Time slot-split NOMA with resource allocation in full-duplex cooperative communications

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Abstract
This paper presents a time slot-split non-orthogonal multiple access (TSS-NOMA) scheme for full-duplex (FD) cooperative communication systems to improve resource utilisation. Aiming at the problem of low bandwidth efficiency when pairing users, TSS-NOMA divides a complete time slot into several parts to improve the pairing process. Users can occupy all bandwidths in different slots to reduce the waste of bandwidth resources. Unlike the scheme of forwarding a single signal, TSS-NOMA decodes the information symbols of relay, and re-encodes the messages through the new power allocation factors of successfully paired users. The hybrid symbols are sent to increase the proportion of central users’ own signals received by themselves, thus improving the ergodic capacity of the system. To maximise the minimum achievable rate of the system, TSS-NOMA optimises the power allocation at the base station, and the relay. The performance of TSS-NOMA is verified by simulation, where numerical results show that this scheme can achieve higher spectral, and energy efficiency.

1 | INTRODUCTION

In wireless communication systems, non-orthogonal multiple access (NOMA) enables users to share the same time-frequency resources, which allows the system to achieve large capacity and low transmission delay, thus serving a large number of users [1–4]. Since NOMA does not depend on feedback channel information, it can adapt to the frequently changing link state in complex environments, thus ensuring transmission rate and providing high spectral efficiency [5, 6]. Moreover, NOMA breaks the principle that resources must be orthogonal in the traditional scheme, and tends to offer several advantages over orthogonal multiple access (OMA) schemes such as improved user fairness, higher cell-edge throughput and massive connectivity support [7, 8].

Cooperative relaying system (CRS) plays a vital role in providing higher diversity gain and expanding network coverage [9, 10]. Capacity analysis of a CRS using NOMA for spatially multiplexed transmissions is performed in [11], the destination receives and combines two independent copies of the same data signal transmitted from the source via the direct and relaying channels during two slots, which improves the reception quality of the signal. In [12], a dual-hop cooperative relaying network where two sources communicate with their corresponding destinations in parallel over the same frequency band through a shared amplify-and-forward (AF) relay. By simultaneously exploiting path loss savings known from relaying scenarios and the diversity inherent to any scheme involving spatially separated transmitters, proving that CRS can make full use of the advantages of relay [13, 14]. Later in [15], a CRS scheme based on AF and decode-and-forward (DF) relay is investigated to improve the throughput of the system. Results from the aforementioned studies generally show that CRS has broad prospects of application in communication systems.

1.1 | Background work

Recently, the combination of cooperative relaying system communication and NOMA (CRS-NOMA) becomes a hot research topic. In [16], an approach based on user pairing is proposed to reduce system complexity, which shows the strong advantages.
of CRS-NOMA in outage performance. Later in [17], a new detection method is proposed to verify the better performance of CRS-NOMA with AF than that with DF. Also, authors in [18] obtained the upper limit of the system’s ergodic rate by studying the shared amplified forwarding relay method, which shows the superior performance of CRS-NOMA.

Besides the half-duplex (HD) CRS-NOMA described above, there has been increased research on CRS-NOMA in full-duplex (FD), where the channel capacity of FD can be twice that of HD by theoretical analysis. Note that [19] focuses on the performance differences between HD and FD systems with limited and tolerant delays, proving that FD has higher energy efficiency than HD in the low signal-to-noise ratio (SNR) region. In [20], a cluster beamforming strategy is proposed to jointly optimise the power allocation coefficients for users in CRS-NOMA with the aim of reducing the total power consumption. In addition, CRS-NOMA systems with a new hybrid forwarding strategy have been considered and their achievable rates have also been studied in [21]. With the assumption of incomplete interference elimination, [22] derives the expressions of the outage probability and ergodic rate, thus concluding that CRS-NOMA has better performance on the premise of intermediate signal to interference and noise ratio (SINR).

1.2 | Motivations and contributions

The current state-of-the-art mainly analyse the performance of the system by efficient channel coding and interference suppression techniques. Authors in [23] adopt new transmission schemes for communication, which conducts research from the perspectives of interference suppression, achievable rate, and power allocation to improve system performance. Nevertheless, it is noteworthy that few papers consider the utilisation of bandwidth resources in NOMA multi-user system. A drawback of the aforementioned schemes is that the performance of the system will decrease when the cell has a large number of NOMA users [24]. Besides, the channel connection of a cell-edge user to a base station may become worse, due to large scale path loss. Later in [25], an interference reduction scheme utilising both cooperating relaying and interference forwarding techniques shows that there is still room for improvement in the scheme proposed in [22], which regards the signals of the cooperative relaying link as interference and cannot achieve the maximum receive diversity.

Along this line, unlike in the previous works reviewed above, we propose a time slot-split non-orthogonal multiple access (TSS-NOMA) scheme for FD cooperative communication systems to improve resource utilisation in this paper. Particularly, the relay in TSS-NOMA no longer forwards a single decoded signal, but re-encodes and forwards the NOMA hybrid signals according to the new power allocation factors of users. The contributions of this paper are as follows:

1. A whole communication time slot is divided into two parts by exploiting slot-split, where the successfully paired users communicate in NOMA to utilise the entire bandwidth of the system, thus improving the spectral efficiency.
2. Provided that the signals from direct and cooperative relaying links can be completely separated by the receiver, thus, they are processed by maximal ratio combining (MRC) to enhance the corresponding SINRs. Also, we derive the closed-form expressions for outage probability and ergodic rate by forwarding hybrid signals, proving that TSS-NOMA can achieve higher performance.
3. Considering the power allocation problem from the perspective of maximising the minimum achievable rate of the system, an algorithm is proposed to optimise the power allocation at the base station and the relay. Furthermore, we evaluated the relevant factors by simulation and provided numerical proofs to prove that the performance of TSS-NOMA is better than that of the existing schemes.

The remainder of the paper is structured as follows. The system model is presented in Section 2. In Section 3, we propose the description of TSS-NOMA. Section 4 illustrates the performance of TSS-NOMA in terms of outage probability and ergodic capacity. Section 5 acquires the numerical results, followed by a conclusion in Section 6.

2 | SYSTEM MODEL

As illustrated in Figure 1, we consider a system consisting of a base station (BS), a relay node R and three NOMA users namely U1, U2 and U3, where U1 communicates directly with the BS.
As edge users of the cell, U2 and U3 cannot constitute a direct link with the BS because of their long distances from the BS. Thus, they must communicate with the BS through the assistance of the relay. Besides, R is equipped with dual antennas that can transmit and receive signals.

Provided that the channels are flat fading Rayleigh channels, therefore, they satisfy $b_q \sim CN(0, \lambda_q)$, where $q = br, b1, r1, r2, r3, R$, and $CN(0, \sigma^2)$ denotes the zero-mean complex Gaussian distribution with variance $\sigma^2$. In this model, $b_{q1}, b_{q2}, b_{q3}$ denote the channel coefficients between BS and R (BS-R), BS and U1 (BS-U1), R and U1 (R-U1), R and U2 (R-U2), R and U3 (R-U3), and $b_0$ denotes the residual self-interference channel coefficient at the relay. Accordingly, the channel gain $|b_q|^2$ is an exponential random variable with parameter $\lambda_q = d_q^{-\alpha}$, where $d_q$ and $\alpha$ denote the distance between two related nodes and the path-loss exponent, respectively. Thus, the functions of cumulative distribution and probability density are as follows,

$$F(x) = 1 - e^{-\lambda x},$$

$$f(x) = \lambda e^{-\lambda x},$$

where $x$ denotes a variable with parameter $\lambda$. Also, the system noise can be denoted as $n_j \sim CN(0, \sigma_j^2) (j = 1, 2, 3)$, where $\sigma_1^2, \sigma_2^2, \sigma_3^2$, and $\sigma_n^2$ denote the noise variances at U1, U2, U3, and R, respectively. Since the channel varies independently in different slots, users in this model can share bandwidth resources to improve spectrum efficiency in multi-user scenarios, and then they occupying the entire bandwidth resources.

3 DESCRIPTION OF TIME SLOT-SPLIT NOMA (TSS-NOMA)

Considering several scenarios as described in Figure 2, let $P_1$, $P_2$, and $P_3$ denote the power of U1, U2, and U3, respectively, and $B$ represents the bandwidth of the system. Obviously, the OMA scheme has poor performance because users share the bandwidth resources equally. Furthermore, the NOMA-OMA scheme causes a certain waste of bandwidth resources in view of the unpaired users utilise OMA mode to communicate. To solve this problem, TSS-NOMA divides an entire communication time slot into several parts for bandwidth-sharing, and the successfully paired users share the entire bandwidth in different slots to maximise the utilisation of bandwidth resources, thus further improving the ergodic capacity.

In this model, a complete communication time slot is divided into $T_1$ and $T_2$, where $T_1$ denotes the paired time of U1-U2, and $T_2$ denotes the paired time of U1-U3. Let $P_b(T_1)$ and $P_b(T_2)$ respectively, denote the transmit power of the BS in $T_1$ and $T_2$, and the overlapping coded signal in $T_1$ can be written as

$$G[T_1] = \sqrt{\alpha_1} P_b(T_1) x_1[T_1] + \sqrt{\alpha_2} P_b(T_1) x_2[T_1],$$

where $x_1[T_1]$ and $x_2[T_1]$ denote the messages sent to U1 and U2, respectively. Also, $\alpha_1$ and $\alpha_2$ denote the power allocation factors of U1 and U2 in the BS, where $\alpha_1 + \alpha_2 = 1$ and $\alpha_1 < \alpha_2$.

Based on NOMA, the relay decodes the received signals to obtain $x_1'[T_1]$ and $x_2'[T_1]$, where $x_1'[T_1]$ and $x_2'[T_1]$ denote the new symbols for U1 and U2, respectively. Besides, $x_1'[T_1]$ and $x_2'[T_1]$ are re-encoded by the relay to obtain the following hybrid symbols,

$$\sqrt{\alpha_1' P_r(T_1)} x_1'[T_1] + \sqrt{\alpha_2' P_r(T_1)} x_2'[T_1],$$

where $\alpha_1'$ and $\alpha_2'$ denote the power allocation factors of U1 and U2 in the relay, and they can be determined by the method presented in [23]. Then the hybrid symbols will be broadcast as

$$\sqrt{\alpha_1' P_r(T_1)} x_1'[T_1 - \tau] + \sqrt{\alpha_2' P_r(T_1)} x_2'[T_1 - \tau] \quad (\tau \geq 1),$$

where $\tau$ and $P_r(T_1)$ indicate the processing delay and power of the relay in $T_1$, respectively. Also, U3 remains silent during the process of U1 and U2 decoding the symbols in $T_1$ by successive interference cancellation (SIC).

In the following, the signal received by the relay can be expressed as

$$y_r[T_1] = b_r G[T_1] + b_r \left( \sqrt{\alpha_1' k P_r(T_1)} x_1'[T_1 - \tau] + \sqrt{\alpha_2' k P_r(T_1)} x_2'[T_1 - \tau] \right) + n_r[T_1],$$

where $x_1'[T_1]$ and $x_2'[T_1]$ denote the messages sent to U1 and U2, respectively.
where \( k (0 \leq k \leq 1) \) represents the FD residual self-interference factor. In particular, \( k = 0 \) implies perfect interference cancellation.

As discussed in [26], note that for transmitted symbol, the corresponding received signals from direct and cooperative relaying links reach U1 asynchronously, due to the processing delay \( \tau \). Hence, we assume that there is some temporal separation between these two signals at U1, and that they can be completely separated and processed by MRC. The signals of direct and cooperative relaying links at U1 in \( T_1 \) are as follows,

\[
y_1^d[T_1] = b_{11} G[T_1] + n_1[T_1],
\]

\[
y_1^r[T_1] = b_{11} \left( \sqrt{\alpha_1^r P(T_1) x_1^r}[T_1 - \tau] + \sqrt{\alpha_2^r P(T_1) x_2^r}[T_1 - \tau] \right) + n_1[T_1],
\]

where \( n_1 \sim CN(0, \sigma_{11}^2) \) denotes the noise involved in the signal from the relay to U1, and it includes the remained noise after SIC at the relay. Also, \( \sigma_{11}^2 \) denotes the noise variance [22].

Similarly, the received signal at U2 is given by

\[
y_2[T_1] = b_2 \left( \sqrt{\alpha_1^r P(T_1) x_1^r}[T_1 - \tau] + \sqrt{\alpha_2^r P(T_1) x_2^r}[T_1 - \tau] \right) + n_2[T_1].
\]

From the analysis of NOMA in [24], the relay first decodes \( x_2 \), and then removes it as interference before decoding \( x_1 \). Thus, the corresponding SINRs are, respectively, expressed as

\[
y_{c2} = \frac{\alpha_2 P_h(T_1) |b_{11}|^2}{\alpha_1 P_h(T_1) |b_{11}|^2 + k P_r(T_1) |b_{11}|^2 + \sigma_r^2},
\]

and

\[
y_{c1} = \frac{\alpha_1 P_h(T_1) |b_{11}|^2}{k P_r(T_1) |b_{11}|^2 + \sigma_r^2}.
\]

According to MRC, we get the SINRs for decoding \( x_2 \) and \( x_1 \) at U1 as

\[
y_{1,2} = \frac{\alpha_2 P_h(T_1) |b_{11}|^2}{\alpha_1 P_h(T_1) |b_{11}|^2 + \sigma_1^2} + \frac{\alpha_2^r P(T_1) |b_{11}|^2}{\alpha_1^r P(T_1) |b_{11}|^2 + \sigma_1^2},
\]

and

\[
y_{1,1} = \frac{\alpha_1 P_h(T_1) |b_{11}|^2}{\sigma_1^2} + \frac{\alpha_1^r P(T_1) |b_{11}|^2}{\sigma_1^2}.
\]

In the following, U2 decodes its own signal \( x_2 \), and the corresponding SINR can be denoted as

\[
y_{2,2} = \frac{\alpha_2^r P(T_1) |b_{11}|^2}{\alpha_1^r P(T_1) |b_{11}|^2 + \sigma_2^2}.
\]

Similarly, we set the power allocation factors of U1 and U3 in the BS to \( \beta_1 \) and \( \beta_3 \), where \( \beta_1 + \beta_3 = 1 \) and \( \beta_1 < \beta_3 \). Then, by decoding the signals of U3 and U1, the received SINRs at the relay are as follows,

\[
y_{c3} = \frac{\beta_1 P_h(T_2) |b_{11}|^2}{\beta_1 P_h(T_2) |b_{11}|^2 + \sigma_2^2},
\]

\[
y_{c1} = \frac{\beta_1 P_h(T_2) |b_{11}|^2}{\sigma_1^2 + \sigma_2^2},
\]

where \( P_r(T_2) \) denotes the power of the relay in \( T_2 \).

Then U1 decodes U3’s signal and its own signal, respectively, and the corresponding SINRs can be described as

\[
y_{1,3} = \frac{\beta_1 P_h(T_2) |b_{11}|^2}{\beta_1 P_h(T_2) |b_{11}|^2 + \sigma_1^2} + \frac{\beta_1^r P(T_2) |b_{11}|^2}{\beta_1^r P(T_2) |b_{11}|^2 + \sigma_1^2},
\]

and

\[
y_{1,1} = \frac{\beta_1 P_h(T_2) |b_{11}|^2}{\sigma_1^2} + \frac{\beta_1^r P(T_2) |b_{11}|^2}{\sigma_1^2},
\]

where \( \beta_1^r \) and \( \beta_3^r \) denote the power allocation factors of U1 and U3 in the relay, respectively.

Similar to (14), when U3 decodes its own signal, the corresponding SINR is given by

\[
y_{3,3} = \frac{\beta_3^r P(T_2) |b_{11}|^2}{\beta_3^r P(T_2) |b_{11}|^2 + \sigma_3^2}.
\]

Next, we maximise the minimum achievable rate of the system by optimising the power allocation at the BS and the relay. Let \( P \) denote the total power of the system, and the joint optimisation problem can be described as follows,

\[
\begin{align*}
(P_h(T_1), P_h(T_2), P_r(T_1), P_r(T_2)) &= \arg\max \{ R \} \\
\begin{array}{l}
P(T_1) + P(T_2) = P \\
P_h(T_1) + P_r(T_1) = P(T_1) \\
P_h(T_2) + P_r(T_2) = P(T_2) \\
0 < P_h(T_1), P_h(T_2) < P \\
0 < P_r(T_1), P_r(T_2) < P
\end{array}
\end{align*}
\]

(20)
where

\[
R = \min \left\{ \begin{array}{l}
R_1 \left( P_B(T_1), P_r(T_1), P_B(T_2), P_r(T_2) \right), \\
R_2 \left( P_B(T_1), P_r(T_1), R_3 \left( P_B(T_2), P_r(T_2) \right) \right)
\end{array} \right\}.
\] (21)

Also, \( P(T_1) \) and \( P(T_2) \) denote the power of \( T_1 \) and \( T_2 \), respectively.

For brevity, parameters \( R_1(P_B(T_1), P_r(T_1), P_B(T_2), P_r(T_2)) \), \( R_2(P_B(T_1), P_r(T_1)) \) and \( R_3(P_B(T_2), P_r(T_2)) \) are written as \( R_1, R_2 \) and \( R_3 \), where \( R_1, R_2 \) and \( R_3 \) denote the achievable rates of U1, U2 and U3, respectively. The corresponding expressions are as follows,

\[
R_1 = \log_2(1 + \min(\gamma_{c,1}, \gamma_{1,1})),
\]
\[
+ \log_2(1 + \min(\gamma'_{c,1}, \gamma'_{1,1})),
\] (22)

\[
R_2 = \log_2(1 + \min(\gamma_{c,2}, \gamma_{2,2}, \gamma_{1,2})),
\] (23)

\[
R_3 = \log_2(1 + \min(\gamma_{c,3}, \gamma_{3,3}, \gamma_{1,3})).
\] (24)

In fact, it is difficult to obtain the optimal solutions by directly taking (21), (22), (23) and (24) into (20), due to many factors and situations. Hence, to obtain the suboptimal solutions, we optimise the power allocation of the BS and the relay in \( T_1 \) and \( T_2 \), respectively, and then allocate the power between \( T_1 \) and \( T_2 \).

Here, U1 has a high SNR due to the fact that signals come from direct and cooperative relaying links. Moreover, edge users are usually with high mobility and time-varying positions, which usually result in users reallocations among different base stations and impact on user-perceived quality-of-service (QoS) [27]. Thus, the corresponding problem becomes maximising the achievable rates of U2 and U3, and the expressions of \( R_2 \) and \( R_3 \) can be denoted as follows,

\[
R_2 = \log_2(1 + \min(\gamma_{c,2}, \gamma_{2,2})).
\] (25)

\[
R_3 = \log_2(1 + \min(\gamma_{c,3}, \gamma_{3,3})).
\] (26)

According to [23], we consider

\[
\gamma_{c,2} = \gamma_{2,2},
\] (27)

maximising the achievable rate of U2 in \( T_1 \). By substituting (10), (14) and

\[
P_B(T_1) = P(T_1) - P_r(T_1),
\] (28)

into (27), we obtain an equation that can be expressed as

\[
AP_r^2(T_1) + BP_r(T_1) + C = 0,
\] (29)

where \( A, B \) and \( C \) are, respectively, expressed as

\[
A = |b_{1,2}|^2 |\alpha'_2| |b_{2}|^2 - \alpha_1 |\alpha'_2| |b_{1,2}|^2 + \alpha'_1 |\alpha_2| |b_{1,2}|^2,
\]

\[
B = |\alpha'_2| |b_{2}|^2 |\sigma_2|^2 + |\alpha_2| |b_{1,2}|^2 |\sigma_2|^2
\]

\[
+ (\alpha_1 |\alpha'_2| - \alpha_2 |\alpha'_1|) |b_{1,2}|^2 |b_{2}|^2 P(T_1),
\]

and

\[
C = -|\alpha'_1| |b_{1,2}|^2 |\sigma_2|^2 P(T_1).
\]

Hence, we get the expression of \( P_r(T_1) \) as follows,

\[
A > 0, \quad P_r(T_1) = \frac{-B + \sqrt{B^2 - 4AC}}{2A},
\]

\[
A < 0, \quad P_r(T_1) = \frac{-B + \sqrt{B^2 - 4AC}}{2A},
\] (30)

\[
A = 0, \quad P_r(T_1) = \frac{-C}{B}.
\]

Similarly, the expression of \( P_r(T_2) \) can be denoted as

\[
A' > 0, \quad P_r(T_2) = \frac{-B' + \sqrt{B'^2 - 4A'C'}}{2A'},
\]

\[
A' < 0, \quad P_r(T_2) = \frac{-B' + \sqrt{B'^2 - 4A'C'}}{2A'},
\] (31)

\[
A' = 0, \quad P_r(T_2) = \frac{-C'}{B'}.
\]

where \( A', B' \) and \( C' \) are, respectively, described as

\[
A' = |b_{3,1}|^2 |\beta'_3| |b_{2}|^2 - \beta_1 |\beta'_3| |b_{3,1}|^2 + |\beta'_3| |b_{1,2}|^2 |\beta_3| |b_{2}|^2,
\]

\[
B' = |\beta'_3| |b_{3,1}|^2 |\sigma_3|^2 + |\beta_3| |b_{1,2}|^2 \sigma_3^2
\]

\[
+ (\beta_1 |\beta'_3| - \beta_3 |\beta'_1|) |b_{1,2}|^2 |b_{3,1}|^2 P(T_2),
\]

and

\[
C' = -|\beta'_1| |b_{1,2}|^2 \sigma_3^2 P(T_2).
\]

According to [28], we consider

\[
R_2 = R_3,
\] (32)

allocating power to \( T_1 \) and \( T_2 \). By substituting (25), (26) and

\[
P(T_2) = P - P(T_1),
\] (33)
into (32), the equation can be denoted as

$$P_r(T_1) = \frac{I_1 P_r(T_2)}{I_2 P_r(T_2) + I_3}$$

(34)

where $I_1$, $I_2$ and $I_3$ are, respectively, described as

$$I_1 = \beta'_1 |b_{c2}|^2 \sigma_2^2,$$

$$I_2 = (\alpha'_2 \beta'_1 - \alpha'_1 \beta'_3) |b_{c2}|^2 |b_{c3}|^2,$$

and

$$I_3 = \alpha'_3 |b_{c2}|^2 \sigma_3^2.$$

Since $P_r(T_1)$ and $P_r(T_2)$ can be denoted as functions of $P_r(T_1)$, we get a polynomial equation of $P_r(T_1)$ by substituting (30) and (31) into (34), and its value can be obtained by solving the equation. Also, the values of $P_r(T_1)$ and $P_r(T_2)$ are given by (30) and (28).

In the following, substituting $P(T_1)$ into (33) yields the value of $P(T_2)$, and the values of $P'_r(T_2)$ and $P'_r(T_2)$ can be acquired from (31) and (20). Hence, the problem of power allocation being solved.

4 | PERFORMANCE ANALYSIS OF TSS-NOMA

4.1 | Outage probability

Suppose that the target SINRs for decoding the signals of U1, U2 and U3 are $\gamma_{1,T} = 2^{L_1} - 1$, $\gamma_{2,T} = 2^{L_2} - 1$ and $\gamma_{3,T} = 2^{L_3} - 1$, where $L_1$, $L_2$ and $L_3$ denote the target rates of U1, U2 and U3 decoding their own signals, respectively.

Since the channels are independent of each other, the outage probability of U1 in $T_1$ can be expressed as

$$p_{out,1} = 1 - \xi_1 \xi_2 \xi_3 \xi_4$$

(35)

where $\xi_1$ and $\xi_2$ are, respectively, given by

$$\xi_1 = \Pr \{\gamma_{1,T} \geq \gamma_{2,T}\}$$

$$= \frac{\lambda_{pr} P_r(T_1)(1 - \alpha_1 - \alpha_1 \gamma_{2,T})}{\lambda_{pr} P_r(T_1)(1 - \alpha_1 - \alpha_1 \gamma_{2,T}) + \gamma_{2,T} k P_r(T_1) \lambda_R}$$

$$\times \exp \left( - \frac{\gamma_{2,T} \sigma_{2}^2}{\lambda_{pr} P_r(T_1)(1 - \alpha_1 - \alpha_1 \gamma_{2,T})} \right),$$

and

$$\xi_2 = \Pr \{\gamma_{1,T} \geq \gamma_{1,T}\}$$

$$= \frac{\lambda_{pr} \alpha_1 P_r(T_1)}{\lambda_{pr} P_r(T_1) \gamma_{1,T} + \lambda_{pr} \alpha_1 P_r(T_1)}$$

(37)

Provided that relay to U1 at a high SNR as

$$\frac{\alpha'_1 P_r(T_1) |b_{c1}|^2}{\alpha'_1 P_r(T_1) |b_{c1}|^2 + \sigma_{11}^2} = \frac{\alpha'_2}{\alpha'_1},$$

(38)

and then $\xi_3$ can be approximated as

$$\xi_3 = \Pr \left\{\frac{\alpha_2 P_r(T_1) |b_{c2}|^2}{\alpha_1 P_r(T_1) |b_{c2}|^2 + \sigma_2^2} + \frac{\alpha'_2}{\alpha'_1} \geq \gamma_{2,T} \right\}$$

$$= \exp \left( - \frac{\sigma_2^2 (\gamma_{2,T} - \alpha'_2)}{\lambda_{pr} P_r(T_1) (\alpha'_1 \gamma_{2,T} + \alpha_1 \alpha'_2)} \right).$$

(39)

According to the double integral, we can obtain the expression of $\xi_4$ as follows,

$$\xi_4 = \Pr \{\gamma_{1,T} \geq \gamma_{1,T}\}$$

$$= f_2 \exp \left( - \frac{\sigma_{2}^2 \gamma_{1,T}}{\lambda_{pr} P_r(T_1)} \right),$$

(40)

where $f_1$ and $f_2$ are, respectively, given by

$$f_1 = \frac{\lambda_{pr} \alpha'_1 P_r(T_1) \sigma_{11}^2}{\lambda_{pr} \alpha'_1 P_r(T_1) \sigma_{11}^2 - \lambda_{pr} \alpha_1 P_r(T_1) \sigma_{11}^2},$$

(41)

and

$$f_2 = \frac{\lambda_{pr} \alpha_1 P_r(T_1) \sigma_{11}^2}{\lambda_{pr} \alpha'_1 P_r(T_1) \sigma_{11}^2 - \lambda_{pr} \alpha_1 P_r(T_1) \sigma_{11}^2}.$$

(42)

Similarly, we can obtain the outage probability of U2 in $T_1$ as

$$p_{out,2} = 1 - \xi'_1 \xi'_2 \xi'_3,$$

(33)
where $\xi_1' = \xi_1$, $\xi_2' = \xi_2$ and $\xi_3'$ can be written as

$$
\xi_3' = \Pr\{\gamma_{2,2} \geq \gamma_{2,T}\}
= \exp\left(-\frac{\gamma_{2,T}\sigma^2}{\lambda_{2r}P_r(T_1)(1 - \alpha_1' - \alpha_2'\gamma_{2,T})}\right). \tag{44}
$$

Since the two slots apply the identical principle, the outage probability of U1 in $T_2$ can be denoted as

$$
P_{out}^{T_2} = 1 - Q_1Q_2Q_3, \tag{45}
$$

where $Q_1$, $Q_2$, and $Q_3$ are, respectively, given by

$$
Q_1 = \frac{P_{out}(T_2)(1 - \beta_1 - \beta_2\gamma_{3,T})}{\lambda_{br}P_b(T_2)(1 - \beta_1 - \beta_2\gamma_{3,T}) + \gamma_{3,T}\kappa P_r(T_2)\lambda_R} \times \frac{\lambda_{br}\beta_1P_b(T_2)}{kP_r(T_2)\gamma_{1,T}\lambda_R + \lambda_{br}\beta_1P_b(T_2)},
$$

$$
Q_2 = \exp\left(-\frac{\gamma_{3,T}\beta_1^2\sigma^2}{\lambda_{br}P_b(T_2)(1 - \beta_1 - \beta_2\gamma_{3,T})}\right) \times \exp\left(-\frac{\gamma_{3,T}\sigma^2}{\lambda_{br}P_b(T_2)(1 - \beta_1 - \beta_2\gamma_{3,T})}\right) \times \exp\left(-\frac{\sigma^2\gamma_{1,T}}{\lambda_{br}\beta_1P_b(T_2)}\right), \tag{46}
$$

and

$$
Q_3 = \frac{\lambda_{br}\beta_1^2P_b(T_2)^2\sigma^2}{\lambda_{br}\beta_1^2P_b(T_2)\sigma^2 - \lambda_{br}\beta_1P_b(T_2)\sigma^2_{11}} \times \exp\left(-\frac{\sigma^2_{11}\gamma_{1,T}}{\lambda_{br}\beta_1P_b(T_2)}\right) \times \exp\left(-\frac{\sigma^2\gamma_{1,T}}{\lambda_{br}\beta_1P_b(T_2)}\right). \tag{47}
$$

In the following, the outage probability of U3 in $T_2$ can be calculated by

$$
P_{out}^{T_2} = 1 - \frac{P_{out}(T_2)(1 - \beta_1 - \beta_2\gamma_{3,T})}{\lambda_{br}P_b(T_2)(1 - \beta_1 - \beta_2\gamma_{3,T}) + \gamma_{3,T}\kappa P_r(T_2)\lambda_R} \times H \frac{\lambda_{br}\beta_1P_b(T_2)}{kP_r(T_2)\gamma_{1,T}\lambda_R + \lambda_{br}\beta_1P_b(T_2)}, \tag{49}
$$

where $H$ can be denoted as

$$
H = \exp\left(-\frac{\gamma_{3,T}\sigma^2}{\lambda_{br}P_b(T_2)(1 - \beta_1 - \beta_2\gamma_{3,T})}\right) \times \exp\left(-\frac{\gamma_{3,T}\sigma^2}{\lambda_{br}P_b(T_2)(1 - \beta_1' - \beta_2'\gamma_{3,T})}\right) \times \exp\left(-\frac{\sigma^2\gamma_{1,T}}{\lambda_{br}\beta_1P_b(T_2)}\right). \tag{50}
$$

Hence, the expressions of outage probability in $T_1$ and $T_2$ are denoted as

$$
P_{out}^{T_1} = 1 - \left(1 - P_{out}^{T_1}\right)\left(1 - P_{out}^{T_1}\right), \tag{51}
$$

and

$$
P_{out}^{T_2} = 1 - \left(1 - P_{out}^{T_2}\right)\left(1 - P_{out}^{T_2}\right). \tag{52}
$$

Finally, the outage probability of the system can be calculated by

$$
P_{out} = 1 - \left(1 - P_{out}^{T_1}\right)\left(1 - P_{out}^{T_2}\right). \tag{53}
$$

### 4.2 Ergodic capacity

Provided that the total bandwidth of the system is normalised to 1 Hz, we can acquire the ergodic rates of users in different time slots.

Let $\theta = \min(\gamma_{r,1}, \gamma_{1,1})$ denote a random variable, according to the SINRs in the previous section, the expression of the ergodic capacity of the BS to U1 in $T_1$ can be written as

$$
R_{U_1}^{T_1} = \mathbb{E}[\log_2(1 + \theta)]
= \int_0^{\infty} \log_2(1 + \theta)f_X(\theta)d\theta \tag{54}
$$

and

$$
= \frac{1}{\ln 2} \int_0^{\infty} \frac{1 - F_X(\theta)}{1 + \theta}d\theta,
$$

where $f_X(\theta)$ and $F_X(\theta)$ denote the probability density function and cumulative distribution function of $\theta$, respectively, and the expression of $F_X(\theta)$ can be described as

$$
F_X(\theta) = \Pr\{\min(\gamma_{r,1}, \gamma_{1,1}) < \theta\}
= 1 - \omega_1\omega_2, \tag{55}
$$

where $\omega_1$ and $\omega_2$ are the lower and upper bounds of the SINR, respectively.
where $\omega_1$ and $\omega_2$ are, respectively, given by

$$
\omega_1 = \Pr \{ y_{r,1} > \theta \} = \frac{\lambda_{br} \alpha_1 \alpha_1' P_b(T_1)}{k \lambda_{br} P_b(T_1) \lambda_R + \lambda_{br} \alpha_1 P_b(T_1)} \times \exp \left( -\frac{\sigma^2 \beta}{\lambda_{br} \alpha_1 P_b(T_1)} \right),
$$

and

$$
\omega_2 = \Pr \{ y_{1,1} > \theta \} = \frac{\lambda_{br} \alpha_1' P_b(T_1) \sigma^2}{\lambda_{br} \alpha_1' P_b(T_1) \sigma^2_1 - \lambda_{br} \alpha_1 P_b(T_1) \sigma^2_1} \times \exp \left( -\frac{\sigma^2 \beta}{\lambda_{br} \alpha_1 P_b(T_1)} \right) \times \exp \left( -\frac{\sigma^2 \beta}{\lambda_{br} \alpha_1 P_b(T_1)} \right) \times \exp \left( -\frac{\sigma^2 \beta}{\lambda_{br} \alpha_1 P_b(T_1)} \right).
$$

Combined with the equation

$$
\int_0^{+\infty} \frac{1}{1 + \theta} e^{-\theta} d\theta = -e^\theta Ei(-\theta)
$$

in [29], the ergodic rate of the BS to U1 in $T_1$ can be expressed as

$$
R_{T_1}^{U_1} = \frac{1}{\ln 2} \left[ -M \exp \left( \frac{\sigma^2}{\lambda_{br} \alpha_1 P_b(T_1)} + \frac{\sigma^2_1}{\lambda_{br} \alpha_1 P_b(T_1)} \right) \times Ei \left( -\frac{\sigma^2}{\lambda_{br} \alpha_1 P_b(T_1)} - \frac{\sigma^2_1}{\lambda_{br} \alpha_1 P_b(T_1)} \right) - N \exp \left( \frac{\sigma^2}{\lambda_{br} \alpha_1 P_b(T_1)} + \frac{\sigma^2_1}{\lambda_{br} \alpha_1 P_b(T_1)} \right) \times Ei \left( -\frac{\sigma^2}{\lambda_{br} \alpha_1 P_b(T_1)} - \frac{\sigma^2_1}{\lambda_{br} \alpha_1 P_b(T_1)} \right) \right],
$$

where $M$ and $N$ are, respectively, denoted as

$$
M = \frac{-\lambda_{br} \lambda_{br} \alpha_1 \alpha_1' P_b(T_1) \sigma^2_1}{\lambda_{br} \alpha_1' P_b(T_1) \sigma^2_1 - \lambda_{br} \alpha_1 P_b(T_1) \sigma^2_1} \times \frac{1}{k \lambda_{br} P_b(T_1) + \lambda_{br} \alpha_1 P_b(T_1)},
$$

and

$$
N = \frac{\lambda_{br} \lambda_{br} \alpha_1 \alpha_1' P_b(T_1) P_b(T_1) \sigma^2_1}{\lambda_{br} \alpha_1' P_b(T_1) \sigma^2_1 - \lambda_{br} \alpha_1 P_b(T_1) \sigma^2_1} \times \frac{1}{k \lambda_{br} P_b(T_1) + \lambda_{br} \alpha_1 P_b(T_1)}.
$$

Also, it is easy to obtain that the ergodic rate of the BS to U2 in $T_1$ is

$$
R_{T_1}^{U_2} = \frac{1}{\ln 2} \int_0^{\sigma_1} \frac{V}{1 + \rho} d\rho,
$$

where $\rho = \min(\gamma_{2,2}, \gamma_{1,2})$ denotes a random variable, and the value of $V$ can be calculated by

$$
V = \frac{\lambda_{br} P_b(T_1)(1 - \alpha_1 - \alpha_1\rho)}{\lambda_{br} P_b(T_1)(1 - \alpha_1 - \alpha_1\rho) + \rho k \lambda_{br} P_b(T_1) \lambda_R} \times \exp \left( -\frac{\rho \sigma^2 \alpha'_1 - \alpha_1^2 \sigma^2}{\lambda_{br} P_b(T_1)(\alpha_2 \alpha'_1 - \alpha_1 \alpha'_1 \rho + \alpha_1 \alpha'_2)} \right) \times \exp \left( -\frac{\sigma^2 \rho}{\lambda_{br} \alpha'_2 P_b(T_1) - \lambda_{br} \alpha_1' P_b(T_1)} \right) \times \exp \left( -\frac{\sigma^2 \rho}{\lambda_{br} \alpha'_2 P_b(T_1) - \lambda_{br} \alpha_1' P_b(T_1)} \right).
$$

Similarly, the ergodic rate of the BS to U1 in $T_2$ can be denoted as

$$
R_{T_2}^{U_1} = \frac{1}{\ln 2} \left[ -M' \exp \left( \frac{\sigma^2}{\lambda_{br} \beta_1 P_b(T_2)} + \frac{\sigma^2_1}{\lambda_{br} \beta_1 P_b(T_2)} \right) \times Ei \left( -\frac{\sigma^2}{\lambda_{br} \beta_1 P_b(T_2)} - \frac{\sigma^2_1}{\lambda_{br} \beta_1 P_b(T_2)} \right) - N' \exp \left( \frac{\sigma^2}{\lambda_{br} \beta_1 P_b(T_2)} + \frac{\sigma^2_1}{\lambda_{br} \beta_1 P_b(T_2)} \right) \times Ei \left( -\frac{\sigma^2}{\lambda_{br} \beta_1 P_b(T_2)} - \frac{\sigma^2_1}{\lambda_{br} \beta_1 P_b(T_2)} \right) \right],
$$

where $M'$ and $N'$ are, respectively, described as

$$
M' = \frac{-\lambda_{br} \lambda_{br} \beta_1 \beta'_1 P_b(T_2) \sigma^2_1}{\lambda_{br} \beta'_1 P_b(T_2) \sigma^2_1 - \lambda_{br} \beta_1 P_b(T_2) \sigma^2_1} \times \frac{1}{k \lambda_{br} P_b(T_2) + \lambda_{br} \beta_1 P_b(T_2)},
$$

and

$$
N' = \frac{\lambda_{br} \lambda_{br} \beta_1 \beta'_1 P_b(T_2) P_b(T_2) \sigma^2_1}{\lambda_{br} \beta'_1 P_b(T_2) \sigma^2_1 - \lambda_{br} \beta_1 P_b(T_2) \sigma^2_1} \times \frac{1}{k \lambda_{br} P_b(T_2) + \lambda_{br} \beta_1 P_b(T_2)}.
$$
and

\[
\mathcal{N}' = \frac{\lambda_{br}\lambda_{br}\beta_1^2\beta_1 P_b(T_2) P_b(T_2) \sigma_1^2}{\lambda_{br}\beta_1^2 P_b(T_2) \sigma_1^2 - \lambda_{br}\beta_1 P_b(T_2) \sigma_{11}^2} \times \frac{1}{\lambda_{br} P_b(T_2) + \lambda_{br}\beta_1 P_b(T_2)}.
\]

Then we can obtain the ergodic rate of the BS to U3 in T_2 as

\[
R_{U3}^{T_2} = \frac{1}{\ln 2} \int_0^{\frac{\gamma_1}{\rho'}} \frac{V'}{1 + \rho'} d\rho',
\]

where \(\rho' = \min(\gamma, \gamma, \gamma, \gamma)\) denotes a random variable, and the value of \(V'\) is given by

\[
V' = \frac{\lambda_{br} P_b(T_2)(1 - \beta_1 - \beta_1 \rho')}{\lambda_{br} P_b(T_2)(1 - \beta_1 - \beta_1 \rho') + \rho' k P_b(T_2) \lambda_R} \times \exp\left(\frac{\rho' \sigma_1^2 \beta_1^2 - \beta_1 P_b(T_2) \sigma_{11}^2}{\lambda_{br} P_b(T_2) \beta_3^2 \beta_3 - \lambda_{br} \beta_3^2 P_b(T_2) \rho'}\right) \times \exp\left(\frac{\sigma_1^2 \rho' \beta_1^2}{\lambda_{br} P_b(T_2)(1 - \beta_1 - \beta_1 \rho')}\right).\]

Therefore, we can obtain the sum ergodic rate of the system by

\[
R_{sum} = R_{U1}^{T_1} + R_{U2}^{T_1} + R_{U1}^{T_2} + R_{U3}^{T_2}.
\]

\section{Numerical Results}

In this section, simulations are implemented to verify the performance of the proposed TSS-NOMA scheme and demonstrate the accuracy of these derived expressions. We consider \(\lambda_{br} = \lambda_{r1} = 0.5, \lambda_{r2} = 0.4, \lambda_{r3} = 0.3, \sigma_1^2 = \sigma_2^2 = \sigma_{11}^2 = 1, k = 0.08^2, \alpha_1 = \beta_1 = 0.05\) and \(\alpha_1' = \beta_1' = 0.01\), and assume the Monte Carlo simulation times are \(10^7\). Furthermore, the total transmit SNR is denoted as \(N_0\), where \(N_0\) denotes the power of noise. The target SNRs of U1, U2 and U3 are defined as \(\gamma_{1,T} = \gamma_{2,T} = \gamma_{3,T} = 1\), respectively. The performance of TSS-NOMA is illustrated by theoretical analysis in the following scenarios.

We consider the scheme proposed in [22] as the comparison scheme to verify the theoretical analysis of outage probability. Figure 3 demonstrates the outage probabilities of users with the change in SNR between the comparison scheme and M-NOMA, where M-NOMA denotes a special TSS-NOMA for dual users. Also, M-NOMA transmits hybrid signals through the new factors of U1 and U2 to optimise the power allocation at the BS and the relay. Obviously, the outage performance of U2 tends to be poor, due to its lower power in M-NOMA. In addition, due to the fact that M-NOMA does not regard the signals from cooperative relaying link as interference, the outage probability of U1 can be further decreased with the increase in SNR. As a result, M-NOMA scheme has better outage performance than that of the comparison scheme.

Figure 4 shows the outage probability as a function of the parameter \(\mu\), where \(\mu\) and \((1 - \mu)\) denote power allocation factors of \(T_1\) and \(T_2\). By taking the total transmit SNR of 40dB into \((20)\), we note that the probabilities of U1 and U2 in \(T_1\) decrease with the increase in \(\mu\), due to the increase of power allocated by \(T_1\). Simultaneously, the outage performance of U1 and U3 in \(T_2\) decreases gradually. As such, the system achieves the best performance when the power allocation factor \(\mu\) is about 0.5.

Figure 5 demonstrates the comparison of the ergodic rate versus SNR between TSS-NOMA and N-NOMA to
validate the advantages of the power allocation method, where N-NOMA represents a special TSS-NOMA scheme without power allocation. Unlike N-NOMA scheme, TSS-NOMA maximises the minimum achievable rate of the system by optimising the power allocation of the BS and the relay in \( T_1 \) and \( T_2 \), respectively. It can be seen from the diagram that the ergodic rate of the system enlarges with the increase in SNR. Also, result shows that TSS-NOMA scheme has higher spectrum efficiency when the bandwidth is limited.

In Figure 6, we show the ergodic rate versus power allocation factor \( \mu \) of \( T_1 \). Results demonstrate that the ergodic rates of U1 and U2 in \( T_1 \) increase with the increase in \( \mu \). By contrast, the rates of U1 and U3 in \( T_2 \) are decreased due to less power allocated, which diminishes the performance of the system. Also, taking the results in Figure 4 into consideration, we should make a tradeoff to balance outage and ergodic capacity when determining the value of the power allocation factor \( \mu \).

Figure 6 shows the variation of system throughput in \( k \) between TSS-NOMA and N-NOMA. We observe that the degree of self-interference cancellation of the system decreases with the increase in \( k \), as a result of which the system throughput reduces accordingly. Furthermore, due to the power allocation between \( T_1 \) and \( T_2 \), the system throughput of the TSS-NOMA is much better than that of N-NOMA.

6 | CONCLUSION

In this work, we have developed a TSS-NOMA scheme for FD cooperative communication systems to improve spectrum and resource efficiency. It has been concluded that better system performance is achieved than other available schemes if users occupy the entire bandwidth when pairing and communicating in different time slots. Meanwhile, the presented relay transmission method, where the relay node re-encodes the decoded signal by a new power allocation factor, proves to improve outage performance and ergodic capacity. It receives and decodes the user signals according to the protocols of SIC and MRC. Also, the method of power allocation between the BS and the relay is presented in the scheme. Through a theoretical analysis, the value of the power allocation factor has a significant impact on maximising the minimum achievable rate of the system. Results indicate that, compared with other schemes mentioned in this paper, TSS-NOMA for FD cooperative communication system has better outage and ergodic capacity, thus improving the performance of the system.

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