Performance Analysis of Spatial Modulation Aided NOMA with Full-Duplex Relay

Qintuya Si, Minglu Jin, *Member, IEEE*, Yunfei Chen, *Senior Member, IEEE*, Nan Zhao, *Senior Member, IEEE*, and Xianbin Wang, *Fellow, IEEE*

***Abstract*—A spatial modulation aided non-orthogonal multiple access with full-duplex relay (SM-NOMA-FDR) scheme is proposed for the coordinated direct and relay transmission in this paper. Specifically, the signal of the near user is mapped to an M-ary modulated symbol and the signal of the far user is mapped to an SM symbol. The base station first transmits signals to the near user and relay via SM-NOMA, and then the relay decodes and retransmits the signal of the far user. An SM-assisted FDR is used in this scheme to improve the spectral efficiency while reducing energy consumption and making full use of the antenna resources at the relay, since SM only activates one antenna in each transmission. We derive the ergodic capacity and bit error rate of the proposed scheme over independent Rayleigh fading channels. Numerical results validate the accuracy of the theoretical analysis and show the superior performance of the proposed SM-NOMA-FDR scheme.**

***Index Terms*—Full-duplex relay, non-orthogonal multiple access, performance analysis, spatial modulation.**

I. Introduction

NON-orthogonal multiple access (NOMA) is an emerging technique to achieve high spectral efficiency (SE) [1], which allows multiple users to share radio resources using same time, frequency and code. Specifically, the base station (BS) mixes the signals from multiple users with different power levels, and the users detect their signals via successive interference cancellation (SIC) [2]. Recently, relaying has been used to enhance the reliability of communications [3]–[5]. A cooperative NOMA scheme was proposed in [3], where the user with strong channel condition serves as a relay to improve the reliability of the poor-channel user. Chen *et al.* presented a secondary NOMA relay in [4], where users communicate with the BS via a NOMA relay, and a selected secondary user acts as a relay for the primary user.

Spatial modulation (SM) has been regarded as a promising multiple-antenna technique [6]. In SM, only a single antenna is activated in each time slot, which reduces system complexity and energy consumption [7]. Consequently, SM is inherently suitable for full-duplex relay (FDR) systems, where one antenna of the relay is activated to send signals, while the remaining antennas can be used to receive the signal from the BS [8]. On the other hand, the combination of NOMA and SM has also attracted growing attention. In particular, Wang *et al.* proposed an SM aided NOMA (SM-NOMA) system in [9], where the BS transmits the superimposed SM symbols of users. In [10], a two-user SM-NOMA scheme was introduced, where the signal of one user is conveyed in the spatial domain and the signal of the other user is conveyed in the signal domain, and thus it completely cancels the intra-cluster interference. In [11], SM-NOMA was invoked for the vehicle-to-vehicle (V2V) system, where Rician channels are considered for V2V links. Li *et al.* proposed a three-node cooperative system using SM-NOMA in [12], where a BS serves two users, and the near user acts as a relay for the far user.

Coordinated direct and relay transmission (CDRT) is an effective strategy to extend the cell coverage and achieve high SE in 5G networks. However, the main issue of realizing CDRT is that the side information is required for interference cancellation. To address this problem, the authors in [13] introduced NOMA into CDRT with the half-duplex (HD) relay. In order to further improve the SE of [13], an FDR cooperative NOMA scheme with imperfect self-interference (SI) removal was developed for CDRT in [14]. However, for the concept of green communications, low energy consumption is also an important goal except the high SE. Motivated by this, in this paper, we focus on introducing SM into NOMA-based CDRT to improve the SE without increasing energy consumption. The main contributions of this paper are summarized as follows:

- We propose a two user SM-NOMA with FDR (SM-NOMA-FDR) scheme for CDRT, where the BS directly communicates with the near user and communicates with the far user through an FDR. Both the BS and the FDR adopt the SM technique.
- Taking into account the impact of residual SI at FDR, the performance of SM-NOMA-FDR in terms of ergodic capacity and bit error rate (BER) for two users are derived with closed-form expressions.
- Numerical results validate the correctness of the theoretical analysis. Meanwhile, we compare the proposed SM-NOMA-FDR with the the state of the arts and demonstrate superior performance of the proposed scheme.

The work of N. Zhao was supported by the National Natural Science Foundation of China (NSFC) under Grant 61871065. *(Corresponding author: Minglu Jin.)*

Q. Si, M. Jin, and N. Zhao are with the Faculty of Electronic Information and Electrical Engineering, Dalian University of Technology, Dalian 116024, China (e-mail: sqty@mail.dlut.edu.cn; mljin@dlut.edu.cn; zhaonan@dlut.edu.cn).

Y. Chen is with the School of Engineering, University of Warwick, Coventry CV4 7AL, U.K. (e-mail: Yunfei.Chen@warwick.ac.uk).

X. Wang is with the Department of Electrical and Computer Engineering, University of Western Ontario, London, ON N6A 5B9, Canada (e-mail: xianbin.wang@uwo.ca).

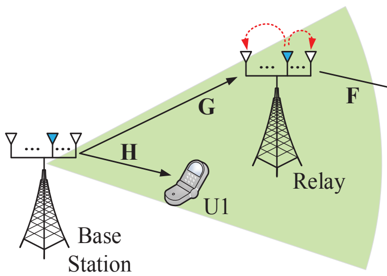

Fig. 1. System model of SM-NOMA-FDR.

II. System Model

The system model of the proposed SM-NOMA-FDR scheme is illustrated in Fig. 1, where both the BS and the FDR are equipped with N antennas and two users are equipped with M antennas. Specifically, user 1 (U1) can directly communicate with the BS, and user 2 (U2) communicates with the BS through an FDR. Moreover, the SM is employed at both the BS and the FDR. We also assume that the SI at the FDR is not fully cancelled. According to SM, only one antenna out of N is activated in each time slot. Thus, the remaining $N-1$ inactive antennas of FDR can be used for receiving signals from the BS simultaneously.

Hereafter, subscripts B, 1, 2 and R denote the BS, U1, U2, and the relay, respectively. Then, the channels from the BS to U1, from the BS to the relay and from the relay to U2 can be denoted by $\mathbf{H} \in \mathbb{C}^{M\times N}$, $\mathbf{G} \in \mathbb{C}^{N\times N}$ and $\mathbf{F} \in \mathbb{C}^{M\times N}$, where the entries of these channels are complex Gaussion random variables with zero mean and variance λ_h, λ_g and λ_f, respectively. We assume that the distance between the relay and the BS is larger than the distance between the BS and U1, hence we have $\lambda_h > \lambda_g$. In the proposed scheme, the information of U1 and U2 are mapped to a conventional modulated symbol and an SM symbol, respectively. According to SM, the first $\log_2 N$ bits of U2 are used for selecting one active antenna and the remaining bits of U2 are mapped to an M_2-ary modulated symbol.

In the first time slot, the BS activates the k-th antenna to transmit the signal $\sqrt{a_1}\gamma_m + \sqrt{a_2}x_n$ based on NOMA, where a_1 and a_2 are power allocation coefficients satisfying $a_1 + a_2 = 1$, and γ_m (x_n) is the M_1-ary (M_2-ary) quadrature amplitude modulation (QAM) symbol of U1 (U2) with $E[|\gamma_m|^2] = 1$ ($E[|x_n|^2] = 1$). Thus, we have $b_1 = \log_2 M_1$ and $b_2 = \log_2 N + \log_2 M_2$. SIC is implemented at U1, and thus U1 can perfectly remove the interference from the relay. Accordingly, the received signals at U1 and $N-1$ inactive antennas of the relay can be given as

$$\mathbf{y}_1 = \sqrt{P_B}\mathbf{h}_k\left(\sqrt{a_1}\gamma_m + \sqrt{a_2}x_n\right) + \mathbf{n}_1, \tag{1}$$

$$\mathbf{y}_R = \sqrt{P_B}\tilde{\mathbf{g}}_{pk}\left(\sqrt{a_1}\gamma_m + \sqrt{a_2}x_n\right) + \sqrt{I}\mathbf{x}_R + \mathbf{n}_R, \tag{2}$$

where: i) P_B is the transmit power of the BS; ii) $\mathbf{h}_k$ is the k-th column of $\mathbf{H}$; iii) $\mathbf{y}_R = [y_1, ..., y_p, y_{p+1}, ..., y_N]^T$; iv) $\tilde{\mathbf{g}}_{pk}$ denotes the channel vector between the k-th transmit antenna at the BS and $\{1, 2, ..., N\}\backslash p$ receive antennas at the relay; v) $\mathbf{x}_R$ denotes a vector with entries of the relay's signal x_R and I is the power of SI; vi) $\mathbf{n}_1$ and $\mathbf{n}_R$ are additive white Gaussian noise (AWGN) vectors with elements of zero mean and variance σ_1^2 and σ_R^2, respectively.

The signal of U2 is first detected at U1 by using the maximum likelihood (ML) method, which can be given by

$$(\hat{k}, x_{\hat{n}})_1 = \arg\min_{k,n} \left\|\mathbf{y}_1 - \sqrt{P_B}\mathbf{h}_k\sqrt{a_2}x_n\right\|^2. \tag{3}$$

After removing the interference of U2, U1 performs another ML detection to detect its own signal, which is expressed as

$$\gamma_{\hat{m}} = \arg\min_{m} \left\|\tilde{\mathbf{y}}_1 - \sqrt{P_B}\mathbf{h}_{\hat{k}}\sqrt{a_1}\gamma_m\right\|^2, \tag{4}$$

where $\tilde{\mathbf{y}}_1 = \mathbf{y}_1 - \sqrt{P_B}\mathbf{h}_{\hat{k}}\sqrt{a_2}x_{\hat{n}}$.

At the relay side, it demodulates the data of U2 by treating the signal of U1 as noise, which can be given as

$$(\hat{k}, x_{\hat{n}})_R = \arg\min_{k,n} \left\|\mathbf{y}_R - \sqrt{P_B}\tilde{\mathbf{g}}_{pk}\sqrt{a_2}x_n\right\|^2. \tag{5}$$

In the second time slot, the BS transmits a new signal to the relay and U1. Meanwhile, the relay activates the $\hat{k}$-th antenna to send the estimated symbol to U2. Let $p = \hat{k}$ and $x_R = x_{\hat{n}}$, then the observation at U2 can be formulated as

$$\mathbf{y}_2 = \sqrt{P_R}\mathbf{f}_p x_R + \mathbf{n}_2, \tag{6}$$

where P_R is the transmit power of the relay and $\mathbf{f}_p$ is the p-th column of $\mathbf{F}$. Finally, U2 can decode the signal via the ML method.

III. Performance Analysis

A. Capacity Analysis

In this subsection, we will derive the instantaneous and ergodic capacities of U1 and U2 under Gaussian inputs.

1) Capacity of U1: Recall that U2 can perfectly eliminate the interference from the relay since the signal of U2 is already known at U1. Then, by assuming that all transmit antennas of the BS are activated with an equal probability of $1/N$, the instantaneous capacity of U1 after SIC can be given by [6]

$$C_1 = \frac{1}{N}\sum_{k=1}^{N}\log_2\left(1 + \frac{P_B\|\mathbf{h}_k\|^2 a_1}{\sigma_1^2}\right). \tag{7}$$

where $\|\mathbf{h}_k\|^2$ obeys the central chi-square distribution with $2M$ degrees of freedom whose probability density function (PDF) is given by [15]

$$f_{\|\mathbf{h}_k\|^2}(x) = \frac{1}{(N-1)!}x^{N-1}e^{-x}. \tag{8}$$

Let $\Theta = P_B\|\mathbf{h}_k\|^2 a_1/\sigma_1^2$, the ergodic capacity of U1 can be expressed as [16]

$$\bar{C}_1 = E_{\mathbf{H}}\left[\log_2(1+\Theta)\right] = \frac{1}{\ln 2}\int_0^{+\infty}\frac{1-F_\Theta(\theta)}{1+\theta}d\theta, \tag{9}$$

where $F_\Theta(\theta)$ is the cumulative distribution function (CDF) of Θ, which can be given by [15]

$$\begin{aligned} F_\Theta(\theta) &= p_r\left(\frac{P_B\|\mathbf{h}_k\|^2 a_1}{\sigma_1^2} < \theta\right) \\ &= p_r\left(\|\mathbf{h}_k\|^2 < \frac{\theta\sigma_1^2}{P_B a_1}\right) \\ &= 1 - e^{-\frac{\theta\sigma_1^2}{P_B a_1\lambda_h}}\sum_{k=0}^{M-1}\frac{1}{k!}\left(\frac{\theta\sigma_1^2}{P_B a_1\lambda_h}\right)^k \end{aligned} \tag{10}$$

$$\begin{aligned}\bar{C}_1 &= \frac{1}{\ln 2}\sum_{k=0}^{M-1}\frac{1}{k!}\int_0^{+\infty}\frac{1}{1+\theta}e^{-\frac{\theta\sigma_1^2}{P_B a_1\lambda_h}}\left(\frac{\theta\sigma_1^2}{P_B a_1\lambda_h}\right)^k d\theta \\ &= \frac{1}{\ln 2}\sum_{k=0}^{M-1}\frac{1}{k!}\left(\frac{\sigma_1^2}{P_B a_1\lambda_h}\right)^k\left[(-1)^{k-1}e^{\frac{\sigma_1^2}{P_B a_1\lambda_h}}Ei\left(-\frac{\sigma_1^2}{P_B a_1\lambda_h}\right)+\sum_{n=1}^{k}(n-1)!(-1)^{k-n}\left(\frac{\sigma_1^2}{P_B a_1\lambda_h}\right)^{-n}\right].\end{aligned} \tag{13}$$

Then, by substituting (10) into (9), we can obtain the ergodic capacity of U1 as in (13), shown at the top of the next page, where $Ei\left(x\right) = \int_{-\infty}^{x} e^t/tdt$ is the exponential integral function [17].

2) Capacity of U2: For the proposed scheme, the capacity of U2 is determined by the weakest link, hence we have

$$C_2 = \min\left(C_{2,R}, C_{2,2}\right), \tag{14}$$

where $C_{2,R}$ and $C_{2,2}$ are the capacity of U2 over the BS-to-relay and relay-to-U2 links, respectively. Since the data of U2 are conveyed in both the signal domain and the spatial domain, $C_{2,R}$ and $C_{2,2}$ can be divided into [11]

$$C_{2,X} = C_{2,X}^{sig} + C_{2,X}^{spa}, \quad \text{for } X \in \{R, 2\}. \tag{15}$$

As stated previously, the index of the active antenna at the relay depends on its input data. Therefore, the active/inactive antenna (s) in each time slot may be different. Hence, $C_{2,R}^{sig}$ in (15) can be formulated as

$$C_{2,R}^{sig} = \frac{1}{N^2}\sum_{k=1}^{N}\sum_{p=1}^{N}\log_2\left(1+\frac{P_B\|\tilde{\mathbf{g}}_{pk}\|^2 a_2}{P_B\|\tilde{\mathbf{g}}_{pk}\|^2 a_1 + I + \sigma_R^2}\right), \tag{16}$$

From (16), it can be seen that the SI of the relay greatly affects the capacity of U2 especially when a_1 is small. For the relay-to-U2 link, $C_{2,2}^{sig}$ can be expressed as

$$C_{2,2}^{sig} = \frac{1}{N}\sum_{k=1}^{N}\log_2\left(1+\frac{P_R\|\mathbf{f}_k\|^2}{\sigma_2^2}\right). \tag{17}$$

On the other hand, the capacity of U2 in the spatial domain for BS-to-relay and relay-to-U2 links can be given by

$$\begin{aligned}C_{2,R}^{spa} &= I\left(k;\mathbf{y}_R\right) \\ &= \frac{1}{N^2}\sum_{k=1}^{N}\sum_{p=1}^{N}\int p_r(\mathbf{y}_R|\tilde{\mathbf{g}}_{pk})\log_2\left(\frac{p_r(\mathbf{y}_R|\tilde{\mathbf{g}}_{pk})}{p_r\left(\mathbf{y}_R\right)}\right)d\mathbf{y}_R,\end{aligned} \tag{18}$$

$$\begin{aligned}C_{2,2}^{spa} &= I\left(k;\mathbf{y}_2\right) \\ &= \frac{1}{N}\sum_{k=1}^{N}\int p_r\left(\mathbf{y}_2|\mathbf{f}_k\right)\log_2\left(\frac{p_r\left(\mathbf{y}_2|\mathbf{f}_k\right)}{p_r\left(\mathbf{y}_2\right)}\right)d\mathbf{y}_2,\end{aligned} \tag{19}$$

where

$$p_r(\mathbf{y}_R) = \frac{1}{N}\sum_{k=1}^{N}p_r\left(\mathbf{y}_R|\tilde{\mathbf{g}}_{pk}\right), \tag{20}$$

$$p_r(\mathbf{y}_2) = \frac{1}{N}\sum_{k=1}^{N}p_r\left(\mathbf{y}_2|\mathbf{f}_k\right) \tag{21}$$

Due to the difficulties of obtaining the closed-form expression of (18) and (19) [11], we use an upper bound to facilitate the theoretical solution. When we assuming that the SI is extremely small, we can obtain

$$C_{2,R}^{spa} = C_{2,2}^{spa} = C^{spa} \approx \log_2 N \tag{22}$$

at the high signal-to-noise ratio (SNR) region (Please refer to [18] for the proof).

Then, we derive the ergodic capacity of U2. Based on (22), the ergodic capacity of U2 can be calculated as

$$\begin{aligned}\bar{C}_2 &= E_{\mathbf{G},\mathbf{F}}\left[\min\left(C_{2,R}^{sig}+C^{spa}, C_{2,2}^{sig}+C^{spa}\right)\right] \\ &= E_{\mathbf{G},\mathbf{F}}\left[\log_2\left(1+\min(\Xi_1,\Xi_2)\right)\right]+C^{spa},\end{aligned} \tag{23}$$

where

$$\min(\Xi_1,\Xi_2) = \min\left(\frac{P_B\|\tilde{\mathbf{g}}_{pk}\|^2 a_2}{P_B\|\tilde{\mathbf{g}}_{pk}\|^2 a_1 + I + \sigma_R^2}, \frac{P_R\|\mathbf{f}_k\|^2}{\sigma_2^2}\right). \tag{24}$$

Similarly, let $\Xi = \min(\Xi_1,\Xi_2)$, $\bar{C}_2$ can be rewritten as

$$\bar{C}_2 = \frac{1}{\ln 2}\int_0^{+\infty}\frac{1-F_\Xi(\xi)}{1+\xi}d\xi + C^{spa}, \tag{25}$$

where $F_\Xi(\xi)$ denotes the CDF of the random variable Ξ as

$$\begin{aligned}F_\Xi(\xi) &= p_r\left(\min\left(\Xi_1,\Xi_2\right)<\xi\right) \\ &= 1-p_r\left(\min\left(\Xi_1,\Xi_2\right)>\xi\right) \\ &= 1-p_r\left(\Xi_1>\xi\right)p_r\left(\Xi_2>\xi\right) \\ &= 1-\left(1-F_{\Xi_1}(\xi)\right)\left(1-F_{\Xi_2}(\xi)\right).\end{aligned} \tag{26}$$

In (26), $F_{\Xi_1}(\xi)$ and $F_{\Xi_2}(\xi)$ can be derived by

$$F_{\Xi_1}(\xi) = \begin{cases} 1-e^{-c_1}\sum\limits_{n=0}^{N-2}\frac{1}{n!}(c_1)^n, & \text{for } \xi < \frac{a_2}{a_1} \\ 1 & \text{, otherwise}\end{cases}, \tag{27}$$

$$F_{\Xi_2}(\xi) = 1-e^{-c_2}\sum_{k=0}^{M-1}\frac{1}{k!}\left(c_2\right)^k, \tag{28}$$

where $c_1 = \xi(I+\sigma_R^2)/(P_B\lambda_g a_2 - P_B\lambda_g a_1\xi)$, $c_2 = \xi\sigma_2^2/P_R\lambda_f$.

Therefore, the ergodic capacity of U2 can be obtained as

$$\begin{aligned}\bar{C}_2 &= \frac{1}{\ln 2}\int_0^{+\infty}\frac{1-F_\Xi(\xi)}{1+\xi}d\xi + C^{spa} \\ &= \frac{1}{\ln 2}\int_0^{\frac{a_2}{a_1}}\frac{1}{1+\xi}e^{-(c_1+c_2)}\sum_{n=0}^{N-2}\frac{1}{n!}\left(c_1\right)^n \\ &\quad \times\sum_{k=0}^{M-1}\frac{1}{k!}\left(c_2\right)^k d\xi + C^{spa}.\end{aligned} \tag{29}$$

Notice that it is difficult to derive the closed-form expression of (29). Thus, numerical integration is used to evaluate the integral.

B. BER Performance Analysis

In this subsection, we will derive the BER of U1 and U2 in closed-form expressions by using the union bound theory [15].

1) BER of U1: The BER of U1 depends on whether the signal of U2 is successfully eliminated. Thus, it can be divided into two parts as

$$BER_1 = (1 - p_{SIC})\, p_{c,1} + p_{SIC} p_{e,1}, \tag{30}$$

where p_{SIC} is the error probability that U1 detects the signal of U2, $p_{c,1}$ is the BER of U1 under the condition that the signal of U2 is correctly detected, and $p_{e,1}$ denotes the BER of U1 when errors occur in SIC.

Let us denote $v = \|\mathbf{e}_k x_n - \mathbf{e}_{\hat{k}} x_{\hat{n}}\|^2$, where $\mathbf{e}_k$ is the k-th row of an N-dimensional unit matrix. Consequently, the formulation of p_{SIC} can be given by [19]

$$p_{SIC} \approx \frac{1}{NM_2} \sum_{k=1}^{N} \sum_{\substack{\hat{k}=1,\\ \hat{k}\neq k}}^{N} \sum_{n=1}^{M_2} \sum_{\substack{\hat{n}=1,\\ \hat{n}\neq n}}^{M_2} f\left(\frac{\lambda_h P_B a_2 v}{4\left(\sigma_1^2 + a_1\right)}, M\right), \tag{31}$$

$$f(x, y) = \Upsilon(x)^y \sum_{t=0}^{y-1} \binom{y-1+t}{t} [1 - \Upsilon(x)]^t, \tag{32}$$

where $\Upsilon(x) = 0.5(1 - \sqrt{x/(1+x)})$.

Recall that the signal of U1 is only transmitted in the signal domain. Thus the expression of $p_{c,1}$ can be given as

$$p_{c,1} \approx \frac{1}{b_1 2^{b_1}} \sum_{m=1}^{M_1} \sum_{\substack{\hat{m}=1,\\ \hat{m}\neq m}}^{M_1} Df\left(\frac{\lambda_h P_B a_1 u}{4\sigma_1^2}, M\right), \tag{33}$$

where $u = |\gamma_m - \gamma_{\hat{m}}|^2$ and D denotes the Hamming distance between the information bits of γ_m and $\gamma_{\hat{m}}$.

On the other hand, if the interference due to failing SIC exists, $p_{e,1}$ can be approximated by $p_{e,1} \approx 1 - n_{M_1}/\log_2 M_1$, where n_{M_1} is the average correct bits of the detection of M_1-ary modulated symbols. n_{M_1} can be expressed as [12]

$$n_{M_1} = \frac{1}{M_1 - 1} \sum_{t=1}^{\log_2 M_1} t \binom{\log_2 M_1}{t}. \tag{34}$$

2) BER of U2: Similarly, the BER of U2 can be given by

$$BER_2 = (1 - p_R)\, p_{c,2} + p_R p_{e,2}, \tag{35}$$

where p_R is the error probability that the relay detects the signal of U2, $p_{c,2}$ is the BER of U2 when the signal of U2 is correctly detected at the relay and $p_{e,2}$ denotes the BER when the relay forwards an erroneous signal.

According to (2) and (6), both in the BS-to-relay and relay-to-U2 links, the SM symbol is used to carry the information of U2. In addition, $N-1$ antennas are used to receive the information at the relay. Therefore, p_R can be given by

$$p_R \approx A \sum_{k=1}^{N} \sum_{\substack{\hat{k}=1,\\ \hat{k}\neq k}}^{N} \sum_{n=1}^{M_2} \sum_{\substack{\hat{n}=1,\\ \hat{n}\neq n}}^{M_2} f\left(\frac{P_B \lambda_g a_2 v}{4\left(\sigma_R^2 + a_1 + I\right)}, N-1\right), \tag{36}$$

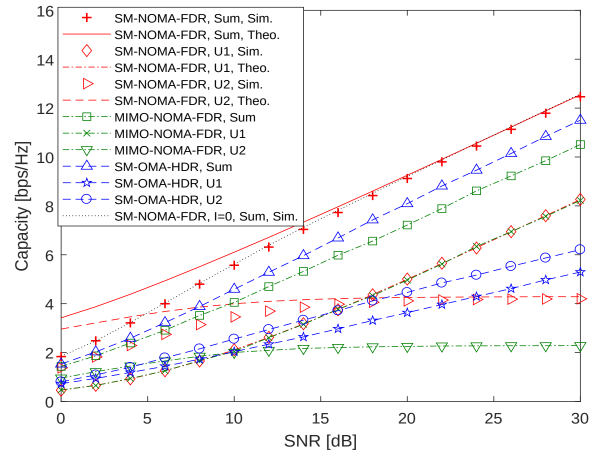

Fig. 2. Achievable capacity and ergodic capacity of SM-NOMA-FDR. Setup: $N = 4$, $M = 2$, $a_1 = 0.2$, and $I = 0.01$.

where $A = 1/NM_2$. The value of $p_{c,2}$ can be determined from $p_{c,2} \approx ABEP_{SM}\left(\lambda_f P_R/\sigma_2^2\right)$, where $ABEP_{SM}\left(\lambda_f P_R/\sigma_2^2\right)$ represents the average BER of SM over the Raleigh fading channel with SNR of $\lambda_f P_R/\sigma_2^2$ at the receiver [19].

Finally, we assume that U2 is less likely to correctly detect its own signal when errors occur at the relay. Thus we consider the worst case, i.e., $p_{e,2} = 1$.

IV. Simulation Results

In this section, the capacity and BER of the proposed scheme are presented and compared with the multi-input multi-output aided NOMA with FDR (MIMO-NOMA-FDR) and SM-aided orthogonal multiple access with half-duplex relay (SM-OMA-HDR) systems. The transmit SNR is defined as SNR$= P/\sigma^2$, where P is the transmit power and σ^2 is the variance of noise, respectively. In the simulation, we assume $\lambda_h = \lambda_f = 1$, $\lambda_g = 0.8$, $\sigma_1^2 = \sigma_2^2 = \sigma_R^2 = \sigma^2$ and $P_B = P_R = P = 1$.

In MIMO-NOMA-FDR, for a fair comparison, we consider that the BS has one transmit antenna, and the relay has one transmit antenna and $N-1$ receive antennas. In SM-OMA-HDR, the BS transmits a modulated symbol to U1 during the $(t-1)$-th time slot. Meanwhile, the relay transmits an SM symbol of U2 that received at the last time slot to U2. Then, during the t-th time slot, the BS transmits a new SM symbol of U2 to the relay.

In Fig. 2 and Fig. 3, the simulation results for the achievable capacity and the ergodic capacity of SM-NOMA-FDR are provided and compared with those of MIMO-NOMA-FDR and SM-OMA-HDR systems. The results verify the accuracy of ergodic capacities obtained from (13) and (29). We can observe that SM-NOMA-FDR provides a significant improvement in the sum capacity compared to MIMO-NOMA-FDR and SM-OMA-HDR. Fig. 2 and Fig. 3 show that U1 achieves the same performance in SM-NOMA-FDR and MIMO-NOMA-FDR. On the other hand, we can find that the capacity of U2 for SM-NOMA-FDR and MIMO-NOMA-FDR becomes a constant at the high SNR regime, which means that the relay suffers form the interference caused by U1 in this case. Moreover, in SM-OMA-HDR, U2 achieves a better capacity performance than

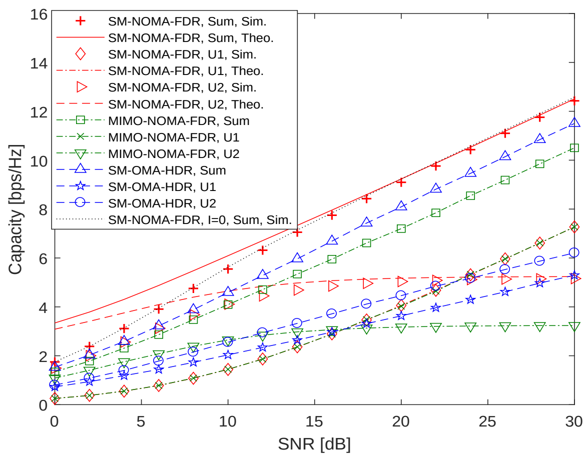

Fig. 3. Achievable capacity and ergodic capacity of SM-NOMA-FDR. Setup: $N = 4$, $M = 2$, $a_1 = 0.1$, and $I = 0.01$.

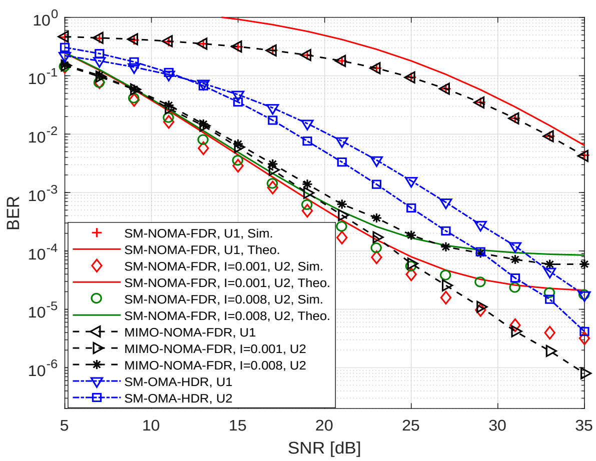

Fig. 4. BER performance of SM-NOMA-FDR. Setup: $N = 4$, $M = 2$, $M_1 = 8$, $M_2 = 2$ ($M_1 = 8, M_2 = 8$ for MIMO-NOMA-FDR and $M_1 = 64$, $M_2 = 16$ for SM-OMA-HDR), $a = 0.01$.

U1, which is due to the fact that U2 uses the spatial domain to convey the additional information and there is no interference from U1 in SM-OMA-HDR. Finally, both Fig. 2 and Fig. 3 reveal that the system capacity is less sensitive to SI. It implies that the proposed system is not strict with the capability of SI cancellation.

Fig. 4 shows the BER performance of SM-NOMA-FDR and the comparison with MIMO-NOMA-FDR and SM-OMA-HDR. Theoretical curves obtained from (30) and (35) are also presented. It is shown that the BER of U1 for MIMO-NOMA-FDR and SM-NOMA-FDR are the same, which implies that U1 correctly detects the signal of U2 with a high probability in this case. We can also find that the sensitivity of proposed SM-NOMA-FDR with respect to SI is less than that of MIMO-NOMA-FDR. Additionally, it can be seen that an error floor occurs at high SNR region for U2 in MIMO-NOMA-FDR and SM-NOMA-FDR. This is owing to the interference of the signal of U1 and SI at the relay, which becomes more dominant compared to the noise effect in high SNR region.

V. Conclusion

In this paper, we have proposed an SM-NOMA-FDR scheme for the CDRT network, where the BS can directly communicate with the near user and communicates with the far user by using an FDR. The SI of the FDR has also been considered. Theoretical analyses of the ergodic capacity and the BER have been derived. Finally, the simulation results have verified the theoretical analyses and revealed that the proposed system achieves superior performances compared with MIMO-NOMA-FDR and SM-OMA-HDR systems.

References

[1] L. Dai, B. Wang, Y. Yuan, S. Han, C.-L. I, and Z. Wang, "A survey of non-orthogonal multiple access for 5G," *IEEE Commun. Mag.*, vol. 53, no. 9, pp. 74–81, Sep. 2018.

[2] B. Chen, Y. Chen, Y. Chen, Y. Cao, Z. Ding, N. Zhao, and X. Wang, "Secure primary transmission assisted by a secondary full-duplex NOMA relay," *IEEE Trans. Veh. Technol.*, vol. 68, no. 7, pp. 7214–7219, Jul. 2019.

[3] Z. Ding, M. Peng, and H. V. Poor, "Cooperative non-orthogonal multiple access in 5G systems," *IEEE J. Sel. Areas Commun.*, vol. 19, no. 8, pp. 1462–1465, Aug. 2015.

[4] B. Chen, Y. Chen, Y. Cao, N. Zhao, and Z. Ding, "A novel spectrum sharing scheme assisted by secondary NOMA relay," *IEEE Wireless Commun. Lett.*, vol. 7, no. 5, pp. 732–735, Oct. 2018.

[5] V. N. Quoc Bao, H. Van Toan, and K. N. Le, "Performance of two-way AF relaying with energy harvesting over nakagami-m fading channels," *IET Commun.*, vol. 12, no. 20, pp. 2592–2599, 2018.

[6] Y. Yang and B. Jiao, "Information-guided channel-hopping for high data rate wireless communication," *IEEE Commun. Lett.*, vol. 12, no. 4, pp. 225–227, Apr. 2008.

[7] P. Yang, M. D. Renzo, Y. Xiao, S. Li, and L. Hanzo, "Design guidelines for spatial modulation," *IEEE Commun. Surveys Tuts.*, vol. 17, no. 1, pp. 6–26, 1st Quart. 2015.

[8] S. Narayanan, H. Ahmadi, and M. F. Flanagan, "On the performance of spatial modulation MIMO for full-duplex relay networks," *IEEE Trans. Veh. Technol.*, vol. 16, no. 6, pp. 3727–3746, Jun. 2017.

[9] X. Wang, J. Wang, L. He, Z. Tang, and J. Song, "On the achievable spectral efficiency of spatial modulation aided downlink non-orthogonal multiple access," *IEEE Commun. Lett.*, vol. 21, no. 9, pp. 1937–1940, Sep. 2017.

[10] C. Zhong, X. Hu, X. Chen, D. W. K. Ng, and Z. Zhang, "Spatial modulation assisted multi-antenna non-orthogonal multiple access," *IEEE Wireless Commun.*, vol. 25, no. 2, pp. 61–67, Apr. 2018.

[11] Y. Chen, L. Wang, Y. Ai, B. Jiao, and L. Hanzo, "Performance analysis of NOMA-SM in vehicle-to-vehicle massive MIMO channels," *IEEE J. Sel. Areas Commun.*, vol. 35, no. 12, pp. 2653–2666, Dec. 2017.

[12] Q. Li, M. Wen, E. Basar, H. V. Poor, and F. Chen, "Spatial modulation-aided cooperative NOMA: Performance analysis and comparative study," *IEEE J. Sel. Topics Signal Process.*, vol. 13, no. 3, pp. 715–728, Jun. 2019.

[13] J. Kim and I. Lee, "Non-orthogonal multiple access in coordinated direct and relay transmission," *IEEE Commun. Lett.*, vol. 19, no. 11, pp. 2037–2040, Nov. 2015.

[14] C. Zhong and Z. Zhang, "Non-orthogonal multiple access with cooperative full-duplex relaying," *IEEE Commun. Lett.*, vol. 20, no. 12, pp. 2478–2481, Dec. 2016.

[15] J. G. Proakis and M. Salehi, *Digital Communications*, 5th ed. New York, USA: McGraw-Hill, 2007.

[16] L. Zhang, J. Liu, M. Xiao, G. Wu, Y. Liang, and S. Li, "Performance analysis and optimization in downlink NOMA systems with cooperative full-duplex relaying," *IEEE J. Sel. Areas Commun.*, vol. 35, no. 10, pp. 2398–2412, Oct. 2017.

[17] I. S. Gradshteyn and I. M. Ryzhik, *Table of Integrals, Series and Products*, 7th ed. New York, NY, USA: Academic, 2007.

[18] W. Wang and W. Zhang, "Huffman coding-based adaptive spatial modulation," *IEEE Trans. Wireless Commun.*, vol. 16, no. 8, pp. 5090–5101, Aug. 2017.

[19] M. Di Renzo and H. Haas, "Bit error probability of SM-MIMO over generalized fading channels," *IEEE Trans. Veh. Technol.*, vol. 61, no. 3, pp. 1124–1144, Mar. 2012.