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Relay-Aided PDMA with Dynamic Power Control for Cell-Edge User Fairness

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Abstract: Cell-edge users in wireless communication networks often suffer from poor performance due to weak channel conditions. To address this issue, we propose a relay-assisted communication system that employs Pattern Division Multiple Access (PDMA). This approach enhances efficiency and capacity for cell-edge users while maintaining acceptable relay performance. The proposed scheme includes a Base Station (BS), a Relay (R) with better channel conditions, and a cell-edge user. Transmission occurs over two time slots: In the first time slot, the base station (BS) transmits a superimposed signal to both the relay and the cell-edge user. In the second time slot, the relay forwards only the decoded information intended for the cell-edge user. The cell-edge user then applies successive interference cancellation (SIC) to recover the desired signal.To further optimize system performance, we implement an optimal power allocation strategy at the base station that: (1) assigns power to both the signal intended for the relay and the cell-edge user in the superimposed transmission, while (2) allocating higher transmit power to the relay compared to the BS, leveraging the relay's superior channel conditions. This approach enhances the overall system capacity and reliability, particularly benefiting cell-edge users with weak direct links. This approach enhances the overall capacity and reliability of the relay-assisted transmission, thereby improving the quality of service (QoS) for cell-edge users with weak direct links to the BS. As a result, the cell-edge user benefits from both the BS and relay transmissions, enabling the decoding of the superimposed signal by using SIC and ultimately improving spectral efficiency. Furthermore, we introduce a fairness metric to assess the received capacity relative to the actual capacity of each user, providing insights into the equitable distribution of resources. The fairness metric is calculated as the ratio of the received capacity to the actual capacity for each user, allowing for a comparison of how fairly the system allocates resources under different schemes.

Keywords: Relay, Non-orthogonal multiple access, Superposition coding, Decode and forward

Introduction

Superposition Coding (SC) has been recognized as an effective capacity-achieving signaling technique in broadcasting and multicasting scenarios (Silva et al.,2010; Wang, et al., 2013). In this approach, multiple encoded sequences (referred to as layers) are linearly combined into a single composite signal prior to transmission. SC functions as a data multiplexing method for a single user and shares similarities with Non-Orthogonal Multiple Access (NOMA), wherein each layer can be interpreted as representing an individual user (Kim et al., 2015).

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At the receiver end, similar to NOMA, low-complexity iterative decoding techniques can be employed. These are enhanced by allocating different power levels to the layers, thereby improving the overall system throughput (Alsakarnah et al., 2017; Chattha et al., 2016). To further enhance the efficiency of superposition-based transmission schemes, Pattern Division Multiple Access (PDMA) has emerged as a promising candidate. PDMA extends the concept of non-orthogonal access by exploiting unique transmission patterns across multiple domains such as power, code, and spatial resources. Unlike conventional SC or NOMA, PDMA allows for more flexible user multiplexing through pattern design, which can effectively reduce inter-user interference and improve spectral efficiency. By integrating PDMA with Superposition Coding, the system can leverage both the layered transmission structure of SC and the pattern diversity of PDMA, leading to improved throughput, user fairness, and overall system performance.

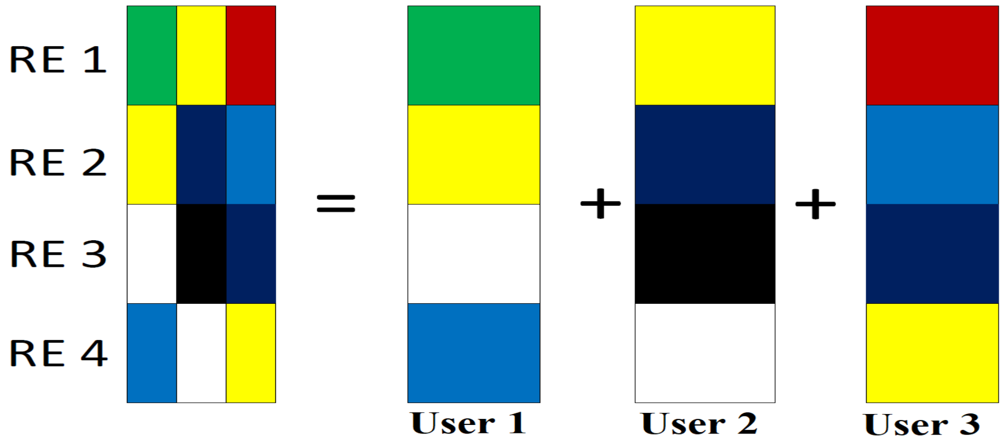

Figure 1. PDMA pattern for three users on 4 Res

Figure 1. shows an example of a a PDMA pattern for a network employing a predefined PDMA pattern, in which a single base station (BS) serves three users across two resource elements (REs). Without loss of generality, it is assumed that User 1 utilizes RE1, RE2, and RE1; User 2 accesses RE1, RE2, and RE3; whereas User 3 makes use of all four available REs. To further enhance system efficiency, cooperative communications will be employed, wherein a user located between the base station (BS) and the cell-edge user acts as a relay, forwarding the data intended for the cell-edge user.

Cooperative communication employing relay nodes has demonstrated the potential to enhance both the transmission rate and diversity of wireless networks (Ngo et al., 2009; Narula et al., 1998). However, when all relay nodes function in half-duplex mode, traditional relaying schemes typically require more time compared to direct transmission, as additional time slots are needed for the relays to forward the received signals to their respective destinations.

This paper investigates and compares four downlink transmission schemes in a system comprising a base station (BS), a decode-and-forward (DF) relay, and a far user. These schemes are designed to improve the achievable rate for the far user through a combination of spatial diversity, power-domain multiplexing, and resource element (RE) pattern design. In addition to evaluating the achievable rate, user fairness will also be discussed by introducing a fairness index, which quantifies the users achieved data rates relative to their rates under direct transmission and total data rates transmitted from the base station.

System Model

We consider a downlink transmission scenario in a network comprising a base station (BS), a user acting as a relay (R), and a destination node (D), as illustrated in Figure 2. All transceivers are equipped with single omnidirectional antennas. In this one-way communication setup, the BS transmits following the proposed scheme, while the relay alternates between receiving from the BS and forwarding data to the cell-edge user, following the proposed scheduling scheme. In the first approach (the baseline scheme), the BS communicates directly with the relay and the cell-edge user in two separate time slots. While this method offers a certain degree of spectral efficiency, its overall performance is significantly degraded in the presence of weak channel conditions, and it requires additional transmission time to serve both the relay and the cell-edge user.

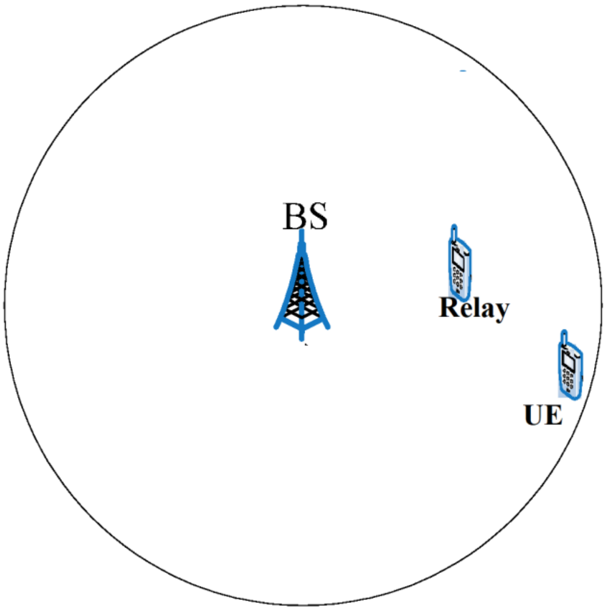

Figure 2. Decode and forward (DF) relay assited wireless communication

To overcome the limitations of direct transmission in serving cell-edge users with poor channel conditions, cooperative relaying has been widely adopted as an effective strategy. In the decode-and-forward (DF) relaying framework, the communication process is divided into two phases: the base station first transmits data to the relay, which then decodes and re-transmits the signal to the far user. This cooperative strategy enhances link reliability by exploiting spatial diversity, though it introduces a loss in spectral efficiency due to the additional time slots required for relaying. The achievable capacity for the cell-edge user is given by:

$$R_{\mathrm{DF}} = \frac{1}{2}\min\left\{\log_2\left(1+\mathrm{SNR}_{\mathrm{BR}}\right), \log_2\left(1+\mathrm{SNR}_{\mathrm{RU}}\right)\right\}$$

Building upon this, non-orthogonal multiple access (NOMA) has been incorporated into relay-assisted systems to improve spectral efficiency by allowing simultaneous transmission to multiple users using power-domain multiplexing. In such configurations, the base station transmits a superimposed signal to both the relay and the far user. In the nth time slot, the BS transmits the signal:

$$s_{BS}(n) = \sqrt{P_T}\cdot\left(\alpha_1 s_1(n) + \alpha_2 s_2(n)\right)$$

Here, $s1(n)$ and $s2(n)$ represent the intended signals for the relay and the cell-edge user, respectively. In this scheme, higher transmission power is allocated to $s1(n)$, so that $s2(n)$ to be treated as interference at the relay. However, The relay assists in canceling this interference at the cell-edge user during the second time slot by forwarding it to the cell-edge user. The operation of the proposed Noma relaying scheme is summarized in Table 1.

Table 1. Transmission schedule for relay-assisted NOMA scheme

Time Slot	Transmitter	Recievers	Signal
1	Basestation (BS)	Relay (R), Cell-edge user	$s_{BS}(n) = \sqrt{P_T}\cdot\left(\alpha_1 s_1(n) + \alpha_2 s_2(n)\right)$
2	Realy (R)	Cell-edge user	s2(n)

The acheivable data rate for the relay after using SIC to cancel s2(n) in this scheme is given by:

$$\log_2\left(1+\frac{|h_1|^2 P_2}{N_0}\right)$$

Where h1 is the channel coeffiecent betweeen the BS and R, P2 is the power allocated to the relay. While the acheivable data rate for the cell edge user is given by:

$$\cdot\log_2\left(1+\frac{|h_2|^2 P_1}{N_0}\right)$$

It can be noticed that the relay, benefiting from a stronger channel, employs successive interference cancellation (SIC) to decode the far user’s message and forwards it in a subsequent time slot. Further enhancement is achieved by enabling both the relay and the far user to apply SIC. In this case, the base station employs superposition coding to transmit a combined signal, while both the relay and cell-edge user decode their respective messages through interference cancellation. The relay then assists the cell-edge user by forwarding its message in the second time slot. This strategy leverages both cooperative and power-domain diversity, improving system performance at the cost of increased receiver complexity. Together, these schemes demonstrate the progressive integration of cooperative and non-orthogonal transmission techniques to support high data rates and reliable communication for users in disadvantaged channel conditions.

To further enhance the efficiency of superposition-based transmission schemes, Pattern Division Multiple Access (PDMA) has emerged as a promising candidate. PDMA extends the concept of non-orthogonal access by exploiting unique transmission patterns across multiple domains such as power, code, and spatial resources. Unlike conventional SC or NOMA, PDMA allows for more flexible user multiplexing through pattern design, which can effectively reduce inter-user interference and improve spectral efficiency. By integrating PDMA with Superposition Coding, the system can leverage both the layered transmission structure of SC and the pattern diversity of PDMA, leading to improved throughput, user fairness, and overall system performance.

Table 2. Transmission schedule for relay-assisted PDMA scheme

Time Slot	Transmitter	Receiver(s)	RE Usage	Signal Flow
1	BS	Relay, Cell-edge user	RE1, RE2	s1(n), s2(n), s3(n)
2	Relay	Cell-edge user	RE1	S2(n)

Table 2 illustrates the operation of the relay-assisted PDMA scheme. In the first time slot, the BS transmits to both the relay and the cell-edge user using two resource elements (REs): $s1(n)$ and $s2(n)$ are superimposed on RE1, while $s3(n)$ is transmitted on RE2 to the cell-edge user. In the second time slot, the relay forwards $s2(n)$ to the cell-edge user. The PDMA pattern matrix for this scheme is expressed as:

$$\mathbf{P}=\begin{bmatrix}1 & 1\\ 1 & 0\end{bmatrix}$$

where the first row corresponds to the cell-edge user access to RE1 and RE2, and the second row indicates the relay's reception on RE1 only. This pattern is designed to ensure that the user benefits from full RE coverage for improved diversity and decoding, while the relay receives selectively to simplify its processing for decode-and-forward operation.

Results and Discussion

In this section, we present a numerical performance evaluation of the proposed PDMA system based on Monte Carlo simulations. The evaluation is carried out by averaging the SNRs and link capacities over 10^5 independent channel realizations for a fixed user position. In the considered scenario, the relay is positioned between the BS and the cell-edge user, such that the channel conditions between the BS and the relay are significantly better than those between the BS and the cell-edge user. We consider the SNR values varying from 0 to 30 dB. It is assumed that the power of the AWGN at both the relay and the cell-edge user is identical, and that the relay transmits with the same power as the BS. Furthermore, we assume that the total transmit power satisfies $P1 + P2 = PT$. In both the NOMA and PDMA schemes, the BS's transmit power is allocated such that the relay and the cell-edge user can successfully decode the transmitted signals using successive interference cancellation (SIC). The fairness index is evaluated by comparing the ratio of each user's received capacity to their ideal or target capacity. A fairness index closer to one indicates a more balanced and fair system. A lower fairness index implies that the relay is being favored, whereas a higher fairness index suggests that the BS is allocating more resources in favor of the cell-edge user. In direct transmission, the BS requires two time slots to serve both the relay and the cell-edge user.

The fairness index for this scheme is equal to one, as no specific enhancement is applied to either the relay or the cell-edge user, and both users are allocated one time slot per transmission cycle. In the decode-and-forward relaying scheme, a complete transmission cycle requires three time slots: two time slots for serving the cell-edge user from the relay, and one time slot for the relay to receive data from the BS. In this scheme, due to the improved link to the cell-edge user through the relay, the fairness index exceeded one but we consider it one as it is the maximum value of the fairness index.

The improvement in fairness is attributed to allocating two time slots to the cell-edge user and utilizing a more reliable link compared to direct transmission. For the NOMA and PDMA schemes, additional improvements were made for the cell-edge user by utilizing non-orthogonal transmission technologies. Moreover, the use of a PDMA pattern, which assigns more radio resources to the cell-edge user, further enhances fairness for that user.

Figure 3 shows the SNR values when the BS uses Pt to transmit to only one user. In contrast, in the NOMA and PDMA schemes, the BS superimposes s1 and s2 by allocating different power levels to the relay and the cell-edge user based on their respective channel conditions. More power is allocated to the cell-edge user, as it experiences poorer channel conditions, whereas the relay benefits from better channel conditions with both the BS and the cell-edge user.

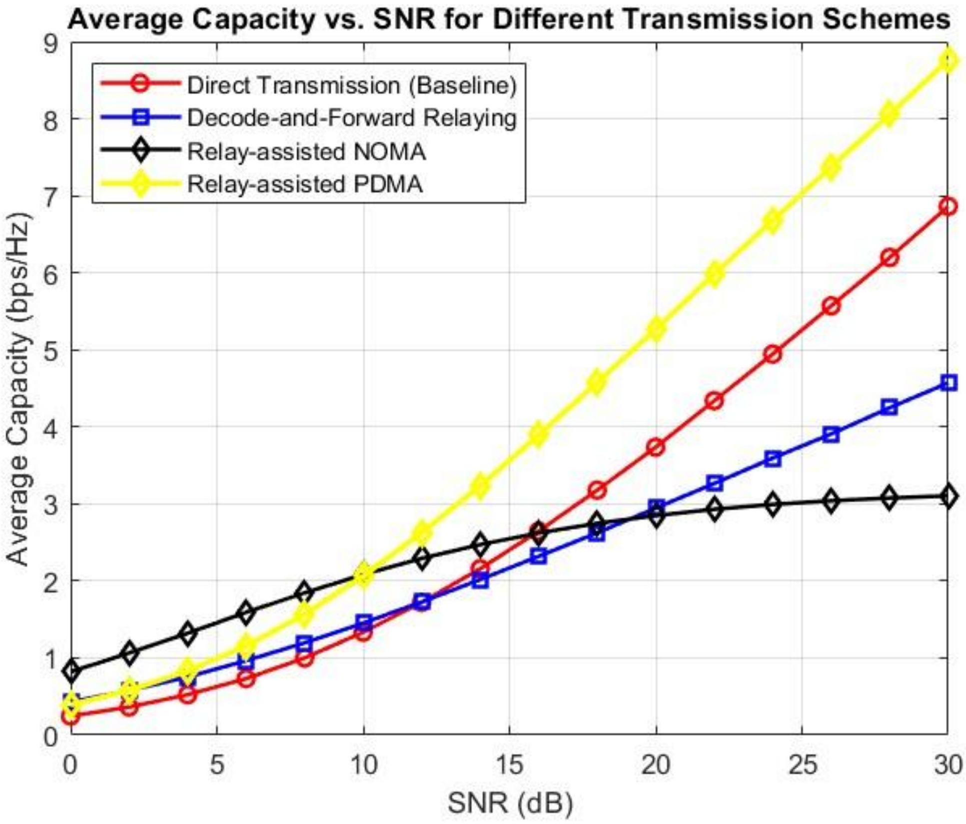

Figure 3. Capacity comparisons of the four different schemes

From Figure 3, the proposed PDMA scheme achieves the highest data rate due to two main factors: (i) the utilization of two radio resources and (ii) the additional gain from the relay. While the relay-assisted NOMA scheme performs well in the low SNR range (0 to 10 dB) and remains acceptable up to around 15 dB, its performance degrades significantly beyond that point. This degradation is primarily due to the interference caused by the superposition of signals in NOMA, specifically, the interference from the data intended for the relay negatively impacts the decoding performance at the cell-edge user.

Conclusion

In this work, we investigate relay-based transmission in a wireless system employing NOMA and PDMA coding schemes. The proposed schemes consist of two key components: (i) signal layering at the source combined with multiplexed coding at the relay, and (ii) power allocation to facilitate SIC (Successive Interference Cancellation) decoding. While source-layering enables the recovery of only the base layer at the destination via the direct path, multiplexed coding through over-the-air signal superposition allows full utilization of system resources for decoding the intended information at the cell-edge user. Using network average capacity as the performance metric, the proposed PDMA scheme demonstrates excellent performance, comparable to single-relay superposition coding schemes, and effectively mitigates interference caused by relaying. The main advantage of the proposed scheme lies in its ability to enhance bandwidth efficiency by leveraging relay assistance, non-orthogonal multiple access, and PDMA patterning.

Scientific Ethics Declaration

* The authors declare that the scientific ethical and legal responsibility of this article published in EPSTEM Journal belongs to the authors.

Conflict of Interest

* The authors declare that they have no conflicts of interest

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