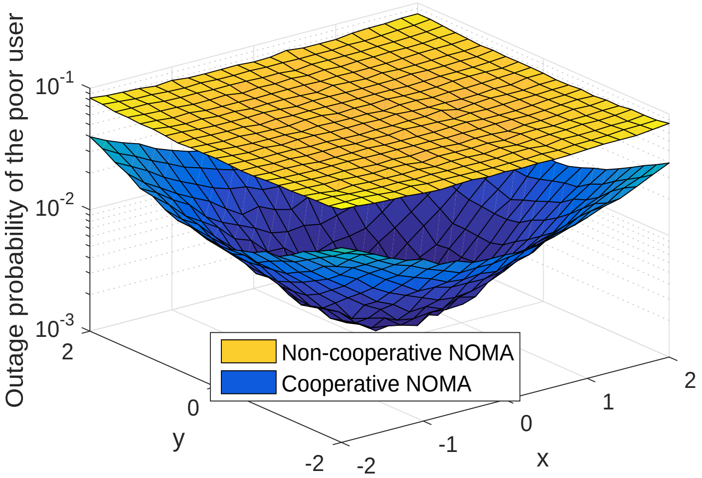

SWIPT—Background (1/2)

Wireless energy Transfer (WET)

- Key Idea: Energy is transmitted from a power source to a destination over the wireless medium.
- Motivation: 1) Ambient radio frequency signals are everywhere; 2) WET could be the only means of increasing useful lifetime of energy constrained networks.
- Tesla had already provided a successful demonstration of lighting an electric bulb wirelessly in 1891, but WET has been forgotten owing to its low energy efficiency.

What has changed then?

- We have numerous low-power devices.
- Advanced energy-beamformers have become available.

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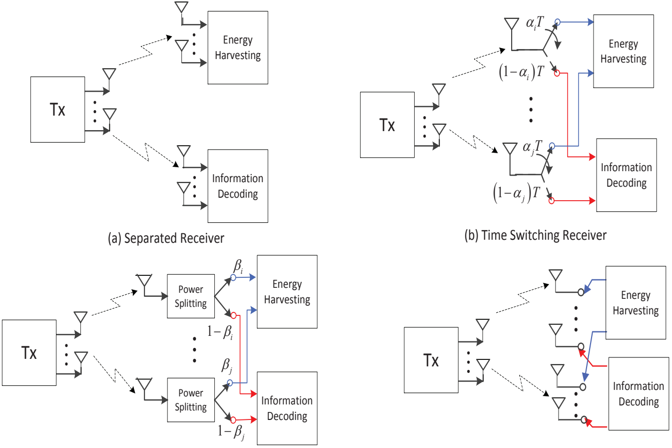
[1] Y. Liu, Z. Ding, M. Elkashlan, and H. V. Poor (2016), "Cooperative Non-orthogonal Multiple Access with Simultaneous Wireless Information and Power Transfer", ***IEEE Journal on Selected Areas in Communications (JSAC)***.

SWIPT—Background (2/2)



(a) Separated Receiver

(b) Time Switching Receiver

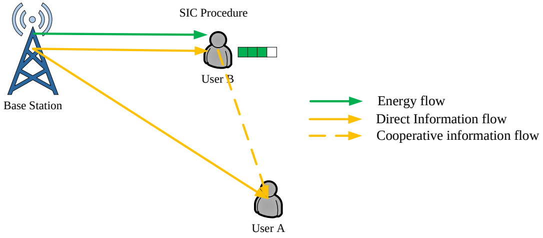
(c) Power Splitting Receiver

(d) Antenna Switching Receiver

[1]Z. Ding, C. Zhong, D. W. Ng, M. Peng, H. A. Suraweera, R. Schober and H. V. Poor, Application of Smart Antenna Technologies in Simultaneous Wireless Information and Power Transfer, IEEE Commun. Magazine, 2015.

Sustainability of NOMA Networks

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



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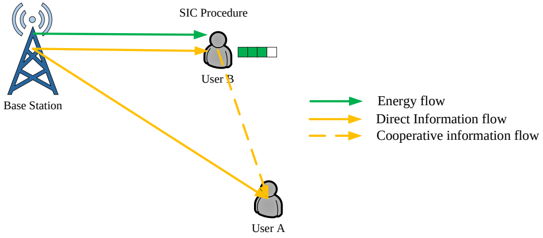

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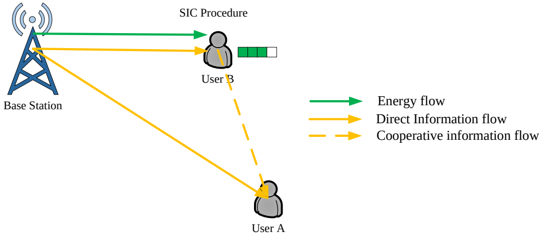

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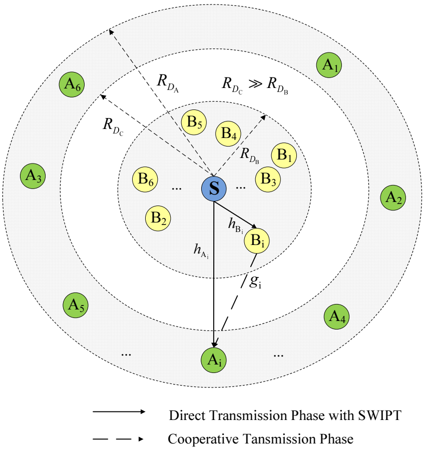
Motivation for SWIPT + Cooperative NOMA

- To improve the reliability of the distant NOMA users without draining the near users' batteries, we consider the application of SWIPT to NOMA, where SWIPT is performed at the near NOMA users.
- Therefore, the aforementioned pair of communication concepts, namely cooperative NOMA and SWIPT, can be naturally linked together.
- Cooperative SWIPT NOMA – a new spectral-efficient and energy-efficient wireless multiple access protocol.

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.

Phase 1: Direct Transmission

- During the first phase, the BS sends two messages $p_{i1}x_{i1} + p_{i2}x_{i2}$ to two selected users $\mathrm{A_i}$ and $\mathrm{B_i}$ based on NOMA, where p_{i1} and p_{i2} are the power allocation coefficients and x_{i1} and x_{i2} are the messages of $\mathrm{A_i}$ and $\mathrm{B_i}$, respectively. The observation at $\mathrm{A_i}$ is given by

$$y_{\mathrm{A_i},1} = \sqrt{P_{\mathrm{S}}} \sum_{k\in\{1,2\}} p_{ik} x_{ik} \frac{h_{\mathrm{A_i}}}{\sqrt{1+d_{\mathrm{A_i}}^{\alpha}}} + n_{\mathrm{A_i},1}. \quad (1)$$

- Without loss of generality, we assume that $|p_{i1}|^2 > |p_{i2}|^2$ with $|p_{i1}|^2 + |p_{i2}|^2 = 1$. The received signal to interference plus noise ratio (SINR) at $\mathrm{A_i}$ to detect x_{i1} is given by

$$\gamma_{\mathrm{S,A_i}}^{x_{i1}} = \frac{\rho |h_{\mathrm{A_i}}|^2 |p_{i1}|^2}{\rho |p_{i2}|^2 |h_{\mathrm{A_i}}|^2 + 1 + d_{\mathrm{A_i}}^{\alpha}}, \quad (2)$$

where $\rho = \frac{P_{\mathrm{S}}}{\sigma^2}$ is the transmit signal to noise ratio (SNR).

Phase 1: Direct Transmission

- We assume that the near users have rechargeable batteries and that power splitting is applied to perform SWIPT. Thus, the observation at $\mathrm{B_i}$ is given by

$$y_{\mathrm{B_i},1} = \sqrt{P_{\mathrm{S}}} \sum_{k\in\{1,2\}} p_{ik} x_{ik} \frac{\sqrt{1-\beta_i} h_{\mathrm{B_i}}}{\sqrt{1+d_{\mathrm{B_i}}^{\alpha}}} + n_{\mathrm{B_i},1}, \qquad (3)$$

where β_i is the power splitting coefficient.

- The receiver's SINR at $\mathrm{B_i}$ used for detecting x_{i1} of $\mathrm{A_i}$ is

$$\gamma_{\mathrm{S,B_i}}^{x_{i1}} = \frac{\rho |h_{\mathrm{B_i}}|^2 |p_{i1}|^2 (1-\beta_i)}{\rho |h_{\mathrm{B_i}}|^2 |p_{i2}|^2 (1-\beta_i) + 1 + d_{\mathrm{B_i}}^{\alpha}}. \qquad (4)$$

- The receiver's SNR at $\mathrm{B_i}$ used for detecting x_{i2} of $\mathrm{B_i}$ is

$$\gamma_{\mathrm{S,B_i}}^{x_{i2}} = \frac{\rho |h_{\mathrm{B_i}}|^2 |p_{i2}|^2 (1-\beta_i)}{1 + d_{\mathrm{B_i}}^{\alpha}}. \qquad (5)$$

Phase 1: Direct Transmission

- Based on (4), the data rate supported by the channel from the BS to $\mathrm{B_i}$ for decoding x_{i1} is given by

$$R_{x_{i1}} = \frac{1}{2}\log\left(1 + \frac{\rho|h_{\mathrm{B_i}}|^2|p_{i1}|^2(1-\beta_i)}{\rho|h_{\mathrm{B_i}}|^2|p_{i2}|^2(1-\beta_i)+1+d_{\mathrm{B_i}}^{\alpha}}\right). \qquad (6)$$

- In order to ensure that $\mathrm{B_i}$ can successfully decode the information of $\mathrm{A_i}$, we have a rate, i.e., $R_1 = R_{x_{i1}}$. Therefore, the power splitting coefficient is set as follows:

$$\beta_i = \max\left\{0, 1 - \frac{\tau_1\left(1+d_{\mathrm{B_i}}^{\alpha}\right)}{\rho\left(|p_{i1}|^2 - \tau_1|p_{i2}|^2\right)|h_{\mathrm{B_i}}|^2}\right\}, \qquad (7)$$

where $\tau_1 = 2^{2R_1} - 1$. Here $\beta_i = 0$ means that all the energy is used for information decoding and no energy remains for energy harvesting.

Phase 1: Direct Transmission

- Based on (3), the energy harvested at $\mathrm{B_i}$ is given by

$$E_{\mathrm{B_i}} = \frac{T\eta P_{\mathrm{S}}\beta_i |h_{\mathrm{B_i}}|^2}{2\left(1 + d_{\mathrm{B_i}}^{\alpha}\right)}, \tag{8}$$

  where T is the time period for the entire transmission including the direct transmission phase and the cooperative transmission phase, and η is the energy harvesting coefficient.

- We assume that the two phases have the same transmission period, and therefore, the transmit power at $\mathrm{B_i}$ can be expressed as follows:

$$P_t = \frac{\eta P_{\mathrm{S}}\beta_i |h_{\mathrm{B_i}}|^2}{1 + d_{\mathrm{B_i}}^{\alpha}}. \tag{9}$$

Phase 2: Cooperative Transmission

- During this phase, $\mathrm{B_i}$ forwards x_{i1} to $\mathrm{A_i}$ by using the harvested energy during the direct transmission phase. In this case, $\mathrm{A_i}$ observes

$$y_{\mathrm{A_i},2} = \frac{\sqrt{P_t} x_{i1} g_{\mathrm{i}}}{\sqrt{1 + d_{\mathrm{C_i}}^{\alpha}}} + n_{\mathrm{A_i},2}. \quad (10)$$

- Based on (9) and (10), the received SNR for $\mathrm{A_i}$ to detect x_{i1} forwarded from $\mathrm{B_i}$ is given by

$$\gamma_{\mathrm{A_i},\mathrm{B_i}}^{x_{i1}} = \frac{P_t |g_i|^2}{\left(1 + d_{\mathrm{C_i}}^{\alpha}\right) \sigma^2} = \frac{\eta \rho \beta_i |h_{\mathrm{B_i}}|^2 |g_i|^2}{\left(1 + d_{\mathrm{C_i}}^{\alpha}\right) \left(1 + d_{\mathrm{B_i}}^{\alpha}\right)}. \quad (11)$$

Phase 2: Cooperative Transmission

- At the end of this phase, $\mathrm{A_i}$ combines the signals from the BS and $\mathrm{B_i}$ using maximal-ratio combining (MRC).
- Combining the SNR of the direct transmission phase (2) and the SINR of the cooperative transmission phase (11), we obtain the received SINR at $\mathrm{A_i}$ as follows:

$$\gamma_{\mathrm{A_i,MRC}}^{x_{i1}} = \frac{\rho|h_{\mathrm{A_i}}|^2|p_{i1}|^2}{\rho|h_{\mathrm{A_i}}|^2|p_{i2}|^2 + 1 + d_{\mathrm{A_i}}^{\alpha}} + \frac{\eta\rho\beta_i|h_{\mathrm{B_i}}|^2|g_i|^2}{\left(1 + d_{\mathrm{B_i}}^{\alpha}\right)\left(1 + d_{\mathrm{C_i}}^{\alpha}\right)}. \tag{12}$$

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.

RNRF Selection Scheme—Outline

- This selection scheme provides a fair opportunity for each user to access the source with the aid of the NOMA protocol.
- **Advantage:** it does not require the knowledge of instantaneous channel state information (CSI).

  1. Outage Probability of the Near Users of RNRF
  2. Outage Probability of the Far Users of RNRF
  3. Diversity Analysis of RNRF
  4. System Throughput in Delay-Sensitive Transmission Mode of RNRF

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:

$$P_{\mathrm{B_i}} = \Pr\left(\frac{\rho|h_{\mathrm{B_i}}|^2|p_{i1}|^2}{\rho|h_{\mathrm{B_i}}|^2|p_{i2}|^2 + 1 + d_{\mathrm{B_i}}^{\alpha}} < \tau_1\right) + \Pr\left(\frac{\rho|h_{\mathrm{B_i}}|^2|p_{i1}|^2}{\rho|h_{\mathrm{B_i}}|^2|p_{i2}|^2 + 1 + d_{\mathrm{B_i}}^{\alpha}} > \tau_1, \gamma_{\mathrm{S,B_i}}^{x_{i2}} < \tau_2\right). \quad (13)$$

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:

$$P_{\mathrm{A_i}} = \Pr\left(\gamma_{\mathrm{A_i,MRC}}^{x_{i1}} < \tau_1,\, \gamma_{\mathrm{S,B_i}}^{x_{i1}}\Big|_{\beta_i=0} > \tau_1\right) + \Pr\left(\gamma_{\mathrm{S,A_i}}^{x_{i1}} < \tau_1,\, \gamma_{\mathrm{S,B_i}}^{x_{i1}}\Big|_{\beta_i=0} < \tau_1\right). \tag{14}$$

Diversity Analysis of RNRF—Near Users

- The diversity gain is defined as follows:

$$d = -\lim_{\rho \to \infty} \frac{\log P(\rho)}{\log \rho}. \tag{15}$$

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

$$F_{Y_i}(\varepsilon) \approx \frac{1}{2} \sum_{n=1}^{N} \omega_N \sqrt{1 - {\phi_n}^2} c_n \varepsilon_{\mathrm{A}_i} (\phi_n + 1). \tag{16}$$

- Substituting (16) into (15), 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, substituting (**??**) into (15), we obtain

$$d = -\lim_{\rho\to\infty} \frac{\log\left(-\frac{1}{\rho^2}\log\frac{1}{\rho}\right)}{\log\rho} = -\lim_{\rho\to\infty} \frac{\log\log\rho - \log\rho^2}{\log\rho} = 2. \quad (17)$$

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.

System Throughput in Delay-Sensitive Transmission Mode of RNRF

- In this mode, the transmitter sends information at a fixed rate but the 'goodput' becomes lower, as determined by the outage probability.
- As a result, the system throughput of RNRF in the delay-sensitive transmission mode is given by

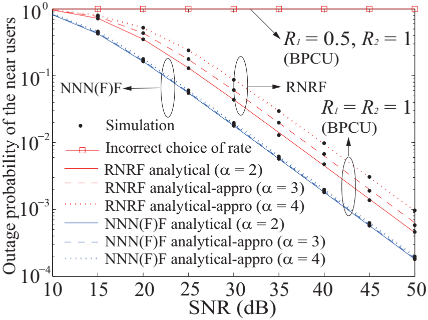
$$R_{\tau_{\mathrm{RNRF}}} = \left(1 - P_{\mathrm{A_i}}\right) R_1 + \left(1 - P_{\mathrm{B_i}}\right) R_2. \tag{18}$$

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.

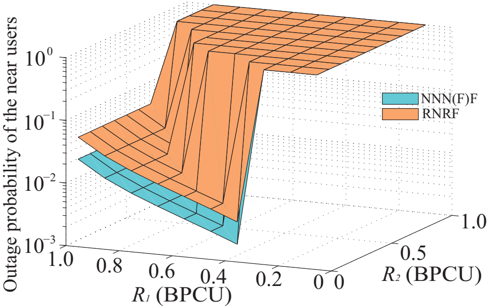
Following a procedure similar to that of RNRF, we can obtain the outage probability, diversity gain, and the throughput of NNNF and NNFF.

Numerical Results



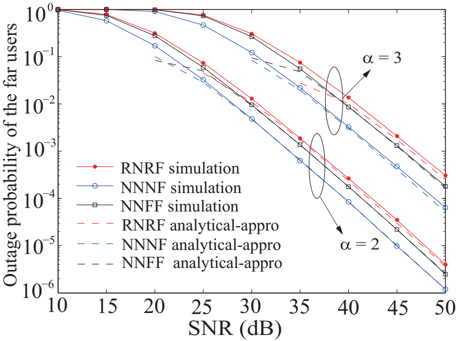
- Lower outage probability is achieved than with RNRF.
- All curves have the same slopes, which indicates the same diversity gains.
- The incorrect choice of rate results in an outage probability for the near users, which is always one.

Numerical Results



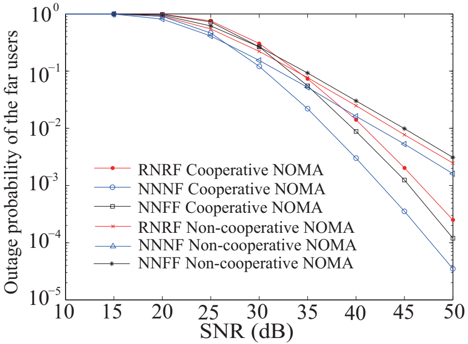
- The outage of the near users occurs more frequently as the rate of the far user, R_1, increases.
- For the choice of R_1, it should satisfy the condition $(|p_{i1}|^2 - |p_{i2}|^2\tau_1 > 0)$.
- For the choice of R_2, it should satisfy the condition that the split energy for detecting x_{i1} is also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

Numerical Results



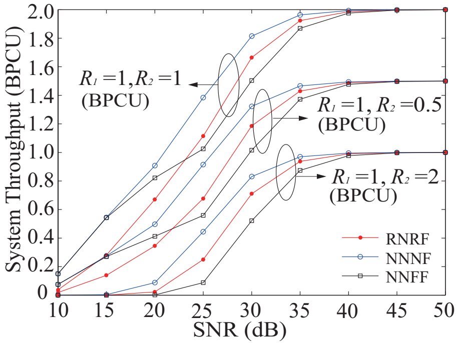
- NNNF achieves the lowest outage probability.
- NNFF achieves lower outage than RNRF, which indicates that the distance of the near users has more impact than that of the far users.
- All of the curves have the same slopes, which indicates that the diversity gains of the far users are the same.

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.

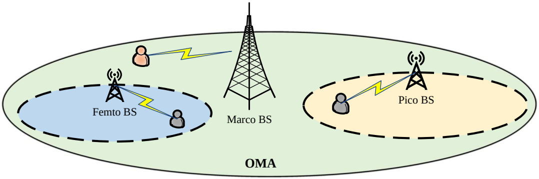
Numerical Results



- NNNF achieves the highest throughput since it has the lowest outage probability.
- The existence of the throughput ceilings in the high SNR region.
- Increasing R_2 from $R_2 = 0.5$ BPCU to $R_2 = 1$ BPCU can improve the throughput; however, for the case $R_2 = 2$ BPCU, the throughput is lowered.

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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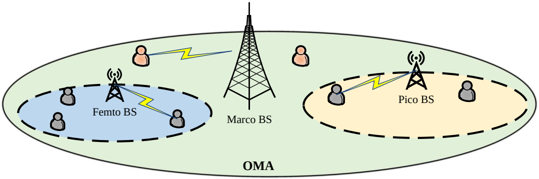

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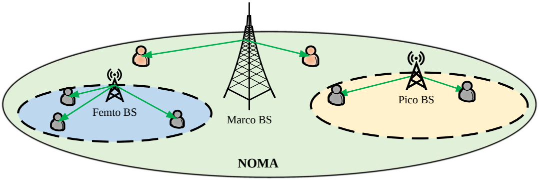

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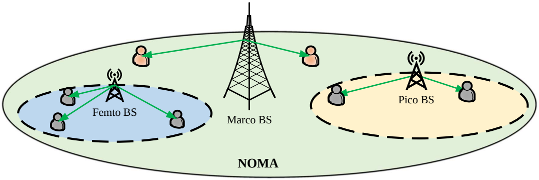

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NOMA in HetNets I — Resource Allocation

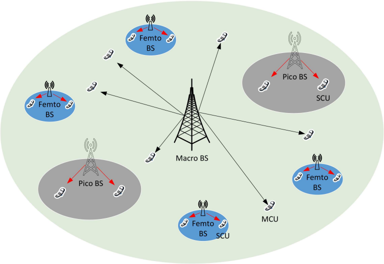


Fig.: System model.

- 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

$$y_{b,k}^{n} = \underbrace{f_{b,k}^{m}\sqrt{p_b a_{b,k}}x_{b,k}^{m}}_{\textbf{desired signal}} + \underbrace{f_{b,k}^{m}\sum\nolimits_{k'=k}^{K}\sqrt{p_b a_{b,k'}}x_{b,k'}^{m}}_{\textbf{interference from NOMA users}} + \underbrace{\zeta_{b,k}^{m}}_{\textbf{noise}}$$
$$+ \underbrace{\sum\nolimits_{m=1}^{M}\lambda_{m,b}h_{m,b,k}\sqrt{p_m}x_m}_{\textbf{cross-tier interference}} + \underbrace{\sum\nolimits_{b*\neq b}\lambda_{b*,b}g_{b*,b,k}^{m}\sqrt{p_{b^*}}x_{b*}^{m}}_{\textbf{co-tier interference}}. \quad (19)$$

- Received SINR:

$$\gamma_{b,k,k}^{m} = \frac{\left|f_{b,k}^{m}\right|^2 p_b a_{b,k}^{m}}{I_N^{k,k} + I_{co}^{k} + I_{cr}^{k} + \sigma^2}, \quad (20)$$

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

Problem Formulation

Maximize the sum-rate:

$$\max_{\lambda} \sum_{b=1}^{B} \sum_{k=1}^{K} \sum_{m=1}^{M} R_{b,k}^{m}(\lambda), \tag{21a}$$

$$s.t. \quad \lambda_{m,b} \in \{0,1\}, \quad \forall m, b, \tag{21b}$$

$$\sum_{m} \lambda_{m,b} \le 1, \quad \forall b, \tag{21c}$$

$$\sum_{b} \lambda_{m,b} \le q_{max}, \quad \forall m, \tag{21d}$$

$$I_m \le I_{thr}, \forall m. \tag{21e}$$

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

$$U_b = \sum_{k=1}^{K} R_{b,k}^{m} - \beta p_b \left| g_{b,m} \right|^2 , \tag{22}$$

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

$$U_m = \sum_{b=1}^{B} \lambda_{m,b} \left(\sum_{k=1}^{K} R_{b,k}^{m} + \beta p_b \left| g_{b,m} \right|^2 \right) , \tag{23}$$

Matching Model (cont')

- ***Peer effects*** among players' preferences$\Longrightarrow$ Swap operations
- Swap matching:

$$\Phi_a^b = \{\Phi \setminus \{(a, \Phi(a)), (b, \Phi(b))\}\} \cup \{(a, \Phi(b)), (b, \Phi(a))\}\,. \tag{24}$$

Φ: matching state

- *Swap-blocking* pair $(a, b) \Leftrightarrow$

1) $\forall s \in \{a, b, \Phi(a), \Phi(b)\}\,, U_s(\Phi_a^b) \geq U_s(\Phi)$ and;
2) $\exists s \in \{a, b, \Phi(a), \Phi(b)\}$, such that $U_s(\Phi_a^b) > U_s(\Phi)$

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

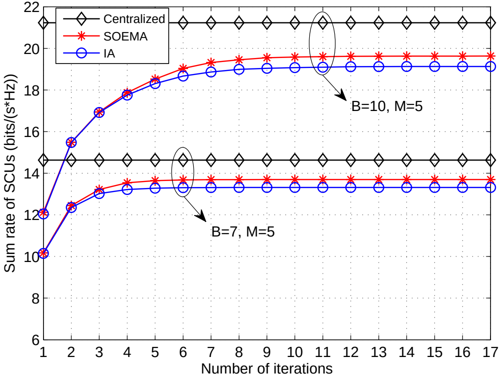


Fig.: Convergence of the proposed algorithms for different number of RBs and SBSs.

Numerical Results (cont')

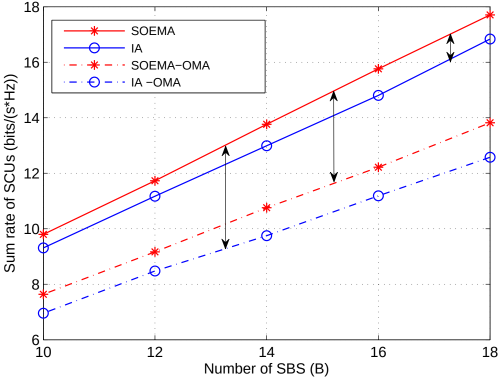


Fig.: Sum-rate of the SCUs for different number of small cells, with $M = 10$.

Numerical Results (cont')

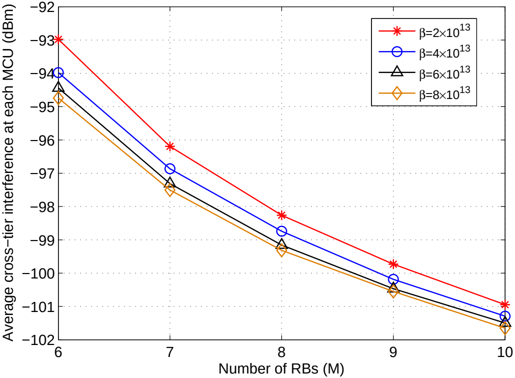


Fig.: Average received cross-tier interference at each MCU, with $B = 12$.

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

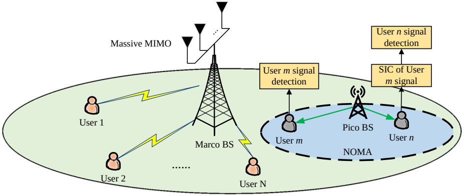


Fig.: System model.

- **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

$$\frac{P_1/N h_{o,1} L\left(d_{o,1}\right)}{I_{M,1} + I_{S,1} + \sigma^2}. \tag{25}$$

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

$$\gamma_{k_n} = \frac{a_{n,k} P_k g_{o,k} L\left(d_{o,k_n}\right)}{I_{M,k} + I_{S,k} + \sigma^2}. \tag{26}$$

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

$$\gamma_{k_{m^*}} = \frac{a_{m,k} P_k g_{o,k} L\left(R_k\right)}{I_{k,n} + I_{M,k} + I_{S,k} + \sigma^2}. \tag{27}$$

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:

$$\tilde{A}_k = \frac{\lambda_k}{\sum\limits_{i=2}^{K} \lambda_i \left(\tilde{P}_{ik}\tilde{B}_{ik}\right)^{\delta} + \lambda_1 \left(\frac{\tilde{P}_{1k} G_M}{N a_{n,k} B_k}\right)^{\delta}}, \qquad (28)$$

and

$$\tilde{A}_1 = \frac{\lambda_1}{\sum\limits_{i=2}^{K} \lambda_i \left(\frac{a_{n,i}\tilde{P}_{i1} B_i N}{G_M}\right)^{\delta} + \lambda_1}, \qquad (29)$$

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.

$$P_{cov,k}\left(\tau_c, \tau_t, x_0\right)\big|_{x_0 \le r_k} = \Pr\left\{\gamma_{k_{n \to m*}} > \tau_c, \gamma_{k_n} > \tau_t\right\}, \quad (30)$$

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

$$P_{cov,k}\left(\tau_t, x_0\right)\big|_{x_0 > r_k} = \Pr\left\{g_{o,k_m} > \frac{\varepsilon_t^f x_0^{\alpha_i}\left(I_k + \sigma^2\right)}{P_k \eta}\right\}. \quad (31)$$

Spectrum Efficiency

- The spectral efficiency of the proposed hybrid Hetnet is

$$\tau_{\mathrm{SE,L}} = A_1 N \tau_{1,L} + \sum_{k=2}^{K} A_k \tau_k, \quad (32)$$

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

$$\Theta_{\mathrm{EE}} = \frac{\text{Total data rate}}{\text{Total energy consumption}}. \tag{33}$$

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

$$\Theta_{\mathrm{EE}}^{\mathrm{Hetnets}} = A_1 \Theta_{\mathrm{EE}}^{1} + \sum_{k=2}^{K} A_k \Theta_{\mathrm{EE}}^{k}, \tag{34}$$

- 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

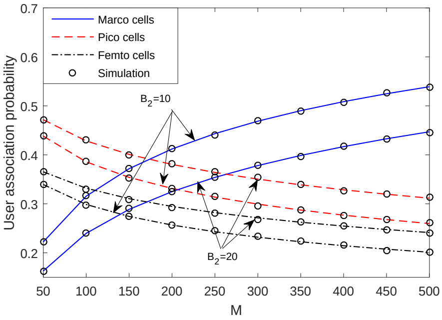


Fig.: User association probability versus antenna number with different bias factor.

- 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

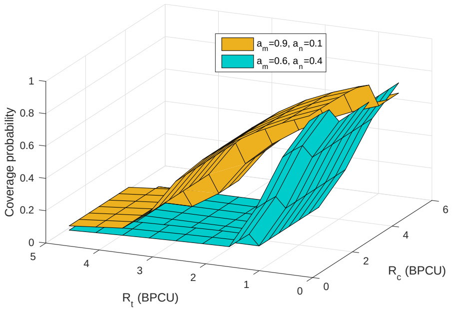


Fig.: Successful probability of typical user versus targeted rates of R_t and R_c.

- 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

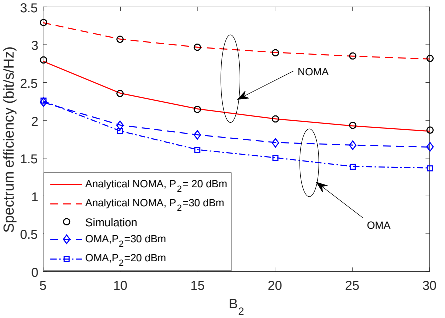


Fig.: Spectrum efficiency comparison of NOMA and OMA based small cells.

- 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

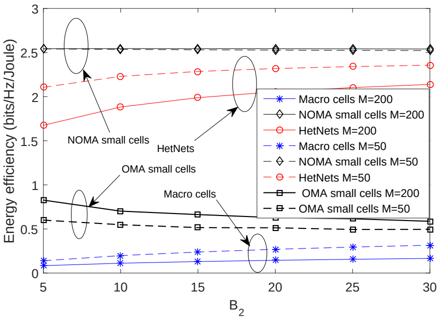


Fig.: Energy efficiency of the proposed framework.

- 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.

NOMA-based D2D Communications

- **D2D** communications underlaying cellular networks
- **Non-Orthogonal Multiple Access (NOMA)** protocol: facilitates the access of multiple users in the power domain
- **New framework**: NOMA-enhanced D2D, to further improve the spectral efficiency
- **Challenge**: Complex co-channel interference environment

$$\Downarrow$$

Intelligent resource allocation design is needed

System Description

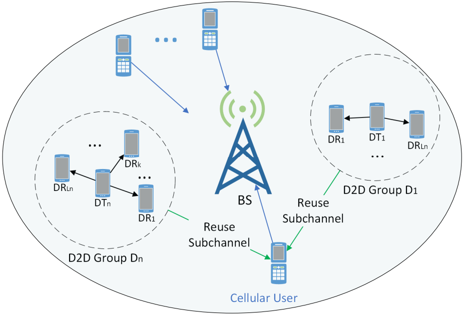


Fig.: System model.

- 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***.

Channel Model

- The signal received by the BS corresponding to subchannel SC_m:

$$y_m = \underbrace{\sqrt{P_c} h_{m,b} x_m}_{\textbf{desired signal}} + \underbrace{\sum_n \eta_{n,m} \sqrt{P_d} g_{n,b} t_n}_{\textbf{interference from D2D links}} + \underbrace{\zeta_m}_{\textbf{noise}}, \qquad (35)$$

- The signal at the k-th receiver in the n-th D2D group:

$$z_{n,k} = \underbrace{f_{n,k} \sqrt{a_{n,k} P_d} s_{n,k}}_{\textbf{desired signal}} + \underbrace{f_{n,k} \sum_{k'=k+1}^{L_n} \sqrt{a_{n,k'} P_d} s_{n,k'}}_{\textbf{interference from NOMA users}} + \underbrace{\zeta_{n,k}}_{\textbf{noise}}$$
$$+ \underbrace{\sum_{n* \neq n} \eta_{n*,n} \sqrt{P_d} g_{n*,n,k} t_{n*}}_{\textbf{interference from other D2D groups}} + \underbrace{\sqrt{P_c} h_{m,n,k} x_m}_{\textbf{interference from CU}}, \qquad (36)$$

Problem Formulation

Maximize the sum-rate:

$$\max_{\eta_{n,m}} R_{sum}, \tag{37a}$$

$$s.t. \quad \gamma_{n,k}^{k} \geq \gamma_{n,k}^{thr}, \quad \forall n, k, \tag{37b}$$

$$\gamma_m \geq \gamma_m^{thr}, \quad \forall m, \tag{37c}$$

$$\eta_{n,m} \in \{0, 1\}, \quad \forall n, m, \tag{37d}$$

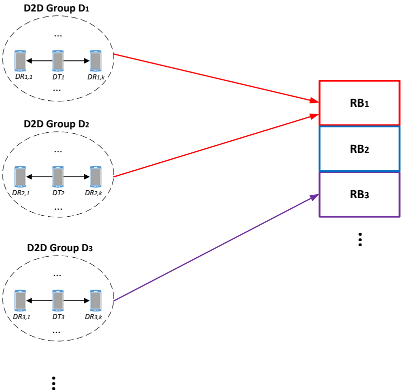
$$\sum_m \eta_{n,m} \leq 1, \quad \forall n. \tag{37e}$$

Solution:

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

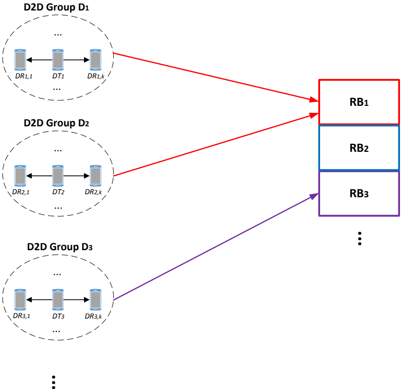
Matching Model

- $\succ$: "Prefer" $\boldsymbol{PL} = \left\{ \boldsymbol{P}(D_1), \ldots, \boldsymbol{P}(D_N), \boldsymbol{P}^{\dagger}(RB_1), \ldots, \boldsymbol{P}^{\dagger}(RB_M) \right\}$
- $RB_m \succ_{D_n} RB_{m'} \Leftrightarrow R_n^m > R_n^{m'}$
- $\mathcal{S} \succ_{RB_m} \mathcal{S}' \Leftrightarrow R_m^{\mathcal{S}} + \sum_{D_n \in \mathcal{S}} R_n^m > R_m^{\mathcal{S}'} + \sum_{D_n \in \mathcal{S}'} R_n^m$



Matching Algorithm

- Step 1: **Initialization**: PL
- Step 2: **Matching Phase**: D2D groups $\xrightarrow{\text{propose to}}$ RBs;
  RBs $\xrightarrow{\text{acceps/reject}}$ D2D groups
- Step 3: **Final matching result**



Numerical Results

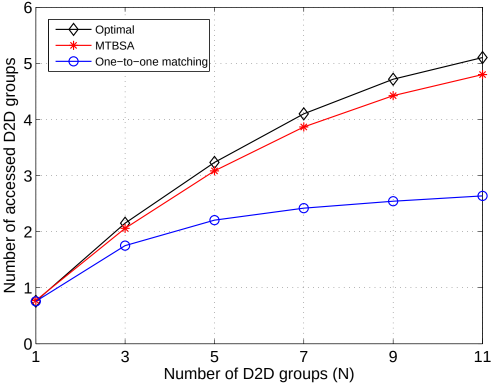


Fig.: Number of accessed D2D groups versus the number of D2D groups in the network, with K=3.

Numerical Results (cont')

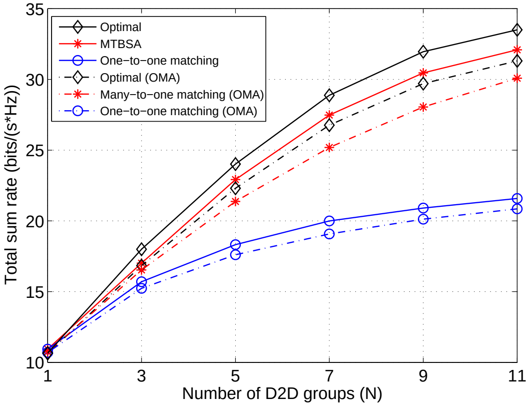


Fig.: Total sum-rate versus the number of D2D groups in the network, with K=3.

Numerical Results (cont’)

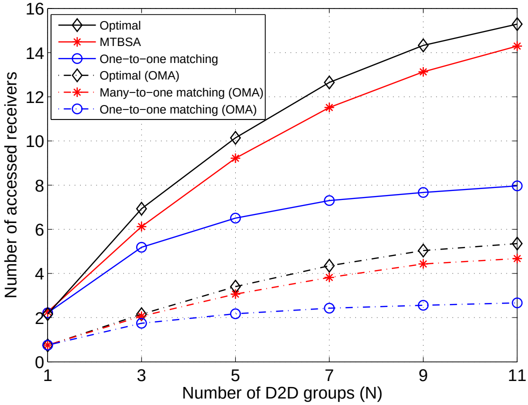


Fig.: Number of accessed receivers versus the number of D2D groups in the network, with K=3.

Numerical Results (cont')

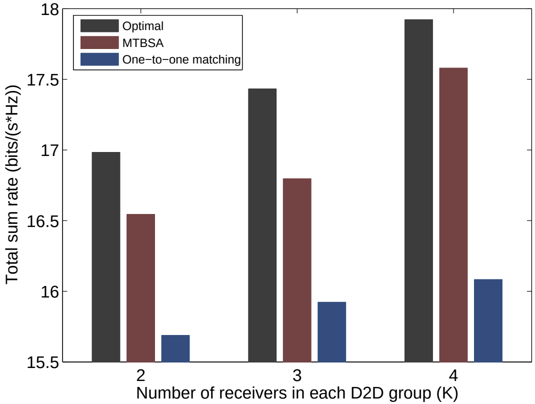


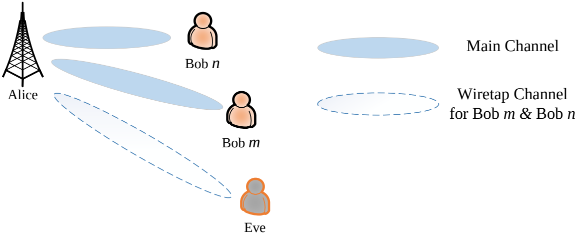
Fig.: Total sum-rate versus the number of receivers in each D2D group, with N=3.

Conclusions

- NOMA-enhanced D2D framework
- Novel resource allocation algorithm based on **matching theory**
  - Complexity: $\mathcal{O}(NM^2)$
  - Performance: near-optimal performance
- NOMA-enhanced D2D framework **outperforms** OMA-based D2D framework
  - sum-rate
  - number of users supported

Security in NOMA Networks

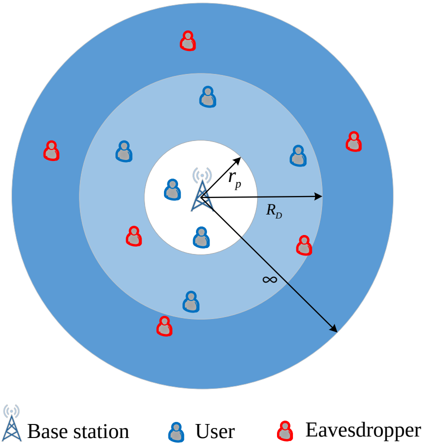
1. **Question**: Is NOMA still secure when there are eavesdroppers in the networks?



2. The use of insecure wireless communication. channels
3. Strong detection ability at the eavesdropper side.

[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)***.

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

$$\gamma_{B_m} = \frac{a_m |h_m|^2}{a_n |h_m|^2 + \frac{1}{\rho_b}}, \tag{38}$$

and

$$\gamma_{B_n} = \rho_b a_n |h_n|^2, \tag{39}$$

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:

$$\gamma_{E_\kappa} = \rho_e a_\kappa \max_{e \in \Phi_e, d_e \geq r_p} \left\{ \left| g_e \right|^2 L\left(d_e\right) \right\}. \tag{40}$$

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

$$I_m = [\log_2(1 + \gamma_{B_m}) - \log_2(1 + \gamma_{E_m})]^+, \quad (41)$$

and

$$I_n = [\log_2(1 + \gamma_{B_n}) - \log_2(1 + \gamma_{E_n})]^+, \quad (42)$$

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 (41), the secrecy outage probability for the m-th and n-th user is given by

$$\begin{aligned} P_m(R_m) &= \Pr\{I_m < R_m\} \\ &= \int_0^\infty f_{\gamma_{E_m}}(x) F_{\gamma_{B_m}}\left(2^{R_m}(1+x)-1\right) dx. \end{aligned} \tag{43}$$

and

$$\begin{aligned} P_n(R_n) &= \Pr\{I_n < R_n\} \\ &= \int_0^\infty f_{\gamma_{E_n}}(x) F_{\gamma_{B_n}}\left(2^{R_n}(1+x)-1\right) dx, \end{aligned} \tag{44}$$

respectively.

Secrecy Diversity Analysis

The secrecy diversity order can be given by

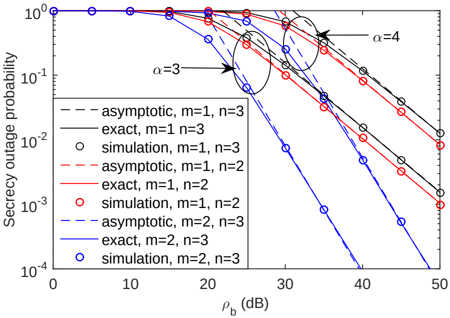
$$d_s = -\lim_{\rho_b \to \infty} \frac{\log\left(P_m^{\infty} + P_n^{\infty} - P_m^{\infty} P_n^{\infty}\right)}{\log \rho_b} = m, \tag{45}$$

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

$$P_{mn}^{\infty} = P_m^{\infty} + P_n^{\infty} - P_m^{\infty} P_n^{\infty} \approx P_m^{\infty} G_m (\rho_b)^{-D_m}. \tag{46}$$

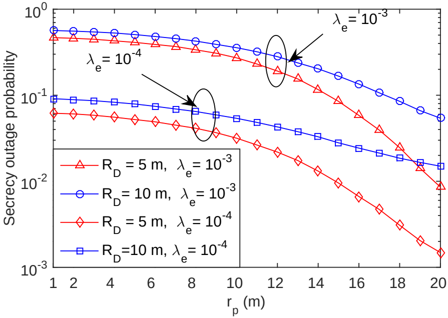
Remarks: It indicates that the secrecy diversity order and the asymptotic secrecy outage probability for the user pair are determined by the m-th user.

Numerical Results



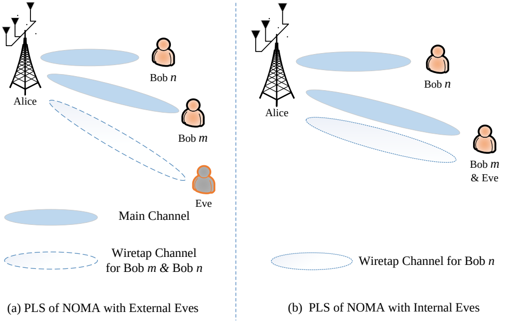
- The red curves and the black curves have the same slopes. While the blue curves can achieve a larger secrecy outage slope.
- It is due to the fact that the secrecy diversity order of the user pair is determined by the poor one m.
- This phenomenon also consists with the obtained insights in **Remark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



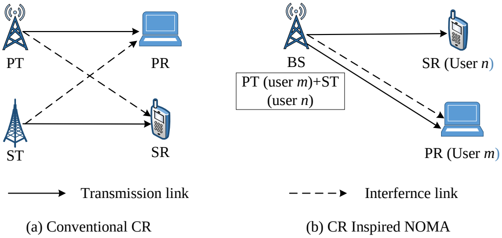
1. Artificial Noise for enhancing the security [1].
2. Multi-antenna to create channel differences [2].

[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. Interplay between NOMA and cognitive radio networks.
2. MIMO-NOMA design.
3. NOMA in mmWave Networks.
4. Cross layer design for NOMA — a QoE perspective.
5. Full-duplex design for NOMA.
6. Relay-selection for NOMA.

Interplay between NOMA and cognitive radio networks

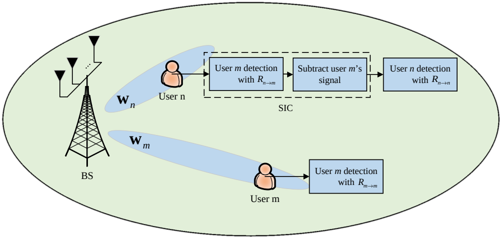


1. Cognitive radio inspired NOMA [1].
2. NOMA in cognitive radio networks [2].

[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)***.

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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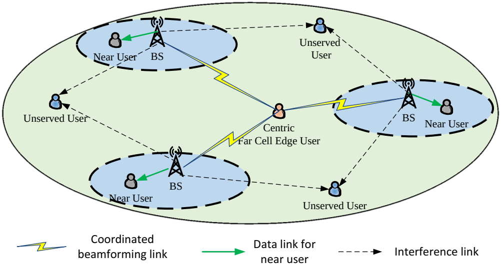
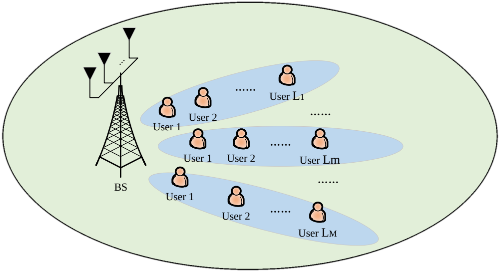


[1] Y. Liu, H. Xing, C. Pan, A. Nallanathan, M. Elkashlan, and L. Hanzo, "Multiple Antenna Assisted Non-Orthogonal Multiple Access", ***IEEE Wireless Communications***.

MIMO-NOMA Design - Cluster Based Structure

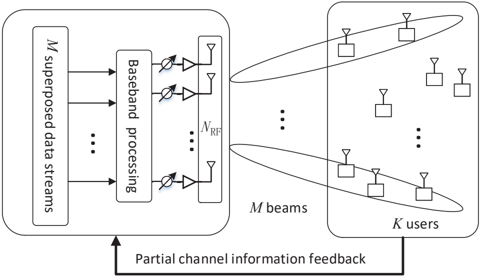
1. Inter-Cluster Interference Free Design.
2. Inter-Cluster Interference Contaminated Design.



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

NOMA in MmWave Networks

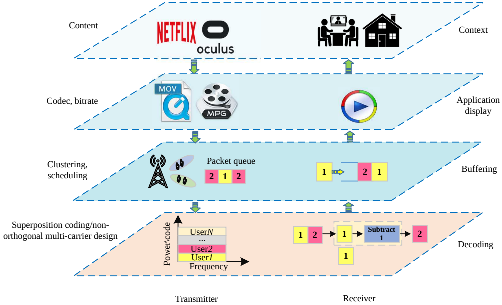
1. User Scheduling — Matching Theory.
2. Power Allocation — Branch-and-bound.



[2] J. Cui, Y. Liu, Z. Ding, P. Fan, and A. Nallanathan, "Optimal User Scheduling and Power Allocation for Millimeter Wave NOMA Systems", ***IEEE Transactions on Wireless Communications (TWC)*** accept to appear.

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*** (Under revision).

[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)*** (Under Review).

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 issues of NOMA
9. Different variants of NOMA

Thank you!