Hybrid Uplink-Downlink NOMA for Secure Coordinated Multi-Point Networks

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Outline

- Introduction
- Hybrid Uplink-Downlink NOMA
- Secrecy Analysis
- Numerical results
- Conclusion

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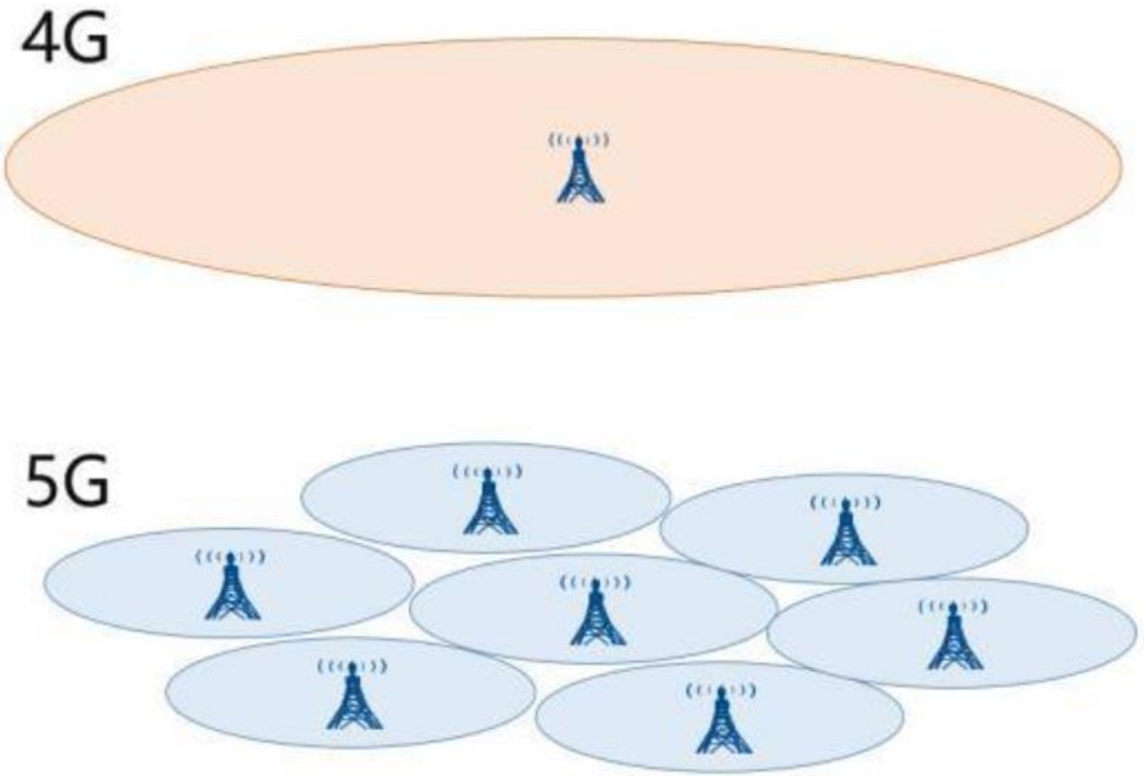
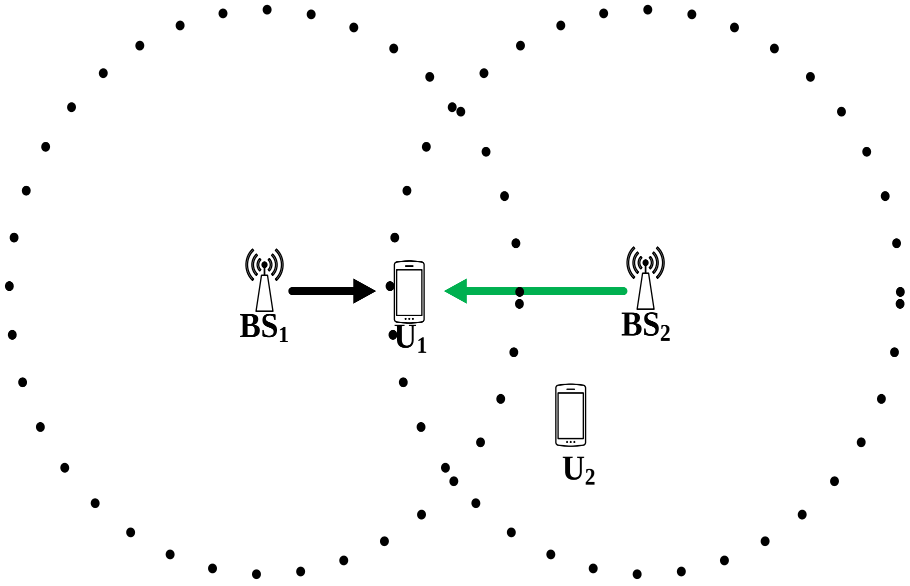
Introduction

- Multiple cells
- Large-scale access
- Edge user
- Spectral efficiency
- Coordinated multi-point (CoMP)

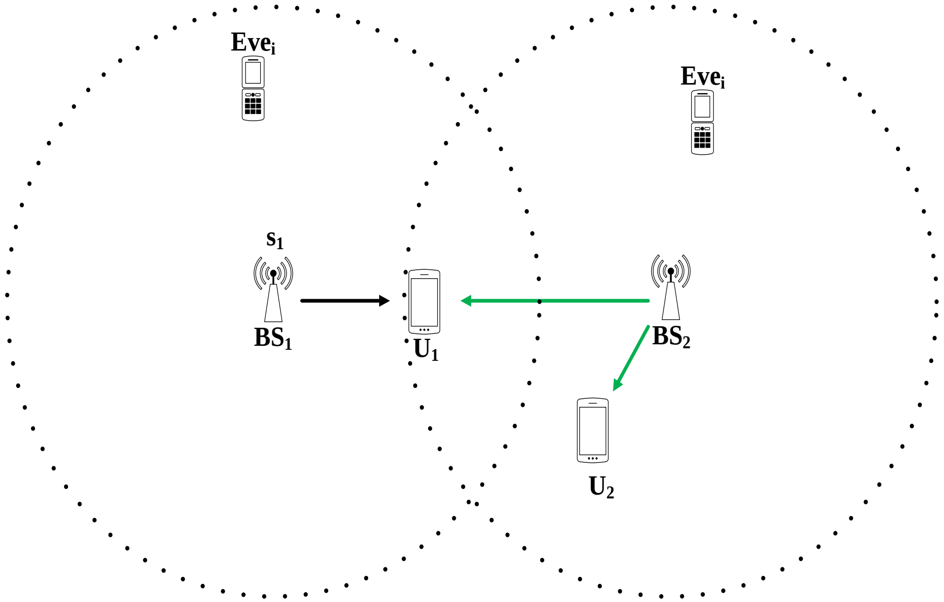


Introduction

- Motivation
  - Conventional OMA-CoMP
    - BS_2 can only help U_1 in another time slot
    - When helping U_1, BS_2 can not serve U_2
    - A quick decrease in spectral efficiency as the number of cell-edge users increases
  - NOMA-CoMP
    - Avoid the exclusivity of OMA's channels
    - Security



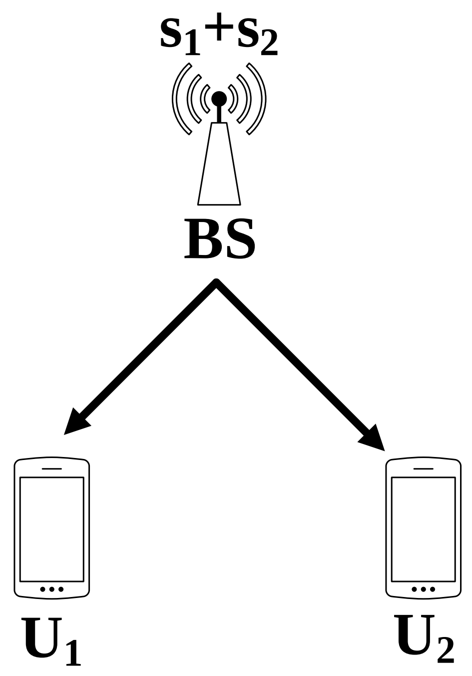
Conventional OMA-CoMP



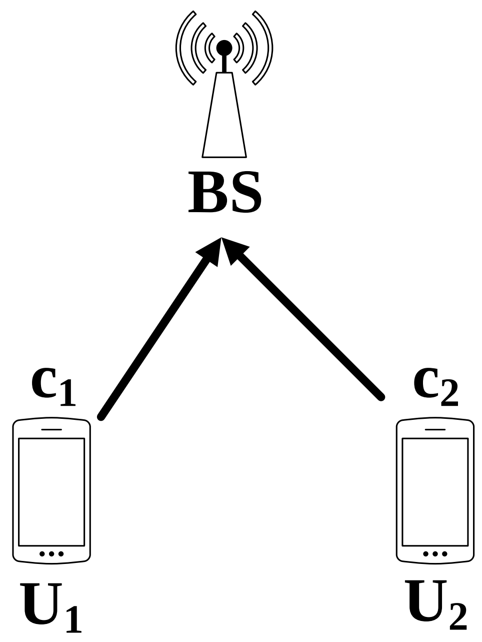
NOMA-CoMP

Introduction

- Downlink NOMA *V.S.* Uplink NOMA



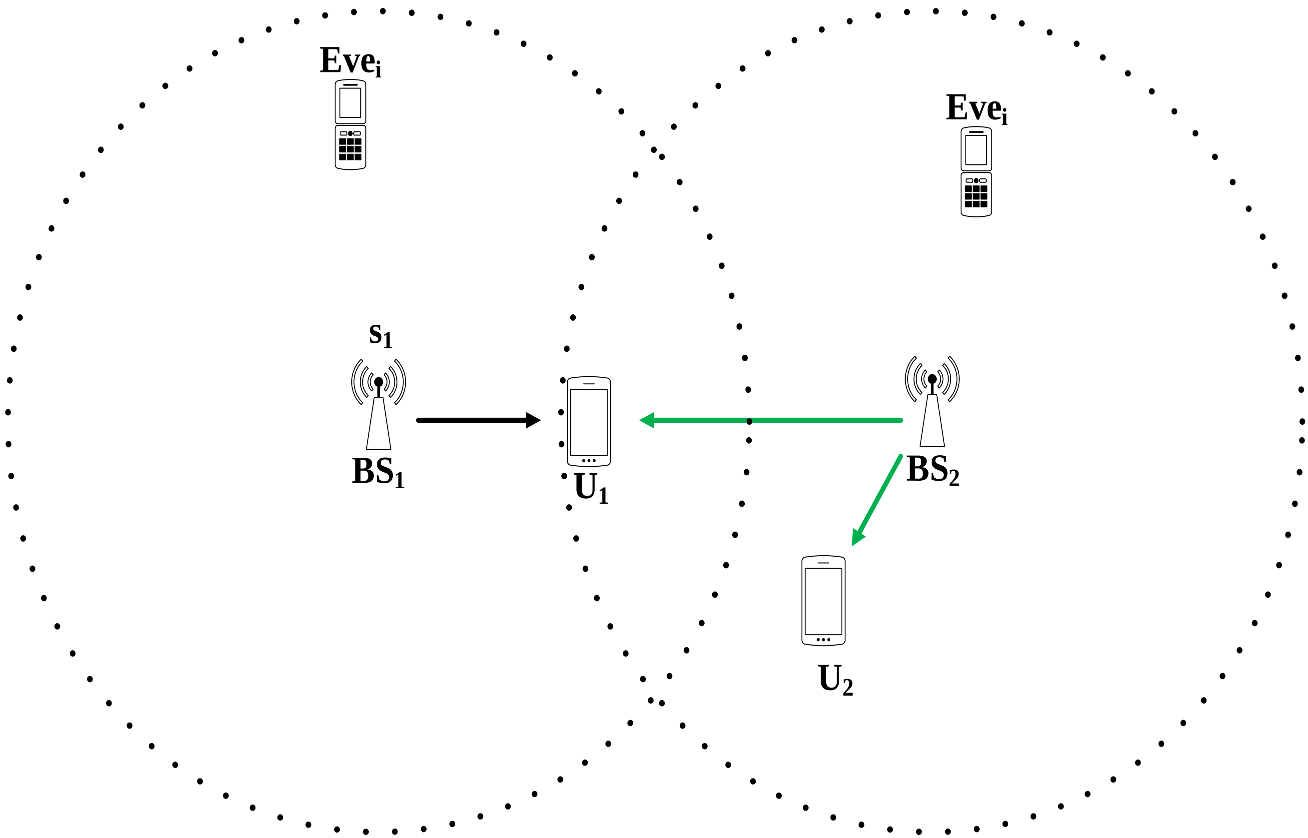
Downlink NOMA



Uplink NOMA

Introduction

- The basic idea of our **Hybrid Uplink-Downlink NOMA (HUD-NOMA)**
  - Downlink NOMA
    - Help U_1 and provide service to U_2
  - Uplink NOMA
    - Save time slots



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- **Hybrid Uplink-Downlink NOMA**
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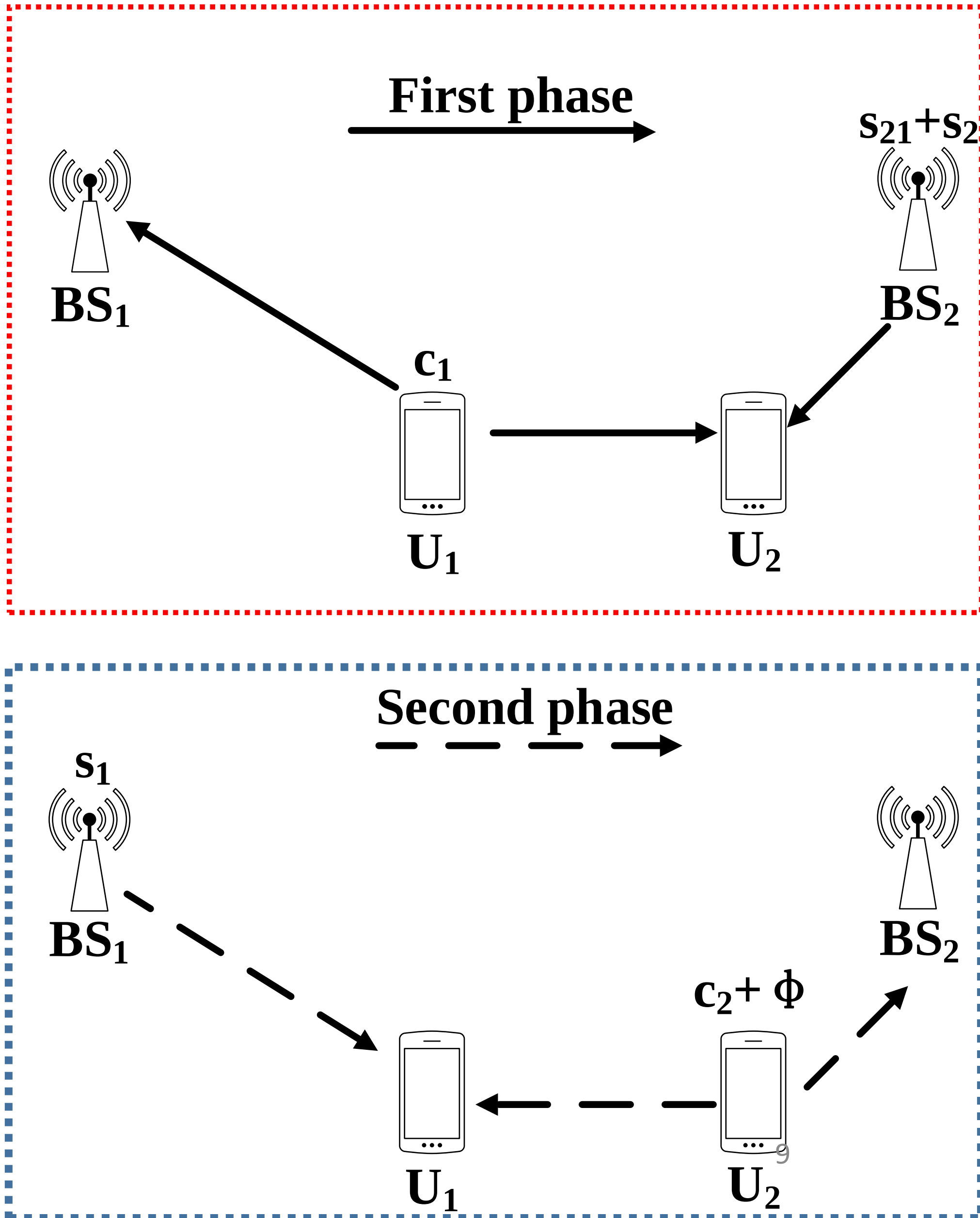
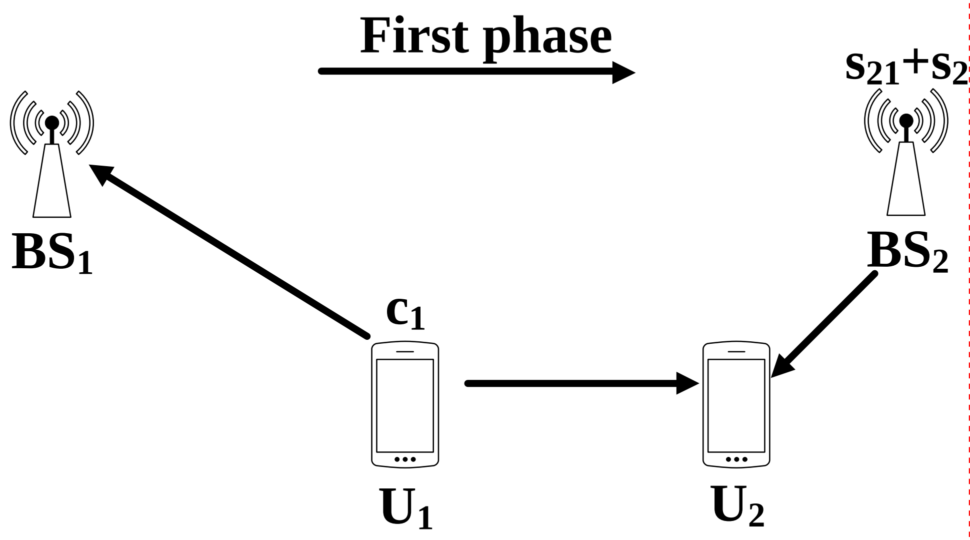
Hybrid Uplink-Downlink NOMA

- System model
  - U_1 is a cell-edge user served by BS_1
  - U_2 is not a cell-edge user served by BS_2
  - A network controller coordinate all the nodes
  - All nodes with single antenna
  - Joint transmission includes two phases
- The first phase
  - U_1 broadcasts its uplink signal c_1
  - BS_2 broadcasts the downlink signal s_{21} of U_1, and the downlink signal s_2 of U_2
- The second phase
  - BS_1 broadcasts the downlink signal of U_1
  - U_2 broadcasts its uplink signal c_2, and $\phi = s_{21} \oplus c_1$, where $\oplus$ is XOR operation in network coding.



Hybrid Uplink-Downlink NOMA



- The received signal in the first phase

$$y_{BS_1} = h_{U_1,BS_1}\sqrt{Q_1}c_1 + n_{BS_1}$$

$$y_{U_2} = h_{BS_2,U_2}(\sqrt{P_2}s_2 + \sqrt{P_{21}}s_{21}) + h_{U_1,U_2}\sqrt{Q_1}c_1 + n_{U_2}$$

- SINR in the first phase
  - At BS_1: $SINR_{c_1}^{BS_1} = \frac{Q_1|h_{U_1,BS_1}|^2}{\sigma^2}$
  - At U_2:
    - W.l.o.g., assume $Q_1|h_{U_1,U_2}|^2 > P_2|h_{BS_2,U_2}|^2 > P_{21}|h_{BS_2,U_2}|^2$
    - Decode c_1, s_2, s_{21} in order

$$SINR_{c_1}^{U_2} = \frac{Q_1|h_{U_1,U_2}|^2}{(P_{21}+P_2)|h_{BS_2,U_2}|^2+\sigma^2},$$

$$SINR_{s_2}^{U_2} = \frac{P_2|h_{BS_2,U_2}|^2}{P_{21}|h_{BS_2,U_2}|^2+\sigma^2},$$

$$SINR_{s_{21}}^{U_2} = \frac{P_{21}|h_{BS_2,U_2}|^2}{\sigma^2}.$$

Hybrid Uplink-Downlink NOMA

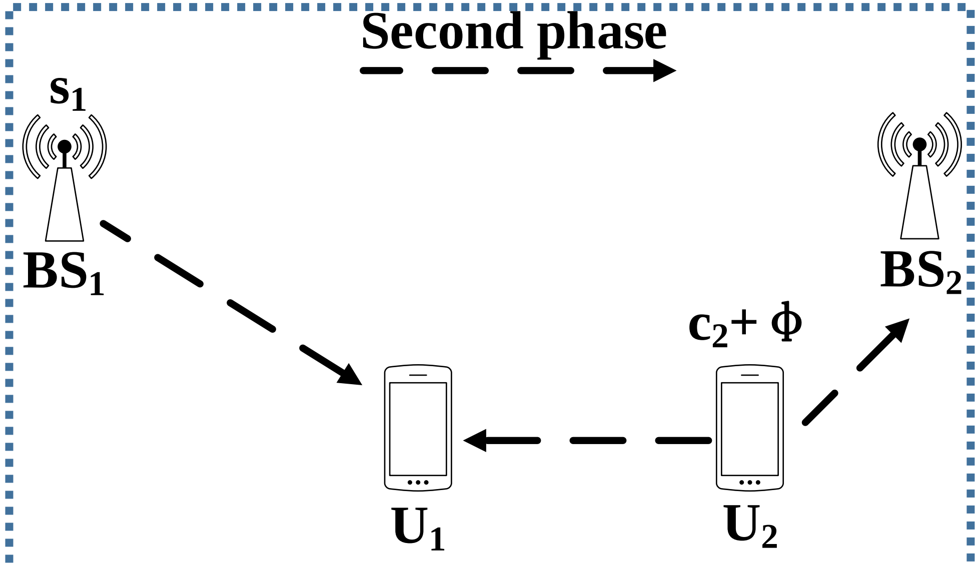
- The received signal in the second phase

$$y_{BS_2} = h_{BS_2,U_2}(\sqrt{Q_2}c_2 + \sqrt{Q_\phi}\phi) + n_{BS_2},$$
$$y_{U_1} = h_{U_1,U_2}(\sqrt{Q_2}c_2 + \sqrt{Q_\phi}\phi) + h_{U_1,BS_1}\sqrt{P_1}s_1 + n_{U_1}$$

- SINR in the second phase
  - At BS_2: assume $Q_2 > Q_\phi$

$$SINR_{c_2}^{BS_2} = \frac{Q_2|h_{BS_2,U_2}|^2}{Q_\phi|h_{BS_2,U_2}|^2 + \sigma^2},$$
$$SINR_{\phi}^{BS_2} = \frac{Q_\phi|h_{BS_2,U_2}|^2}{\sigma^2}.$$

  - At U_1:
    - W.l.o.g., assume
      $P_1|h_{U_1,BS_1}|^2 > Q_2|h_{U_1,U_2}|^2 > Q_\phi|h_{U_1,U_2}|^2$
    - Decode s_1, c_2, and ϕ in order



$$\phi = s_{21} \oplus c_1$$
$$s_{21} = c_1 \oplus \phi = c_1 \oplus s_{21} \oplus c_1$$

$$SINR_{s_1}^{U_1} = \frac{P_1|h_{U_1,BS_1}|^2}{(Q_2 + Q_\phi)|h_{U_1,U_2}|^2 + \sigma^2},$$
$$SINR_{c_2}^{U_1} = \frac{Q_2|h_{U_1,U_2}|^2}{Q_\phi|h_{U_1,U_2}|^2 + \sigma^2},$$
$$SINR_{\phi}^{U_1} = \frac{Q_\phi|h_{U_1,U_2}|^2}{\sigma^2}.$$

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- **Secrecy Analysis**
- Numerical results
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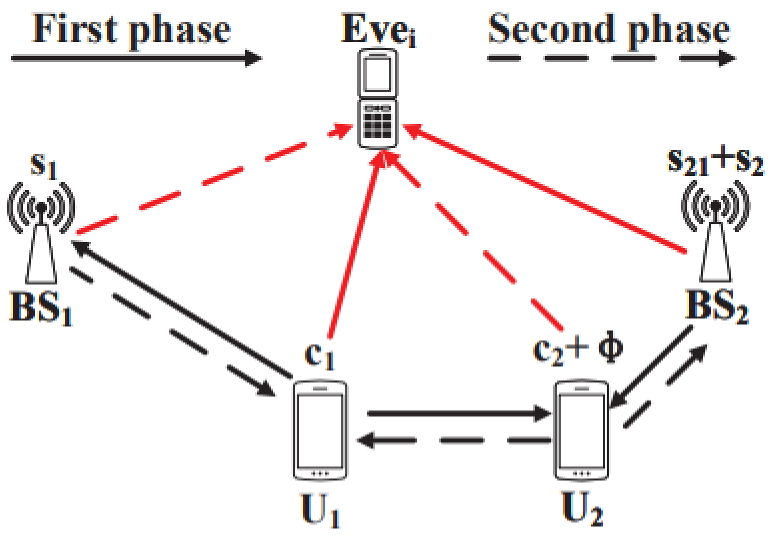
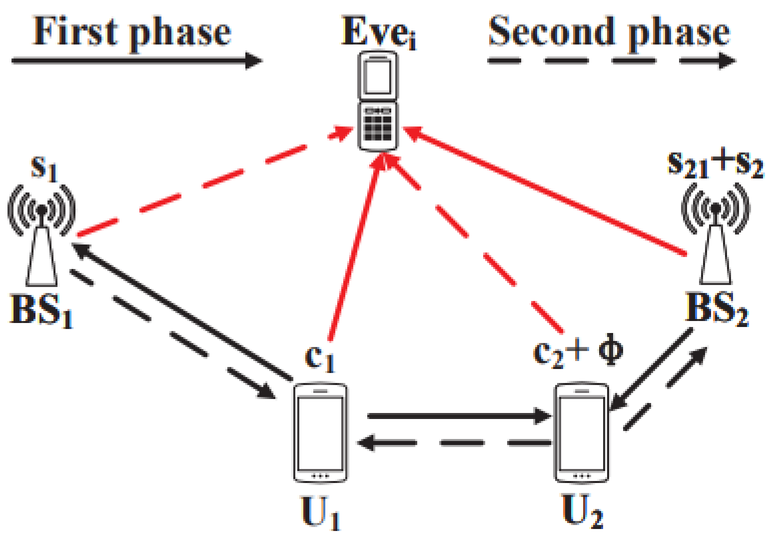
Secrecy Analysis

- Eavesdroppers (Eves)
  - Randomly location
  - Multiple
  - Single antenna
  - Homogeneous Poisson point process (HPPP)
- The received signal at Eve_{i}

$$
\begin{aligned}
y_{Eve_i}^1 =& h_{BS_2,Eve_i}(\sqrt{P_2}s_2 + \sqrt{P_{21}}s_{21}) \\
&+ h_{U_1,Eve_i}\sqrt{Q_1}c_1 + n_{Eve_i}, \\
y_{Eve_i}^2 =& h_{Eve_i,U_2}(\sqrt{Q_2}c_2 + \sqrt{Q_\phi}\phi) \\
&+ h_{Eve_i,BS_1}\sqrt{P_1}s_1 + n_{Eve_i},
\end{aligned}
$$



Secrecy Analysis



- **Definition of secrecy outage**

Definition 1. *During each transmission, Eves may receive many signals. If any useful signal is decoded by Eves, then the secure transmission is interrupted, i.e., secrecy outage.*

- **Secrecy Outage Probability**
  - The achievable secrecy rate of a legitimate user can be given by

$$R_s = \max\{R_b - R_e, 0\}$$

where $R_b = \log(1 + SINR_b)$ and $R_e = \log(1 + SINR_e)$

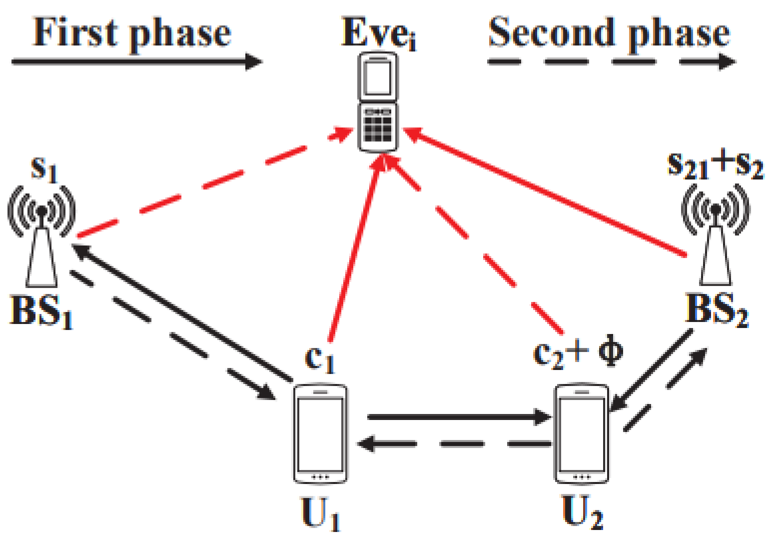
  - Given a target secrecy rate R_{th}, SOP

$$\varepsilon = Pr\{R_s < R_{th}\} = Pr\{SINR_e > 2^{R_{th}+R_b} - 1\}.$$

  - When multiple Eves,

$$\varepsilon = Pr\{\max_{e\in\psi} SINR_e > 2^{R_b+R_{th}} - 1\}.$$

Secrecy Analysis



- The received signal at Eve$_i$

$$\begin{aligned} y^1_{Eve_i} =& h_{BS_2,Eve_i}(\sqrt{P_2}s_2 + \sqrt{P_{21}}s_{21}) \\ &+ h_{U_1,Eve_i}\sqrt{Q_1}c_1 + n_{Eve_i}, \\ y^2_{Eve_i} =& h_{Eve_i,U_2}(\sqrt{Q_2}c_2 + \sqrt{Q_\phi}\phi) \\ &+ h_{Eve_i,BS_1}\sqrt{P_1}s_1 + n_{Eve_i}, \end{aligned}$$

- SINR at Eve$_i$
  - The first phase
    - Recall the previous assumption that

      $$Q_1|h_{U_1,U_2}|^2 > P_2|h_{BS_2,U_2}|^2 > P_{21}|h_{BS_2,U_2}|^2$$

    - First to decode s_2 and first to decode c_1

$$SINR^{Eve_i}_{s_2} = \frac{P_2|h_{BS_2,Eve_i}|^2}{P_{21}|h_{BS_2,Eve_i}|^2 + Q_1|h_{U_1,Eve_i}|^2 + \sigma^2}$$

$$SINR^{Eve_i}_{c_1} = \frac{Q_1|h_{U_1,Eve_i}|^2}{(P_{21} + P_2)|h_{BS_2,Eve_i}|^2 + \sigma^2}$$

  - The second phase
    - First to decode s_1 and first to decode c_2

$$SINR^{Eve_i}_{s_1} = \frac{P_1|h_{Eve_i,BS_1}|^2}{(Q_2 + Q_\phi)|h_{Eve_i,U_2}|^2 + \sigma^2}$$

$$SINR^{Eve_i}_{c_2} = \frac{Q_2|h_{Eve_i,U_2}|^2}{Q_\phi|h_{Eve_i,U_2}|^2 + P_1|h_{Eve_i,BS_1}|^2 + \sigma^2}$$

Secrecy Analysis

- SOP Analysis
  - Channel model

$$h_{i,j} = g_{i,j}\sqrt{\eta\|\mathbf{L}_i - \mathbf{L}_j\|^{-\alpha}},$$

  - HPPP with density λ
  - The first phase

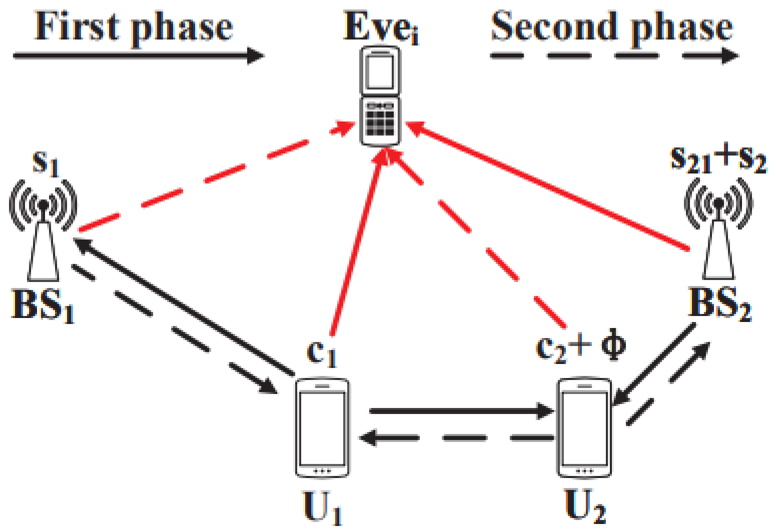
Theorem 1. *Given the maximum acceptable SINR for s_2 and c_1 at Eves, $\mu_{s_2} = 2^{R_{th}+log(1+SINR_{s_2}^{U_2})} - 1$ and $\mu_{c_1} = \max\{2^{R_{th}+log(1+SINR_{c_1}^{U_2})}-1, 2^{R_{th}+log(1+SINR_{c_1}^{BS_1})}-1\}$, the exact expression of the SOP at the first phase is given by*

$$\varepsilon_1 = 1 - (1-\varepsilon_{s_2})(1-\varepsilon_{c_1}), \tag{24}$$

  - The second phase

Theorem 2. *Given the maximum acceptable SINR for s_1 and c_2 at Eves, $\mu_{s_1} = 2^{R_{th}+log(1+SINR_{s_1}^{U_1})} - 1$ and $\mu_{c_2} = \max\{2^{R_{th}+log(1+SINR_{c_2}^{U_1})}-1, 2^{R_{th}+log(1+SINR_{c_2}^{BS_2})}-1\}$, the exact expression of the SOP at the second phase is given by*

$$\varepsilon_2 = 1 - (1-\varepsilon_{s_1})(1-\varepsilon_{c_2}), \tag{26}$$



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Numerical results

- Conventional OMA is compared.
- The thermal noise power to −170 dBm/Hz.
- The carrier frequency is $f_c = 2.4$ GHz.
- $P_{max} = 1$ W and $Q_{max} = 0.5$ W are the maximum transmit power of the base stations and the users.
- $\alpha = 3$, $R = 1000$ m, $\lambda = 10^{-6}$ /m^2 , $R_{th} = 1$ bit/s/Hz, $P_1 = P_{max}$, $P_2 = 0.9P_{max}$, $P_{21} = 0.1P_{max}$, $Q_1 = Q_{max}$, $Q_2 = 0.9Q_{max}$, and $Q_\phi = 0.1Q_{max}$.
- 10^5 independent Monte Carlo trials.

Numerical results

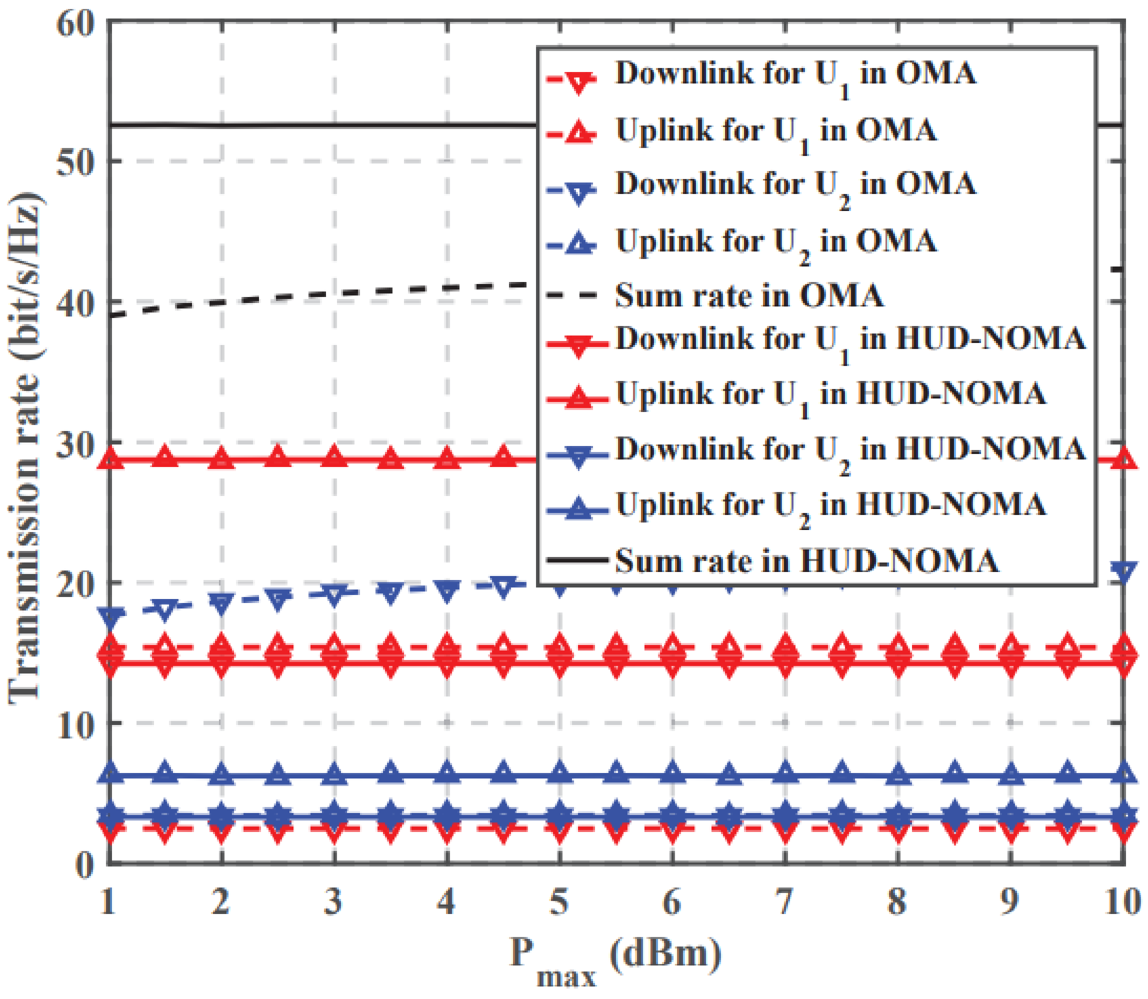

Fig. 2: Transmission rates v.s. $P_{\mathtt{max}}$.

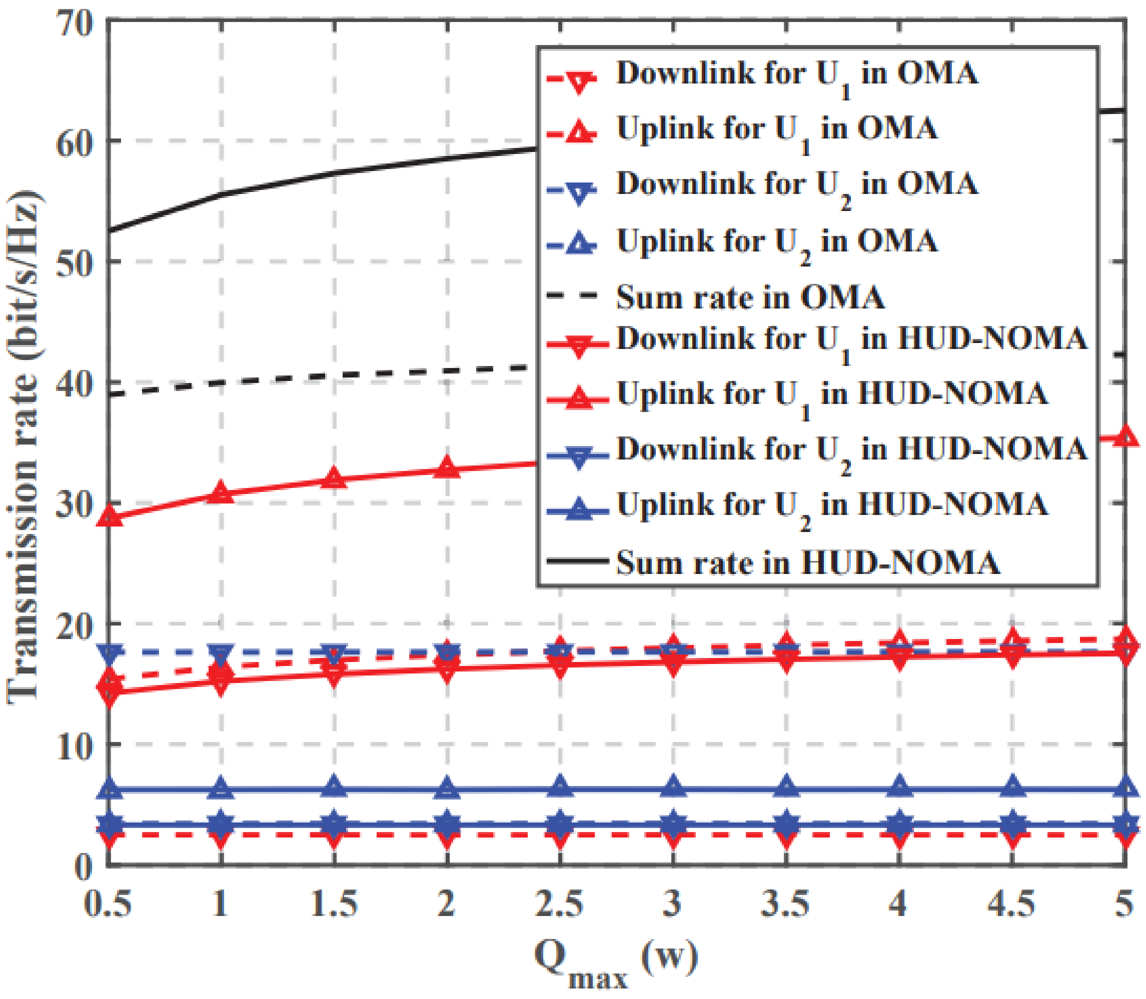

Fig. 3: Transmission rates v.s. $Q_{\mathtt{max}}$.

Numerical results

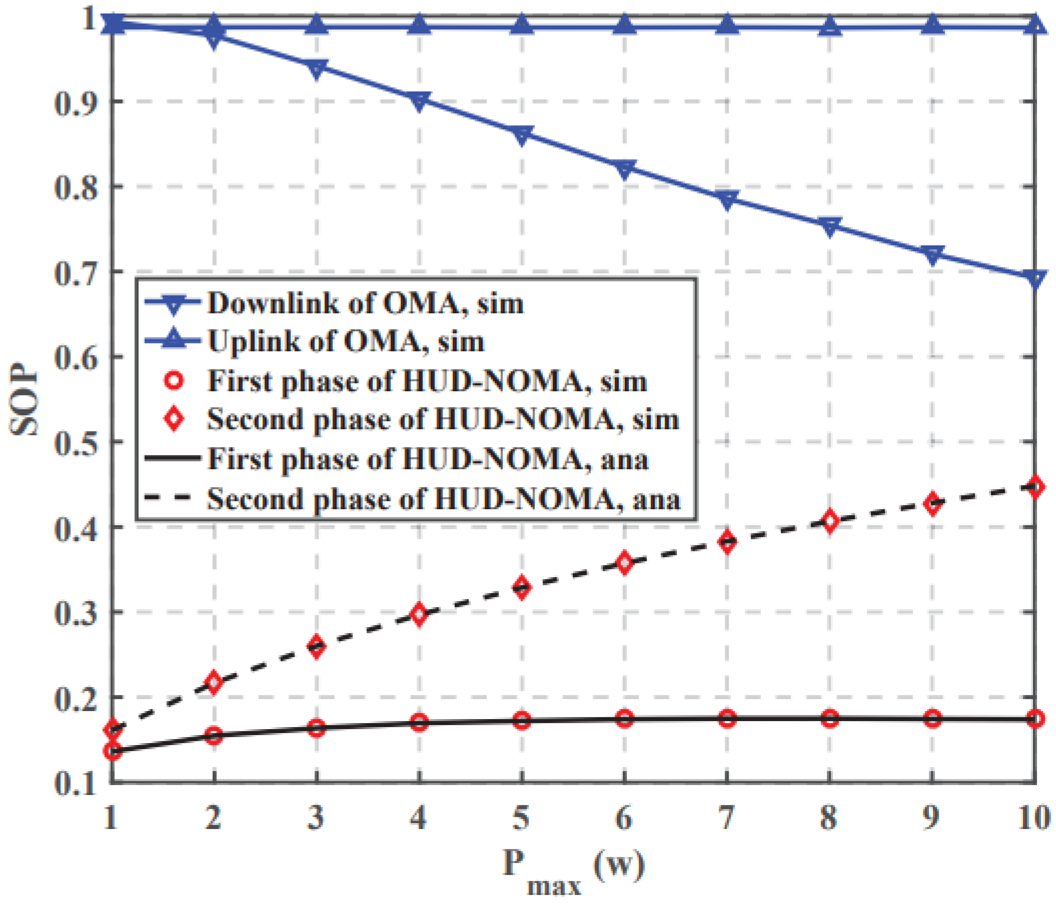

Fig. 5: SOP *v.s.* $P_{\mathtt{max}}$.

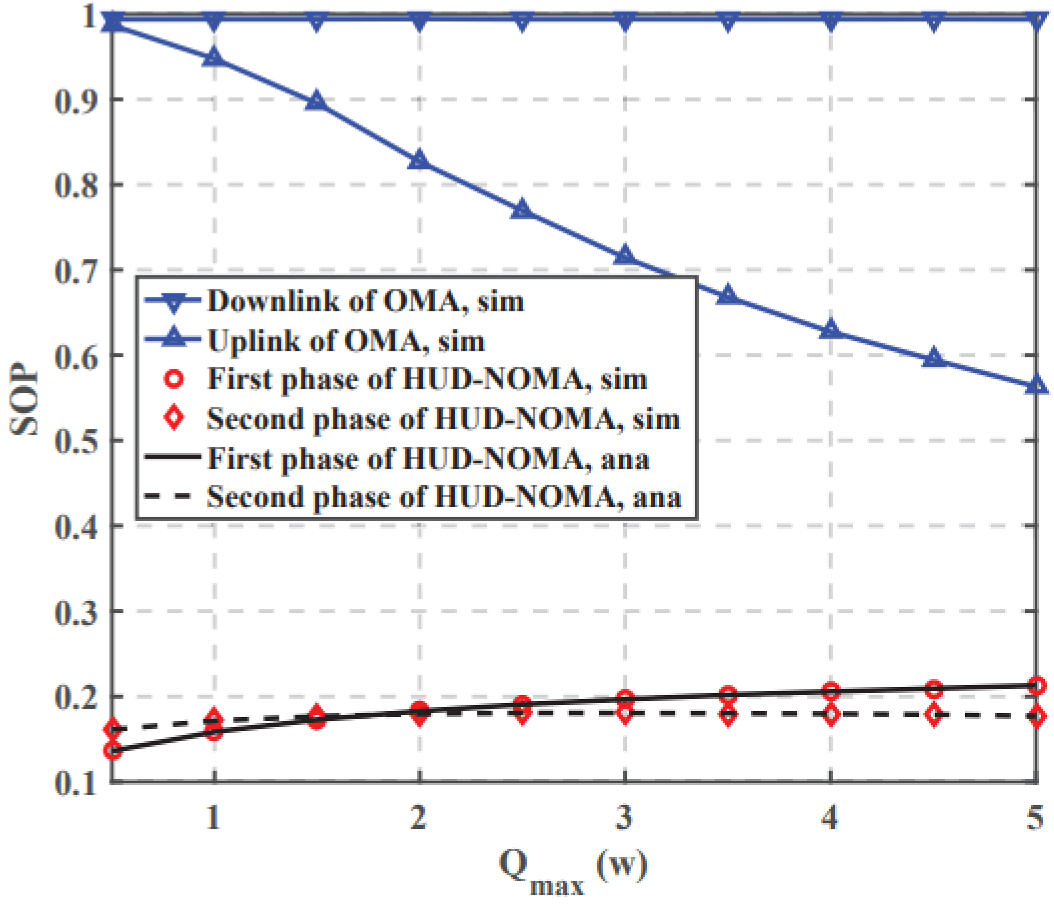

Fig. 6: SOP *v.s.* $Q_{\mathtt{max}}$.

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Conclusion

- We propose a secure HUD-NOMA scheme for CoMP networks in the presence of multiple random located passive eavesdroppers.
- By using NOMA and network coding technologies, the proposed HUD-NOMA scheme not only improve the transmission rate of cell-edge users, but also enhance the secrecy rate of the system.
- It may be a promising direction to promote our scheme to multi-antenna scenarios.

THANK YOU

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