Hardware impairments aware full-duplex non-orthogonal multiple access networks over Nakagami-\(m\) channels

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ABSTRACT

Non-orthogonal multiple access (NOMA) and full-duplex (FD) relaying communications are promising candidates for 5G cellular networks. In this paper, by exploiting the impact of hardware impairment, we study FD NOMA communications with a downlink scheme. In a group of two users, we find that the target rates and power allocation strategies are main factors affecting the system performance metric. We derive the closed-form formula of outage probability for two users. As main contribution, numerical results are considered to illustrate the performance of the FD NOMA. We also study the base station (BS) can adjust its transmit signal to noise ratio (SNR) to achieve relevant outage probability in several scenarios.

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1. INTRODUCTION

As one of promising approach implemented in 5G systems, non-orthogonal multiple access (NOMA) was introduced [1]. To provide massive connections, NOMA can rely on this first main benefit to further serve services with high spectral efficiency and low latency. Those advances are urgent requirements to design new generation of 5G and beyond wireless systems [2]. In NOMA, the multiple users can be shared same frequency but different power levels are assigned to each user effectively. The signal detection technique is required at receiver to extract information exactly with low error. How NOMA treats far users and near users to assign power levels. Fortunately, by detecting the channel gains of different channels, suitable power coefficients are assigned to users reasonably [3]–[5]. As interesting application of NOMA techniques, half-duplex relay stations (RSs) have been studied in order to increase spatial diversity [6]–[14]. The benefit of relay can be reported in [8], [10], and [11], since single relay is placed between transmitters and receivers. Nakagami-\(m\) fading channels [8] and Rayleigh fading channels [11] are popular channel models deployed in the NOMA system relying on a single amplify-and-forward (AF) relay, which outperform the orthogonal multiple access (OMA) in terms of two system performance metrics (outage probability and throughput). Kader et al. in [10] developed a network containing two sources, two destinations, and a relay to form the cooperative NOMA with a half-duplex decode-and-forward (DF). They examined perfect and imperfect successive interference cancellation (SIC) when they evaluated ergodic sum capacity.

As simpler approach, Liang et al. and Xu et al. in [14], [15] studied half-duplex (HD) relay-based NOMA systems. Due to the requirement of additional time resources, HD NOMA just provides low spec-
tral efficiency. Different from HD NOMA, full-duplex (FD) relay-based NOMA deploys the same frequency channel to permit the relay to simultaneously receive and transmit signals and reduce such loss [16]–[19]. The operation of FD benefits from advances of antenna isolation and cancellation of analog self-interference (SI) at the FD relay. FD device-to-device assisted cooperative NOMA system was investigated [20] in which the near user needs the FD relay to support transmission to the far user. Deng et al. [21] adopted Rician fading channels for FD NOMA system by evaluating formulas of the outage probability and the ergodic rate under imperfect conditions such as imperfect SIC and residual hardware impairments at transceivers [22] considered the impact of imperfect SIC and residual inter-relay interference on a DF relaying based NOMA. The authors developed for the considered framework over generalized Nakagami-m fading channels by evaluating outage probability (OP), asymptotic OP, and ergodic rate. The work in [23] studied downlink NOMA short-packet communication systems the average block error rate (BLER) by using stochastic geometry and Nakagami-m fading channels. A few work consider FD at relay for NOMA, for example [24], which motives us to study difference among two destinations under the impact of hardware impairments.

2. SYSTEM MODEL

A dual-hop NOMA transmission with the help of a FD relay (R) is studied, shown in Figure 1. The system model could be examined in the case of a base station (B) serves a dedicated group of two NOMA users. In particular, we design a FD relay (R) which is intermediate device while two NOMA users including D1 and D2. Those users are classified based on channel gains to determine the near and the far users. The FD relay is equipped two antennas to transmit and receive signals simultaneously. To provide general channel model, all the channels are assumed as Nakagami-m channels. We treat power coefficients \( \varepsilon_1, \varepsilon_2 \) to help the base station B serving dedicated group of users and satisfying strict constraints \( \varepsilon_1 + \varepsilon_2 = 1 \) and \( \varepsilon_1 > \varepsilon_2 \).

The transmit signal processed at the base station B is \( \sqrt{\varepsilon_1 P_B} x_1 + \sqrt{\varepsilon_2 P_B} x_2 \), in which \( P_B \) is the total transmitted power of B; \( x_1, x_2 \) are denoted as signals of D1, D2.

The transmit signal from the base station is then processed at the FD relay. It is worth noting that FD relay produces \( x_g \) as the loop self-interference which is expected to eliminate. In particular, we can compute the received signal at the relay as:

\[
y_R = g_0 (y_B + \eta_0) + g_f \xi (\sqrt{P_R} x_g + \eta_R) + \eta_0, \tag{1}
\]

where \( g_0, g_f \) are the channel coefficients of B \( \rightarrow \) R and R \( \rightarrow \) R links. \( \xi \) is denoted for HD/FD modes, i.e. \( \xi = 0 \) and \( \xi = 1 \) are known as HD and FD modes respectively. \( \eta_B \sim \Gamma \left( 0, \kappa_{BR}^2 P_B |g_0|^2 \right) \), \( \eta_R \sim \Gamma \left( 0, \kappa_{gR}^2 P_R |g_f|^2 \right) \), \( \eta_{D_1} \sim \Gamma \left( 0, \kappa_{D_1}^2 P_R |g_i|^2 \right) \), \( (i = 1, 2) \) represents noise distortion, \( \eta_0 \sim \Gamma \left( 0, N_0 \right) \) denotes the additive white Gaussian noise. \( \kappa_{BR}, \kappa_{gR} \) and \( \kappa_{D_1}, \kappa_{D_2} \), \( (i = 1, 2) \) are the levels of residual hardware impairments.

Figure 1. Considering hardware impairment aware FD NOMA system

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The second hop signal processing is conducted based on channels $g_i$, which is referred to links $R \rightarrow D_i$. The NOMA power allocation need be adjusted for the second hop transmission, i.e. $\mu_1, \mu_2$ are allocated to two signals of two users, those factors are satisfied $\mu_1 + \mu_2 = 1$ and $\mu_1 > \mu_2$.

The received signal at $D_1, D_2$ are given as:

$$y_{D_1} = g_i \left( \sqrt{\mu_1 P_R} x_1 + \sqrt{\mu_2 P_R} x_2 + \eta_{D_1} \right) + \eta_0,$$

(2)

The two signals $x_1, x_2$ need be processed at the FD relay based on signal to interference plus noise ratio (SINR) which can be computed by:

$$\gamma_{x_1,R} = \frac{\varepsilon_1 \rho_B |g_0|^2}{(\varepsilon_2 + \kappa_2^{BR}) \rho_B |g_0|^2 + (1 + \kappa_2^{BR}) \rho_R \xi^2 |g_f|^2 + 1},$$

(3)

and

$$\gamma_{x_2,R} = \frac{\varepsilon_2 \rho_B |g_0|^2}{\rho_B \xi^2 |g_0|^2 + (1 + \kappa_2^{BR}) \rho_R \xi^2 |g_f|^2 + \varepsilon_1 \rho_R h_R + 1},$$

(4)

where $\rho_B = \frac{P_n}{N_0}, \rho_R = \frac{P_n}{N_0}$ are the transmit SNR at B and R. $h_R \sim \Gamma \left( 0, \omega |g_0|^2 \right)$ caused by imperfect SIC (ipSIC) and $\omega \in [0, 1]$.

After signals transmitted at the second hop transmission, the destination $D_2$ need to know SINR as below. In particular, $D_2$ detects signal $x_1$ as shown in:

$$\gamma_{x_1,D_2} = \frac{\mu_1 \rho_R |g_2|^2}{\mu_2 \rho_R |g_2|^2 + \rho_R \xi^2 |g_2|^2 + 1},$$

(5)

The first user $D_1$ wants to detect signal $x_1, x_2$ respectively as shown in:

$$\gamma_{x_1,D_1} = \frac{\mu_1 \rho_R |g_1|^2}{\mu_2 \rho_R |g_1|^2 + \rho_R \xi^2 |g_1|^2 + 1},$$

(6)

and

$$\gamma_{x_2,D_1} = \frac{\mu_2 \rho_R |g_1|^2}{\mu_1 \rho_R h_{RD_1} + \rho_R \xi^2 |g_1|^2 + 1},$$

(7)

where $h_{RD_1} \sim \Gamma \left( 0, \omega |g_1|^2 \right)$.

The PDF of the Nakagami-$m$ channel gain $g_k$ ($k = 0, 1, 2, f$) can be expressed as:

$$f_{|g_k|^2}(x) = \frac{x^{m_{g_k} - 1}}{\Gamma \left( m_{g_k} \right) \beta_{g_k}^m} e^{-\frac{x}{\beta_{g_k}}},$$

(8)

where $\beta_{g_k} = \frac{\lambda_{g_k}}{m_{g_k}}$ is the mean value of $g_k$ denoted by $|g_k|^2 \sim \Gamma \left( m_{g_k}, \frac{\lambda_{g_k}}{m_{g_k}} \right)$. The CDF can be written by:

$$F_{|g_k|^2}(x) = 1 - \frac{1}{\Gamma \left( m_{g_k} \right)} \frac{x^{m_{g_k} - 1}}{\beta_{g_k}^m} = 1 - e^{-\frac{x}{\beta_{g_k}}} \sum_{n=0}^{m_{g_k} - 1} \frac{x^n}{m_{g_k} \beta_{g_k}^m}.$$  

(9)

### 3. PERFORMANCE ANALYSIS

#### 3.1. Outage probability of $D_1$

To evaluate system performance, the OP need be compute, the OP of $D_1$ is defined as [19], [20].

$$\text{OP}_{D_1} = \Pr \left( \min \left( \gamma_{x_1,R} < \gamma_{2,th}^{th}, \gamma_{x_2,R} < \gamma_{1,th}^{th} \right) \right) + \Pr \left( \min \left( \gamma_{x_1,R} \geq \gamma_{2,th}^{th}, \gamma_{x_2,R} \geq \gamma_{1,th}^{th} \right) \right) + \Pr \left( \min \left( \gamma_{x_1,D_1} < \gamma_{2,th}^{th}, \gamma_{x_2,D_1} < \gamma_{1,th}^{th} \right) \right)$$

(10)
where the threshold SNRs are $\gamma_1^{th} = 2^{R_1} - 1$, $\gamma_2^{th} = 2^{R_2} - 1$.

Replacing the formulas [3], [4] into [10], we can calculate $\theta_1$ as shown in:

$$
\theta_1 \triangleq \Pr \left( \left| g_0 \right|^2 \leq \frac{\Phi_1^{th} \left| g_f \right|^2}{\varphi_1} + \frac{\gamma_1^{th}}{\varphi_1}, \left| g_f \right|^2 < \Delta_1 \right) + \Pr \left( \left| g_0 \right|^2 \geq \frac{\Phi_1^{th} \left| g_f \right|^2}{\varphi_1} + \frac{\gamma_1^{th}}{\varphi_1}, \left| g_f \right|^2 \geq \Delta_1 \right)
$$

$$
= \tau_1 + \tau_2,
$$

where $\varphi_1 \triangleq \epsilon_1 \rho_B - (\epsilon_2 \kappa_B^2) \rho_B \gamma_2^{th}$, $\varphi_2 \triangleq \epsilon_2 \rho_B - (\epsilon_1 \omega + \kappa_B^2) \rho_B \gamma_1^{th}$, $\Phi \triangleq (1 + \kappa_B^2) \rho_R \xi^2$, $\Delta_1 \triangleq \frac{\gamma_1^{th} \varphi_1 - \gamma_2^{th} \varphi_2}{\Phi_1^{th} \varphi_2 - \Phi_1^{th} \varphi_1}$ and we can be calculated $\tau_1, \tau_2$ as:

$$
\tau_1 \triangleq \Pr \left( \left| g_0 \right|^2 \leq \frac{\Phi_1^{th} \left| g_f \right|^2}{\varphi_1} + \frac{\gamma_1^{th}}{\varphi_1}, \left| g_f \right|^2 < \Delta_1 \right)
$$

$$
= \frac{1}{\Gamma(m_{g1})} \frac{\Delta_1}{\gamma_{g1} \varphi_1} - \sum_{n=0}^{m_{g0} - 1} \frac{\Delta_1}{\gamma_{g1} \varphi_1} \frac{n}{\Gamma(m_{g1})} \frac{\gamma_{g1} \varphi_1}{\Phi_1^{th} \varphi_1} + \frac{\gamma_{g1} \varphi_1}{\Phi_1^{th} \varphi_1} \int_{0}^{\Delta_1} \alpha_1 x^{m_{g1} - 1} e^{-\alpha_2 x} dx
$$

$$
= \frac{1}{\Gamma(m_{g1})} \left( \frac{\Delta_1}{\gamma_{g1} \varphi_1} - \sum_{n=0}^{m_{g0} - 1} \sum_{k=0}^{n} \frac{\Delta_1}{\gamma_{g1} \varphi_1} \frac{n}{\Gamma(m_{g1})} \frac{\gamma_{g1} \varphi_1}{\Phi_1^{th} \varphi_1} \alpha_1 \alpha_2^{k - m_{g1} - 1} e^{-k \varphi_1} \Gamma((k + m_{g1}), \alpha_6 \Delta_1) \right).$$

In which, $\alpha_1 \triangleq \frac{1}{\alpha_2 \varphi_1 \varphi_2 \varphi_{m_{g1}} \Gamma(m_{g1}) \beta_{g1} \beta_{g2} \varphi_2}, \alpha_2 \triangleq \frac{\Phi_2^{th \varphi_1 \varphi_2 \varphi_{m_{g1}} \Gamma(m_{g1}) \beta_{g1} \beta_{g2} \varphi_2}}{1}, \alpha_5 \triangleq \frac{\Delta_1}{\gamma_{g1} \varphi_1 \varphi_2 \varphi_{m_{g1}} \Gamma(m_{g1}) \beta_{g1} \beta_{g2} \varphi_2}, \alpha_6 \triangleq \frac{\Phi_2^{th \varphi_1 \varphi_2 \varphi_{m_{g1}} \Gamma(m_{g1}) \beta_{g1} \beta_{g2} \varphi_2}}{1}$

and $\tau_2$ is computed by.

$$
\tau_2 \triangleq \Pr \left( \left| g_0 \right|^2 \geq \frac{\Phi_1^{th} \left| g_f \right|^2}{\varphi_2} + \frac{\gamma_1^{th}}{\varphi_2}, \left| g_f \right|^2 \geq \Delta_1 \right)
$$

$$
= \int_{\Delta_1}^{\infty} \frac{x^{m_{g1} - 1}}{\Gamma(m_{g1}) \beta_{g1} \beta_{g2} \varphi_2} \frac{\alpha_5 \Delta_1}{\gamma_{g1} \varphi_1 \varphi_2 \varphi_{m_{g1}} \Gamma(m_{g1}) \beta_{g1} \beta_{g2} \varphi_2} \alpha_6 \Delta_1 \left( \frac{\gamma_{g1} \varphi_1}{\Phi_1^{th} \varphi_1} + \frac{\gamma_{g1} \varphi_1}{\Phi_1^{th} \varphi_1} \int_{0}^{\Delta_1} \alpha_1 x^{m_{g1} - 1} e^{-\alpha_2 x} dx \right)
$$

$$
= \beta_{g1} \Gamma(m_{g1}) \frac{\Delta_1}{\beta_{g1} \beta_{g2} \varphi_2} - \sum_{n=0}^{m_{g0} - 1} \sum_{k=0}^{n} \frac{\Delta_1}{\beta_{g1} \beta_{g2} \varphi_2} \frac{n}{\Gamma(m_{g1})} \frac{\gamma_{g1} \varphi_1}{\Phi_1^{th} \varphi_1} \alpha_5 \alpha_6 \frac{\gamma_{g1} \varphi_1}{\Phi_1^{th} \varphi_1} \int_{0}^{\Delta_1} \alpha_1 x^{m_{g1} - 1} e^{-\alpha_2 x} dx
$$

$$
= \beta_{g1} \Gamma(m_{g1}) \frac{\Delta_1}{\beta_{g1} \beta_{g2} \varphi_2} - \sum_{n=0}^{m_{g0} - 1} \sum_{k=0}^{n} \frac{\Delta_1}{\beta_{g1} \beta_{g2} \varphi_2} \frac{n}{\Gamma(m_{g1})} \frac{\gamma_{g1} \varphi_1}{\Phi_1^{th} \varphi_1} \alpha_5 \alpha_6 \frac{\gamma_{g1} \varphi_1}{\Phi_1^{th} \varphi_1} \alpha_6 \Delta_1 .
$$

Similarly $\theta_1, \theta_2$ can be calculated as shown in:

$$
\theta_2 \triangleq \Pr \left( \min \left( \gamma_{x,1} \geq \gamma_2^{th}, \gamma_{x,2} \geq \gamma_1^{th} \right) \right) \Pr \left( \min \left( \gamma_{x,1} \geq \gamma_2^{th}, \gamma_{x,2} \geq \gamma_1^{th} \right) \right)
$$

$$
= \tau_2 \times \tau_4 .
$$

We can calculate $\tau_3$ and $\tau_4$ as shown in:

$$
\tau_3 \triangleq 1 - \Pr \left( \left| g_0 \right|^2 < \min \left( \frac{\Delta_1}{\Delta_2} \left| g_f \right|^2 + \frac{\gamma_2^{th}}{\Delta_2}, \frac{\Delta_1}{\Delta_3} \left| g_f \right|^2 + \frac{\gamma_1^{th}}{\Delta_3} \right) \right)
$$

$$
= 1 - \Psi_1 - \Psi_2
$$

where $\Delta_2 \triangleq \epsilon_1 \rho_B - (\epsilon_2 + \kappa_B^2) \rho_B \gamma_2^{th}, \Delta_3 \triangleq \epsilon_2 \rho_B - \rho_B \kappa_B^2 \gamma_1^{th} - \epsilon_1 \rho_B \gamma_1^{th}, \Delta_4 \triangleq (1 + \kappa_B^2) \rho_B \xi^2$. 

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where

3.2. Outage probability of

Then,

We have applied the formulas \([25], (1.111), [25], (3.381.1), \) and \([25], (3.381.3)\) in the calculation steps above.

Then, \(\tau_4\) can be expressed as:

\[
\tau_4 = \left(1 - e^{-\frac{\mu_1\rho_n|g_1|^2}{n!\beta_{g_1}^n}}\right) \sum_{n=0}^{m_{g_1}-1} \frac{(\min(\Delta_5, \Delta_6))^n}{n!\beta_{g_1}^n}.
\]

with \(\Delta_5 \triangleq \frac{\rho_n - \rho_n \gamma_1 \gamma_2^{\frac{1}{2}} - \rho_n \gamma_1 \gamma_2^{\frac{1}{2}}}{\gamma_1}, \Delta_6 \triangleq \frac{\rho_n - \rho_n \gamma_1 \gamma_2^{\frac{1}{2}} - \rho_n \gamma_1 \gamma_2^{\frac{1}{2}}}{\gamma_1} \frac{\gamma_1}{\gamma_2^{\frac{1}{2}}}
\)

We have applied the formulas \([25], (1.111), [25], (3.381.1), \) and \([25], (3.381.3)\) in the calculation steps above.

3.2. Outage probability of \(D_2\)

The OP of \(D_2\) can be written as:

\[
\text{OP}_{D_2} = \text{Pr}\left(\gamma_{x_1, R} < \gamma_1^{th}, \gamma_{x_1, D_2} < \gamma_2^{th}, \gamma_{x_2, R} < \gamma_1^{th}\right)
= \text{Pr}\left(\gamma_{x_1, R} < \gamma_1^{th}, \gamma_{x_2, R} < \gamma_1^{th}\right) \times \text{Pr}\left(\gamma_{x_1, D_2} < \gamma_2^{th}\right)
= \theta_3 \times \theta_4,
\]

where \(\theta_1\) was calculated in the previous section and after substituting \(\gamma_1\) into \(19\), \(\theta_3\), we obtain:

\[
\theta_3 = \left(1 - e^{-\frac{\gamma_1^{th}}{\mu_1\rho_n|g_1|^2}}\right) \sum_{n=0}^{m_{g_1}-1} \frac{(\min(\Delta_5, \Delta_6))^n}{n!\beta_{g_1}^n}.
\]
4. SIMULATION RESULTS

In this section, we assume that the levels of RHIs $\kappa = \kappa_{BR} = \kappa_{g1} = \kappa_{D1} = \kappa_{D2}$, the mean values of channel power gains $\lambda_{g0} = \lambda_{g2}, \lambda_{g1}, \lambda_{g f}$, the target rates of $D_1, D_2$ are respectively $R_1, R_2$, $\omega = 0.01$ and power allocation coefficients $\varepsilon_1 = \mu_1, \varepsilon_2 = \mu_2$. The better quality of channels (higher $m$) leads to improvement of OP performance for two users, shown in Figure 2. In addition, in Figure 3, higher requirement of data rate $R_1, R_2$ results in worse OP performance. The reason is that in (10), OP depends on the target rates.

We then see the impact of level of self-interference channel at the relay on OP in Figure 4 performance. $\lambda_{g f} = 0.1$ is reported as the best case for two users. The difference among two users is decided by different power allocation factor assigned. The impact of hardware impairment can be observed in Figure 5. Less impact of hardware impairment $\kappa = 0.001$ is the best OP performance.

![Outage probability versus transmit SNR (\(\rho\)) with different \(m\) with \(R_1 = 2\) (bits/s/Hz), \(R_2 = 1\) (bits/s/Hz), \(\varepsilon_1 = \mu_1 = 0.6\), \(\kappa = 0.05\), \(\lambda_{g0} = \lambda_{g2} = 8\), \(\lambda_{g1} = 1\), \(\lambda_{g f} = 0.5\)](image)

![Outage probability versus transmit signal to noise ratio (SNR) (\(\rho\)) with different target rates, \(\varepsilon_1 = \mu_1 = 0.7\), \(\kappa = 0.05\), \(\lambda_{g0} = \lambda_{g2} = 5\), \(\lambda_{g1} = 1\), \(\lambda_{g f} = 0.5\), \(m = 2\)](image)

![Outage probability versus transmit SNR (\(\rho\)) with different of \(\lambda_{g f}\), \(R_1 = 0.5\) (bits/s/Hz), \(R_2 = 0.5\) (bits/s/Hz), \(\varepsilon_1 = \mu_1 = 0.6\), \(\kappa = 0.01\), \(\lambda_{g0} = \lambda_{g2} = 5\), \(\lambda_{g1} = 1\), \(m = 3\)](image)

![Outage probability versus transmit SNR (\(\rho\)) with different of \(\kappa\), \(R_1 = 2\) (bits/s/Hz), \(R_2 = 1\) (bits/s/Hz), \(\varepsilon_1 = \mu_1 = 0.66\), \(\lambda_{g0} = \lambda_{g2} = 8\), \(\lambda_{g1} = 1\), \(\lambda_{g f} = 0.5\), \(m = 2\)](image)
5. CONCLUSION

In this article, a downlink FD NOMA system was studied under the impact of hardware impairment. To illustrate advantage of NOMA scheme, the closed-form expressions of outage probability were provided. Numerical results were presented to corroborate the theoretical analysis, demonstrating that the quality of channel, level of hardware noise yield significant performance gains over Nakagami-\(m\) fading. Moreover, all the results showed that the system performance is limited by the target rates. NOMA with more users can be addressed in the future work.

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