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

Orthogonal multiple access: FDMA, TDMA and CDMA
Intentional DS-CDMA Spreading

Signal

Interferer

Spreading code

Despreading code
Unintentional Spreading in the FD
Capacity of OMA vs. NOMA in AWGN channel: (a) Uplink; (b) Downlink.
Diverse NOMA contributions


Diverse NOMA contributions


NOMA Beamforming Example

NOMA Beamforming Example
Uplink/Downlink Beamforming

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

\[ y = w^H x \]
Weights are calculated in order to minimize:

$$\epsilon(t)^2 = (w^H x(t) - r(t))^2$$

- \(w\): Beamformer weights
- \(x(t)\): 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.
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
NOMA SDMA Example
Evolution from CDMA-NOMA to SDMA-NOMA
Quantum-Search Aided MUD in NOMA

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

NOMA CDMA vs SDMA
## DS-CDMA vs SDMA NOMA Systems

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

BER

\( E_b/N_0 \) per Receive Antenna (dB)

ML MUD
DHA QMUD

\[ U = 15, P = 15 \]
\[ U = 14, P = 7 \]
\[ U = 15, SF = 15 \]
\[ U = 14, SF = 7 \]

SDMA DS-CDMA
Iterative Joint Channel & Data Estimation Turbo- Receivers for NOMA
Future 5G network architecture.

Applications

Virtualization

Forwarding

- Ultra Wideband (cmWave, mmWave)
- 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).
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.
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
1. Supports multiple access within a given resource block (time/frequency/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.


**Question:** Why NOMA is a popular proposition for 5G?

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

- NOMA for 5G
- Security
- Compatibility
- Sustainability
Transmission reliability - cooperative NOMA.

Energy consumption - radio signal energy harvesting.

Propose a wireless powered cooperative NOMA protocol [1].

The first contribution on wirelessly powered NOMA networks.

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Sustainability of NOMA Networks

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2. **Energy consumption** - radio signal energy harvesting.

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The first contribution on wirelessly powered NOMA networks.

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 $\Phi_\kappa (\kappa \in \{A, B\})$ with densities $\lambda\Phi_\kappa$.
- The near users are uniformly distributed within the disc and the far users are uniformly distributed within the ring.
- The users in $\{B_i\}$ are energy harvesting relays that harvest energy from the BS and forward the information to $\{A_i\}$ using the harvested energy as their transmit powers.
- The DF strategy is applied at $\{B_i\}$ and the cooperative NOMA system consists of two phases.
- It is assumed that the two phases have the same transmission periods.
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.
An outage of $B_i$ can occur for two reasons:

1. $B_i$ cannot detect $x_{i1}$.
2. $B_i$ can detect $x_{i1}$ but cannot detect $x_{i2}$.

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

$$P_{B_i} = \Pr\left(\frac{\rho|h_{Bi}|^2|p_{i1}|^2}{\rho|h_{Bi}|^2|p_{i2}|^2 + 1 + d_{Bi}^{\alpha}} < \tau_1\right)$$

$$+ \Pr\left(\frac{\rho|h_{Bi}|^2|p_{i1}|^2}{\rho|h_{Bi}|^2|p_{i2}|^2 + 1 + d_{Bi}^{\alpha}} \geq \tau_1, \gamma_{S,Bi}^{x_{i2}} < \tau_2\right). \quad (1)$$
Outage experienced by $A_i$ can occur in two situations.

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

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

$$P_{A_i} = \Pr \left( \gamma_{A_i, MRC}^{x_{i1}} < \tau_1, \gamma_{S, B_i}^{x_{i1}} \big| \beta_i = 0 > \tau_1 \right)$$

$$+ \Pr \left( \gamma_{S, A_i}^{x_{i1}} < \tau_1, \gamma_{S, B_i}^{x_{i1}} \big| \beta_i = 0 < \tau_1 \right).$$  \hspace{1cm} (2)
Diversity Analysis of RNRF—Near Users

- The diversity gain is defined as follows:

\[
d = - \lim_{\rho \to \infty} \frac{\log P(\rho)}{\log \rho}.
\]  

(3)

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

\[
F_{Y_i}(\varepsilon) \approx \frac{1}{2} \sum_{n=1}^{N} \omega_N \sqrt{1 - \phi_n^2 c_n \varepsilon A_i (\phi_n + 1)}.
\]  

(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.
Far users: For the far users, we obtain

\[
\begin{align*}
d &= - \lim_{\rho \to \infty} \frac{\log \left( -\frac{1}{\rho^2} \log \frac{1}{\rho} \right)}{\log \rho} \\
&= - \lim_{\rho \to \infty} \frac{\log \log \rho - \log \rho^2}{\log \rho} = 2.
\end{align*}
\]

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 \( \frac{1}{\rho^2} \log \rho \).
- The outage probability of using NOMA with SWIPT decays at a rate of \( \frac{\ln \text{SNR}}{\text{SNR}^2} \). However, for a conventional cooperative system without energy harvesting, a faster decreasing rate of \( \frac{1}{\text{SNR}^2} \) 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.
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 $x_{i2}$ ($\varepsilon_{A_i} \geq \varepsilon_{B_i}$).
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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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

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

$$y_{b,k}^n = f_{b,k}^m \sqrt{p_b a_{b,k}^m} x_{b,k}^m + f_{b,k}^m \sum_{k'=k}^{K} \sqrt{p_b a_{b,k'}^m} x_{b,k'}^m + \zeta_{b,k}^m,$$

where $\zeta_{b,k}^m$ represents the noise.

$$ + \sum_{m=1}^{M} \lambda_{m,b} h_{m,b,k} \sqrt{p_m} x_m + \sum_{b* \neq b} \lambda_{b*,b} g_{b*,b,k}^m \sqrt{p_{b*}} x_{b*}^m.$$

Cross-tier interference

Co-tier interference

Received SINR:

$$\gamma_{b,k,k}^m = \frac{|f_{b,k}^m|^2 p_b a_{b,k}^m}{I_N^{k,k} + I_{co}^k + I_{cr}^k + \sigma^2},$$

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

\[
\max_{\lambda, a} \sum_{b=1}^{B} \sum_{m=1}^{M} U_\alpha (R^m_b (\lambda, a)),
\]  

(8a)

\[
s.t. \quad \sum_{b=1}^{B} \lambda_{m,b} p_b |t_{b,m}|^2 \leq I^\text{thr}_m \quad \forall m,
\]  

(8b)

\[
\Delta(\lambda) \geq 0, \quad \forall m, b,
\]  

(8c)

\[
\lambda_{m,b} \in \{0, 1\}, \quad \forall m, b,
\]  

(8d)

\[
\sum_{m} \lambda_{m,b} \leq 1, \quad \forall b,
\]  

(8e)

\[
\sum_{b} \lambda_{m,b} \leq q_{\text{max}}, \quad \forall m,
\]  

(8f)

\[
a_{b,k} \geq 0, a_{b,j} \geq 0, \quad \forall b,
\]  

(8g)

\[
a_{b,k} + a_{b,j} \leq 1, \quad \forall b.
\]  

(8h)
Solution:

- NP-hard $\implies$ 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 $m$

$$U_b = \sum_{k=1}^{K} R_{b,k}^{m} - \beta p_b |g_{b,m}|^2,$$  \hspace{1cm} (9)

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

$$U_m = \sum_{b=1}^{B} \lambda_{m,b} \left( \sum_{k=1}^{K} R_{b,k}^{m} + \beta p_b |g_{b,m}|^2 \right),$$  \hspace{1cm} (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 $SR_{a,b}$ to record the time that SBS $a$ and $b$ swap their allocated RBs → 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: $O(B^2)$
  - Performance: near-optimal performance

- NOMA-enabled HetNets outperform OMA-based one
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.
The signal-to-interference-plus-noise ratio (SINR) that a typical user experiences at a macro BS is

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

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

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

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

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

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

(14)

and

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

(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.

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

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

   $$P_{cov,k}(\tau_t, x_0)|_{x_0 > r_k} = \Pr\left\{g_{o,k_m} > \frac{\varepsilon^f_t x_0^{\alpha_i} (l_k + \sigma^2)}{P_k \eta}\right\}. \quad (17)$$
Spectrum Efficiency

The spectral efficiency of the proposed hybrid Hetnet is

$$\tau_{SE,L} = A_1 N_{\tau_1,L} + \sum_{k=2}^{K} A_k \tau_k,$$

(18)

where $N_{\tau_1}$ and $\tau_k$ are the lower bound spectrum efficiency of macro cells and the exact spectral efficiency of the $k$-th tier small cells.
The energy efficiency is defined as

$$\Theta_{EE} = \frac{\text{Total data rate}}{\text{Total energy consumption}}.$$  \hfill (19)

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

$$\Theta_{EE}^{\text{Hetnets}} = A_1 \Theta_{EE}^1 + \sum_{k=2}^{K} A_k \Theta_{EE}^k,$$  \hfill (20)

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

- 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.

Fig.: User association probability versus antenna number with different bias factor.
Numerical Results — Coverage Probability

- 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.

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

<table>
<thead>
<tr>
<th>Coverage probability</th>
<th>$R_t$ (BPCU)</th>
<th>$R_c$ (BPCU)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>0.2</td>
<td>0</td>
<td>2</td>
</tr>
<tr>
<td>0.4</td>
<td>0</td>
<td>4</td>
</tr>
<tr>
<td>0.6</td>
<td>0</td>
<td>6</td>
</tr>
<tr>
<td>0.8</td>
<td>2</td>
<td>0</td>
</tr>
<tr>
<td>1.0</td>
<td>4</td>
<td>2</td>
</tr>
</tbody>
</table>
Numerical Results — Spectrum Efficiency

- 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.

**Fig.:** Spectrum efficiency comparison of NOMA and OMA based small cells.
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.
1 **Question**: Is NOMA still secure when there are eavesdroppers in the networks?

![Diagram](image)

2 Propose to use **Artificial Noise** to enhance the security of NOMA [1].

3 The first work of considering the security in NOMA.

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

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

Propose to use Artificial Noise to enhance the security of NOMA [1].

The first work of considering the security in NOMA.

Network Model

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

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

and

$$\gamma_{B_n} = \rho_b a_n |h_n|^2, \quad (22)$$

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 $\sigma_b^2$ 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:

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

It is assumed that $\kappa \in \{m, n\}$, $\rho_e = \frac{P_A}{\sigma^2_e}$ is the transmit SNR with $\sigma^2_e$ 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.
The secrecy rate of the $m$-th user and the $n$-th user can be expressed as

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

and

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

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

$$P_m (R_m) = \Pr \{ I_m < R_m \} = \int_0^\infty f_{\gamma_{Em}} (x) F_{\gamma_{Bm}} \left( 2^{R_m} (1 + x) - 1 \right) dx.$$  \hspace{1cm} (26)

and

$$P_n (R_n) = \Pr \{ I_n < R_n \} = \int_0^\infty f_{\gamma_{En}} (x) F_{\gamma_{Bn}} \left( 2^{R_n} (1 + x) - 1 \right) dx,$$  \hspace{1cm} (27)

respectively.
Secrecy Diversity Analysis

The secrecy diversity order can be given by

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

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

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

**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.
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.
The secrecy outage probability decreases as the radius of the protected zone increases, which demonstrates the benefits of the protected zone.

- Smaller density $\lambda_e$ of Eves can achieve better secrecy performance, because smaller $\lambda_e$ 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].


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. Centralized Beamforming.

2. Coordinated Beamforming.

MIMO-NOMA Design - Cluster Based Structure

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

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. Construct $M$ **orthogonal beams** at BS in spatial domain.

2. Realize **NOMA transmission in each beam** and apply successive interference cancellation (SIC) at users.

Based on the NOMA principle, the received \textbf{SINR} of user $k$ to decode user $j$ on beam $m$ is given by

\[
\text{SINR}_{j \rightarrow k}^m = \frac{g_k^m \beta_j^m}{g_k^m \sum_{\pi(i) \succ \pi(j)} \beta_i^m + \sum_{n \neq m} g_n^m \beta_n^m + \sigma^2}
\]  \hspace{1cm} (30)

Note that the achievable SINR for user $j$ on beam $m$ can be obtained with $k = j$.

The corresponding decoding rate is

\[
R_{j \rightarrow k}^m = \log_2(1 + \text{SINR}_{j \rightarrow k}^m), \text{ for any } \pi(k) \geq \pi(j), \ j, \ k \in C_m.
\]

\textbf{SIC condition of success:} $R_{j \rightarrow k}^m \geq R_{j \rightarrow j}^m$ for $\pi(k) \geq \pi(j)$, $j, k \in C_m$. 
The considered **sum rate maximization** problem:

\[
\max_{c,\beta} \quad \sum_{m=1}^{M} \sum_{j=1}^{q_m} R_{j\to j}^m \\
\text{s.t.} \quad R_{j\to k}^m \geq R_{j\to j}^m, \quad \sum_{m=1}^{M} \sum_{j \in C_m} \beta_j^m \leq P_{\text{tot}}, \\
\sum_{k=1}^{K} c_k^m = q_m, \quad \sum_{m=1}^{M} c_k^m \leq 1, \quad R_{j\to j}^m \geq \bar{R}_j, \\
\pi_m \in \Pi, \quad \pi(k) > \pi(j), \quad j, k \in C_m, \quad m \in M. 
\]  

- \(c\) denotes the index set, where term \(c_k^m\) indicates the indicators for user \(k\) on beam \(m\), \(c_k^m \in \{0, 1\}\).
- \(\Pi\) 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.
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 $\Gamma_1$ and $\Gamma_2$.
- $\mathcal{G}$ 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 $f^*$ belongs to the interval between $f(A)$ and $f(B)$. 
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
  \[ L = \min\{f(A), f(D)\} \].
- The upper bound
  \[ U = \min\{f(C), f(B)\} \].
- Note that
  \[ U - L \leq f(A) - f(B) \],
the potential interval for
  \( f^* \) decreases.
4 Pruning operations:

- Split $D_1$ and $D_2$ along its longest edge, respectively.
- Remove $D_5$, which will not affect the optimality.
For given the **selected users** and the corresponding **decoding order**, the power allocation subproblem can be formulated as follows.

\[
\min_{\beta, \Gamma} \sum_{m=1}^{M} \sum_{j_m=1}^{q_m} \log_2 (1 + \Gamma_{j_m \rightarrow j_m}^m) \quad (32a)
\]

\[
\text{s.t.} \quad \Gamma_{j_m \rightarrow j_m}^m \leq \frac{g_{j_m}^m \beta_{j_m}^m}{g_{j_m}^m \sum_{i_m=j_m+1}^{q_m} \beta_{i_m}^m + \sum_{n \neq m} g_{j_m}^n \beta_n^m + \sigma^2}, \quad (32b)
\]

\[
\sum_{m=1}^{M} \sum_{j_m=1}^{q_m} \beta_{j_m}^m \leq P_{\text{tot}}, \quad R_{j_m \rightarrow j_m}^m \geq \bar{R}_{j_m}, \quad (32c)
\]

\[
\sum_{n \neq m} \left( g_{k_m}^m g_{j_m}^n - g_{j_m}^m g_{k_m}^n \right) \beta_n^m + (g_{k_m}^m - g_{j_m}^m) \sigma^2 \geq 0, \quad (32d)
\]

\[
k_m > j_m, \quad j_m, k_m \in C_m, \quad m \in M. \quad (32e)
\]
1 **Construct box constraint sets:**

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

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

- The equivalent reformulation of power allocation problem is given by

\[
\min_{\Gamma} U(\Gamma) \quad \text{s.t.} \quad \Gamma \in \mathcal{G}.
\] (33)
Key Steps for Branch and Bound (BB) Algorithms

2 Construct bound functions:

- The lower bound function:
  \[ g(\Gamma) = \begin{cases} 
    U(\Gamma), & \Gamma \in G \\
    0, & \text{o.w.,} 
  \end{cases} \]

- The upper bound function:
  \[ \bar{g}(\Gamma) = \begin{cases} 
    U(\Gamma), & \Gamma \in G \\
    0, & \text{o.w.,} 
  \end{cases} \]

Observations:

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

\[
\text{Find } \mathbf{s} \quad \text{s.t. } \mathbf{\Gamma} \in \mathcal{G}. \quad (34)
\]

*Observations:*
- Problem (34) is feasible for A, D and F.
- One cannot find a feasible PA coefficients for $\mathcal{D}_5$. 

![Diagram](image.png)
Given the user power allocation coefficients, the user selection problem can be transformed into

$$\max_c \mathcal{H} = \sum_{m=1}^{M} \sum_{j=1}^{R_m^{j}} q_m$$

s.t. \[ \sum_{k=1}^{K} c_k^m = q_m, \quad \sum_{m=1}^{M} c_k^m \leq 1, \]
\[ \pi_m \in \Pi, \quad \pi(k) > \pi(j), \quad j, k \in C_m, \quad m \in M. \]

Problem (35) is a combinational problem.

Exhaustive search provides an optimal approach but it suffers 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 $m$:
     \[
     \mathcal{H}_k^m = \log_2 \left( 1 + \Gamma_k^m \right).
     \] (36)
   - The preference value of beam $m$ is the sum rate of all users on beam $m$:
     \[
     \mathcal{H}^m = \sum_{k \in \varphi(m)} \log_2 \left( 1 + \Gamma_k^m \right).
     \] (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**.
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.
The proposed BB algorithm is converged for different SNR.

The convergence becomes 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

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


D2D Enabled NOMA

Fig.: System model.

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

Cross layer design for NOMA — a QoE perspective

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


Multiple antenna aided NOMA for UAV networks

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).

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.
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.

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

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

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 $x_l$, the received SINR at $R$ to detect $x_t$ is given by

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

(39)

where $\epsilon = 0$ and $\epsilon = 1$ 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 $\Omega_I$. 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

$$\gamma_{D_k \rightarrow x_t} = \frac{\rho |h_k|^2 b_t}{\rho |h_k|^2 b_l + \rho \omega_2 |h_k|^2 + 1},$$

(40)

where $\omega_2 \in [0, 1]$ denotes the impact level of IS at the user nodes. Then $D_k$ detects $x_l$ and gives the corresponding SINR as follows:

$$\gamma_{D_k \rightarrow x_l} = \frac{\rho |h_k|^2 b_l}{\varepsilon \rho |g|^2 + \rho \omega_2 |h_k|^2 + 1}.$$

(41)

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

$$\gamma_{D_r \rightarrow x_t} = \frac{\rho |h_r|^2 b_t}{\rho |h_r|^2 b_l + \rho \omega_2 |h_r|^2 + 1}.$$

(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

$$P_{x_l}^{ipSIC} = 1 - \Pr(\gamma_{R \rightarrow x_l} > \gamma_{th_l}) \times \Pr(\gamma_{D_k \rightarrow x_t} > \gamma_{th_t}, \gamma_{D_k \rightarrow x_l} > \gamma_{th_l}),$$

(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 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

$$P_{ip}^{SIC}_t = 1 - \Pr(\gamma_{R \rightarrow x_t} > \gamma_{th_t}, \gamma_{R \rightarrow x_l} > \gamma_{th_l}) \times \Pr(\gamma_{D_k \rightarrow x_t} > \gamma_{th_t}) \Pr(\gamma_{D_r \rightarrow x_t} > \gamma_{th_t}),$$  \hspace{1cm} (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

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

(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.
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 $\Omega_I = 0 \text{ dB}$, 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

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!