IEEE Access
Multidisciplinary ⋮ Rapid Review ⋮ Open Access Journal

Received August 15, 2016, accepted August 27, 2016, date of publication August 30, 2016, date of current version September 16, 2016.

Digital Object Identifier 10.1109/ACCESS.2016.2604341

Hybrid Decode-Forward & Amplify-Forward Relaying With Non-Orthogonal Multiple Access

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This work was supported by the National Natural Science Foundation of China under Grant 61372117, Grant 61471055, Grant 61401372, and Grant 61302090.

ABSTRACT Cooperative communication has used to be a hot topic and it has been studied extensively in the past 10 years, but in recent years, it becomes less likely to find substantial innovation in this field as before. In this paper, we propose a new hybrid decode-forward and amplify-forward with non-orthogonal multiple access (NOMA) (HDAF-NOMA) transmission scheme for a cellular system with multiple relays. To the best of our knowledge, this is the first work that attempts to integrate decode-forward (DF), amplify-forward, and NOMA into one strategy design to improve system performance. To verify the performance advantages, the proposed HDAF-NOMA scheme is compared with the other four traditional schemes in terms of channel capacity and average system throughput, and the optimal number of selected DF relays is also determined for the HDAF-NOMA scheme. Simulation results show that compared with the traditional schemes, the proposed HDAF-NOMA scheme can achieve larger sum channel capacity for the transmission of x_1 and x_2, and it can also achieve larger average system throughput at high SNR region.

INDEX TERMS NOMA, non-orthogonal multiple access, DF, decode-forward, AF, amplify-forward, relay.

I. INTRODUCTION

Cooperative communication is basically to improve the capacity or the reliability of a wireless network by having a number of relays help a source communicating with a destination. It is one of the most effective ways to combat multipath fading of wireless channels and improve system throughput performance. A fundamental structure of cooperative systems can be traced back to the relay systems in the early works of van der Meulen [1] and Cover and El Gamal [2]. Some protocols have been proposed to implement cooperative communication including fixed relaying and adaptive relaying [3]. Among these protocols, amplify forward (AF) and decode forward (DF) are two categories of well known cooperative relaying protocols. By AF protocols, a relay amplifies and forwards the received signal from the source to the destination, while by DF protocols a relay first decodes the received signal, then re-encodes and forwards it to the destination.

These cooperative relaying protocols all have their problems, e.g., in AF relaying, an AF relay amplifies not only the desired signal but also the noise; while in DF relaying, a DF relay cannot help the destination if it cannot successfully decode the signal from the source, so that in DF relaying the system resources may not be fully utilized, and that may lead to some loss in system performance. In [4], focusing on the worst case scenarios, it was shown that the performance of fixed decode forward (FDF) and AF modes is not much different, and is pretty bad for both cases. To improve spectral efficiency, a variety of cooperative relaying strategies have been studied. Among them, one category of the strategies is hybrid cooperative relaying. A hybrid decode-amplify-forward protocol was proposed in [5]–[11], which has better performance than both the AF and the DF protocols. Specifically, [5] proposed a hybrid decode-amplify-forward protocol in which the relay performs soft coding and forwards the reliability information, it has the merit of soft information representation in AF and coding gain in DF. In [6] and [7], a hybrid fixed decode-forward and amplify-forward (HDAF) relaying protocol was investigated, it was shown that HDAF outperforms adaptive decode forward (ADF) and AF in terms of symbol error performance, and the performance gain depends on the relay's location. Reference [8] proposed a hybrid decode-amplify-forward protocol in which the relays close to the source amplify-and-forward the received signal while other relays decode-and-forward the received signal if they can decode successfully. Reference [9] studied the outage performance of a hybrid decode-amplify-forward protocol with the n-th best-relay selection scheme. Reference [10] proposed an incremental hybrid decode-amplify-forward protocol in which a relay can keep silent or transmit message by DF or AF, and the mode selection is based on channel qualities. In [11] a hybrid DF and AF with network coding (HDAF-NC) scheme was proposed for a wireless two-way relay network, where the relay nodes can still forward the network coded information when one of the packets from the two source nodes cannot be correctly decoded.

Another category of the cooperative relaying strategies is the NOMA relaying which has been shown as an effective way to improve spectral efficiency. It was shown in [12]–[14] that NOMA schemes can have larger sum channel capacity than orthogonal multiple access schemes such as time-division multiple access (TDMA) and frequency-division multiple access (FDMA) for both single and multiple antenna systems, and the performance gap between the NOMA and the orthogonal schemes is enlarged as the disparity between the channel gains of the two receivers increases. Originally, NOMA was named as superposition coding, and it was introduced for efficient broadcasting, by which the throughput of a broadcast/multicast system can be improved. For a wireless system with relays, a two-step relaying scheme based on NOMA was introduced for improving the rates in [15], and the problem was further studied in [16] and [17]. Other works on cooperative NOMA can also be found in [18]–[22], and other works on relay networks can be found in [23]–[27].

In this paper, we propose a new hybrid DF & AF with NOMA transmission scheme for a cellular system with multiple relays. The channel capacity for the transmission of x_1 and x_2 is first given for the HDAF-NOMA scheme, and as a benchmark the channel capacity for the transmission of x_1 and x_2 is also given for the other four traditional schemes, namely, the DF with NOMA Best Relay (DF-NOMA-BR), the DF with NOMA Multi-Relay (DF-NOMA-MR), the DF with Time-Division Multiple Access Best Relay (DF-TDMA-BR), and the DF with Time-Division Multiple Access Multi-Relay (DF-TDMA-MR) schemes. Then the average system throughput of the HDAF-NOMA scheme is compared with that of the other four traditional schemes. Finally, the optimal number of selected DF relays is determined for the HDAF-NOMA scheme. Compared with existing works, the main contribution of this paper can be summarized as:

- To the best of our knowledge, the proposed HDAF-NOMA scheme is the first work that attempts to integrate DF, AF, and NOMA into one strategy design to improve system performance.
- Simulation results show that the proposed HDAF-NOMA scheme can achieve larger sum channel capacity for the transmission of x_1 and x_2, and at high SNR region the proposed HDAF-NOMA scheme can achieve larger average system throughput than the traditional schemes.

The rest of this paper is organized as follows. In Section II background knowledge of NOMA is introduced. System model is presented in Section III. In Section IV the proposed HDAF-NOMA scheme is described in terms of channel capacity, average system throughput, and the optimal number of selected DF relays. Simulation results are given in Section V. Finally, conclusions are summarized in Section VI.

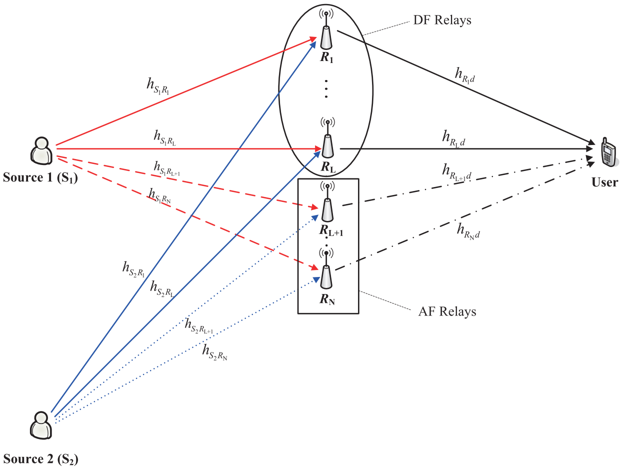


FIGURE 1. **A wireless communication system with two sources, one user and multiple relays.**

II. SYSTEM MODEL

Consider a wireless communication system as shown in Fig. 1 where two sources (S_1, S_2) transmit data to a user (d) with the help of N ($N \geq 1$) relays. Each node is equipped with a single antenna and work in half-duplex mode. All wireless channels are assumed to be quasi-static independent and identically distributed (i.i.d.) Rayleigh fading with zero mean and unit variance, the channel gains are shown in Fig. 1. The distance from source i to relay j is $r_{S_iR_j}$ ($i \in \{1, 2\}$, $j \in \{1, 2, \ldots, N\}$), and the distance from relay j to the user is r_{R_jd} ($j \in \{1, 2, \ldots, N\}$). To simplify the problem, it is assumed that there is no direct link between the two sources and the user. We assume that all channel state information (CSI) is known to the two sources, and all relay-related CSI (i.e., $\left|h_{S_iR_j}\right|^2$ and $\left|h_{R_jd}\right|^2$, $i \in \{1, 2\}, j \in \{1, 2, \ldots, N\}$) is known to the relays. Let P_1 and P_2 be the transmit power at S_1 and S_2, respectively, $P = P_1 + P_2$ be the total transmit power and it is equally shared by all the relays, hence the transmit power at each relay is $P_R = (P_1 + P_2)/N$. The noises observed by each node are assumed to have a Gaussian distribution with zero mean and variance N_0, the total transmit SNR at source i is defined as $\rho_i \triangleq P_i/N_0$ ($i \in \{1, 2\}$), and hence the transmit SNR at each relay is $\rho_{\mathrm{R}} = (\rho_1 + \rho_2)/N$.

In the HDAF-NOMA scheme, the transmission of source data is completed within two equal-length time slots. In the first time slot, source S_1 and S_2 simultaneously broadcast message x_1 and x_2 to all the relays (R_j, $j \in \{1, 2, \ldots, N\}$) and the user ($d$) at the same frequency, respectively. Thus signal x_1 and x_2 will meet and superimpose with each other in the air. Without loss of generality, we assume the average received SNR of signal x_1 is greater than that of signal x_2 at the relays, let $I = \{1, 2, \ldots, N\}$ be the index set associated with the ordered received SNR of signal x_1 at the relays such that $\frac{\rho_1|h_{S_1R_1}|^2}{1+\rho_2|h_{S_2R_1}|^2} \geq \frac{\rho_1|h_{S_1R_2}|^2}{1+\rho_2|h_{S_2R_2}|^2} \geq \cdots \geq \frac{\rho_1|h_{S_1R_N}|^2}{1+\rho_2|h_{S_2R_N}|^2}$. At the relays, each relay tries to decode strong signal x_1 first, treating weak signal x_2 as interference. We assume that in the first time slot a total of L ($L \in \{1, 2, \ldots, N\}$) relays can successfully decode signal x_1, and hence a total of $N - L$ relays cannot decode signal x_1. In the second time slot, each of the L relays which have successfully decoded signal x_1 in the first time slot performs a DF relaying for signal x_1, i.e., re-encodes and forwards x_1 to the user; and each of the other $N - L$ relays which have failed in decoding signal x_1 in the first time slot performs an AF relaying for signal x_1 and x_2, i.e., amplifies the received superimposed signal of x_1 and x_2, and forwards it to the user. Then successive interference cancellation (SIC) is used for decoding signal x_1 and x_2 at the user. The main idea of SIC is that one user message is first decoded under the interference of the other users' messages, then its signal is stripped away from the overall received signal before the next user message is decoded. An application of the proposed system model is that two neighboring base stations transmitting data to a user who is located at the overlapped area of the two cells, with the help of multiple relays.

III. HYBRID DF & AF WITH NOMA

In this section mathematical expressions are used to describe the HDAF-NOMA scheme. Specifically, the capacity for the transmission of x_1 and x_2 is first given for the HDAF-NOMA scheme, and as a benchmark the channel capacity for the transmission of x_1 and x_2 is also given for the other four traditional schemes, namely, the DF with NOMA Best Relay (DF-NOMA-BR), the DF with NOMA Multi-Relay (DF-NOMA-MR), the DF with Time-Division Multiple Access Best Relay (DF-TDMA-BR), and the DF with Time-Division Multiple Access Multi-Relay (DF-TDMA-MR) schemes. Then for the case that source S_1 and S_2 transmit with fixed rate R_1 and R_2, the average system throughput of the HDAF-NOMA scheme is compared with that of the other four traditional schemes. Finally, the optimal number of selected DF relays is determined for the HDAF-NOMA scheme. In this paper a TDMA scheme is the one in which time is split for source S_1 and S_2 broadcasting data, and a NOMA scheme is the one in which power is split for source S_1 and S_2 broadcasting data.

A. CHANNEL CAPACITY

In the first time slot, source S_1 and S_2 simultaneously broadcast signal x_1 and x_2 to all the relays and the user at the same frequency with transmit power P_1 and P_2, respectively. We assume there is no direct link between the two sources and the user. Then the received signal at relay i ($i \in \{1, 2, \ldots, N\}$) is

$$y_{R_i} = \sqrt{P_1}h_{S_1R_i}x_1 + \sqrt{P_2}h_{S_2R_i}x_2 + z_{R_i}, \tag{1}$$

where $i \in \{1, 2, \ldots, N\}$, z_{R_i} is the additive white Gaussian noise at relay R_i. Among these relays, we assume there are L ($L \in \{1, 2, \ldots, N\}$) relays which can successfully decode signal x_1 in the first time slot, treating signal x_2 as interference.

In the second time slot, each of the L relays which have successfully decoded signal x_1 in the first time slot performs a DF relaying for signal x_1, i.e., re-encodes and forwards x_1 to the user with a transmit power of $P_R = (P_1 + P_2)/N$, and each of the other $N - L$ relays which have failed in decoding signal x_1 in the first time slot performs an AF relaying for signal x_1 and x_2, i.e., amplifies the received superimposed signal of x_1 and x_2, and forwards it to the user with the same transmit power of $P_R = (P_1 + P_2)/N$. Let the amplifier gain at relay n be $\beta_n = \sqrt{\frac{\rho_R/N}{\rho_1|h_{S_1R_n}|^2+\rho_2|h_{S_2R_n}|^2+1}}$ ($n \in \{L + 1, \ldots, N\}$), where $\rho_R = \rho_1 + \rho_2$, $\rho_1 = P_1/N_0$, $\rho_2 = P_2/N_0$, then after two time slots the received signal at the user is given by

$$\begin{aligned} y_d &= \sqrt{\frac{P_R}{N}}\sum_{m=1}^{L} h_{R_md}x_1 + \sum_{n=L+1}^{N} \beta_n h_{R_nd}y_{R_n} + z_d \\ &= \sqrt{\frac{P_R}{N}}\left[\left(\sum_{m=1}^{L} h_{R_md}\right)x_1 + \sqrt{P_1}\left(\sum_{n=L+1}^{N} \alpha_n h_{S_1R_n}\right)x_1\right. \\ &\quad \left. + \sqrt{P_2}\left(\sum_{n=L+1}^{N} \alpha_n h_{S_2R_n}\right)x_2 + \left(\sum_{n=L+1}^{N} \alpha_n z_{R_n}\right)\right] + z_d \end{aligned} \tag{2}$$

where $\alpha_n = \frac{h_{R_nd}}{\sqrt{P_1|h_{S_1R_n}|^2+P_2|h_{S_2R_n}|^2+N_0}}$, z_d is the additive white Gaussian noise at the user.

As in the second time slot a total of L relays perform a DF relaying for x_1, and the other $N - L$ relays perform an AF relaying for the superimposed signal of x_1 and x_2, so that if the transmit power for x_2 at S_2 is not much higher than that for x_1 at S_1, signal x_1 can be seen as a strong signal and signal x_2 can be seen as a weak one at the user. Assuming that the signals from separate transmitters can be perfectly synchronized at the user, the two signals (x_1 and x_2) will meet and superimpose with each other in the air, then SIC can be used for decoding signal x_1 and x_2 at the user, i.e., at the user x_1 is first decoded under the interference of x_2, then signal x_1 is reconstructed and cancelled from the overall received signal, obtaining a clean signal x_2 for decoding. So this type of transmission scheme can be seen as a form of Hybrid DF & AF with NOMA (HDAF-NOMA) scheme.

As we know, the maximum mutual information for DF relaying is [3]

$$\begin{aligned} I_{DF} = \frac{1}{2}\min\Big\{&\log\left(1 + SNR|\partial_{sr}|^2\right), \\ &\log\left(1 + SNR|\partial_{sd}|^2 + SNR|\partial_{rd}|^2\right)\Big\}, \end{aligned} \tag{3}$$

therefore, assuming that there is no direct link between the two sources and the user, and assuming that the signals from separate transmitters can be perfectly synchronized at the user, if the channel capacity between S_1 and the L-th relay is greater than the total channel capacities between all the N relays and the user, then the maximum mutual information between input signal at S_1 and output signal y_d at the user will be restricted by the latter in Eq. (3) (i.e., the total channel capacities between all the N relays and the user) [28]. Therefore within two time slots, the maximum mutual information between input signal at S_1 and output signal y_d at the user is given by

$$I_1\left(x_1, y_d\right) = \frac{1}{2}\log_2\left(1+\frac{\frac{\rho_R}{N}\left(\sum\limits_{m=1}^{L}\left|h_{R_m d}\right|^2+\sum\limits_{n=L+1}^{N}\rho_1\beta_n\left|h_{S_1R_n}\right|^2\right)}{\frac{\rho_R}{N}\left(\sum\limits_{n=L+1}^{N}\rho_2\beta_n\left|h_{S_2R_n}\right|^2+\sum\limits_{n=L+1}^{N}\beta_n\right)+1}\right) \tag{4}$$

where $\beta_n = \frac{\left|h_{R_n d}\right|^2}{\rho_1\left|h_{S_1R_n}\right|^2+\rho_2\left|h_{S_2R_n}\right|^2+1}$, $L \in \{1, \ldots, N\}$.

On the other hand, if the channel capacity between S_1 and the L-th relay is less than the total channel capacities between all the N relays and the user, then the maximum mutual information between input signal at S_1 and output signal y_d at the user will be restricted by the former in Eq. (3) (i.e., the channel capacity between S_1 and the L-th relay) [28], and can be expressed as

$$I_2\left(x_1, y_d\right) = \frac{1}{2}\log_2\left(1+\frac{\rho_1\left|h_{S_1R_\mathrm{L}}\right|^2}{\rho_2\left|h_{S_2R_\mathrm{L}}\right|^2+1}\right). \tag{5}$$

where $L \in \{1, 2, \ldots, N\}$.

In summary, the maximal transmission rate for x_1, which is restricted by the average maximum mutual information between input signal x_1 at S_1 and output signal y_d at the user, is given by

$$\begin{aligned}
&R_1^{HDAF-NOMA}\\
&\leq I\left(x_1, y_d\right) = \min\left\{I_1\left(x_1, y_d\right), I_2\left(x_1, y_d\right)\right\}\\
&= \frac{1}{2}\min\left\{\log_2\left(1+\frac{\frac{\rho_R}{N}\left(\sum\limits_{m=1}^{L}\left|h_{R_m d}\right|^2+\sum\limits_{n=L+1}^{N}\rho_1\beta_n\left|h_{S_1R_n}\right|^2\right)}{\frac{\rho_R}{N}\left(\sum\limits_{n=L+1}^{N}\rho_2\beta_n\left|h_{S_2R_n}\right|^2+\sum\limits_{n=L+1}^{N}\beta_n\right)+1}\right),\right.\\
&\qquad\left.\log_2\left(1+\frac{\rho_1\left|h_{S_1R_\mathrm{L}}\right|^2}{\rho_2\left|h_{S_2R_\mathrm{L}}\right|^2+1}\right)\right\}
\end{aligned} \tag{6}$$

where $\beta_n = \frac{\left|h_{R_n d}\right|^2}{\rho_1\left|h_{S_1R_n}\right|^2+\rho_2\left|h_{S_2R_n}\right|^2+1}$, $L \in \{1, \ldots, N\}$.

And the maximal transmission rate for x_2, which is restricted by the average maximum mutual information between input signal x_2 at S_2 and output signal y_d at the user, is given by

$$\begin{aligned}
R_2^{HDAF-NOMA} &\leq I\left(x_2, y_d\left|x_1\right.\right)\\
&= \frac{1}{2}\log_2\left(1+\frac{\frac{\rho_R}{N}\sum\limits_{n=L+1}^{N}\rho_2\beta_n\left|h_{S_2R_n}\right|^2}{\frac{\rho_R}{N}\sum\limits_{n=L+1}^{N}\beta_n+1}\right),
\end{aligned} \tag{7}$$

where $\beta_n = \frac{\left|h_{R_n d}\right|^2}{\rho_1\left|h_{S_1R_n}\right|^2+\rho_2\left|h_{S_2R_n}\right|^2+1}$, $L \in \{1, \ldots, N\}$. Therefore, the maximal sum transmission rate for x_1 and x_2 is restricted by

$$R_1^{HDAF-NOMA}+R_2^{HDAF-NOMA} \leq I\left(x_1, y_d\right)+I\left(x_2, y_d\left|x_1\right.\right). \tag{8}$$

For comparison, we will also show the maximal transmission rate of x_1 and x_2 for the other four traditional schemes. In the DF with NOMA Best Relay (DF-NOMA-BR) scheme, source S_1 and S_2 simultaneously broadcast signal x_1 and x_2 to all the relays and the user with transmit power P_1 and P_2 in the first time slot. Let $I = \{1, 2, \ldots, N\}$ be the index set associated with the ordered received signal-to-interference-plus-noise ratio (SINR) of signal x_1 at the relays such that $\frac{\rho_1\left|h_{S_1R_1}\right|^2}{1+\rho_2\left|h_{S_2R_1}\right|^2} \geq \frac{\rho_1\left|h_{S_1R_2}\right|^2}{1+\rho_2\left|h_{S_2R_2}\right|^2} \geq \cdots \geq \frac{\rho_1\left|h_{S_1R_\mathrm{N}}\right|^2}{1+\rho_2\left|h_{S_2R_\mathrm{N}}\right|^2}$, if only the best relay with the highest ordered received SINR of signal x_1 is selected to perform DF relaying for x_1 with transmit power P_R, and the other $N-1$ relays keep silent in the second time slot, then in this DF-NOMA-BR scheme the maximal transmission rate for x_1 and x_2 is

$$\begin{aligned}
R_1^{DF-NOMA-BR} \leq \frac{1}{2}\min&\left\{\log_2\left(1+\frac{\rho_R}{N}\left|h_{R_1 d}\right|^2\right),\right.\\
&\left.\log_2\left(1+\frac{\rho_1\left|h_{S_1R_1}\right|^2}{\rho_2\left|h_{S_2R_1}\right|^2+1}\right)\right\},
\end{aligned} \tag{9}$$

$$R_2^{DF-NOMA-BR} = 0. \tag{10}$$

Similar to the DF-NOMA-BR scheme, in the DF with NOMA Multi-Relay (DF-NOMA-MR) scheme, in the second time slot each of the L relays which have successfully decoded signal x_1 in the first time slot performs a DF relaying for signal x_1 with transmit power P_R, and the other $N-L$ relays which have failed in decoding signal x_1 in the first time slot keep silent, then in this DF-NOMA-MR scheme the maximal transmission rate for x_1 and x_2 is

$$\begin{aligned}
R_1^{DF-NOMA-MR} \leqslant \frac{1}{2}\min&\left\{\log_2\left(1+\frac{\rho_R}{N}\sum_{m=1}^{L}\left|h_{R_m d}\right|^2\right),\right.\\
&\left.\log_2\left(1+\frac{\rho_1\left|h_{S_1R_\mathrm{L}}\right|^2}{\rho_2\left|h_{S_2R_\mathrm{L}}\right|^2+1}\right)\right\},
\end{aligned} \tag{11}$$

$$R_2^{DF-NOMA-MR} = 0, \tag{12}$$

where $L \in \{1, \ldots, N\}$.

In the DF with Time-Division Multiple Access Best Relay (DF-TDMA-BR) scheme, source S_1 and S_2 broadcast signal x_1 and x_2 to all the relays and the user with transmit power P_1 and P_2 by time-division multiple access (TDMA), i.e., S_1 broadcasts signal x_1 to all the relays and the user with transmit power P_1 in the first time slot, the relays perform DF relaying for x_1 in the second time slot, in the third time slot S_2 broadcasts signal x_2 to all the relays and the user with transmit power P_2, and in the fourth time slot the relays perform DF relaying for x_2. Let $I_1 = \{1, 2, \ldots, N\}$ be the index set associated with the ordered received SNR of signal x_1 at the relays such that $\rho_1 \left|h_{S_1R_1}\right|^2 \geq \rho_1 \left|h_{S_1R_2}\right|^2 \geq \cdots \geq \rho_1 \left|h_{S_1R_{\mathrm{N}}}\right|^2$, and $I_2 = \{1, 2, \ldots, N\}$ be the index set associated with the ordered received SNR of signal x_2 at the relays such that $\rho_2 \left|h_{S_2R'_1}\right|^2 \geq \rho_2 \left|h_{S_2R'_2}\right|^2 \geq \cdots \geq \rho_2 \left|h_{S_2R'_{\mathrm{N}}}\right|^2$, if in the second (or the fourth) time slot only the best relay with the highest ordered received SNR of signal x_1 (or x_2) in set I_1 (or I_2) is selected to perform DF relaying for x_1 (or x_2) with transmit power P_R, and the other $N - 1$ relays keep silent in the next time slot, then in this DF-TDMA-BR scheme the maximal transmission rate for x_1 and x_2 is

$$R_1^{DF-TDMA-BR} \leq \frac{1}{4} \min\left\{\log_2\left(1 + \frac{\rho_R}{N}\left|h_{R_1d}\right|^2\right), \log_2\left(1 + \rho_1\left|h_{S_1R_1}\right|^2\right)\right\}, \tag{13}$$

$$R_2^{DF-TDMA-BR} \leq \frac{1}{4} \min\left\{\log_2\left(1 + \frac{\rho_R}{N}\left|h_{R'_1d}\right|^2\right), \log_2\left(1 + \rho_2\left|h_{S_2R'_1}\right|^2\right)\right\}. \tag{14}$$

Similar to the DF-TDMA-BR scheme, in the DF with Time Division Multiple Access Multi-Relay (DF-TDMA-MR) scheme, if in the second (or the fourth) time slot each of the L (or L') relays which have successfully decoded signal x_1 (or x_2) in the first (or the third) time slot performs a DF relaying for signal x_1 (or x_2) with transmit power P_R, and the other $N - L$ (or $N - L'$) relays which have failed in decoding signal x_1 (or x_2) in the first (or the third) time slot keep silent in the next time slot, then in this DF-TDMA-MR scheme the maximal transmission rate for x_1 and x_2 is

$$R_1^{DF-TDMA-MR} \leq \frac{1}{4} \min\left\{\log_2\left(1 + \frac{\rho_R}{N}\sum_{m=1}^{L}\left|h_{R_md}\right|^2\right), \log_2\left(1 + \rho_1\left|h_{S_1R_L}\right|^2\right)\right\}, \tag{15}$$

$$R_2^{DF-TDMA-MR} \leq \frac{1}{4} \min\left\{\log_2\left(1 + \frac{\rho_R}{N}\sum_{m=1}^{L'}\left|h_{R'_md}\right|^2\right), \log_2\left(1 + \rho_2\left|h_{S_2R'_{L'}}\right|^2\right)\right\}, \tag{16}$$

where $L \in \{1, \ldots, N\}$, $L' \in \{1, \ldots, N\}$.

B. AVERAGE SYSTEM THROUGHPUT

In a real system the transmission rate can be either adaptive or fixed, and an outage may occur. "Average transmission rate" is often used as a metric to evaluate the performance of average system throughput. For the HDAF-NOMA scheme, if the transmission rate for x_1 at S_1 is fixed R_1, and the transmission rate for x_2 at S_2 is fixed R_2, then the outage probability of the transmission of x_1 is

$$P_1^{out} = P\left(I\left(x_1, y_d\right) < R_1\right), \tag{17}$$

where $I\left(x_1, y_d\right)$ is given by Eq. (6). Due to the complexity of Eq. (6), the expression of P_1^{out} is not given in this paper.

As signal x_2 is not decodable if its superimposed signal x_1 has not been successfully decoded, then the outage probability of the transmission of x_2 is

$$P_2^{out} = 1 - P\left(I\left(x_1, y_d\right) \geq R_1\right) \times P\left(I\left(x_2, y_d\left|x_1\right.\right) \geq R_2\right), \tag{18}$$

where $I\left(x_1, y_d\right)$ and $I\left(x_2, y_d\left|x_1\right.\right)$ is given by Eq. (6) and (7), respectively. Then the average system throughput for the HDAF-NOMA scheme is

$$\overline{R^{HDAF-NOMA}} = R_1\left(1 - P_1^{out}\right) + R_2\left(1 - P_2^{out}\right). \tag{19}$$

Similarly, the average system throughput can be derived for the other four traditional schemes (i.e., DF-NOMA-BR, DF-NOMA-MR, DF-TDMA-BR, and DF-TDMA-MR).

C. OPTIMAL NUMBER OF SELECTED DF RELAYS FOR THE HDAF-NOMA SCHEME

Next, the optimal number of selected DF relays is determined for the HDAF-NOMA scheme to maximize system throughput. According to Eq. (6), (7) and (8), the optimal number of selected DF relays can be determined by performing a line search on $L \in \{1, 2, \ldots, N\}$ to maximize the sum rate of R_1 and R_2, i.e.,

$$L^* = \mathop{\arg\max}_{L \in \{1,2,\ldots,N\}} \left\{I\left(x_1, y_d\right) + I\left(x_2, y_d\left|x_1\right.\right)\right\}, \tag{20}$$

where $I\left(x_1, y_d\right)$ and $I\left(x_2, y_d\left|x_1\right.\right)$ is given by Eq. (6) and (7), respectively.

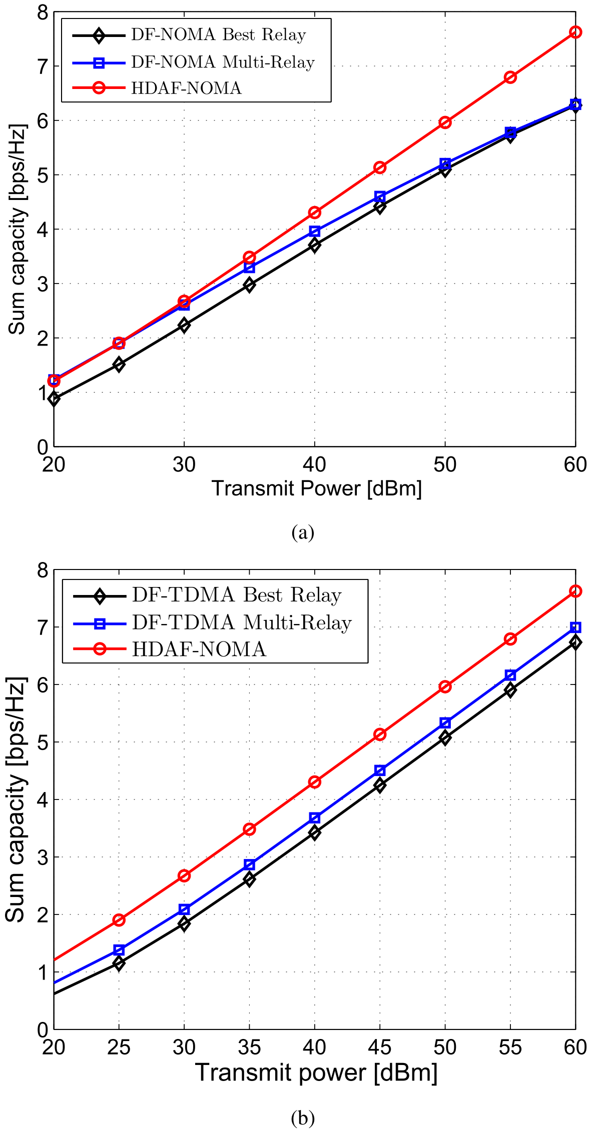
IV. SIMULATION RESULTS

In this section, the performance of the proposed HDAF-NOMA scheme is compared with the other four traditional schemes (i.e., DF-NOMA-BR, DF-NOMA-MR, DF-TDMA-BR, and DF-TDMA-MR) in terms of sum capacity, outage probability, and average sum rate for the transmission of x_1 and x_2, by using Monte-Carlo simulations. System parameters for performance evaluation are given in Table 1.

Fig. 2(a) compares the sum capacity for the transmission of x_1 and x_2 in the proposed HDAF-NOMA scheme with that in the DF-NOMA Best Relay (DF-NOMA-BR) and the DF-NOMA Multi-Relay (DF-NOMA-MR) schemes. In these three schemes, in the first time slot and at the same frequency, source S_1 and S_2 simultaneously broadcast signal x_1 and x_2 to

TABLE 1. System parameters.

Parameter	Value
Channel bandwidth	10 [MHz]
Thermal noise density	-174 [dBm/Hz]
Path-loss model	$L = r^n/G$, r in meter, $L = 128.1 + 37.6\log_{10}R$, R in kilometer, G = 0.029512, n = 3.76
Number of relays	5
Distance from S_1 to relay i, $i \in \{1, 2, \cdots, 5\}$	$S_1R_i = \{100, 180, 260, 340, 420\}$
Distance from S_2 to relay i, $i \in \{1, 2, \cdots, 5\}$	$S_2R_i = \{820, 740, 660, 580, 500\}$
Distance from relay i to the user, $i \in \{1, 2, \cdots, 5\}$	$R_id = 500$, $i \in \{1, 2, \cdots, 5\}$



(a)

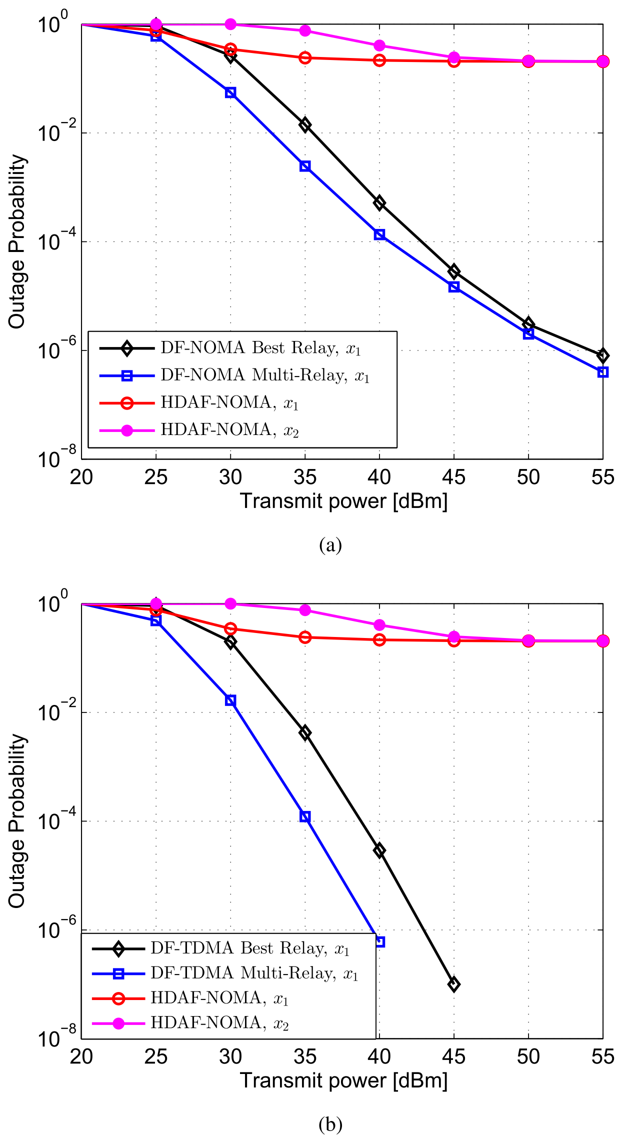
(b)

FIGURE 2. Sum capacity for the transmission of x_1 and x_2 versus varying transmit power P. (a) The HDAF-NOMA scheme is compared with the DF-NOMA Best Relay and the DF-NOMA Multi-Relay schemes. (b) The HDAF-NOMA scheme is compared with the DF-TDMA Best Relay and the DF-TDMA Multi-Relay schemes.

all the relays and the user with transmit power P and $0.15P$, respectively. From Fig. 2(a) we see that the HDAF-NOMA scheme can achieve larger sum capacity for the transmission of x_1 and x_2 than the DF-NOMA-BR and the DF-NOMA-MR schemes, and the gap becomes more pronounced at high SNR region. The reason for such gain on sum capacity can be explained by the following: in the HDAF-NOMA scheme after S_1 and S_2 simultaneously broadcast signal x_1 and x_2 at the same frequency to all the relays and the user, besides a DF relaying for signal x_1 at each of the L relays, there is also an AF relaying for signal x_1 and x_2 at each of the other $N - L$ relays, and x_1 and x_2 are then performed a SIC decoding at the user. Therefore, in the HDAF-NOMA scheme the total number of transmit channels for signal x_1 is N and there are also $N - L$ transmit channels for signal x_2; In contrast, in the DF-NOMA-BR and the DF-NOMA-MR schemes, after S_1 and S_2 simultaneously broadcast signal x_1 and x_2 at the same frequency, only signal x_1 is given a DF relaying at each of the L relays and only signal x_1 is decoded at the user, so there are no more than L transmit channels for signal x_1. Therefore the sum capacity for the transmission of x_1 and x_2 in the HDAF-NOMA scheme is larger than that in the DF-NOMA-BR and the DF-NOMA-MR schemes.

Fig. 2(b) compares the sum capacity for the transmission of x_1 and x_2 in the proposed HDAF-NOMA scheme with that in the DF-TDMA Best Relay (DF-TDMA-BR) and the DF-TDMA Multi-Relay (DF-TDMA-MR) schemes. In the DF-TDMA-BR and the DF-TDMA-MR schemes, source S_1 and S_2 broadcast signal x_1 and x_2 to all the relays and the user at the same frequency by Time-Division Multiple Access (TDMA) with transmit power P and $0.15P$, respectively. From Fig. 2(b) we find that the HDAF-NOMA scheme can achieve larger sum capacity for the transmission of x_1 and x_2 than the DF-TDMA-BR and the DF-TDMA-MR schemes. This is due to the fact that the HDAF-NOMA scheme is a NOMA scheme in nature, while the DF-TDMA-BR and the DF-TDMA-MR schemes are orthogonal ones. As we know, NOMA schemes are strictly better than orthogonal schemes in sum capacity, therefore the sum capacity for the transmission of x_1 and x_2 in the HDAF-NOMA scheme is larger than that in the DF-TDMA-BR and the DF-TDMA-MR schemes.

Fig. 3 shows the outage probability of the transmission of x_1 and x_2 versus varying transmit power P, the transmit power for x_1 and x_2 at S_1 and S_2 is set as P and $0.15P$, respectively. Fig. 3(a) compares the outage probability of the transmission of x_1 and x_2 in the proposed HDAF-NOMA scheme



(a)

(b)

FIGURE 3. Outage probability of the transmission of x_1 and x_2 versus varying transmit power P. (a) The HDAF-NOMA scheme is compared with the DF-NOMA Best Relay and the DF-NOMA Multi-Relay schemes. (b) The HDAF-NOMA scheme is compared with the DF-TDMA Best Relay and the DF-TDMA Multi-Relay schemes.

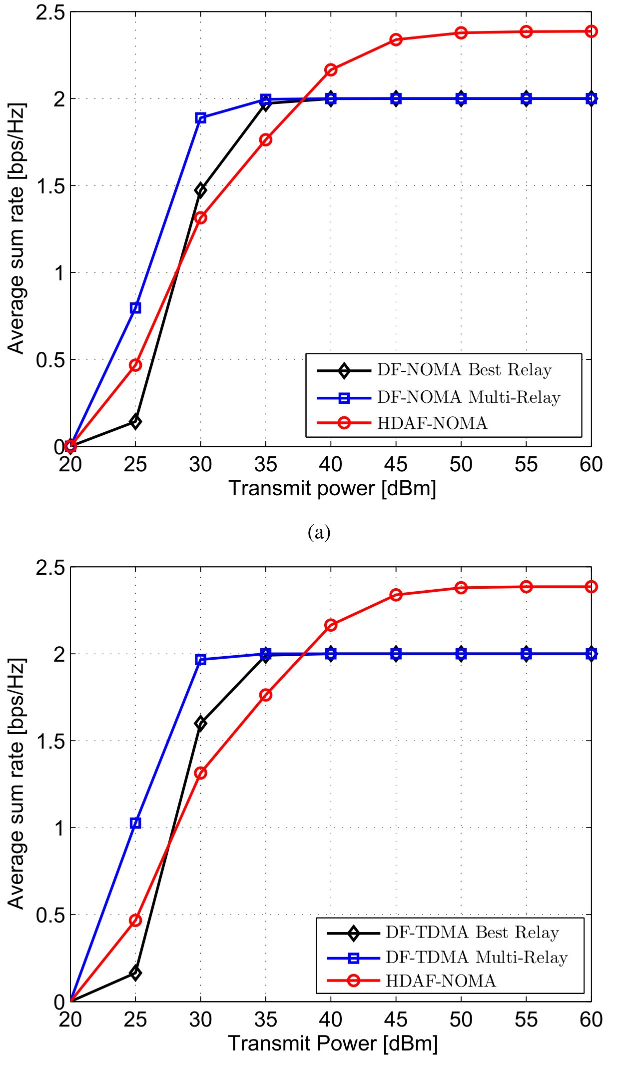
with that in the DF-NOMA Best Relay (DF-NOMA-BR) and the DF-NOMA Multi-Relay (DF-NOMA-MR) schemes, and Fig. 3(b) compares the outage probability of the transmission of x_1 and x_2 in the proposed HDAF-NOMA scheme with that in the DF-TDMA Best Relay (DF-TDMA-BR) and the DF-TDMA Multi-Relay (DF-TDMA-MR) schemes. We find that the outage performance for the transmission of x_1 and x_2 in the proposed HDAF-NOMA scheme is much worse than that in the other four traditional schemes, and at high SNR region we find that there is no diversity gain for the transmission of x_1 and x_2 in the proposed HDAF-NOMA scheme.

For the outage probability of the transmission of x_1 in the proposed HDAF-NOMA scheme, the reason can be explained by the fact that with increasing transmit power P, signal x_2 and the noise received at each AF relay (the total number is $N-L$) are amplified-and-forwarded to the user, and the amplified signal x_2 and the amplified noise are treated as interference in decoding signal x_1 at the user, thus limiting the channel capacity for the transmission of x_1, and that leads to no diversity gain for the transmission of x_1 at high SNR region. The reason can also be well explained by mathematics, i.e., in our simulation the system parameters for the HDAF-NOMA scheme are: at source S_1 and S_2 the transmit power for x_1 and x_2 is set as P and $0.15P$ respectively, and at each relay the transmit power is set as $P_R = (P + 0.15P)/N$, where N is the total number of relays. Therefore, according to Eq. (6) and (17), at high SNR region there is no diversity gain for the transmission of x_1.

For the outage probability of the transmission of x_2 in the proposed HDAF-NOMA scheme, as x_2 is not decodable if its superimposed x_1 has not been successfully decoded, therefore the outage probability of the transmission of x_2 will be larger than that of the transmission of x_1, and at high SNR region there will be no diversity gain for the transmission of x_2.

From Fig. 2 we see that the HDAF-NOMA scheme can achieve larger sum capacity for the transmission of x_1 and x_2 than the other four traditional schemes. From Fig. 3 we see that HDAF-NOMA has much larger outage probability for the transmission of x_1 and x_2 than the other four traditional schemes, therefore we find that the HDAF-NOMA scheme sacrifices its outage performance to have the gain on sum capacity. Here in Fig. 4 a metric "Average sum rate" is used to evaluate the schemes' overall performance on average system throughput. In our simulation, the fixed transmission rate at S_1 and S_2 is set as $R_1 = 2$ bps/Hz and $R_2 = 1$ bps/Hz, and the transmit power for x_1 and x_2 at S_1 and S_2 is set as $P_1 = P$ and $P_2 = 0.15P$, respectively. As can be seen from Fig. 4, compared with the other four traditional schemes, the HDAF-NOMA scheme has a smaller average sum rate when transmit power P_1 at S_1 is less than $P_1 = P = 38$dBm (in such case, transmit power P_2 at S_2 is less than $0.15P$), and the HDAF-NOMA scheme has a larger average sum rate when transmit power P_1 at S_1 is greater than $P_1 = P = 38$dBm (in such case, transmit power P_2 at S_2 is greater than $0.15P$). This indicates that although the HDAF-NOMA scheme has a worse outage performance than the other four traditional schemes, however, as in the HDAF-NOMA scheme the user can receive the data of both x_1 and x_2, while in the other four traditional schemes the user can only receive the data of x_1, and as SNR increases the user tends to be able to decode all the data it receives, therefore at high SNR region the HDAF-NOMA scheme has a better performance on average system throughput as compared with the other four traditional schemes.

Fig. 5 shows the capacity for the transmission of x_1 and x_2 for the HDAF-NOMA scheme, in which the transmit power for x_1 and x_2 at S_1 and S_2 is set as P and $0.15P$, respectively. We see that the capacity for the transmission of x_1 approaches a constant with the increasing transmit power, this is because



(a)

(b)

FIGURE 4. **Average sum rate of the transmission of x_1 and x_2 versus varying transmit power P. (a) The HDAF-NOMA scheme is compared with the DF-NOMA Best Relay and the DF-NOMA Multi-Relay schemes. (b) The HDAF-NOMA scheme is compared with the DF-TDMA Best Relay and the DF-TDMA Multi-Relay schemes.**

the capacity for the transmission of x_1 is limited by the interference from the transmission of x_2 and the noise. From Eq. (6) we can also find that the capacity for the transmission of x_1 has an upper bound at high SNR region.

Besides, from Fig. 5 we also observe that the capacity for the transmission of x_2 increases with the growth of transmit power P, it can be explained by Eq. (7), which shows that the capacity for the transmission of x_2 will increase with the growth of the transmit power for x_2 (i.e., $P_2 = 0.15P$).

Fig. 6 shows the optimal average number of selected DF relays for the HDAF-NOMA scheme, when the number of total relays is $N = 5$, and the transmit power for x_1 and x_2 at S_1 and S_2 is set as P and $0.15P$, respectively. Please note that this is an "average number" rather than "actual number" of selected DF relays, hence the values are not integers.

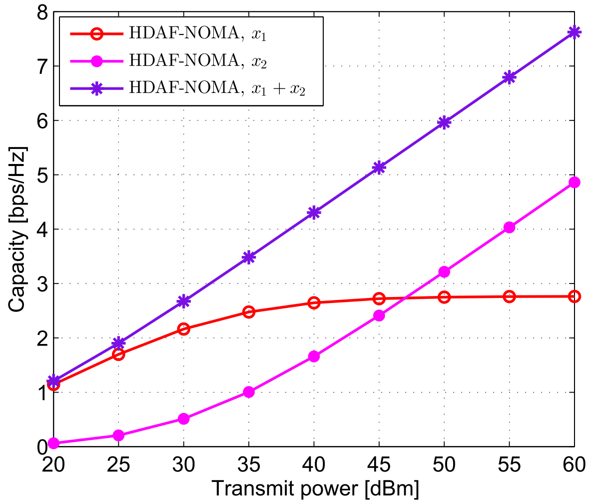


FIGURE 5. **Capacity for the transmission of x_1 and x_2 versus varying transmit power P for the HDAF-NOMA scheme.**

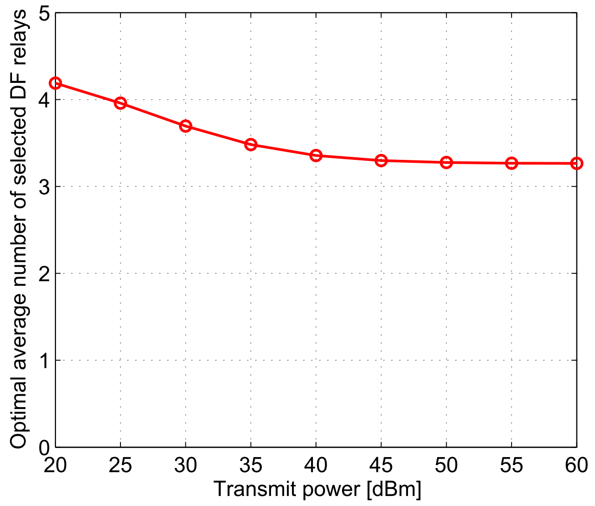


FIGURE 6. **Optimal average number of selected DF relays in the HDAF-NOMA scheme, the number of total relays is $N = 5$.**

From Fig. 6 it can be found that in the HDAF-NOMA scheme, the optimal average number of selected DF relays at low SNR region is greater than that at high SNR region, which indicates that at low SNR region, more average number of DF relays and less average number of AF relays leads to a maximal sum capacity for the transmission of x_1 and x_2; and at high SNR region, less average number of DF relays and more average number of AF relays leads to a maximal sum capacity for the transmission of x_1 and x_2.

V. CONCLUSION

In this paper, we proposed a new hybrid DF & AF with NOMA (HDAF-NOMA) transmission scheme to improve system throughput for a cellular system with multiple relays. The proposed HDAF-NOMA scheme is evaluated and compared with the other four traditional schemes in terms of channel capacity and average system throughput, and the optimal number of selected DF relays is also determined for the HDAF-NOMA scheme. The simulation results have shown that the proposed HDAF-NOMA scheme can achieve larger sum capacity for the transmission of x_1 and x_2, which means that if source S_1 and S_2 transmit signal x_1 and x_2 with adaptive rate such as maximal ones, then the proposed HDAF-NOMA scheme can achieve larger system throughput than the traditional schemes. Besides, if source S_1 and S_2 transmit signal x_1 and x_2 with fixed rate, the simulation results have also shown that at high SNR region the proposed HDAF-NOMA scheme can achieve larger average system throughput than the traditional schemes.

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