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Cooperative Relaying in a Three User Downlink NOMA System Using Dynamic Power Allocation

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ABSTRACT

Non-orthogonal multiple access (NOMA) represents the latest addition to the array of multiple access techniques, enabling simultaneous servicing of multiple users within a singular resource block in terms of time, frequency, and code. A typical NOMA configuration comprises a base station along with proximate and distant users. The proximity users experience more favorable channel conditions in contrast to distant users, resulting in a compromised performance for the latter due to the less favorable channel conditions. When cooperative communication is integrated with NOMA, the overall system performance, including spectral efficiency and capacity, is further elevated. This study introduces a cooperative NOMA setup in the downlink, involving three users, and employs dynamic power allocation (DPA). Within this framework, User 2 acts as a relay, functioning under the decode-and-forward protocol, forwarding signals to both User 1 and User 3. This arrangement aims to bolster the performance of the user positioned farthest from the base station, who is adversely affected by weaker channel conditions. Theoretical and simulation outcomes reveal enhancements within the system's performance.

Keywords: NOMA; Cooperative NOMA; Decode and forward; Dynamic power allocation

1. Introduction

Future wireless communication requires high data rates, low latency, improved accuracy, enhanced quality of service, and more. These demands intro-

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duce challenges due to signal degradation caused by factors like random fades, diffraction, noise, and other performance-reducing phenomena [1]. Addressing these challenges necessitates technological advancements. The emerging 5G technique known as Non-Orthogonal Multiple Access (NOMA) offers superior performance in terms of boosting spectral efficiency compared to conventional multiple access methods. NOMA enables the support of multiple users within a single resource block, thereby enhancing both individual user and overall system throughput [2]. In a typical NOMA setup, users communicate individually with the base station, treating signals from other users as interference. Orthogonal Multiple Access (OMA) frameworks struggle to accommodate high-speed communication applications and a growing user base. Consequently, the shift toward NOMA techniques for 5G is evident, as it outperforms OMA techniques across various parameters, including user fairness, throughput, and data rates [3]. Scientific research confirms that the integration of Non-Orthogonal Multiple Access with recommended wireless technologies yields superior results [4], especially when incorporating features like antenna diversity, massive multiple-input multiple-output architecture, equitable data rates, energy efficiency, cooperative relaying, beamforming and equalization, network coding, and space-time coding [5].

This article primarily focuses on enhancing the performance of distant users within a Non-Orthogonal Multiple Access (NOMA) system by introducing the concept of cooperative relay communication.

The exploration of cooperative relay networks has attracted significant research attention due to its potential to enhance efficiency and system capacity [6]. The fundamental principle of cooperative NOMA involves designating one of the NOMA users as a relay. To elaborate, the transmission process of cooperative NOMA unfolds in two distinct phases or time slots. During the initial phase, the Base Station (BS) disseminates superimposed messages to M NOMA users. In the subsequent phase, a user endowed with strong channel conditions (referred to as the strong user) assumes the role of a relay. This relay user employs Amplify-and-Forward (AF), Decode-and-Forward (DF), or a hybrid AF/DF approach to transmit the deciphered messages to a user possessing weaker channel conditions. This cooperative action enhances the reliability of the weaker user [7].

2. Literature review

Cooperative communications in conjunction with NOMA presents an additional avenue for augmenting user performance. Non-Orthogonal Multiple Access (NOMA) is an auspicious radio access approach for the upcoming generation of wireless networks. Research on NOMA-based cooperative relay networks has been detailed in research by D. Wan, M. Wen, F. Ji et al. [8]. They initiate by introducing current relay-assisted NOMA systems, categorizing them into uplink, downlink, and composite architectures. The principles and key characteristics of these systems are explored, followed by an extensive comparison encompassing aspects like spectral efficiency, energy efficiency, and total transmit power. A new approach termed hybrid power allocation is proposed for the composite architecture. This strategy reduces computational complexity and signaling overhead while incurring a minor sum rate decline.

An innovative concept of Cooperative Communication has been researched to manage challenges like abundant channel access, intricate interference settings, varying networks, and energy-intensive environments. This concept, geared towards high signal coverage and capacity among mobile devices, hinges on resource allocation techniques for robust interference management, resource scheduling, and user matching. Several strategies addressing various technological facets of cooperative communication allocation techniques, including relay nodes, signal forwarding, and transceiver diversity gain, are investigated by W. Guo, N. M. F. Qureshi, I. F. Siddiqui, and D. R. Shin [9].

In a separate study, M. Ajmal and M. Zeeshan [1] introduce a novel hybrid cooperative communication method for multiuser power domain NOMA. This approach leverages amplify-and-forward (AF) and decode-and-forward (DF) techniques through a strong user acting as a relay for a weak user in a cellular system. This exploits NOMA's inherent feature that a strong user possesses prior knowledge of a weak user with poor channel conditions. Analysis of Bit Error Rate (BER) curves demonstrates that cooperative communication enhances the performance of weak users situated at the cellular system's edge.

Another proposal presents a two-stage superposed transmission for the Cooperative Relay Network (CRN) within a finite time slot framework of the NOMA system by W. Duan et al. [6]. The scheme employs Maximum Ratio Combining (MRC) and Successive Interference Cancellation (SIC) to jointly decode source and relay node receptions across multiple time slots, utilizing a superposition code for the relay node's transmitted signal. The performance of this system is evaluated in terms of ergodic sum rate, outage probability, and outage capacity, substantiated by corresponding closed-form expressions. The scheme's theoretical derivations align well with simulation results, exhibiting notably enhanced transmission rates compared to TDMA and conventional NOMA schemes.

Additionally, a two-stage relay selection strategy for NOMA networks encompassing DF and AF relaying protocols has been introduced in research by Z. Yang, Z. Ding, and P. Fan [10]. The architecture involves a base station communicating with two users through multiple relays. Lastly, a dual-hop cooperative relaying scheme using NOMA has been explored by M. F. Kader, M. B. Shahab, and S. Y. Shin [11]. This system enables two sources to communicate with their corresponding destinations in parallel over the same frequency band, facilitated by a shared relay.

To our best understanding, the majority of investigations into cooperative NOMA have centered around fixed power allocation methodologies, neglecting the dynamic aspect of power allocation that takes the channel's condition into account. Inadequate power allocation could significantly impact the effectiveness of a cooperative network. Therefore, this study delves into the implications of dynamic power allocation on the operational efficiency of cooperative NOMA, particularly focusing on its potential to enhance the system's performance in terms of outage probability and system capacity. The key focal points of this research are as follows:

1) We propose and thoroughly explore the concept of dynamic power allocation within a three-user cooperative NOMA configuration involving a relay that employs the Decode-and-Forward (DF) protocol.

2) To facilitate accurate comparison, we devise a cooperative network integrating reference Orthogonal Multiple Access (NOMA) as a benchmark. The findings demonstrate that the proposed Cooperative NOMA (CNOMA) scheme surpasses the latter approach when perfect Successive Interference Cancellation (SIC) is employed at the relay and at User 3.

3. System model

Figure 1 depicts a simplified scenario of a downlink NOMA system involving three users, namely User 1 (U1), User 2 (U2), and User 3 (U3), along with a solitary base station (BS) situated within a single cell. In this illustration, U2 is designated as the robust user and simultaneously serves as a relay. It is worth noting that in reality we would have several number of users as well as relays and the system model will always differ, but just for the sake of simplicity we decided to use three users with one acting as a relay. In this research, we considered a downlink scenario where the base station communicates with multiple users that power allocation is being performed at the base station and at the relay is essential to optimize the relays amplification and forwarding process. This configuration assumes ideal successive interference cancellation (SIC) receivers and employs Rayleigh fading for all signal links. The diagram showcases the transmission of signals from the BS to U1 and subsequently through an intermediary U2 functioning as a relay. Each node in this setup is outfitted with a sole antenna, while the relay operates in a half-duplex mode utilizing the decode-forward strategy.

The cooperative NOMA paradigm is governed by two distinct phases, namely the transmission phase

(Phase 1) and the cooperative phase (Phase 2) [7].

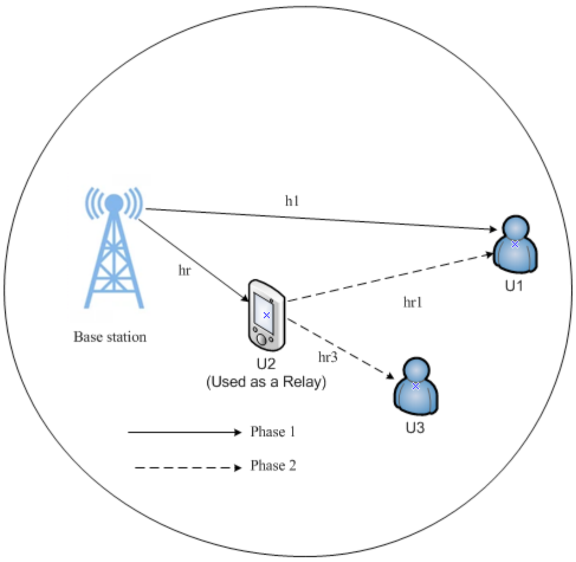

Figure 1. The three-user cooperative NOMA network.

Phase 1

The BS transmits a superposition-coded signal to User 1 and relay, which is generally given by:

$$S_t = \sum_{i=1}^{n} \sqrt{P\alpha_i} x_i \quad (1)$$

where, P = total transmitted power, α_i = power allocation coefficient, and x_i = modulated information of users.

For the cooperative NOMA system under consideration, the transmitted signal for User 1 and User 2 will be written as:

$$\sqrt{P_A\alpha_1}x_1 + \sqrt{P_A\alpha_2}x_2 \quad (2)$$

where, P_A denotes the transmit power of the BS, α_1 and α_2 denote the power allocation coefficients for User 1 and User 2 respectively for the symbol x_1 and x_2.

Assuming that User 1 is the cell edge from the viewpoint of the BS, thus:

$$\alpha_1 > \alpha_1,\ \alpha_1 + \alpha_2 = 1$$

The received signal at U1 and relay during the first phase are given by:

$$R_{BR} = h_{BR}\left(\sqrt{P_A\alpha_1}x_1 + \sqrt{P_A\alpha_2}x_2\right) + n_R \quad (3)$$

$$R_{BU1} = h_{BU1}\left(\sqrt{P_A\alpha_1}x_1 + \sqrt{P_A\alpha_2}x_2\right) + n_{U1}(t_1) \quad (4)$$

where h_{BR} and h_{BU1} are the channel coefficients between BS and relay as well as BS and U1. Whereas $n(.)$ represent the additive white Gaussian noise at the receivers respectively and (t_1) denotes the first phase.

The general expression for the received SNR is given by:

$$\gamma = \frac{signal\ power}{interference + noise}$$

The received SNRs for symbols at the relay are respectively given by:

$$\gamma_{BR}^{X1} = \frac{|h_{BR}|^2\alpha_1 P_A}{|h_{BR}|^2\alpha_1 P_A + \sigma^2} \quad (5)$$

$$\gamma_{BR}^{X2} = \frac{|h_{BR}|^2\alpha_2 P_A}{\sigma^2} \quad (6)$$

On the other hand, U1 treats the symbol x_2 as noise to acquire a symbol x_1 from (4). The received SNR for the symbol x_1 at U1 is given by:

$$\gamma_{BU1}^{X1} = \frac{|h_{BU1}|^2\alpha_1 P_A}{|h_{BU1}|^2\alpha_1 P_A + \sigma^2} \quad (7)$$

Phase 2

In C-NOMA, the relay forwards x_2 to U1 and also transmits its superposed signal given by:

$$\sqrt{P_R\beta_1}x_2 + \sqrt{P_R\beta_2}x_R \quad (8)$$

where, P_R denotes the transmit power of the relay, β_1 and β_2 denotes the power allocation coefficients for the symbol x_2 and x_R. It is assumed that U1 is the far user from the viewpoint of the relay, therefore:

$$\beta_1 > \beta_2,\ \beta_1 + \beta_2 = 1$$

The received signal in the second phase at U1 and U3 are respectively given by:

$$R_{RU1} = h_{RU1}\left(\sqrt{P_R\beta_1}x_2 + \sqrt{P_R\beta_2}x_R\right) + n_{U1}(t_2) \quad (9)$$

$$R_{RU3} = h_{RU3}\left(\sqrt{P_R\beta_1}x_2 + \sqrt{P_R\beta_2}x_R\right) + n_{U3} \quad (10)$$

where h_{RU1} and h_{RU3} are the channel coefficients between R and U1 as well as R and U3. Whereas $n(.)$ represent the additive white Gaussian noise at the receivers denoted users respectively and (t_2) denotes the second phase.

U3 performs SIC by decoding the symbol x_2 and treating symbol x_R as noise, and then cancels it to acquire a symbol $x_R$from (10). The received SNRs for the symbol x_2 and x_R at U3 are respectively given by;

$$\gamma_{RU3}^{X2} = \frac{|h_{RU3}|^2\beta_1 P_R}{|h_{RU3}|^2\beta_2 P_R + \sigma^2} \quad (11)$$

$$\gamma_{RU3}^{XR} = \frac{|h_{RU3}|^2 \beta_2 P_R}{\sigma^2} \quad (12)$$

U1 treats symbol x_R as noise when decoding x_2 from (9). The received SNR for the symbol x_2 at U1 is obtained as:

$$\gamma_{RU1}^{X2} = \frac{|h_{RU1}|^2 \beta_1 P_R}{|h_{RU1}|^2 \beta_2 P_R + \sigma^2} \quad (13)$$

The achievable rates for each symbol are given as follows. For SIC, the relay should decode x_1, and the achievable rate associated with x_1 is obtained from (5) and (7) as:

$$C_{X1} = \frac{1}{2} min \left\{log_2(1+\gamma_{BU1}^{X1}), log_2(1+\gamma_{BR}^{X1})\right\} \quad (14)$$

As the achievable rate of DF relaying is dominated by the weakest link, U3 must decode x_2 for SIC, and the achievable rate related to x_2 is obtained from (6), (13), and (11) as:

$$C_{X2} = \frac{1}{2} \log_2 \left\{1 + min\left(\gamma_{BR}^{X2}, \gamma_{RU1}^{X2}, \gamma_{RU3}^{X2}\right)\right\} \quad (15)$$

When U3 succeeds in decoding x_2, the achievable rate associated with x_R *is* given by:

$$C_{XR} = \frac{1}{2} \log_2 \left(1 + \gamma_{RU3}^{XR}\right) \quad (16)$$

Performance analysis

This part of the research paper explains ergodic capacity (EC) which is used as a performance metric in wireless communication systems to characterize the average achievable data rate of a communication link over a long period, considering the statistical variations of the channel conditions.

Ergodic capacity (EC)

EC is a concept used in information theory and communication systems to quantify the average data rate that can be reliably transmitted between the transmitter and receiver under varying channel conditions. Ergodic capacity is calculated by taking the average of the capacity achieved over different channel realizations, considering the probability distribution of the channel conditions [12]. For a wireless channel with signal-to-noise ratio (SNR) γ, the ergodic capacity can be expressed mathematically as:

$$C = E[\log_2(1+\gamma)] \quad (17)$$

where, $E[.]$ is the expectation operator and $\log_2(1+\gamma)$ is the instantaneous capacity of the channel for a given SNR (γ).

4. Simulation results

Figure 2 below gives a comparison of the simulation results for the proposed C-NOMA employing decode-forward and existing CNOMA with decode-forward. NOMA's power allocation scheme plays a crucial role in the determination of results. In these results, dynamic power allocation has been considered and it can be seen that the system performance shows an improvement in terms of ergodic system capacity. As the transmit SNR increases, the quality of the received signal improves, which leads to higher capacity which is dependent on the power allocation strategy. At 10dB, the rate gain of proposed CNOMA over existing CNOMA is 10% meanwhile when the SNR is at 30 dB, there's about a 25% increase in rate gain over existing CNOMA.

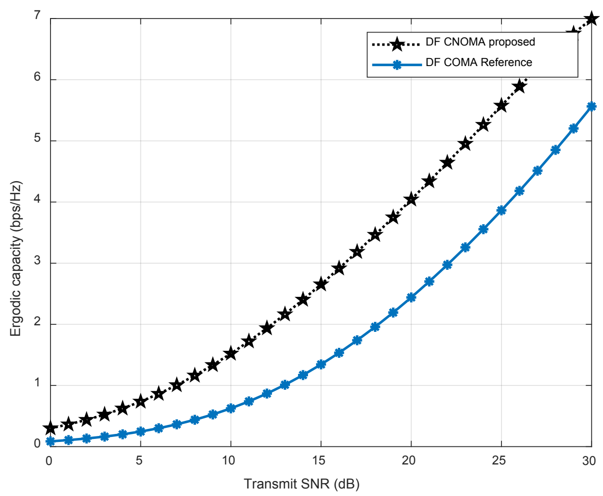

Figure 2. Comparison of DF CNOMA and DF COMA.

5. Conclusions

We introduced a cooperative NOMA framework involving three users, where the user situated closer to the base station serves as a relay using the decode-and-forward relaying protocol. Additionally, we formulated a cooperative OMA setup utilizing the decode-and-forward protocol, serving as a reference point for comparison. The outcomes of our investigation demonstrate that the decode-and-forward protocol, coupled with dynamic power allocation in NOMA, outperforms the decode-and-forward protocol in OMA. As a next step, our research aims to explore the potential of incorporating a hybrid amplify-and-forward/amplify-and-forward approach in more complex scenarios involving multiple participants. Secondly, since wireless channels are often frequency selective we intend to consider it as well as frequency offset in our research in order to see how the performance will be. Finally, we will analyse the system performance considering bit error rate (BER) vs average signal to noise ratio (SNR) per bit of NOMA and OMA systems.

Author Contributions

Author 1: Came up with the idea of researching on how NOMA would behave when it's incorporated with cooperative relaying using dynamic power allocation with a relay employing decode and forward. The system design was proposed of a three user case scenario.

Author 2: The main contribution was that, he being the main supervisor was responsible to see to it that the research objectives were met and that the system was designed accordingly.

Author 3: Co-supervisor, was responsible for grammatical and spelling corrections. He had to peer review the entire document.

Conflict of Interest

There is no conflict of interest.

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