

PERFORMANCE ANALYSIS OF SUM-RATE AND OUTAGE IN USER PAIRING FOR HYBRID NOMA NETWORKS UNDER NAKAGAMI-M FADING

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Abstract

Non-orthogonal Multiple Access (NOMA) enhances system radio capacity and offers superior spectral efficiency. However, the intricacy of Successive Interference Cancellation (SIC) poses a significant challenge for NOMA implementation. To address this, dividing users into orthogonal frequency groups and employing hybrid NOMA within each group is recommended. Our simulation results for single-carrier NOMA (SC-NOMA) sum rate analysis demonstrate that increasing the number of users beyond a certain threshold leads to a decline in network sum throughput. Consequently, it's not feasible to indefinitely increase the number of users per carrier. Furthermore, we investigated user pairing strategies within the hybrid NOMA framework. Our simulation results for Near-Near (N-N), far-far (F-F), and near-far (N-F) user pairing schemes demonstrate that user pairing can significantly reduce computational costs. To further evaluate network sum rate performance, we compared these pairing schemes using both SC-NOMA and Time Division Multiple Access (TDMA) over a Nakagami-m fading channel. Our findings show that pairing the nearest user with the farthest user dramatically increases the total sum rate. While NOMA still outperforms TDMA with respect to sum rate when using N-N and F-F pairings, the improvement is less pronounced. SC-NOMA, on the other hand, underperforms TDMA. At low Signal-to-Noise Ratios (SNR), N-N, F-F pairing yields a higher sum rate than N-F pairing. However, this trend reverses at high SNR, where N-F pairing offers a superior sum rate. Consequently, N-F pairing can also lead to increased sum rates at high SNR.

Keywords:

Hybrid NOMA, SC-NOMA, TDMA, User Pairing, Sum-Rate, Outage, Nakagami-M Fading Channel

1. INTRODUCTION

Non-Orthogonal Multiple Access (NOMA) has evolved into a key subject as a part of advancement of modern wireless systems, especially as networks transition from 5G toward early 6G architectures. Its ability to allow the sharing of the same resource block among multiple users through power domain multiplexing makes it a promising option for improving spectral efficiency. Despite these advantages, NOMA's performance is sensitive to channel fluctuations and becomes increasingly challenging to manage as the number of connected users grows. To overcome these limitations, hybrid access schemes that combine NOMA with traditional Orthogonal Multiple Access (OMA) have gained significant attention. In conventional NOMA, users are gathered as per their channel gains; higher transmission power is assigned to users with weaker channels. This strategy provides the system with greater flexibility and enables more efficient utilization of available resources [1].

One major advantage of hybrid NOMA over Time Division Multiple Access (TDMA) is its ability to serve multiple users simultaneously, unlike TDMA's dedicated time slot structure that may lead to underutilized resources and reduced throughput. This performance gap becomes even more prominent in scenarios where users experience significantly different channel conditions.

NOMA can effectively exploit these differences through appropriate user pairing and power allocation strategies.

Decoding in NOMA relies on Successive Interference Cancellation (SIC) or adaptive SIC, both of which are essential for separating the superimposed signals at the receiver. By combining SIC with suitable user pairing and power allocation strategies, NOMA supports an increased number of users without substantially increasing complexity [2-6]. In practical implementations, users are typically paired into groups, while orthogonal resources are assigned across groups to balance capacity and computational feasibility [7].

Several studies have analyzed different user pairing strategies for NOMA. For instance, the work in [8] focuses on maximizing the system sum rate by pairing users based on channel state information. In [9], proportional fairness is incorporated into the pairing and power allocation framework, while studies such as [10] and [11] emphasize fairness-oriented power allocation approaches. However, as highlighted in [12] and [13], overall throughput begins to decline once the number of users accessing the common carrier exceeds a certain threshold. This limitation makes it impractical to scale pure NOMA indefinitely. Hybrid NOMA offers a more feasible alternative by supporting a larger pool of users while maintaining manageable system complexity.

Despite its advantages, hybrid NOMA introduces its own challenges. Identifying optimal user pairings can be computationally demanding in large networks, and rapidly varying channel conditions require frequent reevaluations of pairing decisions, adding to system overhead.

In this paper, we analyze the achievable sum rate of a single carrier NOMA (SC NOMA) system under Nakagami m fading. We investigate how the sum rate changes as the number of multiplexed users increases, and we evaluate a two-user hybrid pairing strategy. The performance is measured against conventional SC NOMA and TDMA. The major contributions of this work are outlined below:

- Analysis of SC NOMA sum rate performance for multiple users under Nakagami m fading,
- Sum rate evaluation for near–near (N–N), far–far (F–F), and near–far (N–F) user pairing approaches,
- Comparison of these pairing strategies with TDMA and conventional SC NOMA,
- Investigation of sum rate and outage performance across different Nakagami m fading parameters.

The remainder of the paper is arranged as follows. The system model is described in Section 2, derives the sum rate expressions for the two user pairing schemes, and introduces a power allocation method for SC NOMA when the number of users increases. Section 3 presents the simulation results and compares the performance of NOMA and OMA schemes. Section 4 concludes the paper.

2. SYSTEM MODEL

We employed a power allocation method for multi-user SC-NOMA to address the SIC complexity in strong users, the interference issues in weak users, and the overall power allocation challenge. We begin by selecting fractions smaller than 1. Starting with the weakest user U_1 , we choose $\frac{3}{4}$. For U_1 , set the fading coefficient of this user $\alpha_1=3/4$, for the number of users, i.e., $K=n$, set the related power allocation coefficient, $\alpha_n = 1 - (\alpha_1 + \alpha_2 + \alpha_3 + \dots + \alpha_{n-1})$, otherwise set $\alpha_n = \frac{3}{4} (1 - (\alpha_1 + \alpha_2 + \alpha_3 + \dots + \alpha_{n-1}))$.

Applying this technique to every user, we devised a power allocation method that satisfies all the requirements. However, we immediately noticed a new issue: even with an algorithm designed to ensure proper power distribution, the strongest user's power allocation gradually decreases as more users join the network. This may result in a decline in their achievable data rate. In section 3, we will explore some of the challenges observed in SC-NOMA and later apply a hybrid model to resolve this issue.

As an illustration, consider TDMA+NOMA, a combination of OMA and NOMA, as depicted in Fig.1. We aim to assume a time window of 4 ms, during which four users need to be supported.

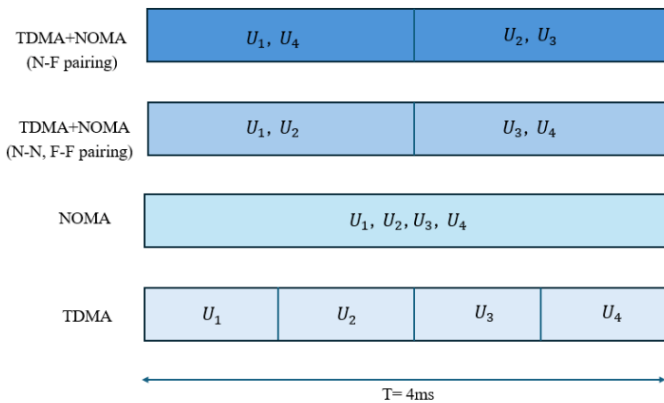


Fig.1. Users of various multiple access methods.

In a conventional TDMA system, a 4-ms transmission window is divided into four separate 1-ms slots, with each user receiving one slot exclusively. This approach keeps the structure simple but restricts the system to serving only one user in each time interval. Under a pure NOMA scheme, however, all four users would share the entire 4-ms window at the same time. While this simultaneous access can improve spectral efficiency, it also increases processing latency and adds to the complexity of SIC at the receiver [14].

Hybrid NOMA attempts to strike a balance between these two extremes. In the same 4-ms window, the frame can be divided among two 2-ms time slots. A pair of NOMA users are then assigned per slot. This significantly reduces SIC complexity compared to pure NOMA, yet it still allows a level of simultaneous transmission that TDMA alone cannot provide. Overall, hybrid NOMA helps simplify service delivery while ensuring that users are efficiently connected to any available orthogonal resource. To form the NOMA groups within each slot, two-user pairing techniques are typically employed.

We explored a downlink transmission circumstance using four users, as illustrated in Fig.2. The spacing of users U_1, U_2, U_3 and U_4 from the base station are indicated by the variables d_1, d_2, d_3 and d_4 . The nearest user is U_1 , and the farthest user is U_4 . Their channel specifications are thus classified in the following order: $|h_1|^2 > |h_2|^2 > |h_3|^2 > |h_4|^2$ and h_1, h_2, h_3, h_4 represent Nakagami- m fading conditions.

The fading parameter m , which defines the degree of signal fading and can vary from 1/2 to infinity, is used to classify Nakagami- m fading, with 1/2 representing the most severe fading and infinity representing no fading. When the parameter m equals 1, Nakagami- m fading has a specific form. The Rayleigh distribution replaces the Nakagami- m distribution in this case [15]-[18]. Nakagami- m fading coefficient for each user can be represented as:

$$h_i = \sqrt{d_i^{-\eta}} \left(\sqrt{\text{gamrnd}\left(m, \frac{\Omega}{m}, 1, N\right)} \right) \quad (1)$$

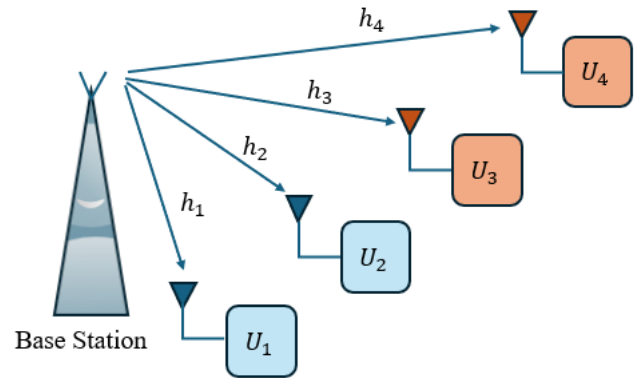


Fig.2. System model

Two users are allocated to each of the two orthogonal resource blocks, containing time, frequency, and subcarriers. Users are paired as per their distances. In [19, 20], two easy ways for achieving this are given below:

2.1 NEAR-FAR PAIRING (N-F)

In this pairing strategy, the nearest user to the base station is paired with the distant user. The subsequently closest user is paired with the subsequently farthest user, and this behaviour persists accordingly. However, condition, the nearest user is U_1 , however the most distant user is U_4 . Therefore, near-far (N-F) pairing joins U_1 and U_4 surrounded by the same resource block. In the subsequent resource block, users U_2 and U_3 are paired together.

In the first user pair, U_1 is associated as the near user, while U_4 is the far user. Hence, the power allocation coefficients are chosen such that $\alpha_1 < \alpha_4$. Consequently, U_1 operates direct decoding, though U_4 uses successive interference cancellation (SIC). Likewise, in the second user pair, U_2 acts as the near user and U_3 as the far user, indicating to choosing of $\alpha_2 < \alpha_3$. In this case, U_2 employs SIC, however U_3 carries out direct decoding.

The following rates are achievable by the users in the first pair:

$$R_{i, \text{nf}} = \frac{1}{2} \log_2 \left(1 + \frac{P\alpha_i |h_i|^2}{\sigma^2} \right) \text{ (following SIC)} \quad (2)$$

$$R_{4,nf} = \frac{1}{2} \log_2 \left(1 + \frac{P\alpha_4 |h_4|^2}{P\alpha_1 |h_4|^2 + \sigma^2} \right) \quad (3)$$

In the same way, for the second pair,

$$R_{2,nf} = \frac{1}{2} \log_2 \left(1 + \frac{P\alpha_2 |h_2|^2}{\sigma^2} \right) \text{ (following SIC)} \quad (4)$$

$$R_{4,nf} = \frac{1}{2} \log_2 \left(1 + \frac{P\alpha_4 |h_4|^2}{P\alpha_2 |h_4|^2 + \sigma^2} \right) \quad (5)$$

The N-F method's sum rate is as follows:

$$R_{nf} = R_{1,nf} + R_{2,nf} + R_{3,nf} + R_{4,nf} \quad (6)$$

2.2 NEAR-NEAR, FAR-FAR PAIRING (N-N, F-F)

Combining the users who are closest to one another and the users who are farthest apart is another method for pairing users. This approach pairs U_1 and U_2 in one resource block and U_3 and U_4 in the other. We should select $\alpha_1 < \alpha_2$ for the initial user pair as U_1 stays nearer to the base station than U_2 . U_1 is supposed to handle SIC, whereas U_2 is supposed to handle direct decoding. Like the first user pair, we should select $\alpha_3 < \alpha_4$ since U_3 is located nearer to the base station compared to U_4 . SIC will be carried out by U_3 , and direct decoding by U_4 .

The following rates are achievable by the users in the first pair:

$$R_{1,nn} = \frac{1}{2} \log_2 \left(1 + \frac{P\alpha_1 |h_1|^2}{\sigma^2} \right) \text{ (following SIC)} \quad (7)$$

$$R_{2,nn} = \frac{1}{2} \log_2 \left(1 + \frac{P\alpha_2 |h_2|^2}{P\alpha_1 |h_2|^2 + \sigma^2} \right) \quad (8)$$

In the same way for the other pair,

$$R_{3,nn} = \frac{1}{2} \log_2 \left(1 + \frac{P\alpha_3 |h_3|^2}{\sigma^2} \right) \text{ (following SIC)} \quad (9)$$

$$R_{4,nn} = \frac{1}{2} \log_2 \left(1 + \frac{P\alpha_4 |h_4|^2}{P\alpha_3 |h_4|^2 + \sigma^2} \right) \quad (10)$$

The N-N, F-F method's sum rate is as follows:

$$R_{nn} = R_{1,nn} + R_{2,nn} + R_{3,nn} + R_{4,nn} \quad (11)$$

3. SIMULATION RESULTS AND DISCUSSION

We examined the performance of an SC-NOMA system under Nakagami- m fading using transmit power values of 10 dBm, 20 dBm, and 30 dBm. Monte Carlo simulations were conducted with a 15 kHz bandwidth and fading parameters of $m = 0.5, 1, \text{ and } 5$. As illustrated in Fig.3, adding more users to the SC-NOMA configuration initially increases the overall sum rate. This behaviour aligns with the general advantage of NOMA over OMA, where efficient power distribution and controlled interference allow the strongest user to maintain a reasonable throughput even when allocated less power than weaker users.

The Fig.3 also reveals a point at which the total capacity begins to decline. This "drop-off point" indicates the maximum number of users the system can support before performance starts to deteriorate. The position of this point varies with the transmit

power level. For instance, when the transmit power is set to 10 dBm, the sum rate starts decreasing once more than four users are included, regardless of the value of m . However, with a transmit power of 30 dBm, the drop-off occurs only after more than eight users.

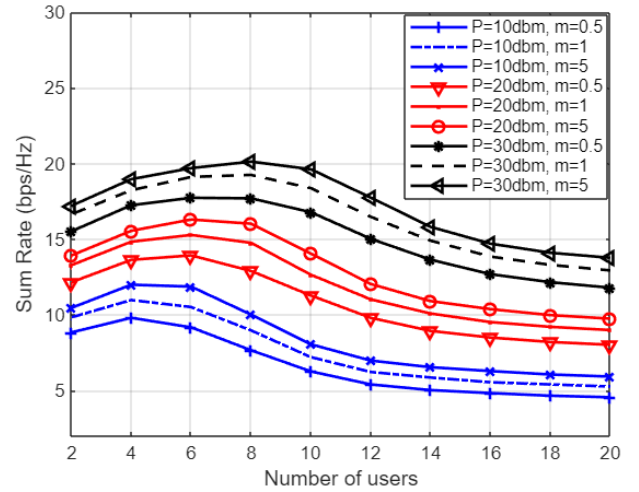


Fig.3. Sum-rate of SC-NOMA with multiple users

This trend is closely connected to the adopted power-allocation method. The weakest user receives the smallest portion of the total power, and even this small share of 30 dBm is significantly larger than the same proportion taken from 10 dBm. Consequently, supporting additional users without degrading performance requires increasing the total transmit power. As the number of users in the system increases, choosing an appropriate user-pairing method becomes essential for making effective use of available power and bandwidth. Random pairing, although simple, often fails to take advantage of the network's full performance capabilities.

To study this in more detail, we examined how two different pairing strategies influence performance in a four-user scenario. The results are shown in Fig.4, where the sum-rate trends of each strategy are compared with those of conventional SC-NOMA and TDMA. The analysis was carried out under Nakagami- m fading with m values of 0.5, 1, and 5 to observe the effects of varying channel conditions. In general, TDMA tends to outperform SC-NOMA when the network includes many users with highly uneven channel qualities. In such cases, interference management in SC-NOMA becomes increasingly challenging, and the decoding complexity can significantly reduce performance. This is especially evident when the channel gains of the users are not well separated, leading to substantial interference during SIC and causing SC-NOMA to fall behind the simpler, interference-free time-slot approach of TDMA.

Among the pairing options, using N-N and F-F combinations instead of N-F pairing can offer advantages in terms of more balanced interference handling and potentially higher overall throughput. Grouping users with similar channel conditions allows the system to better exploit channel diversity and reduces the dominance of interference between widely separated users. As a result, both near and far users can experience improved performance, particularly in challenging or rapidly varying channel environments.

The Fig.5 confirms the well-established principle that NOMA performs best when users have significantly different channel conditions. This supports the findings in [10], which state that pairing a near user with a far user maximizes the sum rate. While NOMA with N-N and F-F pairing still outperforms TDMA, the improvement is less significant. SC-NOMA, on the other hand, underperforms TDMA due to excessive interference caused by overloading all users onto the same carrier, emphasizing the trade-off between increasing the number of users and maintaining performance.

The advantage of N-F pairing over N-N-F-F pairing stems from the strategic selection of users experiencing interference. The N-F scheme, assuming perfect SIC provides interference-free reception to both near users. In contrast, the N-N-F-F scheme provides interference-free transmission to only one near user and one far user. Therefore, N-F pairing typically yields a better sum rate. However, when noise power dominates the interference power, the choice of users experiencing interference becomes less critical. In such noise-limited scenarios, both schemes are expected to perform similarly.

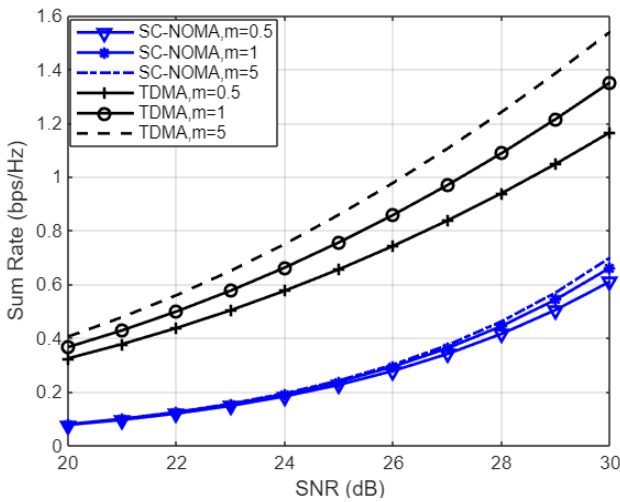


Fig.4. Sum rate of TDMA and SC-NOMA over Nakagami- m fading channel

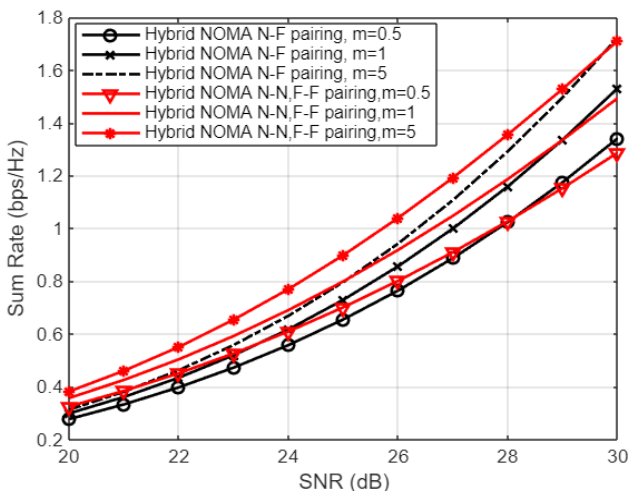


Fig.5. Sum rate of hybrid NOMA using near-near, far-far and near-far pairing over Nakagami- m fading channel

Table.1. Sum-rate using TDMA, SC-NOMA, Hybrid NOMA with N-N, F-F and N-F Pairing for different Fading parameters of Nakagami- m channel

| SNR (dB) | m | Sum rate (bps/Hz) | | | |
|----------|-----|-------------------|---------|------------------|-------------|
| | | TDMA | SC-NOMA | N-N, F-F Pairing | N-F pairing |
| 20 | 0.5 | 0.3256 | 0.0789 | 0.32635 | 0.2794 |
| | 1 | 0.3643 | 0.0789 | 0.3524 | 0.2946 |
| | 5 | 0.4046 | 0.0789 | 0.3836 | 0.3136 |
| 30 | 0.5 | 1.1653 | 0.6127 | 1.2941 | 1.3446 |
| | 1 | 1.3482 | 0.6587 | 1.4878 | 1.5215 |
| | 5 | 1.5388 | 0.6988 | 1.7155 | 1.7156 |

The Table.1 shows that the sum rate increases with the fading parameter m . Furthermore, at a 20 dB SNR, N-N and F-F pairing yields a higher sum rate than N-F pairing. However, this trend reverses at a 30 dB SNR, where N-F pairing offers a superior sum rate. This indicates that at high SNRs, N-F pairing can also lead to increased sum rates.

4. CONCLUSION

The main findings of this paper show that the number of users multiplexed on a single carrier cannot be increased without limit. When around 100 users are placed on one carrier, issues such as higher SIC complexity, increased latency, more difficult power allocation, and reduced achievable rates begin to appear. In our simulation, the point where performance starts to decline indicates the maximum number of users that can be supported.

Hybrid NOMA, which combines OMA and NOMA, can be used to accommodate all 100 users on a single carrier. Employing N-N and F-F user pairing schemes, NOMA demonstrates superior performance compared to TDMA, although the advantage becomes smaller. The results highlight a trade-off: adding too many users eventually causes SC-NOMA to perform worse than TDMA because of the heavy interference created by placing all users on one carrier.

It should also be noted that NOMA with user pairing requires more complex signal processing at both the transmitter and receiver compared to TDMA. Its performance also depends on having clear channel gain differences between paired users, which may not always be available in practical situations. Sum-rate performance can still be improved by combining hybrid NOMA pairing with an optimized power-allocation approach.

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