GRAND-AM in uplink MIMO NOMA systems

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***Abstract*—Multiple input multiple output (MIMO) systems and nonorthogonal multiple access (NOMA) methods are both valuable techniques for modern and future communication systems. MIMO is commonly used in scenarios such as mobile communications and the Internet of Things in order to improve signal quality or increase channel capacity, while NOMA is important as its methods can be used to service the growing number of users. A combination of the two techniques should thus be investigated. We integrate MIMO methods such as the Alamouti space time block code (STBC) with Guessing Random Additive Noise Decoding Aided Macrosymbol (GRAND-AM), which was previously proposed for single input single output (SISO) systems. Originally, GRAND-AM handled the multiple access interference (MAI) using multiple access channel (MAC) codes assigned to each user, along with joint multiuser detection and decoding. We consider how using the Alamouti STBC as a replacement of the MAC codes performs with GRAND-AM. We show that GRAND-AM is able to outperform the multiuser Vertical-Bell Laboratories Layered Space-Time (V-BLAST) receiver by $\sim$ 2.5dB when used to handle two users using the Alamouti STBC. We show how GRAND-AM with Alamouti STBCs outperforms the V-BLAST receiver, even when there is a larger number of users in the MIMO NOMA system. We additionally investigate methods of reducing the complexity of GRAND-AM, as the MIMO NOMA problem is more complex than the SISO NOMA problem. We then show that the complexity reducing measures do not lead to large losses and can still outperform V-BLAST receivers, giving incentive to use GRAND-AM for MIMO NOMA systems.**

***Index Terms*—MIMO, NOMA, joint detection, joint decoding**

I. Introduction

Nonorthogonal multiple access (NOMA) has become an important field of research owing to its potential for increasing spectral efficiency and lowering latency by allowing multiple users to transmit using the same resource [1], [2]. In a world where the number of devices that need to communicate is exponentially growing, primarily due to machine-type communications such as the Internet of Things (IoT) [3], [4], traditionally used OMA methods will begin to struggle due to the limited number of orthogonal resources and large number of devices requiring resources. This will lead to network congestion issues under high loads, especially as these loads are expected to continuously grow [5], [6]. This makes NOMA increasingly attractive as a solution to reliably service all of these devices.

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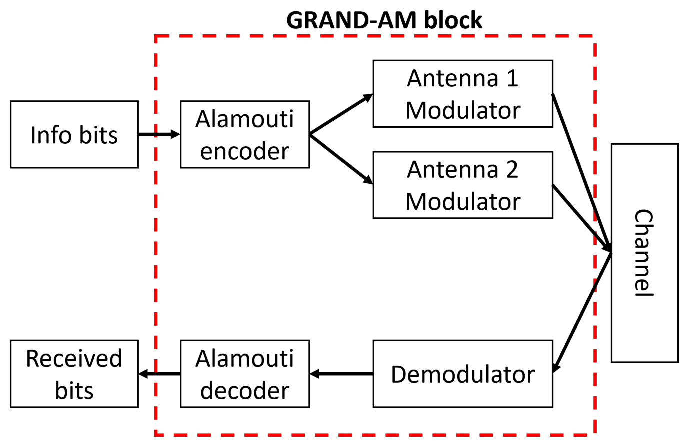

Fig. 1: The Alamouti STBC can directly replace the MAC code to handle the MIMO NOMA problem. GRAND-AM can jointly detect and decode across all the users and their associated Alamouti STBCs.

Previously, we presented Guessing Random Additive Noise Decoding Aided Macrosymbol (GRAND-AM) as a NOMA method for single input single output (SISO) uplink systems [7]. GRAND-AM is a method that primarily handles the multiple access interference (MAI) generated due to the simultaneous user transmissions, and does so by using joint multiuser detection (MUD) and joint decoding with multiple access channel (MAC) codes. The MAC codes are distinct from the forward error correcting (FEC) codes, and are only used to handle the MAI. The joint MUD and decoding process of GRAND-AM avoids concerns such as error propagation and unequal treatment of users that iterative based receivers for power domain NOMA may face [1], [8]–[10], and the MAC codes used to handle the MAI avoid the codebook design that is necessary for codebook domain NOMA as any well known code such as a cyclic redundancy check (CRC) code can be used [11]–[13].

While NOMA methods are important for future communication systems, they need to be integrated with commonly used techniques such as multiple input multiple output (MIMO) systems. MIMO can be used to improve signal quality through diversity or increase channel capacity through multiplexing, and is used for a variety of applications such as mobile networks and IoT [14], [15]. In particular, Alamouti space time block codes (STBC) are commonly used owing to its simple structure and ability to improve signal quality [16].

MIMO has been investigated in the context of downlink power domain NOMA methods, which require iterative based receivers, and has primarily been used for beamforming, intra-beam, precoding, and multiplexing purposes [17]–[20]. There has been work investigating how antenna diversity methods such as STBCs can help improve error rates in MIMO NOMA systems, but these are in conjunction with other methods such as beamforming, precoding, or cooperative downlink NOMA [19], [21], [22].

In contrast to these applications of MIMO in power domain NOMA systems, we consider how to integrate MIMO into GRAND-AM and how to use MIMO specific techniques. In order to do so, we focus solely on exploiting diversity with STBCs - we integrate the STBC by using it as the MAC code for GRAND-AM as shown in Fig. 1. We will begin by discussing the MIMO NOMA system model, as well as describing the Alamouti STBC, which is the primary focus of this work. We will then discuss how the joint detection and decoding of GRAND-AM is modified for the MIMO NOMA system model, as well as how to handle the joint decoding when an Alamouti STBC is used to handle the MAI. We will compare the performance of GRAND-AM with the Alamouti STBC versus the performance of the Vertical-Bell Laboratories Layered Space-Time (V-BLAST) receiver and the linear minimum squared error (MMSE) receiver, show its performance in handling multiple users, and discuss methods of reducing GRAND-AM's complexity.

II. System Model

We begin by describing the MIMO NOMA system model, with the assumption that the users all have the same number of transmit antennas N_{Tx} and the receiver has N_{Rx} receive antennas. Consider a NOMA system with u users transmitting simultaneously using the same time and frequency resource. Assuming a Rayleigh fading channel model, the received signal vector $\vec{y}$ is

$$\vec{y} = \sum_{i=1}^{u} \mathbf{H}_i \sqrt{P_i/N_{Tx}} \vec{x}_i + \vec{w} \tag{1}$$

where $\vec{y}$ contains the elements $[y_1 \; y_2, \ldots \; y_{N_{Rx}}]^T$ corresponding to the receive antennas, $\mathbf{H}_i$ is the $N_{Rx} \times N_{Tx}$ channel matrix corresponding to the ith user with entries $h_{i,(r,g)}$ sampled iid from $\mathcal{N}_{\mathcal{C}}(0,1)$, P_i is the average power constraint for each user, $\vec{x}_i$ is the transmit symbol vector for user i with entries $[x_{i,1} \;\; x_{i,2}, \ldots \;\; x_{i,N_{Tx}}]^T$, and w is the $N_{Rx} \times 1$ complex additive white Gaussian noise (AWGN) vector with entries sampled iid from $\mathcal{N}_{\mathcal{C}}(0,1)$. The symbols corresponding to each transmit antenna are randomly chosen from the set of symbols $\mathcal{S}_{i,g} = \{x_{(i,g),1}, x_{(i,g),2}, \ldots, \;\; x_{(i,g),m_{i,g}}\}$ which represents a discrete modulation with size $m_{i,g}$ and unitary power. Note that in this work, the power has been equally split between the user's transmit antennas. We assume that the receiver has knowledge of the modulation $\mathcal{S}_{i,g}$, the average transmit power P_i, and a perfect channel estimate of $\mathbf{H}_i$ for each user $i \in [1, U]$, transmit antenna $g \in [1, N_{Tx}]$, and receive antenna $r \in [1, N_{Rx}]$.

Now that we have defined the MIMO NOMA system model for a single sample in time, we will now discuss how to take advantage of the diversity offered by MIMO with space time block codes. In particular, we will focus on the Alamouti STBC, which is the only orthogonal space time block code known to achieve rate 1 with complex modulations [16], [23]. The Alamouti STBC is applicable for 2 transmit antennas, and any number of receive antennas. For the Alamouti STBC, there are two transmissions over time, with the channel outputs over these two time slots being

$$\begin{aligned} \vec{y}[1] &= \sum_{i=1}^{U} \mathbf{H}_i \sqrt{P_i/N_{Tx}} \begin{bmatrix} x_{i,1} \\ x_{i,2} \end{bmatrix} + \vec{w}[1] \\ \vec{y}[2] &= \sum_{i=1}^{U} \mathbf{H}_i \sqrt{P_i/N_{Tx}} \begin{bmatrix} -x_{i,2}^* \\ x_{i,1}^* \end{bmatrix} + \vec{w}[2] \end{aligned} \tag{2}$$

with the indices defined as before. In a single user MIMO system, a simple combining algorithm could be used to detect the transmitted symbols, but for the MIMO NOMA system, other detection algorithms must be used. We will discuss this in the next section.

Note here that the Alamouti STBC codes over the symbols. If a symmetric modulation such as quadrature amplitude modulation (QAM) or phase shift keying (PSK) is used, the coded symbols remain within the set. This reduces the set of known information to a user level with symbols corresponding to each user and its transmit antennas being contained in the set $\mathcal{S}_i$ with size m_i.

III. Using GRAND-AM in MIMO NOMA systems

GRAND-AM has three key components to handle NOMA problems: joint detection, MAC codes, and joint decoding of the MAC codes across all users. In this section, we will detail all three of these components and discuss how they work in the MIMO system. Furthermore, we will also discuss complexity reducing measures for the GRAND-AM method.

A. Multiuser detection

GRAND-AM previously introduced the concept of a macrosymbol [7], which is formed from an aggregate of all user transmissions. In the MIMO system, the macrosymbol is formed from the aggregate of all user transmissions across all transmit antennas, and each receive antenna must detect the corresponding macrosymbol, as shown in Fig. 2. Using the estimate for the channel matrix for all users, the definition of the aggregate constellation, the set of all possible macrosymbols, at receiver antenna r in the MIMO NOMA model is

$$\mathcal{S}_{\mu_r} = \{\mu_r\} = \left\{ \sum_{i=1}^{u} \sum_{g=1}^{N_{Tx}} h_{i,(r,g)} x_{(i,g),j_i} \right\} \tag{3}$$

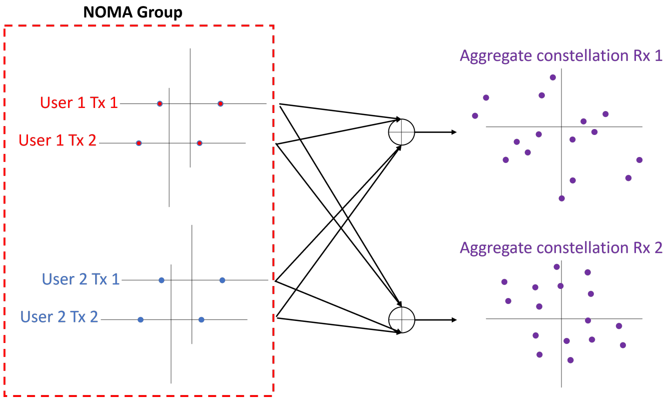

Fig. 2: In a MIMO system, there exists a macrosymbol at each of the receive antennas. The macrosymbols are generated from unique combinations of the symbols transmitted from each transmit antenna. In a 2 user, BPSK, 2×2 MIMO NOMA scenario, the size of the macrosymbols set at each receive antenna is 16.

With this definition of the macrosymbols, we can now define the estimator for the joint ML MUD detector for GRAND-AM in MIMO systems

$$\hat{\vec{\mu}} = \arg\max_{\vec{\mu}} f_{\mathbf{Y}|\mathcal{M}}(\vec{y}|\vec{\mu}) \tag{4}$$

with

$$f_{\mathbf{Y}|\mathcal{M}}(\vec{y}|\vec{\mu}) = f_{\mathbf{W}}(\vec{y} - \vec{\mu}) \tag{5}$$

where $f_{\mathbf{W}}(\cdot)$ is the multivariate PDF of the complex AWGN. Note that due to the independence of the noise at each of the receiver antennas, this estimator reduces down to a minimum distance problem between the received vector $\vec{y}[t]$ and all possible sets of the macrosymbol vector $\vec{\mu}[t]$ while taking into account the different macrosymbol sets at each receive antenna. While computational complexity grows with the number of users, transmit antennas, and modulation size, note that the joint ML MUD only requires sums and multiplications while a conventional ML MUD requires logarithmic operations on sums of exponential functions. This detector generates soft information that is used for the joint decoding. The soft information is the distance between the received vector and the macrosymbols $||\vec{y} - \vec{\mu}||^2$. Smaller distances indicate a higher likelihood while larger distances indicate a smaller likelihood.

B. Handling MAI with STBCs and joint decoding

The MAC codes used in GRAND-AM are short codes meant to handle the MAI introduced by overlapping user signals at the uplink receiver. They are short codes, with a limited number of parity bits such that they do not consume too much rate and code length from the FEC and such that the joint decoding step can be performed with relatively low complexity. In the case of the MAC code for MIMO systems, we must address how to incorporate the Alamouti STBC into GRAND-AM in order to take advantage of the diversity introduced by MIMO.

In Fig. 1, the Alamouti STBC replaces the MAC code within the GRAND-AM block to handle the MAI. In order to facilitate this incorporation with the GRAND-AM method, we must formulate the Alamouti STBC in terms of a codebook such that the joint decoding component of GRAND-AM can later be used. Based on (2), the Alamouti codebook is a $(4\log_2(m_i), 2\log_2(m_i))$ code, with fixed rate of $1/2$. Each codeword contained within the codebook is of the form $[x_{i,1} \;\; x_{i,2} \;\; -x_{i,2}^* \;\; x_{i,1}^*]$ where $x_{i,1}$ and $x_{i,2}$ are symbols randomly selected from $\mathcal{S}_i$, and the symbols map to bits depending on the modulation used. Given that the Alamouti space time block code can be represented as a structured codebook, GRAND-AM is compatible with it, and could be used for the joint decoding of it at the receiver. When the Alamouti STBC replaces the MAC code, each user will have a $(4\log_2(m_i), 2\log_2(m_i))$ codebook, which scales with the size of the modulation.

For the joint decoding aspect of the MAC codes across all users, we use symbol level ordered bit reliability GRAND which is a universal, near ML decoding algorithm [24], [25]. This algorithm queries noise sequences from least to most likely based on the soft information from the detector, and subtracts the noise sequence from the detected string of symbols and checks the difference against the codebook. It works for the joint decoding across all users in the uplink NOMA system owing to the users all sharing the same noise sequence generated from multiple time samples of $\vec{w}$. Each noise sequence that is tested must simultaneously satisfy all user MAC codebooks, leading to an effective aggregate codebook of size $(4\sum_{i=1}^{i}\log_2(m_i), 2\sum_{i=1}^{u}\log_2(m_i))$.

Before we show results for GRAND-AM in MIMO NOMA systems, we will first discuss the issue of complexity. Here, we focus on reducing the complexity of the joint decoder. Compared to our previous work on GRAND-AM, MIMO introduces some further complexity owing to the macrosymbol. In theory, this effect would grow exponentially with the number of users, number of transmit antennas, and modulation size. We will show how to limit this potential complexity issue while retaining the core performance benefits.

The number of possible macrosymbols at the receiver is $\prod_{g=1}^{N_{Tx}}\prod_{i=1}^{U} m_{i,g}$, indicating that generating noise sequences for the decoding based off of soft information for these macrosymbols can be complex. A nearest neighbor limit can be used, where rather than looking at the entire search space of the macrosymbols, only β nearest neighbor macrosymbols' soft information is used. This prevents the likelihood list from growing exponentially with the number of users and transmit antennas, while still retaining the most likely symbols that were incorrectly detected.

IV. Simulation Results

Throughout the results, we consider the scenario where each user has 2 transmit antennas due to the focus on Alamouti STBCs, and the scenario where the receiver has 2 receive antennas to investigate the MIMO problem. We will consider

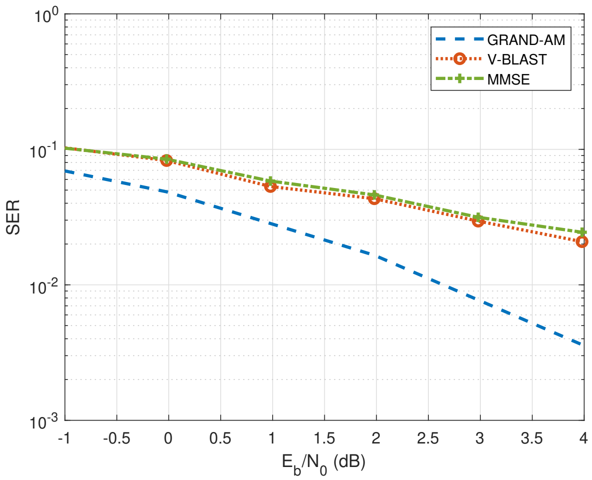

Fig. 3: Comparison between the GRAND-AM detection/decoding method, the V-BLAST iterative detection method, and the MMSE linear detector when detecting information coded with the Alamouti space time block code. There are 2 users, each with 2 transmit antennas and modulated with 4QAM, and the receiver has 2 receive antennas.

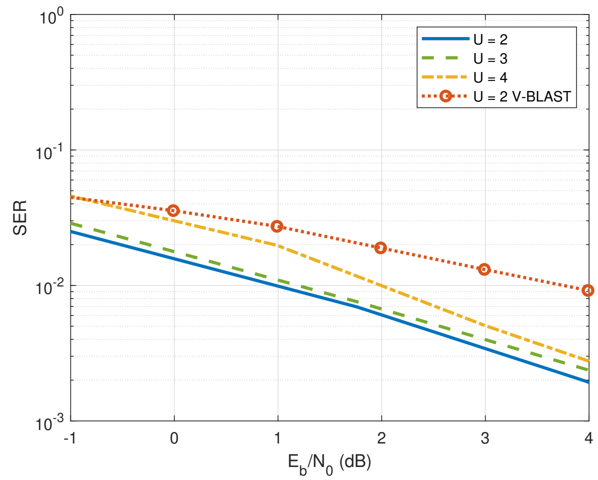

Fig. 4: Effect of increasing the number of users within the MIMO NOMA system when using GRAND-AM with the Alamouti STBC acting as the MAC code. Each user has equal power and is modulated with BPSK, there are 2 transmit antennas per each user, and the receiver has 2 receive antennas. The V-BLAST receiver is also used for the 2 user comparison.

the performance of GRAND-AM algorithms solely through its ability to remove MAI due to the NOMA problem.

We first begin by considering the scenario where there are 2 users within the MIMO NOMA scenario, each of which are modulated with 4QAM and have equal powers. We consider three methods at the receiver: GRAND-AM, MMSE, and V-BLAST. MMSE is first considered owing to it being a linear detector, which is simpler than the ML methods used within GRAND-AM [14], [15]. V-BLAST, while more complex than the MMSE receiver due to its iterative based detection and cancellation technique, allows for better performance at the cost of higher complexity [26]–[28]. While these methods are mainly used in the context of single user MIMO systems, the Alamouti STBC can be simplified to a larger scale single user MIMO system, allowing for these methods to be used. Thus, it is relevant to consider how the MMSE and V-BLAST based receivers perform compared to GRAND-AM.

V-BLAST slightly outperforms the MMSE receiver, owing to it ranking the users' post channel SNR from highest to lowest, and detecting the highest powered users first, similar to SIC. This similar performance may be due to the users being of equal powers and the channel gains being generated using Rayleigh random variables. This will lead to the users having similar post channel SNRs, leading to very little gain when using iterative methods. In this scenario, the V-BLAST based receiver should not be considered over the MMSE based receiver owing to the small gains. While V-BLAST and MMSE perform similarly, GRAND-AM outperforms these two less complex methods by at least 1 dB in the low E_b/N_0 regime, to 2.5 dB in the higher E_b/N_0 regime. Despite the lower complexity associated with V-BLAST and MMSE receivers, they perform poorly compared to GRAND-AM, indicating that iterative or linear detection based receivers may not be well suited for NOMA systems. Especially, iterative based detection methods should not be considered in scenarios where the users are of similar powers.

Another aspect to consider with GRAND-AM over the V-BLAST and MMSE based receivers is its flexibility. While the main focus of this work is on the Alamouti STBC with 2 transmit antennas, GRAND-AM is universal and can be applied to any modulation, STBC, and number of users, without having to be reformulated to fit the scenario. In contrast, the previously discussed MMSE and V-BLAST receivers have used the structure of the Alamouti STBC to reformulate the MIMO NOMA problem into a single user MIMO problem as both methods have traditionally been used in the single user context [26]. This flexibility and good performance of GRAND-AM over the V-BLAST and MMSE methods motivates its application in the MIMO NOMA domain.

While the 2 user scenario is important to consider as a baseline, it is interesting to also investigate the ability of GRAND-AM to handle MIMO NOMA with a larger number of users. Here we consider multiple users within the MIMO NOMA scenario, each with BPSK modulation and equal powers. Fig. 4 shows how the error rates increase with 3 and 4 users with BPSK modulations communicating simultaneously in the MIMO NOMA system, compared to the case with 2 users. The joint detection and decoding method of GRAND-AM is effective in suppressing the effects of the MAI, even as the number of users increases. Increasing the number of users from 2 to 3 users only results in a loss of ~ 0.5dB, while increasing the number of users to 4 results in a loss of

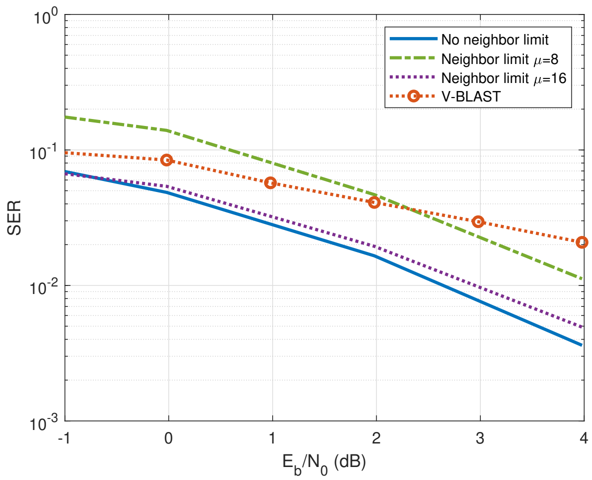

Fig. 5: Effect of limiting the likelihood list generation to the β nearest neighbors to reduce the decoding complexity of GRAND-AM with Alamouti STBCs in the MIMO NOMA system when there are 2 users modulated with 4QAM and of equal powers.

up to $\sim$ 1.5dB. GRAND-AM is effective in removing MAI, especially when compared to other receivers such as the V-BLAST receiver. Even when increasing the number of users in the MIMO NOMA system to 4, GRAND-AM outperforms the V-BLAST receiver with 2 users by up to $\sim$ 2dB. This further indicates the effectiveness of GRAND-AM in NOMA systems, as well as in MIMO systems.

One aspect to consider when using GRAND-AM is that the macrosymbol scales with the number of users, transmit antennas, and modulation. It is important to address this scaling, especially as the size of the macrosymbol at the receiver antenna increases. For example, with 2 users modulated with 4QAM and 2 transmit antennas, the aggregate constellation has 256 macrosymbols, as in the case of Fig. 3. This is also true for the 4 user case with BPSK modulation in Fig. 4. This leads to the noise sequence generation in the GRAND decoding algorithm becoming complex as the size of the user modulations, transmit antennas, or number of users grows. The total amount of soft information that must be considered for the 4QAM scenario is 512 symbol likelihoods. To address this, we consider the nearest neighbor limitation previously discussed.

Fig. 5 shows how reducing the search space introduces loss, but also reduces the number of symbol likelihoods necessary for ordering the noise sequences. For the figure, $\beta = 8, 16$ nearest neighbors are considered, which corresponds with likelihood list lengths of 16 and 32. It can be seen that a careful tuning of the number of nearest neighbors must be considered. In the case of 8 nearest neighbors, there is a $\sim$ 1.5dB loss, and for 16 nearest neighbors, there is at most $\sim$ 0.5dB loss. For the $\beta = 16$ nearest neighbors scenario, the loss is minimal while there is a $16\times$ reduction in the size of the likelihood list that must be generated and ordered. If the parameters are carefully chosen, then the complexity of the decoding can be greatly lowered while minimizing the loss, which is crucial in the MIMO NOMA system model with the aggregate user constellation size increasing with both the number of users and antennas.

Owing to the minimal loss when carefully choosing the nearest neighbor limits, the reduced complexity GRAND-AM method with Alamouti STBCs outperforms the V-BLAST receiver when there is the nearest neighbor limit of 16. While limiting the search space to 8 nearest neighbors does increase the error rates, it can outperform the V-BLAST receiver at higher E_b/N_0. The nearest neighbor limit is attractive for GRAND-AM, as it can lower the complexity of the decoding aspect of GRAND-AM without much loss, as seen in the previous figure. While the nearest neighbor limit limits the search space for the likelihoods used in the decoding component, it preserves the relationship between all the users transmitting simultaneously when used with the ML joint MUD, unlike the linear MMSE receiver or iterative V-BLAST receiver. In addition, we have focused on using the ML joint MUD for GRAND-AM, but that is not the only possible detector. Other lower complexity than ML detectors, such as the sphere decoder, may be compatible with the joint detection requirement of GRAND-AM, and even compatible with the concept of the nearest neighbor limits [29], [30]. The sphere decoder limits the search space for received symbols in a radius around the received signal, which is similar in nature to the nearest neighbor limit only searching for the β nearest neighbors.

V. Conclusion

In this work, we have proposed how to integrate GRAND-AM, a joint MUD and joint decoding method meant to handle the MAI for NOMA systems, into a MIMO system. We focused on the Alamouti STBC, the only orthogonal rate 1 STBC, and used it to replaced the previously proposed MAC codes within the GRAND-AM method, thereby integrating GRAND-AM with MIMO while also considering the NOMA problem. We compared the performance of GRAND-AM with the Alamouti STBC versus receiver methods such as the MMSE receiver and V-BLAST receiver and showed that it outperforms both the linear and iterative methods. We then further considered GRAND-AM and Alamouti STBC's performance when handling a larger number of users and showed that it is effective at removing MAI in the MIMO NOMA system, and outperforms the V-BLAST receiver even when there are larger number of users within the system. Then, we address methods of reducing the complexity of the GRAND-AM method, and show how using the nearest neighbor methods can reduce the complexity of the GRAND-AM method with minimal losses when careful tuning is performed when selecting thresholds.

Here we have proposed one method of integrating GRAND-AM into a MIMO NOMA system. This is hardly the only method of doing so. There are some other methods, such as simply using a MAC code as is instead of an STBC, or using a combined STBC and MAC code method. The MAC codes, while not as optimal as the Alamouti STBC, can be more flexible in that any ECC can be used to handle the MAI from the MIMO NOMA system rather than be restricted to a 2 transmit antenna system over 2 symbol times. Alternatively, other orthogonal STBCs can be used based on the number of transmit antennas assigned to each user, but like the Alamouti STBC, they are also more restrictive than a MAC code as they also have an associated number of symbol times and transmit antennas. For the other option of the combined STBC and MAC code method, it entails first encoding with the MAC code, and then encoding with the STBC before transmission. For the joint decoding process in GRAND-AM, the receiver must first generate the codebook for the combined STBC and MAC code before the decoding. This results in a larger, lower rate code, but it improves the ability to remove the MAI effect from simultaneous user transmissions compared to using just the STBC in the GRAND-AM process.

References

[1] Y. Saito, Y. Kishiyama, A. Benjebbour, T. Nakamura, A. Li, and K. Higuchi, "Non-orthogonal multiple access (NOMA) for cellular future radio access," in *IEEE VTC Spring*, 2013, pp. 1–5.

[2] L. Dai, B. Wang, Y. Yuan, S. Han, I. Chih-lin, and Z. Wang, "Non-orthogonal multiple access for 5G: solutions, challenges, opportunities, and future research trends," *IEEE Communications Magazine*, vol. 53, no. 9, pp. 74–81, 2015.

[3] International Telecommunication Union, "Global connectivity report 2022," 2022.

[4] ——, "IMT traffic estimates for the years 2020 to 2030," 2015.

[5] G. A. Akpakwu, B. J. Silva, G. P. Hancke, and A. M. Abu-Mahfouz, "A survey on 5G networks for the internet of things: Communication technologies and challenges," *IEEE Access*, vol. 6, pp. 3619–3647, 2018.

[6] L. Iiyambo, G. Hancke, and A. M. Abu-Mahfouz, "A survey on NB-IoT random access: Approaches for uplink radio access network congestion management," *IEEE Access*, vol. 12, pp. 95 487–95 506, 2024.

[7] K. Yang, M. Médard, and K. R. Duffy, "Nonorthogonal multiple access with guessing random additive noise decoding-aided macrosymbol (GRAND-AM)," *IEEE Internet of Things Journal*, vol. 11, no. 17, pp. 28 036–28 049, 2024.

[8] Y. Saito, A. Benjebbour, Y. Kishiyama, and T. Nakamura, "System-level performance evaluation of downlink non-orthogonal multiple access (NOMA)," in *IEEE PIMRC*, 2013, pp. 611–615.

[9] J. Andrews and T. Meng, "Performance of multicarrier CDMA with successive interference cancellation in a multipath fading channel," *IEEE Transactions on Communications*, vol. 52, no. 5, pp. 811–822, 2004.

[10] Y. Liu, Z. Qin, M. Elkashlan, Z. Ding, A. Nallanathan, and L. Hanzo, "Nonorthogonal multiple access for 5G and beyond," *Proceedings of the IEEE*, vol. 105, no. 12, pp. 2347–2381, 2017.

[11] R. Hoshyar, F. P. Wathan, and R. Tafazolli, "Novel low-density signature for synchronous CDMA systems over AWGN channel," *IEEE Transactions on Signal Processing*, vol. 56, no. 4, pp. 1616–1626, 2008.

[12] S. Chaturvedi, Z. Liu, V. A. Bohara, A. Srivastava, and P. Xiao, "A tutorial on decoding techniques of sparse code multiple access," *IEEE Access*, vol. 10, pp. 58 503–58 524, 2022.

[13] H. Nikopour and H. Baligh, "Sparse code multiple access," in *2013 IEEE 24th Annual International Symposium on Personal, Indoor, and Mobile Radio Communications (PIMRC)*, 2013, pp. 332–336.

[14] D. Tse and P. Viswanath, *Fundamentals of Wireless Communication*. Cambridge University Press, 2005.

[15] A. Goldsmith, *Wireless Communications*. Cambridge University Press, 2005.

[16] S. Alamouti, "A simple transmit diversity technique for wireless communications," *IEEE Journal on Selected Areas in Communications*, vol. 16, no. 8, pp. 1451–1458, 1998.

[17] K. Higuchi and Y. Kishiyama, "Non-orthogonal access with random beamforming and intra-beam SIC for cellular MIMO downlink," in *IEEE VTC Fall*, 2013, pp. 1–5.

[18] Z. Ding, R. Schober, and H. V. Poor, "A general MIMO framework for NOMA downlink and uplink transmission based on signal alignment," *IEEE Transactions on Wireless Communications*, vol. 15, no. 6, pp. 4438–4454, 2016.

[19] H. Wang, S.-H. Leung, and R. Song, "Precoding design for two-cell MIMO-NOMA uplink with CoMP reception," *IEEE Communications Letters*, vol. 22, no. 12, pp. 2607–2610, 2018.

[20] B. Clerckx, Y. Mao, R. Schober, E. A. Jorswieck, D. J. Love, J. Yuan, L. Hanzo, G. Y. Li, E. G. Larsson, and G. Caire, "Is NOMA efficient in multi-antenna networks? a critical look at next generation multiple access techniques," *IEEE Open Journal of the Communications Society*, vol. 2, pp. 1310–1343, 2021.

[21] H. Wang, C. Liu, Z. Shi, Y. Fu, and R. Song, "On the design of high power efficiency uplink MIMO-NOMA systems: A STBC and joint detection perspective," *IEEE Transactions on Vehicular Technology*, vol. 70, no. 1, pp. 627–638, 2021.

[22] M. N. Jamal, S. A. Hassan, and D. N. K. Jayakody, "A new approach to cooperative NOMA using distributed space time block coding," in *IEEE PIMRC*, 2017, pp. 1–5.

[23] X.-B. Liang, "Orthogonal designs with maximal rates," *IEEE Transactions on Information Theory*, vol. 49, no. 10, pp. 2468–2503, 2003.

[24] W. An, M. Médard, and K. R. Duffy, "Soft decoding without soft demapping with ORBGRAND," in *IEEE ISIT)*, 2023, pp. 1080–1084.

[25] K. R. Duffy, W. An, and M. Médard, "Ordered reliability bits guessing random additive noise decoding," *IEEE Transactions on Signal Processing*, vol. 70, pp. 4528–4542, 2022.

[26] C. W. Tan and A. R. Calderbank, "Multiuser detection of alamouti signals," *IEEE Transactions on Communications*, vol. 57, no. 7, pp. 2080–2089, 2009.

[27] P. Wolniansky, G. Foschini, G. Golden, and R. Valenzuela, "V-BLAST: an architecture for realizing very high data rates over the rich-scattering wireless channel," in *1998 URSI International Symposium on Signals, Systems, and Electronics. Conference Proceedings (Cat. No.98EX167)*, 1998, pp. 295–300.

[28] H. Zhu, Z. Lei, and F. Chin, "An improved square-root algorithm for BLAST," *IEEE Signal Processing Letters*, vol. 11, no. 9, pp. 772–775, 2004.

[29] J. Jalden and B. Ottersten, "On the complexity of sphere decoding in digital communications," *IEEE Transactions on Signal Processing*, vol. 53, no. 4, pp. 1474–1484, 2005.

[30] B. Hassibi and H. Vikalo, "On the sphere-decoding algorithm I. expected complexity," *IEEE Transactions on Signal Processing*, vol. 53, no. 8, pp. 2806–2818, 2005.