Wireless Powered Cooperative Relaying using NOMA with Imperfect CSI

Dinh-Thuan Do, Mojtaba Vaezi,
and Thanh-Luan Nguyen

Thursday, December 13, 2018
Globecom 2018

CONTENTS

INTRODUCTION

- **Non-Orthogonal Multiple Access (NOMA)**
  - *A key role for high data rate transmission and massive connectivity.*
  - *Improving spectral efficiency and increasing number of connections.*
- **Energy Harvesting (EH)**
  - *Prolong the lifetime of energy-constrained nodes by allowing wireless nodes to recharge their batteries from the radio frequency signals.*
- **Simultaneous Wireless Information and Power Transfer (SWIPT)**
  - *Enabling transmission of both power and information at the same time.*
- **Imperfect Channel State Information (CSI)**
  - *The performance of NOMA highly depends on the quality of CSI, thus the analysis of NOMA networks with imperfect CSI is important.*

SYSTEM MODEL

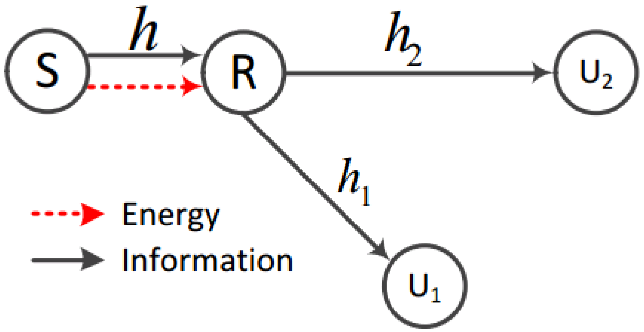
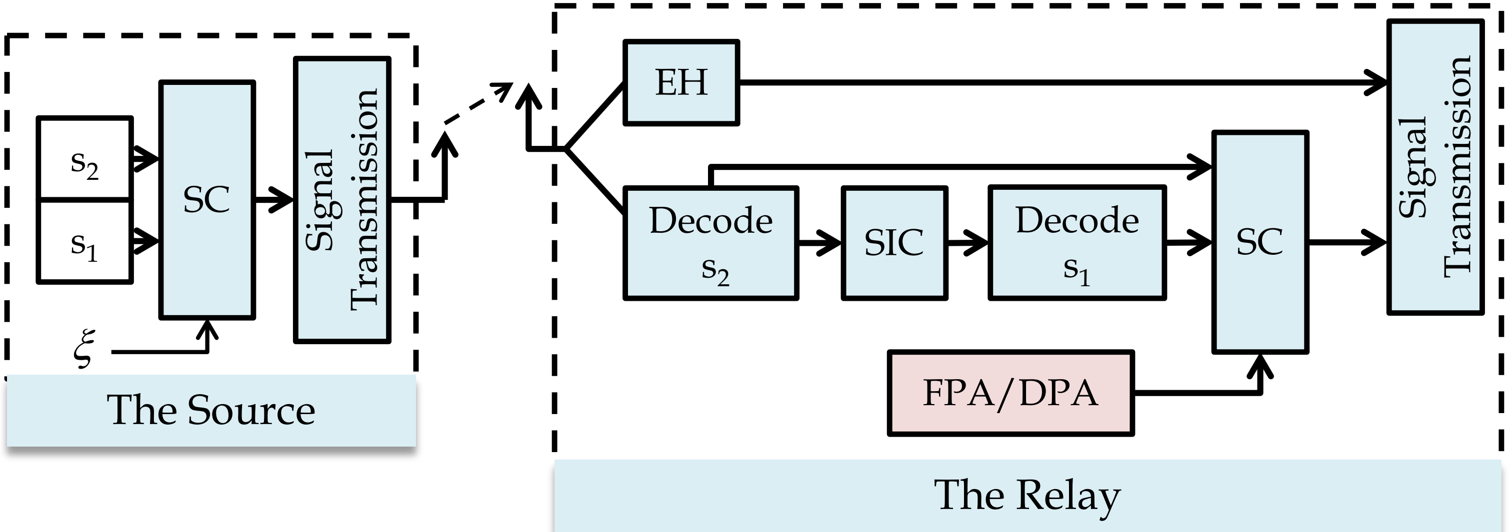


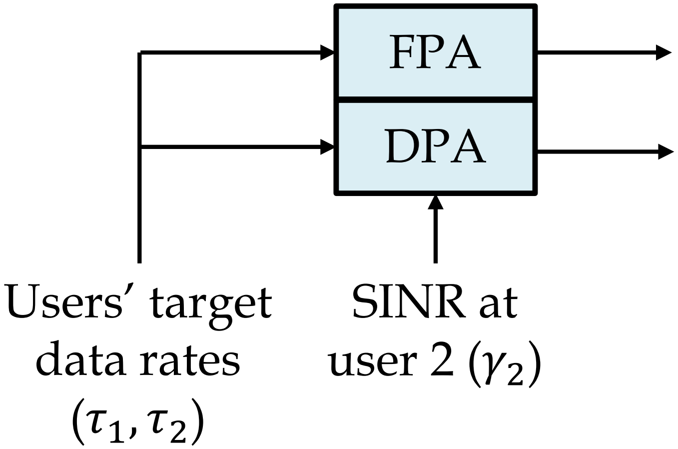
Fig. 1. *A cooperative EH-NOMA consisting of a source (S) with two users (U_1 and U_2) simultaneously through an intermediate EH relay (R). Both S and R use NOMA for transmission.*



- Superposition Coding (SC)
- Successive Interference Cancellation (SIC)

SYSTEM MODEL

FPA vs. DPA at the Relay



FPA

DPA

Users' target data rates (τ_1, τ_2)

SINR at user 2 (γ_2)

δ satisfying: $\delta > \frac{\tau_2}{\tau_2+1}$.

δ satisfying: $\gamma_2 = \tau_2$ or

$$\delta = 1 - \max\left\{0, \frac{P' g_2 - \tau_2\left(\sigma_e^2 P' + 1\right)}{\left(1+\tau_2\right) P' g_2}\right\} \quad (1)$$

Fixed Power Allocation (DPA): power allocation coefficients $(\delta, 1-\delta)$ **are manually chosen** with respect to τ_1 and/or τ_2.

Dynamic Power Allocation (DPA): the power allocation coefficients **are dynamically varied** to ensure signal detection at the weaker user (user 2).

***Note**: Choosing δ larger than that in (1) will result in a better performance at user 2, but a higher outage at user 1.*

SYSTEM MODEL

Channel Model

	source-relay	relay-user	Complexity in Analysis
FPA	+ perfect CSI + Nakagami-m fading	+ imperfect CSI + Rayleigh fading	Normal
DPA	+ perfect CSI + Rayleigh fading	+ imperfect CSI + Rayleigh fading	High

- For FPA case, we assume a *Nakagami-m fading* at the source-relay link to provide a more general insight.
- For the DPA case, we let m = 1 (*Rayleigh fading*) to avoid extreme mathematical complexity.

SYSTEM MODEL

Channel Model

	Rayleigh fading	Nakagami-m fading	Perfect CSI	Imperfect CSI	FPA	DPA
Complexity in Analysis	Low	High	Low	High	Low	High

- The base statin (BS) can adopt complicated strategies (e.g., relay selection) to ensure *perfect CSI* of the source-relay link.
- Adopting *Nakagami-m fading* to *DPA* could lead to very complicated results.
- The relay may have line-of-sight (LoS) with the BS, thus *Nakagami-m fading* is more preferable in modeling source-relay link.

SYSTEM MODEL

- Maximum transmit power ensuring signal decoding at the relay [1]

$$P' = \frac{P_r}{\sigma^2} = \eta(Pg - \tau_0), \quad g > \frac{\tau_0}{P}.$$

- Signal-to-interference-plus-noise ratio (SINR) at user 1 before and after SIC

$$\gamma_{1/2} = \frac{\delta P' g_1}{\left(1-\delta\right) P' g_1 + \sigma_e^2 P' + 1}, \ \gamma_1 = \frac{\left(1-\delta\right) P' g_1}{P' \sigma_e^2 + 1}.$$

The SINR at user 2 to decode its own signal

$$\gamma_2 = \frac{\delta P' g_2}{\left(1-\delta\right) P' g_2 + P' \sigma_e^2 + 1}.$$

SYSTEM MODEL

Outage Probability

Outage Probability provide information about how well can the system meet the predefined quality-of-service (QoS), especially in delay-sensitive networks, where information is transmit at a fixed rate.

The outage probability at an user is defined as the probability

At user 1:

1) the relay fails to decode user 1's or user 2's information signal, or
2) user 1 fails to decode user 2's signal or its own signal after SIC.

At user 2:

1) the relay fails to decode user 1's or user 2's information signal, or
2) user 2 fails to decode its own signal.

FIXED POWER ALLOCATION

Lemma 1. *For the FPA case, the outage probability of user 1 when* $\delta > \frac{\tau_2}{\tau_2+1}$ *can be expressed as*

$$p_{\mathrm{F}}^{(1)} = 1 - \sum_{i=0}^{m-1} \binom{m-1}{i} e^{-\frac{\tau_0 m}{d^{-\alpha} P}} \left(\frac{\tau_0 m}{d^{-\alpha} P} \right)^{m-i-1}$$

$$\times \sum_{k=1}^{3} \frac{(-1)^{k-1}}{2^i \Gamma(m)} e^{-\frac{\Phi_{\mathrm{n1}}}{\Omega_k}} \beta_{n,k}^{i+1} K_{i+1}\left(\beta_{n,k}\right),$$

in which $K_v(z)$ *is the* v^{th} *order Bessel function of the second kind,* $\beta_{n,k} = 2\sqrt{\frac{m}{d^{-\alpha} P} \frac{\Phi_{\mathrm{n2}}}{\Omega_k}}$ *in which*

$$\begin{bmatrix} \Phi_{11} & \Phi_{12} \\ \Phi_{21} & \Phi_{22} \end{bmatrix} \square \begin{bmatrix} \frac{\tau_2}{\delta(\tau_2+1)-\tau_2} & \frac{\tau_1}{1-\delta} \end{bmatrix}^T \begin{bmatrix} \sigma_e^2 & \frac{1}{\eta} \end{bmatrix},$$

$\Omega_1 = d_2^{-\alpha} + \sigma_e^2$, $\Omega_2 = \frac{\Omega_1 \Omega_3}{\Omega_1 + \Omega_3}$ *and* $\Omega_3 = d_1^{-\alpha} + \sigma_e^2$. *Also note that* $p_{\mathrm{F}}^{(1)} = 0$ *when* $\delta \le \frac{\tau_2}{\tau_2+1}$.

FIXED POWER ALLOCATION

Diversity Order

The diversity order as a function of the outage probability at each user is given as

$$D_{\mathrm{F}}^{(n)} = -\lim_{P\to\infty} \frac{\log p_{\mathrm{F}}^{(n)}}{\log P}$$

Through calculation we found that zero diversity order is obtained at both users, thus increasing the transmit power at the source in the high SNR regime may not affect the outage performance at all users.

DYNAMIC POWER ALLOCATION

Lemma 2. *For the DPA case, the outage probability of user 1 is given*

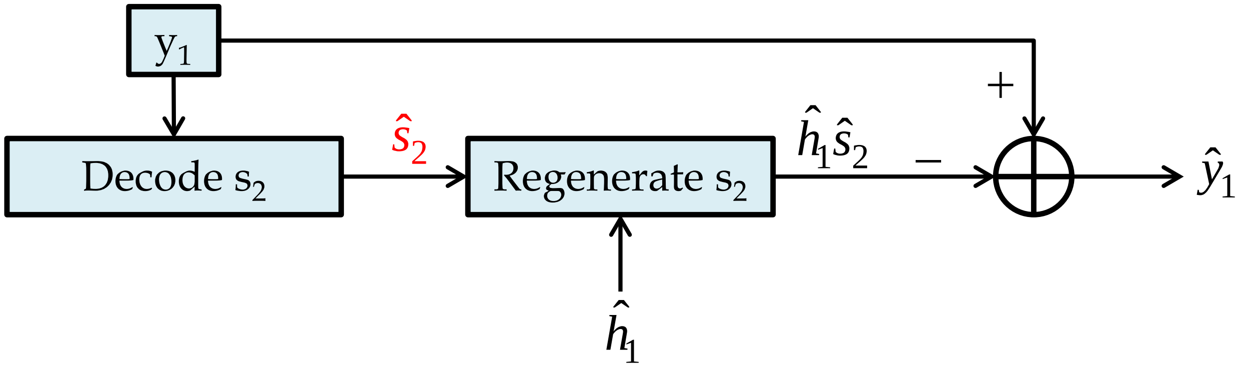
$$p_{\mathrm{D}}^{(1)} = 1 - e^{-\sigma_e^2 \frac{\tau_0}{\Omega_2} - \frac{\tau_0 d^{\alpha}}{P}} \omega_0 K_1(\omega_0) - \Upsilon_{\mathrm{II}},$$

in which Υ_{II} *is defined in (B-3) and* $\omega_\ell = 2\sqrt{\frac{1}{\eta P d^{-\alpha}} \frac{\tau_\ell}{\Omega_2}}$, $\ell \in \{0, 2\}$.

Further, the outage probability for user 2 is given by

$$p_{\mathrm{D}}^{(2)} = 1 - e^{-\sigma_e^2 \frac{\tau_2}{\Omega_2} - \frac{d^{\alpha} \tau_0}{P}} \omega_2 K_1(\omega_2).$$

THE EFFECT OF IMPERFECT SIC



y_1

Decode s_2

$\hat{s}_2$

Regenerate s_2

$\hat{h}_1\hat{s}_2$

$+$

$-$

$\hat{y}_1$

$\hat{h}_1$

- With the imperfect CSI assumption, the received signal at user 1 (i.e. the stronger user) is given by

$$y_1 = \sqrt{P_r}\left(\sqrt{\delta}s_2 + \sqrt{1-\delta}s_1\right)(\hat{h}_1 + e) + n_1$$

- Then the received signal after the imperfect SIC process is given by

$$\hat{y}_1 = \sqrt{P_r(1-\delta)}s_1\hat{h}_1 + \sqrt{P_r\delta}\hat{h}_1(s_2 - \hat{s}_2) + (\sqrt{P_r(1-\delta)}s_1 + \sqrt{P_r\delta}s_2)e + n_1,$$

where $\hat{s}_2$ is the estimated signal of user 2.

THE EFFECT OF IMPERFECT SIC

The outage probability of user 1 and user 2 with imperfect SIC is similar to the perfect SIC case with some substitution as

$$\Lambda_{\max} = \begin{cases} \Phi_{11} + \dfrac{\Phi_{12}}{Pg - \tau_0}, & \dfrac{\tau_2}{\tau_2 + 1} < \delta < \min\left[\dfrac{\tau_0 - \tau_1}{\tau_0 + \tau_1 \tau_2 \sigma_{ic}^2}, \dfrac{1}{\tau_1 \sigma_{ic}^2 + 1} \right] \\ \Phi_{21} + \dfrac{\Phi_{22}}{Pg - \tau_0}, & \dfrac{1}{\tau_1 \sigma_{ic}^2 + 1} > \delta \geq \dfrac{\tau_0 - \tau_1}{\tau_0 + \tau_1 \tau_2 \sigma_{ic}^2} \end{cases},$$

in which

$$\begin{bmatrix} \Phi_{11} & \Phi_{12} \\ \Phi_{21} & \Phi_{22} \end{bmatrix} \triangleq \left[\frac{\tau_2}{\delta(\tau_2 + 1) - \tau_2}, \frac{\tau_1}{1 - \delta(\tau_1 \sigma_{ic}^2 + 1)} \right]^T \left[\sigma_e^2, \frac{1}{\eta} \right].$$

where $\sigma_{ic}^2 \triangleq \mathsf{E}[|s_2 - \hat{s}_2|^2]$ denotes the expected residual power level after SIC, $\sigma_{ic}^2 = 0$ means perfect SIC and otherwise.

** Refer to page 18 for the joint impact of imperfect CSI and imperfect SIC (imperfect signal estimation).*

NUMERICAL RESULTS

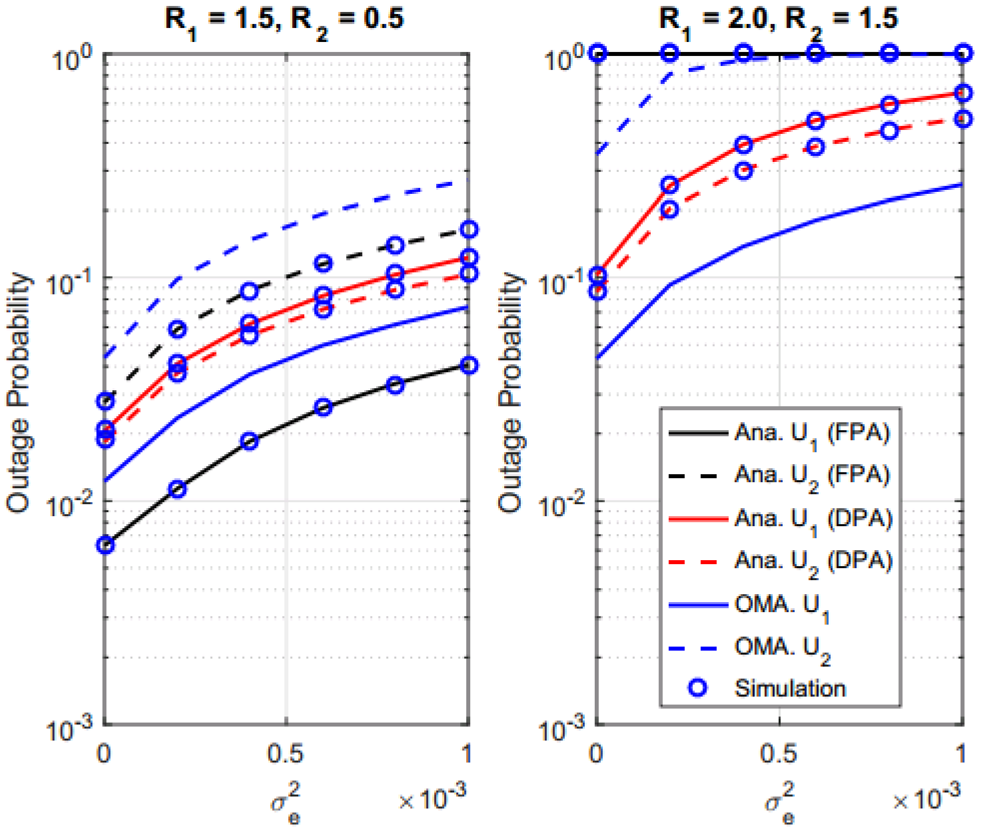


Fig. 2. *Outage probability of FPA-NOMA/DPA-NOMA cases versus* $\sigma_e{}^2$*, where* $P_s = 15$ *dB.*

NUMERICAL RESULTS

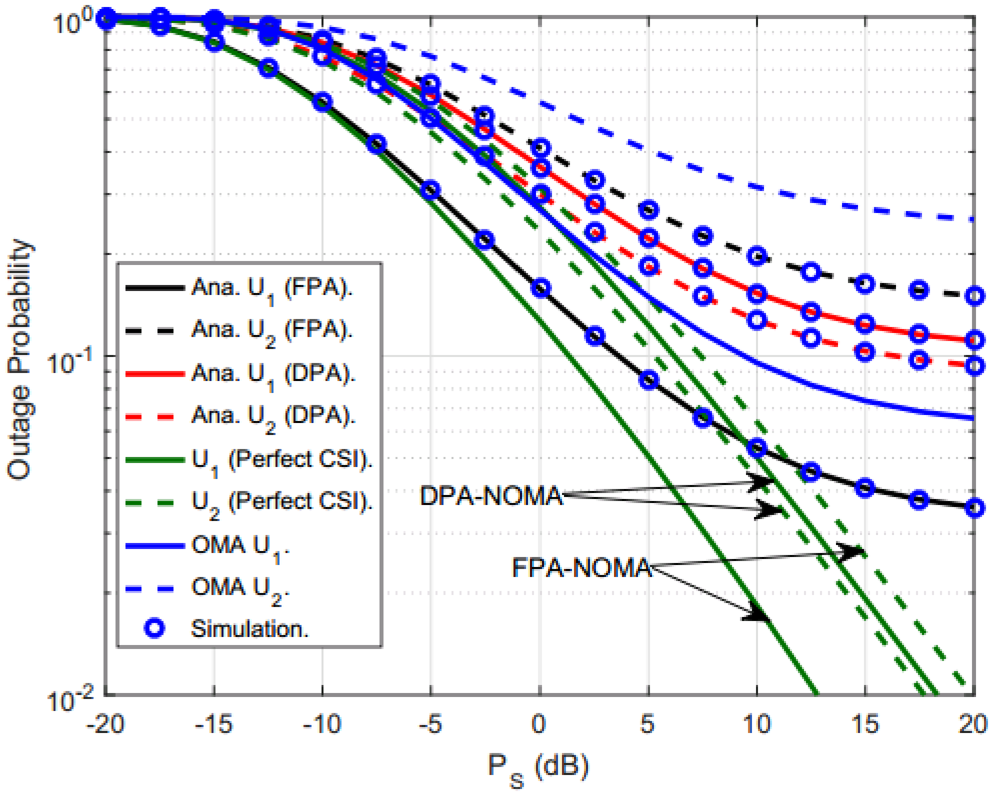


Fig. 3. *Outage probability of FPA-NOMA/DPA-NOMA cases versus* P_s, *where* $R_1 = 1.5$ *and* $\sigma_e^2 = 0.001$.

NUMERICAL RESULTS

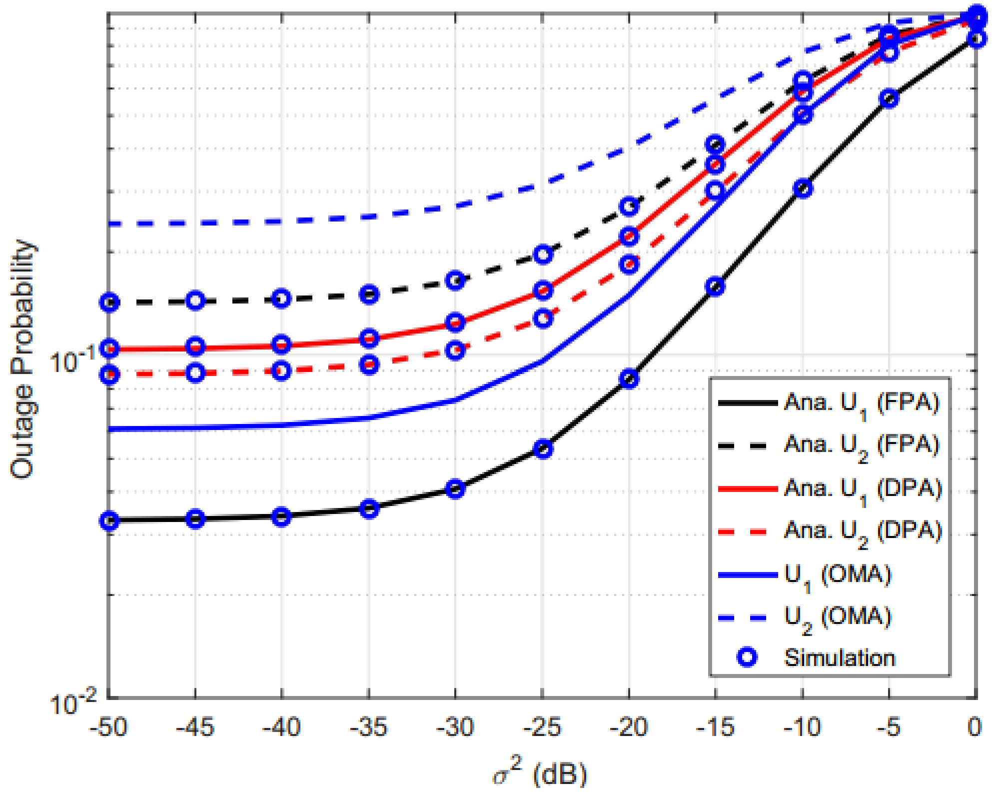


Fig. 4. *Outage probability of FPA-NOMA/DPA-NOMA cases versus versus noise power, where R2 = 0.5, R1 = 1.5,* $\sigma_e^2 = 0.001$ *and* P_s *= 15 dB.*

NUMERICAL RESULTS

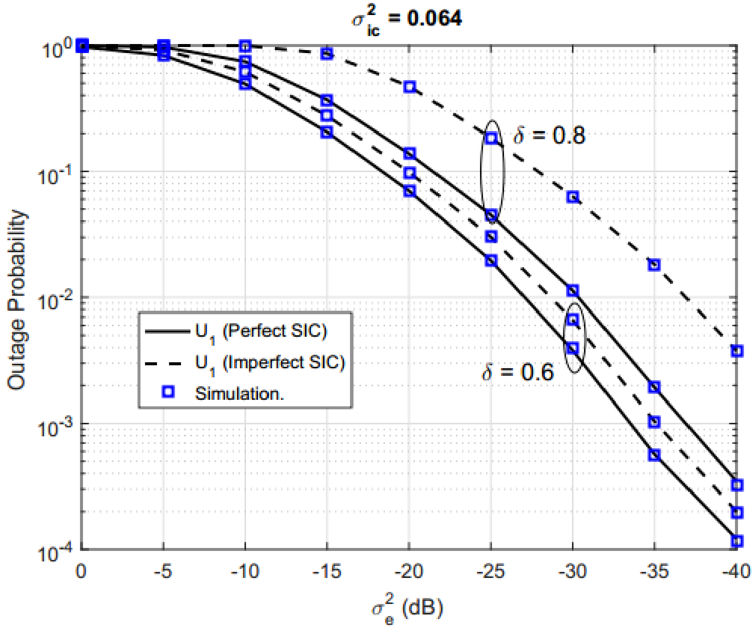


Fig. 5. *Outage probability of FPA-NOMA cases versus σ_e^2, where $R_2 = 0.5$, $R_1 = 1.5$,* $d = d_1 = 1$, $d_2 = 10$ *and* $P_s = 30$ *dB.*

- *Allocating more power for the weak user (user 2) could:*

  + increase the probability the strong user (user 1) successfully decodes user 2's signal, but

  + lead to higher outage with a same value of the expected residual power level after SIC, σ_{ic}^2.

- *Thus, allocating more power for the strong user (user 1) could narrow the gap between perfect and imperfect SIC.*

- *Note that higher channel estimation accuracy could lead to higher degradation in the outage performance with a same expected residual power level after SIC*.*

** In Fig. 5, at $\sigma_e^2 = -40$ dB the outage probability with imperfect SIC is reduced more than 10 times from that with perfect SIC but when $\sigma_e^2 = -20$ dB it only reduces 4 times.*

NUMERICAL RESULTS

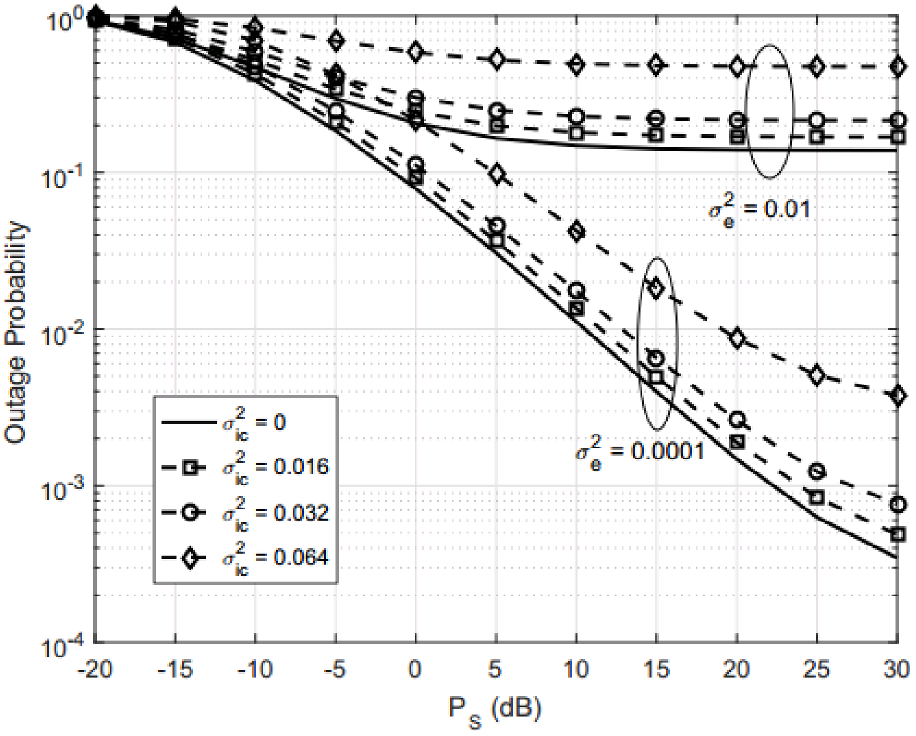


Fig. 6. *Outage probability of FPA-NOMA cases versus* P_s, *where* $R_2 = 0.5$, $R_1 = 1.5$, $d = d_1 = 1$ *and* $d_2 = 10$.

By increasing the transmit power, the outage performance can be improved but reaches different outage floor depending on ${\sigma_{ic}}^2$.

CONCLUSION

- NOMA can improve the outage probability of both users in comparison with OMA.
- FPA-NOMA achieves better performance for user 1 than DPA-NOMA but poor fairness. DPA-NOMA provides a higher success probability for user 2 than FPA-NOMA and a better fairness.
- FPA-NOMA can outperform traditional OMA. DPA-NOMA provide better outage performance for the weaker user.
- Allocating more power for the weak user could lead to higher outage at the other user.
- Higher channel estimation accuracy could lead to higher degradation in the outage performance with a same expected residual power level after SIC.

REFERENCE

[1] Z. Yang, Z. Ding, P. Fan, and N. Al-Dhahir, “The impact of power allocation on cooperative non-orthogonal multiple access networks with SWIPT}” *IEEE Trans. Wireless Commun.*, vol. 16, no. 7, pp. 4332-4343, 2017.

[2] A. Jeffrey and D. Zwillinger, *Table of integrals, series, and products*. Academic press, 2007.

THANK YOU FOR LISTENING