Non-Orthogonal Multiple Access for 5G and IoT Networks

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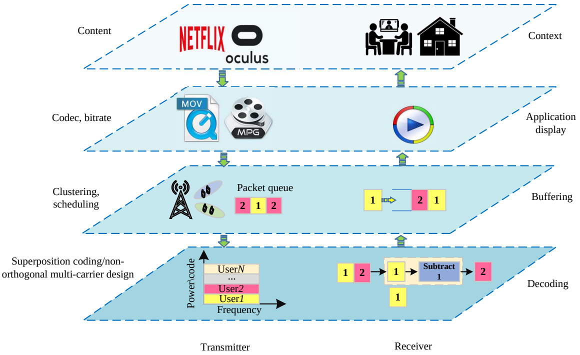
Outline

Recognize My Research

1. Cross-layer system structure for communications.
2. Multiple access technique in **Physical Layer**.



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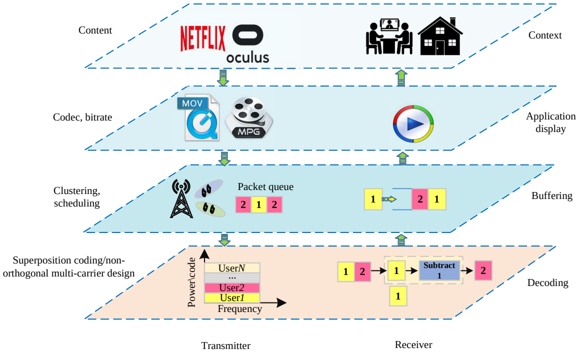
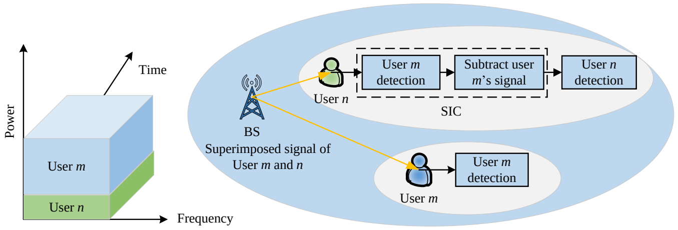


From OMA to NOMA

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).

NOMA Basics



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

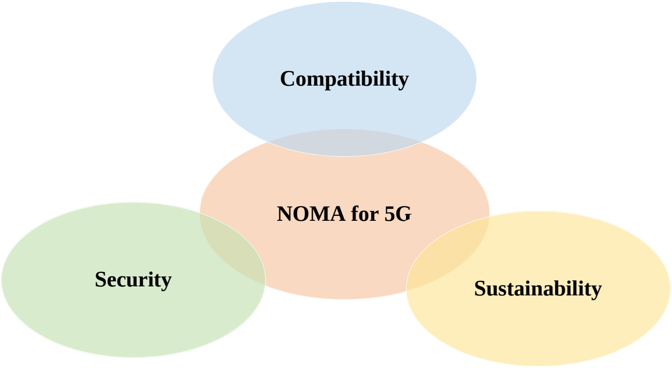
[1] **Y. Liu** *et al.*, "Non-Orthogonal Multiple Access for 5G and Beyond", ***Proceedings of the IEEE***; vol. 105, no. 12, pp. 2347-2381, Dec. 2017. (**Impact Factor: 9.24**)

NOMA Basics

1. **Question**: Why NOMA is an ideal solution for 5G?
2. Consider the following two scenarios.
    - If one user has a very poor channel condition
        - The bandwidth allocated to this user via OMA is not used efficiently.
        - NOMA - **high spectrum efficiency**.
    - If one user only needs to be served with a low data rate, e.g. IoT networks.
        - The use of OMA gives the sensor more than it needs.
        - NOMA - **heterogeneous QoS** and **massive connectivity**.

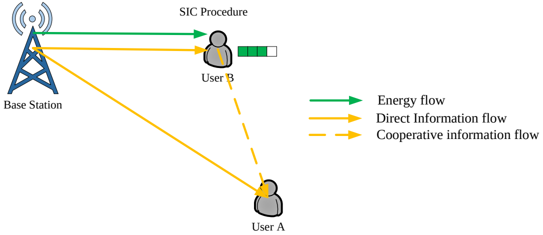
[1] Z. Ding, **Y. Liu** *et al.* (2017), "Application of Non-orthogonal Multiple Access in LTE and 5G Networks", ***IEEE Communication Magazine***. (**Web of Science Highly Cited paper, Top 5 Most Popular Article on Commun. Mag.**)

Research Contributions in NOMA



Sustainability of NOMA Networks

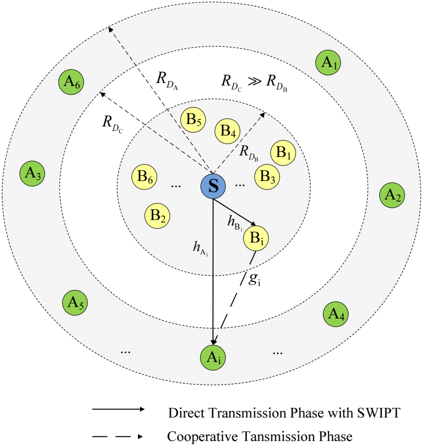
1. **Transmission reliability** - cooperative NOMA.
2. **Energy consumption** - radio signal energy harvesting.



3. Propose a wireless powered cooperative NOMA protocol [1].

[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**)

Network Model



- An 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) follow homogeneous PPPs.

Non-Orthogonal Multiple Access with User Selection

A natural question arises: which near NOMA user should help which far NOMA user?
To investigate the performance of one pair of selected NOMA users, three opportunistic user selection schemes are proposed, based on 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.

Advantage of RNRF, NNNF, and NNFF

- **Advantage of RNRF:** it does not require the knowledge of instantaneous channel state information (CSI).
- **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.

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:

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

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:

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

Diversity Analysis of RNRF—Far Users

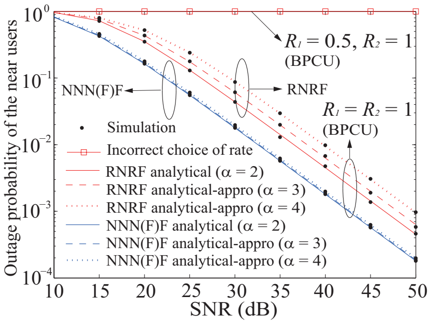
Far users: For the far users, the diversity gain is

$$d = -\lim_{\rho\to\infty} \frac{\log\left(-\frac{1}{\rho^2}\log\frac{1}{\rho}\right)}{\log\rho}$$
$$= -\lim_{\rho\to\infty} \frac{\log\log\rho - \log\rho^2}{\log\rho} = 2. \quad (3)$$

Remarks:

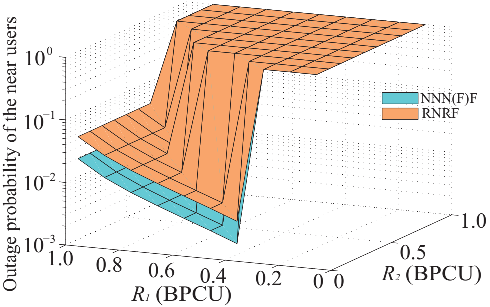
- This result indicates that using NOMA with an energy harvesting relay will not affect the diversity gain.
- At high SNRs, the dominant factor for the outage probability is $\frac{1}{\rho^2}\ln\rho$.
- The outage probability of using NOMA with SWIPT decays at a rate of $\frac{\ln SNR}{SNR^2}$. However,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

Numerical Results



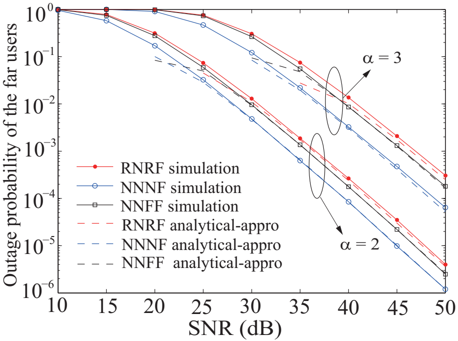
- Lower outage probability is achieved than with RNRF.
- All curves have the same slopes, which indicates the same diversity gains.
- Incorrect choice of rate make the outage probability of the near users be always one.

Numerical Results



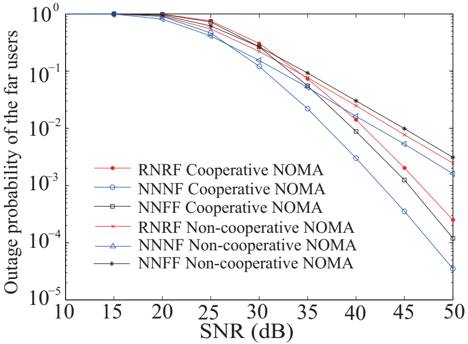
- The outage of the near users occurs more frequently as the rate of the far user, R_1, increases.
- For the choice of R_1, it should satisfy the condition $(|p_{i1}|^2 - |p_{i2}|^2\tau_1 > 0)$.
- For the choice of R_2, it should satisfy the condition that the split energy for detecting x_{i1} is also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

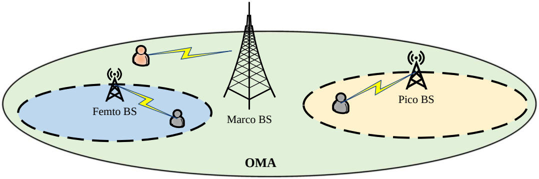
Numerical Results



- Cooperative NOMA has a larger 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.

Compatibility of 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 spectrum utilization of HetNets?



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

[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***; accept to appear

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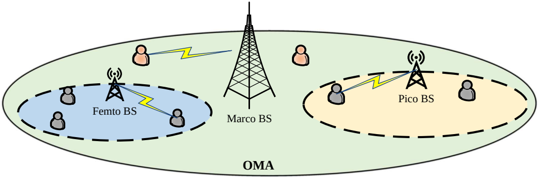

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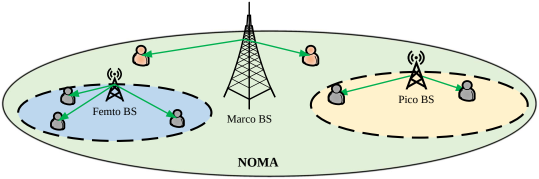

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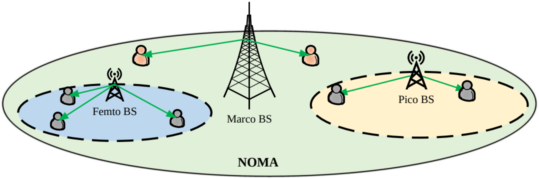

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NOMA in HetNets I — Resource Allocation

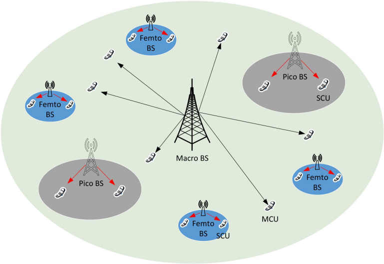


Fig.: System model.

- 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 (TWC)***. (**Top 2 Most Popular Article on TWC**)

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

$$y_{b,k}^{n} = \underbrace{f_{b,k}^{m}\sqrt{p_b a_{b,k}} x_{b,k}^{m}}_{\textbf{desired signal}} + \underbrace{f_{b,k}^{m} \sum_{k'=k+1}^{K} \sqrt{p_b a_{b,k'}} x_{b,k'}^{m}}_{\textbf{interference from NOMA users}} + \underbrace{\zeta_{b,k}^{m}}_{\textbf{noise}}$$
$$+ \underbrace{\sum_{m=1}^{M} \lambda_{m,b} h_{m,b,k} \sqrt{p_m} x_m}_{\textbf{cross-tier interference}} + \underbrace{\sum_{b* \neq b} \lambda_{b*,b} g_{b*,b,k}^{m} \sqrt{p_{b^*}} x_{b*}^{m}}_{\textbf{co-tier interference}}. \quad (4)$$

- Received SINR:

$$\gamma_{b,k,k}^{m} = \frac{\left|f_{b,k}^{m}\right|^2 p_b a_{b,k}^{m}}{I_N^{k,k} + I_{co}^{k} + I_{cr}^{k} + \sigma^2}, \quad (5)$$

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:

$$\max_{\lambda} \sum_{b=1}^{B} \sum_{k=1}^{K} \sum_{m=1}^{M} R_{b,k}^{m}(\lambda), \tag{6a}$$

$$s.t. \quad \lambda_{m,b} \in \{0,1\}, \quad \forall m, b, \tag{6b}$$

$$\sum_{m} \lambda_{m,b} \leq 1, \quad \forall b, \tag{6c}$$

$$\sum_{b} \lambda_{m,b} \leq q_{max}, \quad \forall m, \tag{6d}$$

$$I_m \leq I_{thr}, \forall m. \tag{6e}$$

Solution:

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

Matching Model

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

$$U_b = \sum_{k=1}^{K} R_{b,k}^{m} - \beta p_b \left| g_{b,m} \right|^2, \tag{7}$$

- RBs' utility: sum rate of the occupying SCUs

$$U_m = \sum_{b=1}^{B} \lambda_{m,b} \left(\sum_{k=1}^{K} R_{b,k}^{m} + \beta p_b \left| g_{b,m} \right|^2 \right), \tag{8}$$

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

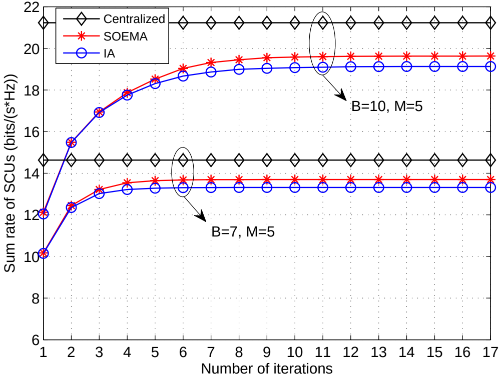


Fig.: Convergence of the proposed algorithms for different number of RBs and SBSs.

Numerical Results (cont')

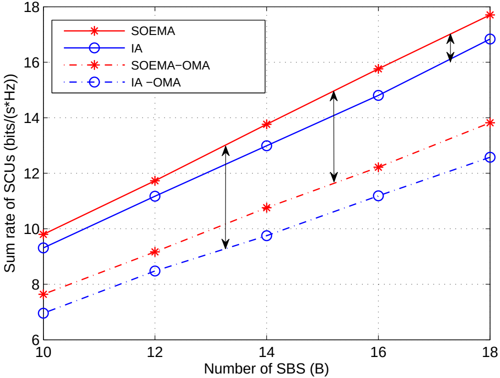


Fig.: Sum rate of the SCUs with different number of small cells, with $M = 10$.

NOMA in HetNets II — Large-Scale Analysis

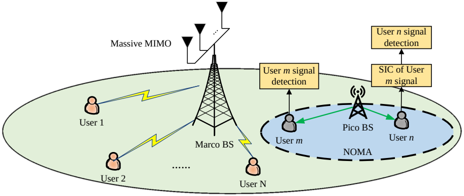


Fig.: System model.

- **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**, and *et al.* (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 technologies to macro cells and NOMA transmission to small cells.
- **Flexible User association**: based on on the maximum average received power.

Coverage Probability

A typical user can successfully transmit signals with a targeted data rate R_t.

1. **Near User Case**: successful decoding when two conditions holds
   - 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.

$$P_{cov,k}\left(\tau_c, \tau_t, x_0\right)\big|_{x_0 \le r_k} = \Pr\left\{\gamma_{k_{n \to m*}} > \tau_c, \gamma_{k_n} > \tau_t\right\}, \quad (9)$$

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

$$P_{cov,k}\left(\tau_t, x_0\right)\big|_{x_0 > r_k} = \Pr\left\{g_{o,k_m} > \frac{\varepsilon_t^f x_0^{\alpha_i}\left(I_k + \sigma^2\right)}{P_k \eta}\right\}. \quad (10)$$

Spectrum Efficiency

The spectrum efficiency of the proposed hybrid Hetnets is

$$\tau_{\mathrm{SE,L}} = A_1 N \tau_{1,L} + \sum_{k=2}^{K} A_k \tau_k, \tag{11}$$

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

Numerical Results—User Association Probability

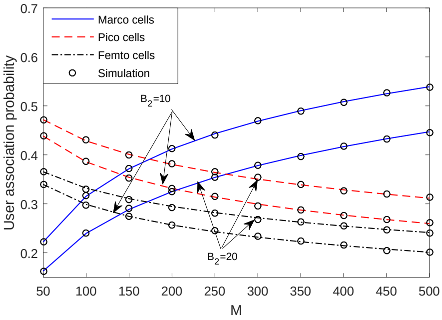


Fig.: User association probability versus antenna number with different bias factor.

- 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

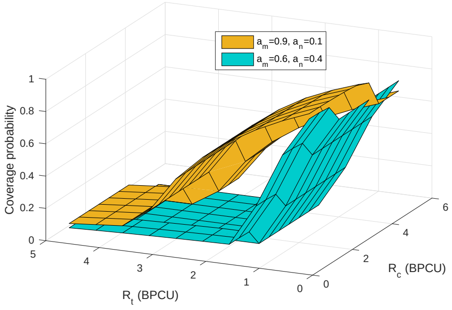


Fig.: Successful probability of typical user versus targeted rates of R_t and R_c.

- A cross between these two plotted surfaces — optimal power sharing allocation scheme for the given targeted rate.
- For inappropriate power and targeted rate selection, the coverage probability is always zero.

Numerical Results — Spectrum Efficiency

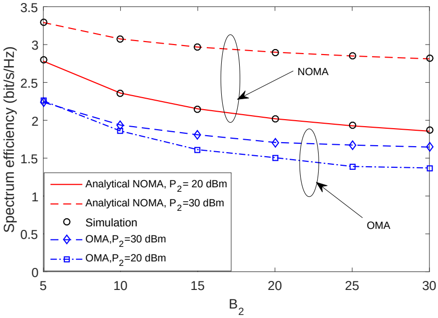
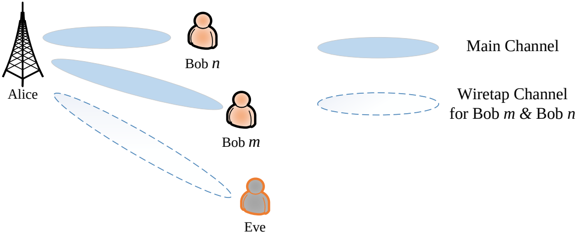


Fig.: Spectrum efficiency comparison of NOMA and OMA based small cells.

- NOMA enhanced small cells outperforms the conventional OMA based small cells.
- The spectrum efficiency of the small cells decreases as the bias factor increases — larger bias factor associates more macro users with low SINR to 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.
channels

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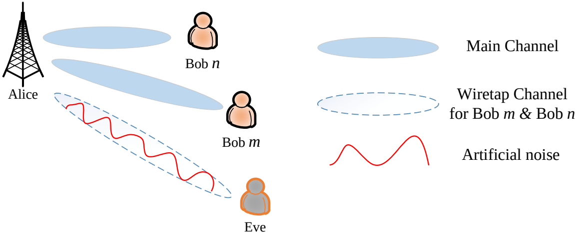

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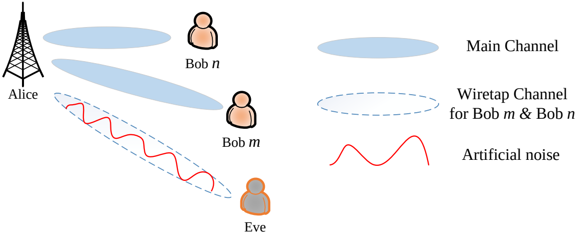

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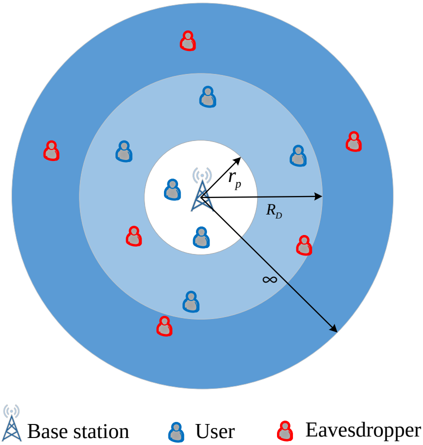
Network Model



- 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

$$\gamma_{B_m} = \frac{a_m |h_m|^2}{a_n |h_m|^2 + \frac{1}{\rho_b}}, \tag{12}$$

and

$$\gamma_{B_n} = \rho_b a_n |h_n|^2, \tag{13}$$

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:

$$\gamma_{E_\kappa} = \rho_e a_\kappa \max_{e \in \Phi_e, d_e \geq r_p} \left\{ |g_e|^2 L(d_e) \right\}. \tag{14}$$

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

$$I_m = [\log_2(1+\gamma_{B_m}) - \log_2(1+\gamma_{E_m})]^+, \tag{15}$$

and

$$I_n = [\log_2(1+\gamma_{B_n}) - \log_2(1+\gamma_{E_n})]^+, \tag{16}$$

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

$$\begin{aligned} P_m(R_m) &= \Pr\{I_m < R_m\} \\ &= \int_0^\infty f_{\gamma_{E_m}}(x) F_{\gamma_{B_m}}\left(2^{R_m}(1+x)-1\right) dx. \end{aligned} \tag{17}$$

and

$$\begin{aligned} P_n(R_n) &= \Pr\{I_n < R_n\} \\ &= \int_0^\infty f_{\gamma_{E_n}}(x) F_{\gamma_{B_n}}\left(2^{R_n}(1+x)-1\right) dx, \end{aligned} \tag{18}$$

respectively.

Secrecy Diversity Analysis

The secrecy diversity order can be given by

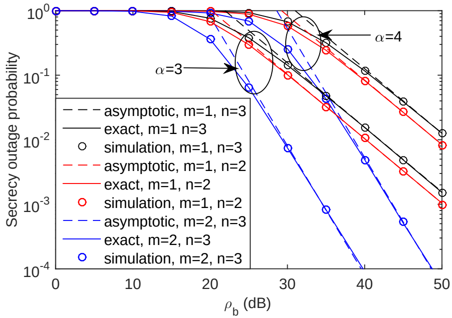
$$d_s = -\lim_{\rho_b \to \infty} \frac{\log\left(P_m^\infty + P_n^\infty - P_m^\infty P_n^\infty\right)}{\log \rho_b} = m, \tag{19}$$

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

$$P_{mn}^\infty = P_m^\infty + P_n^\infty - P_m^\infty P_n^\infty \approx P_m^\infty G_m(\rho_b)^{-D_m}. \tag{20}$$

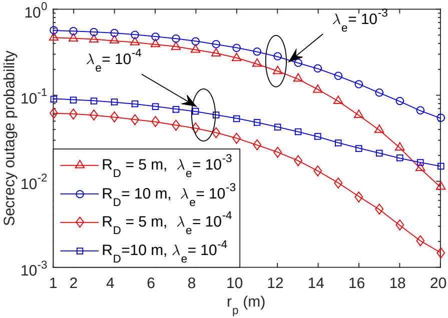
Remarks: It indicates that the secrecy diversity order and the asymptotic secrecy outage probability for the user pair are determined by the *m*-th user.

Numerical Results



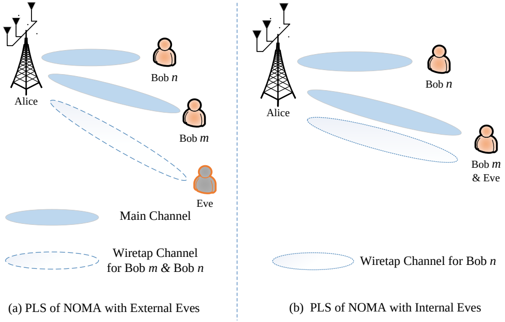
- The red curves and the black curves have the same slopes. While the blue curves can achieve a larger secrecy outage slope.
- It is due to the fact that the secrecy diversity order of the user pair is determined by the poor one m.
- This phenomenon also consists with the obtained insights in **Remark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

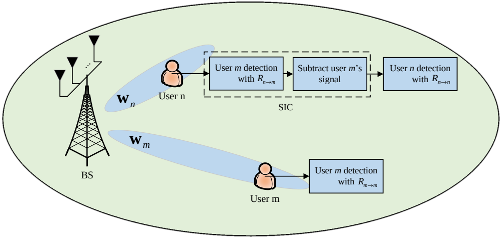
[1] **Y. Liu**, Z. Qin, M. Elkashlan, Y. Gao, and L. Hanzo(2017), "Enhancing the Physical Layer Security of Non-orthogonal Multiple Access in Large-scale Networks", ***IEEE Transactions on Wireless Communications (TWC)***.
[2] Z. Ding, Z. Zhao, M. Peng, and H. V. Poor (2017), "On the Spectral Efficiency 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. Relay-selection for NOMA.
6. Full-duplex design for NOMA.

MIMO-NOMA Design - Beamformer Based Structure

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



[1] **Y. Liu**, *et al.*, "Multiple Antenna Assisted Non-Orthogonal Multiple Access", ***IEEE Wireless Communications*** (Under revision).

MIMO-NOMA Design - Beamformer Based Structure

1. Centralized Beamforming.
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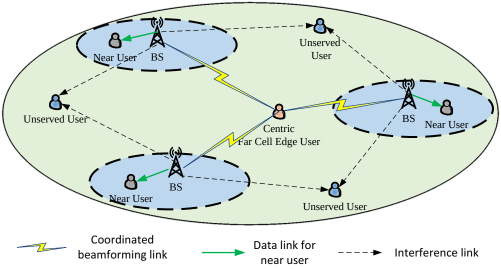
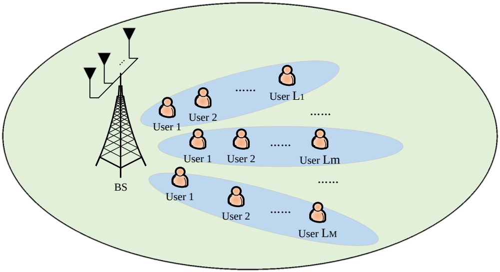


[1] **Y. Liu**, *et al.*, "Multiple Antenna Assisted Non-Orthogonal Multiple Access", ***IEEE Wireless Communications*** (Under revision).

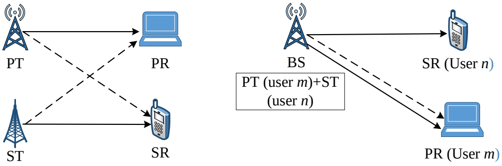
MIMO-NOMA Design - Cluster Based Structure

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



[1] **Y. Liu**, *et al.*, "Multiple Antenna Assisted Non-Orthogonal Multiple Access", ***IEEE Wireless Communications*** (Under revision).

Interplay between NOMA and cognitive radio networks



(a) Conventional CR

(b) CR Inspired NOMA

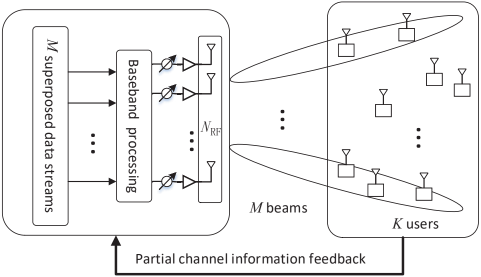
1. Cognitive radio inspired NOMA [1].
2. NOMA in cognitive radio networks [2].

[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)***.

NOMA in MmWave Networks

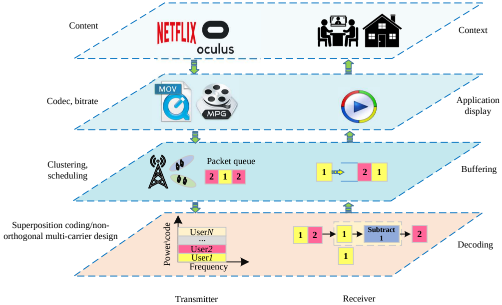
1. User Scheduling — Matching Theory.
2. Power Allocation — Branch-and-bound.



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

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

Questions?

Thanks for your attention.