Investigation of Transmit Antenna Selection for MU-VASM Systems over Correlated Channels

Kieu Xuan Thuc[1], Tran Viet Vinh[2], Phu Liem Nguyen[3], Tong Van Luyen[1], Hoang Manh Kha[1], and Nguyen Thu Phuong[2(✉)]

[1] Hanoi University of Industry, No. 298, Cau Dien Street, Ha Noi, Viet Nam
{thuckx,luyentv,khahm}@haui.edu.vn
[2] Advanced Wireless Communications Group, Le Quy Don Technical University, No. 236, Hoang Quoc Viet, Ha Noi, Viet Nam
{tranvietvinhsqtt,phuong.nt}@lqdtu.edu.vn
[3] Le Quy Don Technical University, No. 236, Hoang Quoc Viet, Ha Noi, Viet Nam

Abstract. In a variable active antenna spatial modulation (VASM) system, the number of activated antennas adjusts dynamically according to the input spatial bitstream. Thus, it is a typical variation of spatial modulation techniques, known for its high flexibility and outstanding spectral efficiency. In this paper, the operation of the multi-user (MU) VASM system is investigated under correlated channel conditions. Furthermore, three transmit antenna selection (TAS) methods, including channel gain-based TAS (CG-TAS), Euclidean distance-based TAS (ED-TAS), and hierarchical combination-based TAS (HC-TAS), are applied to enhance the quality of the MU-VASM system. The effect of the correlated channel on the bit error rate (BER) performance of every user as well as the average BER (ABER) performance of the whole system is investigated for three TAS methods. The simulation results indicate that correlated channels degrade the system's performance. Nevertheless, the application of these TAS methods has noticeably improved the system's quality. In particular, HC-TAS with low computational complexity consistently delivers superior ABER improvement for the system compared to other TAS methods, even in scenarios with correlated channels.

Keywords: Transmit antenna selection · Variable active antenna spatial modulation · Correlated channel

1 Introduction

In the present day, telecommunications systems are increasingly developing, with increasing requirements for speed and transmission quality. In this context, multiple input multiple output (MIMO) systems [1,2], a combination of precoding and equalizer technologies [3,4], a non-orthogonal multiple access scheme [5,6], a radio frequency energy harvesting techniques [7,8] and multiple hops systems

N. Thi Dieu Linh et al. (Eds.): ADHOCNETS 2023, LNICST 558, pp. 112–124, 2024.
https://doi.org/10.1007/978-3-031-55993-8_9

[9,10] stand out as potent solutions for fifth-generation (5G) and beyond networks. However, the aforementioned systems and technologies utilize multiple radio frequency chains at the same time, leading to increased costs and requiring synchronization between antennas as well as inter-channel interference. To address these problems, the idea of using spatial modulation (SM) techniques in MIMO systems was first proposed in [11] and quickly became a prominent research trend in recent years [12].

The basic principle of the SM technique is to employ the index of only one activated antenna to carry additional bits of information in addition to the traditional amplitude and phase modulation (APM) symbols [11]. This approach aims to significantly increase spectral efficiency, reduce multi-antenna interference, and save on costs caused by RF chains. With such outstanding advantages, SM has been expanded into many different fields, and various variations of SM have been proposed to further improve the quality of this technique [12]. Among them, variable active antenna spatial modulation (VASM) emerges as a typical variant [13].

VASM operates on the principle of spatial modulation, that is, transmits information using both the APM symbol and the activated transmit antenna (TA) index. In contrast to SM, where a combination of some spatial bits represents the index of an activated TA, in VASM, each spatial bit represents the on/off state of a TA. Specifically, when the spatial bit is 1, the corresponding TA is activated, whereas if the spatial bit is 0, the corresponding TA is deactivated. This way, VASM activates from 1 to almost all of the system's antennas to carry additional information. It thus attains higher spectral efficiency when compared to SM and its renowned extensions, like generalized SM (GSM) [14] and quadrature SM (QSM) [15]. Additionally, VASM offers much greater flexibility than SM because it allows operation with an optional number of TAs instead of having to be a power of two like SM.

For systems operating on the SM principle in general and VASM in particular, the activated antennas are both a means of transmitting signals, but at the same time, their indices also carry a part of the information. For this reason, employing the VASM technique in MIMO systems requires careful transmit antenna selection (TAS) because it greatly affects the quality of the system [16].

The TAS algorithms for the downlink multi-user (MU) VASM system have been investigated in [17]. In this work, the authors proposed applying conventional antenna selection algorithms commonly used in SM systems, specifically channel gain-based TAS (CG-TAS) and Euclidean distance-based TAS (ED-TAS) [18,19], to the MU-VASM system. They also introduced a low-complexity but highly effective algorithm called hierarchical combination-based TAS (HC-TAS) to enhance the bit error rate (BER) performance of this system. However, it's important to note that this research is limited to the assumption of a completely uncorrelated transmission channel.

In another aspect, MIMO systems employ antenna arrays at both the transmitter and receiver can significantly enhance spectral efficiency and system performance. Nonetheless, spatial constraints often restrict scattering, resulting in a correlated channel, commonly referred to as spatial correlation [20].

The presence of correlation reduces the reliability of spatial bit detection [21]. Because of spatial correlation, it becomes challenging to differentiate between the channels connecting various transmit and receive antennas. Consequently, in such situations, uncertainties arise during the detection of spatial bits, which are utilized to choose active antennas. This, in turn, leads to a significant increase in BER. Previous studies [22] and [23] have evaluated the performance of SM and GSM under correlated Rayleigh and Rician channel conditions. The results show that the performance experiences a significant degradation as the correlation increases.

Inspired by these studies, this paper investigates the impact of spatial correlation on the performance of the downlink MU-VASM system. This work also evaluates the effectiveness of TAS algorithms in improving BER performance for the system in correlated channel scenarios.

The remaining sections of the paper are organized as follows: Sect. 2 provides an explanation of the system model for the MU-VASM transceiver over correlated channels. In Sect. 3, various TAS schemes for the MU-VASM system are presented. Section 4 contains the presentation of Monte Carlo simulation results and discussion. Finally, Sect. 5 concludes the paper.

Notations: Lowercase italic letters, lowercase bold letters, and uppercase bold letters represent variables, vectors, and matrices, respectively. $\mathbf{W} \in \mathbb{C}^{M \times N}$ denotes the size of the matrix $\mathbf{W}$, with M rows and N columns. $||.||$ and $||.||_F^2$ correspondingly describe the operations for calculating the norm and Frobenius norm of a vector or matrix. $(.)^T$ is the transpose operation of a vector or matrix. C_a^b is the symbol for the combination of b elements out of a total of a elements. $(.)^*$ denotes complex conjugate.

2 System Model Description

A typical downlink MU-VASM system model is depicted in Fig. 1 [17]. Equipped with a total of N_{total} TAs, the base station (BS) transmits K data bitstreams to K mobile users. Each data bitstreams is modulated utilising the VASM technique and emitted over a cluster consisting of N_t TAs. Precoders $\mathbf{W}_k$ are employed to mitigate multi-user interference. Each terminal user is equipped with N_r receiving antennas (RAs). We impose the constraint that, in this system, each TA is designated to transmit signals to only one user without being reused for transmitting multiple distinct signal streams, leading to the condition $N_{\text{total}} \geq KN_t$.

Prior to initiating the data transmission process, users send channel state information (CSI) back to the BS. Using the gathered CSI, the BS picks a subset of N_t TAs to perform signal modulation using VASM principle. Subsequently, these selected TAs are employed for transmission the signals to the users. Assuming that the transmission channel belongs to the slowly varying flat-fading Rayleigh and spatially correlated channel category, the channel state from the BS to the users remains stable within a certain duration of signal transmission. When channel conditions change, the antenna selection process is reinitiated from the beginning.

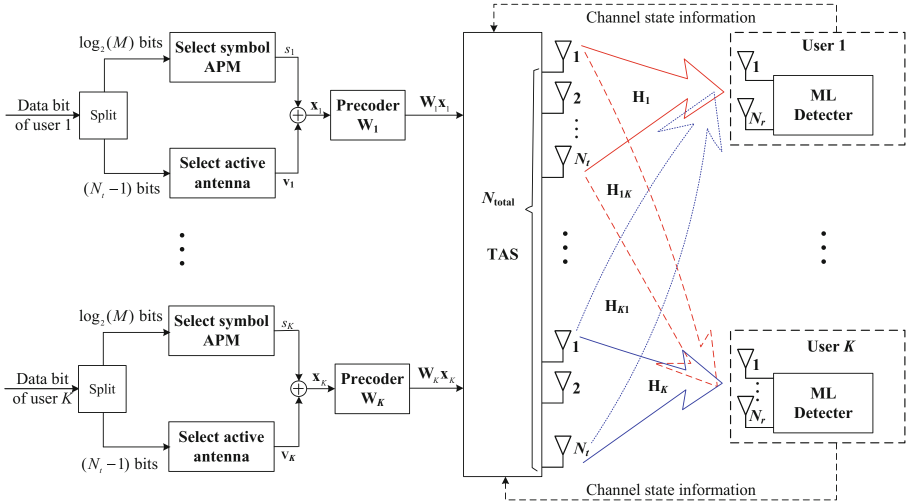

Fig. 1. Downlink MU-VASM system model

Without diminishing generality, we focus exclusively on the signal processing procedure for transmitting data bit streams from the BS to the k-th user's terminal device in this system, $1 \leq k \leq K$.

Firstly, we delve into the process of modulating the data bit sequence of the user k using the VASM technique. Specifically, within each signaling cycle, a sequence comprising $b = b_1 + b_2$ data bits is fed into the VASM mapping. In particular, $b_1 = \log_2(M)$ symbol bits are utilized for selecting an M-APM signal symbol. $b_2 = N_t - 1$ remaining spatial bits are employed for choosing the spatial vector $\mathbf{v}_k$, where non-zero positions correspond to activated antennas. The VASM signal vector, denoted as $\mathbf{x}_k$, is formed by mapping the symbol s_k into the spatial vector $\mathbf{v}_k$. Note that both the vector $\mathbf{x}_k$ and its elements must be normalized to ensure the transmit power constraint conditions, specifically, $E({\mathbf{x}_k}^H \mathbf{x}_k) = 1$ and $x_k^i = 1/\sqrt{N_a}$, where $i \in [1; N_t - 1]$ and N_a is the number of activated TAs in a subset of TAs.

It should be noted that for the VASM technique, each element in the spatial bits b_2 corresponds to a state of one TA, meaning that if the bit is 1, the TA is activated; conversely, if the bit is 0, the TA is in a sleep mode. Notably, in the scenario where all bits of b_2 are zero, the last antenna in the antenna array is exclusively designated for transmitting the signal symbol. Under this operational principle, the quantity of activated TAs in the VASM may range from 1 to $N_t - 1$ TAs. As a result, the spectral efficiency achieved by VASM is $\log_2(M) + N_t - 1$ bit per channel user, which is significantly higher than that of other variants of SM [17]. The interrelation among spatial bits, spatial vector, and transmitted signal vector is elucidated in Table 1 below, where $N_t = 3$, i.e., $b_2 = 2$ bits.

At the transmitter, once N_t TAs are chosen and their indices used to modulate the signal using the VASM principle, the modulated signal is transmitted

Table 1. Antenna activation rule in the VASM technique with $N_t = 3$

Spatial bit b_2	Spatial vector $\mathbf{v}_k$	Transmit signal vector $\mathbf{x}_k$
00	$[0,0,1]^T$	$[0,0,s_k]^T$
10	$[1,0,0]^T$	$[s_k,0,0]^T$
01	$[0,1,0]^T$	$[0,s_k,0]^T$
11	$[1,1,0]^T$	$\frac{1}{\sqrt{2}}[s_k,s_k,0]^T$

through these selected antennas. Note that, prior to transmission, the modulated signal vector has been multiplied by a precoding matrix, $\mathbf{W}_k \in \mathbb{C}^{N_t \times N_t}$, to mitigate multi-user interference, i.e., $\mathbf{W}_k\mathbf{x}_k$.

The received signal at the k-th terminal user is represented as follows:

$$\mathbf{y}_k = \mathbf{H}_k\mathbf{W}_k\mathbf{x}_k + \sum_{j=1,j\neq k}^{K} \mathbf{H}_{jk}\mathbf{W}_j\mathbf{x}_j + \mathbf{n}_i. \tag{1}$$

wherein $\mathbf{H}_k$ and $\mathbf{H}_{jk}$ are $N_r \times N_t$-sized matrices, representing the channels from the N_t selected TAs for users k and j at the BS to the N_r RAs at the terminal user k, respectively. $\mathbf{W}_k$ and $\mathbf{W}_j$ are precoder matrices, which are designed such that $\mathbf{H}_{jk}\mathbf{W}_j\mathbf{x}_j = 0$, if $j \neq k$, in order to eliminate multi-user interference. $\mathbf{n}_k$ represents the $N_r \times 1$ vector of independently and identically distributed (i.i.d.) $\mathcal{CN}\left(0,\sigma^2\right)$ additive white Gaussian noise.

In our MU-VASM system, we employ the well-established Kronecker [24] model to describe spatially correlated Rayleigh fading channel, which for the k-th user can be expressed as follows:

$$\mathbf{H}_k = \mathbf{L}_{r,k}^{1/2}\hat{\mathbf{H}}_k\mathbf{L}_{t,k}^{1/2}, \tag{2}$$

where $\hat{\mathbf{H}}_k \in \mathbb{C}^{N_r \times N_t}$ is a matrix with i.i.d. Gaussian entries having a zero mean and unit variance. $\mathbf{L}_{r,k}$ and $\mathbf{L}_{t,k}$ represent $N_r \times N_r$ receive and $N_t \times N_t$ transmit spatial correlation matrices of k-th user, respectively. The elements of $\mathbf{L}_{r,k}$ and $\mathbf{L}_{t,k}$ are given by [25]

$$l_{mn} = \begin{cases} l^{n-m}, & m \leq n \\ l^*_{nm}, & m > n \end{cases}, \quad |l| \leq 1\,, \tag{3}$$

where l is the correlation coefficient that characterizes the spatial correlation between the channel elements.

Due to $\mathbf{H}_{jk}\mathbf{W}_j\mathbf{x}_j = 0$, if $j \neq k$, the received signal at terminal user k can be expressed as follows:

$$\mathbf{y}_k = \mathbf{H}_k\mathbf{W}_k\mathbf{x}_k + \mathbf{n}_k. \tag{4}$$

Assuming that users have full CSI, both the conventional symbol s_k and the spatial vector $\mathbf{v}_k$ are jointly detected through an ML optimization problem that can be represented as follows:

$$\hat{\mathbf{x}}_k = [\hat{s}_k, \hat{\mathbf{v}}_k] = \arg\min_{s\in S,\mathbf{v}\in\mathbf{V}} ||\mathbf{y}_k - \mathbf{H}_k\mathbf{W}_k\mathbf{x}_k||_F^2. \tag{5}$$

3 Transmit Antenna Selection

TAS in the MU-VASM system is defined as the problem of selecting subsets of N_t TAs from the total number of N_{total} TAs in the BS to transmit each data stream independently to each user. This is aimed at improving the BER performance for each user and the average BER (ABER) performance for the system as a whole. In this section, the paper explores how TAS methods, including channel gain (CG) criteria, Euclidean distance (ED) criteria, and the hierarchical combination (HC) of CG and ED criteria, perform in the MU-VASM system under Rayleigh fading-correlated channel conditions. Without loss of generality, we consider the process of selecting N_t TAs at the BS to transmit data to the user k. Assuming the antennas are only used to transmit data to one user, that is, after a TA is selected to transmit data to a user, it is dropped from the antenna set to choice for the subsequent user. Thus the total number of antennas selected for the user k is $N_{\text{total}} - (k-1)N_t$ TAs.

3.1 Channel Gain Criteria

The MIMO channel from a total of $N_{\text{total}}-(k-1)N_t$ TAs located at the BS to N_r RAs at the k-th user is characterized as $\mathbf{H}_k^{\text{total}} \in \mathbb{C}^{N_r \times [N_{\text{total}}-(k-1)N_t]}$. Utilizing the CG criteria, the magnitudes of the column vectors within the $\mathbf{H}_k^{\text{total}}$ are quantified and subsequently arranged in descending order:

$$\underbrace{||\mathbf{h}_k^1||^2 \geq ||\mathbf{h}_k^2||^2 \geq ... \geq ||\mathbf{h}_k^{N_t}||^2}_{N_t \text{ selected elements}} \geq ... \geq ||\mathbf{h}_k^{N_{\text{total}}-(k-1)N_t}||^2. \tag{6}$$

The N_t column vectors with the largest gain are chosen to form the transmission channel matrix from the BS to the k-th terminal user, which corresponds to the N_t selected TAs for signal modulation and delivery to user k.

In this approach, TAS relies solely on channel characteristics, making it simple and straightforward to implement. However, it does not yield a significant improvement in BER performance for the system.

3.2 Euclidean Distance Criteria

The ED criterion is an antenna selection algorithm in which a combination of TAs, $A_k^{\text{opt}} \in \mathcal{A}$, is selected to maximize the minimum Euclidean distance between all signal vectors as follows:

$$A_k^{\text{opt}} = \arg \max_{A_k \in \mathcal{A}} \{ \min_{\mathbf{x}_i \neq \mathbf{x}_j \in \mathbf{X}} \|\mathbf{H}_{A_k}(\mathbf{x}_i - \mathbf{x}_j)||_F^2 \}, \tag{7}$$

where $\mathcal{A} = \{A_1, A_2, ..., A_c\}$, $c = C_{N_{\text{total}}-(k-1)N_t}^{N_t}$, is the set containing all possible combinations of TAs selecting N_t elements from $N_{\text{total}} - (k-1)N_t$ elements.

It can be seen that the ED criterion will be tested with all possible combinations of TAs, i.e., $C_{N_{\text{total}}-(k-1)N_t}^{N_t}$ combinations, to find the combination of TAs that satisfies 7. Obviously, an exhaustive search over all available combinations of TAs will optimize the system's performance, but on the contrary, it requires a huge amount of computation.

3.3 Hierarchical Combination Criteria

The HC criteria, proposed in [17], aims to achieve a balance between improving BER performance and reducing the computational burden of the system. In this approach, CG-TAS initially selects N_s temporary TAs, $N_t < N_s \ll N_{\text{total}}$, satisfying (6), followed by ED-TAS, which chooses N_t from the N_s selected by CG-TAS, satisfying (7).

HC-TAS performs a two-step sequential combination of CG-TAS and ED-TAS. This approach significantly reduces computational complexity while ensuring a high level of effectiveness in improving the BER performance of the system.

4 Simulation Results and Discussion

In this section, we simulate the MU-VASM system with the system configuration as follows: $N_{\text{total}} = 10$, $N_t = 3$, $K = 3$, $N_r = 4$, and QPSK modulation ($M = 4$). In the case of using HC-TAS, $N_s = 4$. In a sequential manner, TAS is conducted in the order of user 1, user 2, and user 3. No-TAS is the case where antennas are not selected but assigned randomly to users. The ABER performance is calculated as the average of the BER performance of the entirety of system users. Assume that the noise power at the users is the same, i.e., $\sigma_1^2 = \sigma_2^2 = ... = \sigma_K^2$.

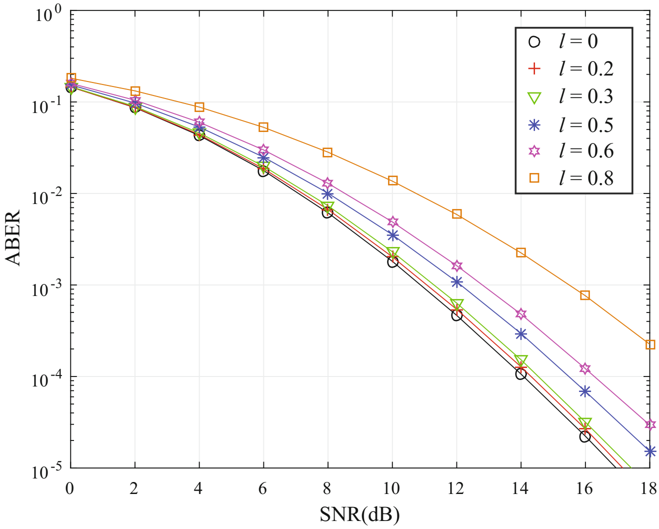

Fig. 2. ABER vs. signal-to-noise ratio (SNR) of the MU-VASM system with different channel correlation coefficients and without TAS

At the beginning, we study how the MU-VASM system works in correlated channel conditions. We vary the correlation coefficients and don't use antenna selection algorithms. Instead, TAs are randomly assigned to each user. The simulation results are depicted in Fig. 2. It is evident that as the correlation coefficient increases, the system's ABER performance deteriorates. This underscores the pronounced influence of channel correlation on the system's quality.

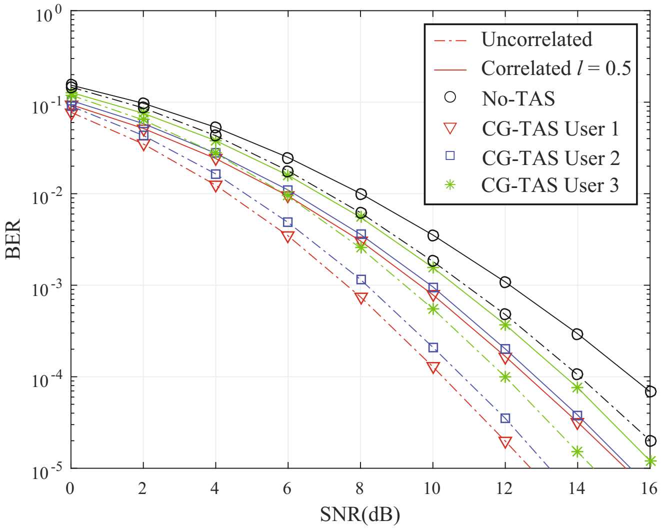

Fig. 3. BER vs. SNR for individual users in the MU-VASM system with channel correlation coefficient $l = 0.5$ employing CG-TAS

Subsequently, we selected a correlation coefficient of $l = 0.5$ due to its common usage to assess the potential enhancement in BER performance for the antenna selection methods CG-TAS, ED-TAS, and HC-TAS in the MU-VASM system. The BER performance of each user using these TAS methods is shown correspondingly in Fig. 3, 4, and 5. A common feature in these results is that users granted priority to select antennas initially attain superior BER performance compared to those who come after. More specifically, in this scenario, the BER performance decreases sequentially for user 1, user 2, and user 3.

Notably, with a relatively high channel correlation coefficient, i.e., $l = 0.5$, the BER quality of each user is significantly degraded compared to the uncorrelated channel scenario. However, thanks to the use of TAS methods, all users in the system achieve better BER performance than in the case of uncorrelated channels and without antenna selection. This confirms the role of TAS in enhancing the system's quality.

Figure 3 clearly illustrates that, when CG-TAS is employed under the influence of correlated channels, all three users (referred to as Users 1, 2, and 3) within the system achieve worse BER performance compared to all users in the case of uncorrelated channels. In addition, in the context of correlated channels, the disparity in BER performance among system users appears less pronounced when

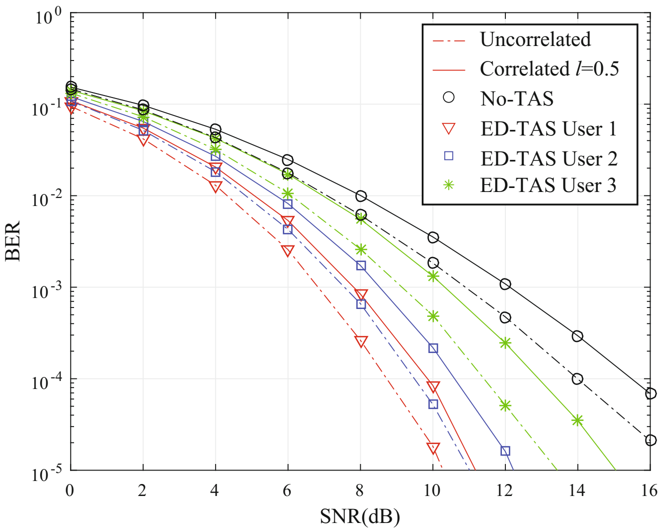

Fig. 4. BER vs. SNR for individual users in the MU-VASM system with channel correlation coefficient $l = 0.5$ employing ED-TAS

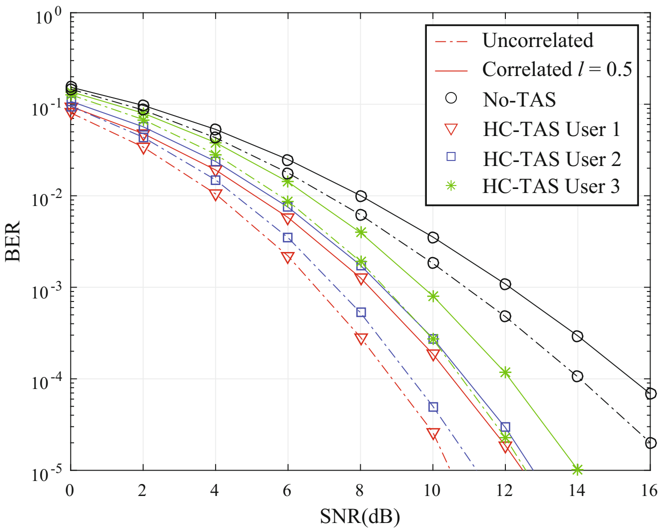

Fig. 5. BER vs. SNR for individual users in the MU-VASM system with channel correlation coefficient $l = 0.5$ employing HC-TAS

compared to the case of uncorrelated channels. This observation suggests that CG-TAS operates less effectively in improving BER performance for the system under correlated channels. This phenomenon can be attributed to the fact that

CG-TAS solely relies on the channel gain of each transmission path for antenna selection, and the channel gain is notably sensitive to channel correlation.

Figures 4 and 5 clearly depict that the variations in BER performance among individual users are not substantially pronounced in both scenarios of uncorrelated and correlated channels when the system employs ED-TAS and HC-TAS. This underscores the remarkable effectiveness of ED-TAS and HC-TAS in enhancing BER performance for users, even in the presence of channel correlation. This can be attributed to the fact that both ED-TAS and HC-TAS utilize channel characteristics as well as transmitted signals for antenna selection, thereby mitigating the impact of channel correlation. It is worth noting that the performance difference in BER among individual users of HC-TAS is moderate, in contrast to the significant discrepancy observed among users of ED-TAS. This is the reason behind HC-TAS achieving better overall system performance (ABER) compared to ED-TAS when averaged. This observation is further illustrated in Fig. 6 below.

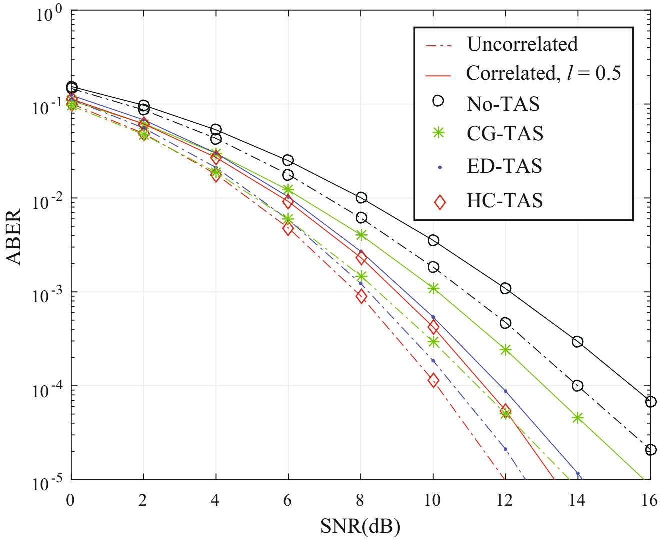

Fig. 6. Comparing ABER vs. SNR in the MU-VASM system using various TAS methods for both uncorrelated and correlated channels ($l = 0.5$)

In Fig. 6, we compare the extent of ABER performance improvement for the entire MU-VASM system utilising different TAS methods over uncorrelated channels and correlated channels ($l = 0.5$). The results show that, with the same channel correlation coefficient, all TAS algorithms achieve superior ABER performance compared to the No-TAS case. Even in the presence of channel correlation, using TAS still results in better system performance compared to the scenario of uncorrelated channels and without employing TAS. This result emphasizes the effectiveness of using TAS methods to improve the ABER performance of the system.

In a more specific analysis, we compare the required SNR (dB) to achieve ABER = 10^{-4} among TAS methods in the MU-VASM system over uncorrelated and correlated channels. The results are presented in Table 2. It is implied that the lower the required SNR, the better the TAS method.

Table 2. Comparing the required SNR (dB) to achieve ABER = 10^{-4} among TAS methods in the MU-VASM system over uncorrelated and correlated channels

TAS method	Uncorrelated (dB)	Correlated (dB)	SNR Difference (dB)
HC-TAS	10.10	11.41	1.31
ED-TAS	10.56	11.85	1.29
CG-TAS	11.22	13.06	1.84
No-TAS	14.00	15.45	1.45

It can be easily seen that, in the case of correlated channels, there is a noticeable increase in the required SNR across all TAS methods compared to uncorrelated channels. This increase highlights the influence of channel correlation on system performance. Notably, the No-TAS method demands significantly higher SNR values than TAS-based approaches to achieve an ABER of 10^{-4}. This underscores the potential for TAS methods to enhance communication performance within the MU-VASM system. When aiming to achieve an ABER of 10^{-4}, it is evident that HC-TAS and ED-TAS require lower SNR values compared to CG-TAS and No-TAS, both in uncorrelated and correlated channel scenarios. This implies that HC-TAS and ED-TAS exhibit superior performance in meeting the specified ABER threshold.

In particular, the third column in Table 2 compares the required SNR distances for each TAS method in correlated and uncorrelated scenarios. These data indicate that CG-TAS performs the least effectively when the channel is correlated, whereas ED-TAS remains the most reliable TAS method. HC-TAS experiences only a slight degradation compared to ED-TAS. However, HC-TAS still achieves better overall system ABER performance improvement than ED-TAS. It should be noted that HC-TAS has much lower complexity than ED-TAS. This demonstrates the superiority of HC-TAS as a simple yet highly effective antenna selection method for enhancing system ABER performance. This observation has been validated in [17], and it remains consistent even in the presence of correlated channel conditions.

5 Conclusion

In this paper, we have investigated the MU-VASM system in a correlated channel environment. Simulation results have demonstrated that as the channel correlation coefficient increases, the BER (or ABER) performance of the system deteriorates. Furthermore, the paper explored the application of well-known TAS algorithms, specifically CG-TAS, ED-TAS, and HC-TAS, to enhance the system's performance. Simulation results have clearly shown that, despite the detrimental impact of channel correlation on the BER (or ABER) performance, the employment of TAS methods has significantly improved the system's quality. In fact, even when channel correlation is present, the utilization of TAS continues to yield improved system performance compared to the scenario of uncorrelated channels without TAS implementation. ED-TAS and HC-TAS perform well even in correlated channels, with HC-TAS continuing to demonstrate superiority in enhancing ABER performance for the system.

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