Generalized Space-Time Coded Massive MIMO System

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Abstract —This paper introduces a generalization of space-time block coding techniques for a massive multiple-input multiple output (MIMO) system. This generalized space-time coded massive (STCM) MIMO technique uses N_t number of transmit antenna arrays and N_r number of receive antennas. This allows the system to be more openly customizable to fit the needs of the wireless community and industry. With this generalization, the wireless system exploits the symbol diversity provided by the space-time coding and the interference cancelling abilities of the massive MIMO antenna arrays and linear pre-coding. This technique treats each massive MIMO transmit antenna array similarly to how a traditional space-time system would treat each antenna. Our results show that the proposed STCM-MIMO technique significantly outperforms traditional massive MIMO.

Index Terms—Massive MIMO, space-time coding, wireless systems, diversity, interference cancellation

I. Introduction

Future wireless communications technology needs to be able to address the interference of an ever-growing user density and to combat the attenuation of wireless channels due to the presence of multipaths. Interference cancellation and communication channel reliability can be attained through space-time coding and employing massive MIMO technology. Space-time coding permits the system to take advantage of symbol diversity, which allows the receiver to recover data by evaluating redundant transmitted symbols. Space-time codes can also be evaluated with relative ease through linear processing at the receiver, due to the intrinsic orthogonal nature of space-time codes, which was explored by [1], [2]. Diversity was explored further by [3], who generalized space-time coding configurations to permit the use of N_t transmit antennas and N_r receive antennas. The authors demonstrated that the diversity of the system increases significantly as the number of transmit and receive antennas increases. Although the spacetime coding schemes can increase diversity, they do not permit the system to function efficiently with the interference from a large user density–for this problem, massive MIMO techniques excel.

The large user density interference problem can be tackled by incorporating a large number of transmit antennas with linear pre-coding [4]. The linear pre-coding at the transmitter allows the system to process the data and recover the transmitted symbol by cancelling the interference from other users–this is accomplished by massive MIMO's asymptotic orthogonal structure of the channel vectors with respect to the matched pre-coded parameter vectors [5]–[13]. The pre-coded parameter vector used in the system is the conjugate-transpose (Hermitian) of the matched channel vector utilized from the transmitter to the receiver. In [14], the authors explain that the pre-coded Hermitian parameter vector can be combined with a very large number of antennas at the base station to retrieve the transmitted symbol. This allows the system to be evaluated through the law of large numbers, as shown in [15]–[17], where the matched pre-coded parameter vectors' and channel vectors' product is the squared magnitude of the matched channel vector, and the mismatched vectors are treated as being asymptotically orthogonal to one another. The linear evaluation of the pre-coded transmit symbol permits the signal to occupy the same bandwidth as the other users without any significant detriment to the desired user's signal.

STCM-MIMO techniques have been explored in the past, in [18], the authors propose a system in which a single array of M transmit antennas at the base station transmit to K users with one antenna each. The system uses linear pre-coding at the base station to address interference from other users, and after pre-coding the signal, the signal is coded with a rateless space-time code, then transmitted from the M transmit antennas. This paper specifically addresses antenna failure and takes into account a system with a random number of the M transmission antennas having failed during transmission. They accomplish this by sending signal $\mathbf{X}$, a $t \times M$ quasi-orthogonal matrix, which they demonstrated could utilize the Alamouti code. $\mathbf{X}$ is space-time encoded over every 2×2 index, corresponding with the Alamouti code, within the t and M dimensions of the matrix. Similarly, in [19], the authors discuss using a base station equipped with M transmit antennas and a receiver with one receive antenna, which also uses space-time coding at the receiver with the linear precoding. They show that signal $\mathbf{S} = \mathbf{WX}$ where $\mathbf{W}$ is a unique $M \times N$ pre-coder matrix whose alternating entries are 0 and N is the number of symbols being transmitted, and $\mathbf{X}$ is the $t \times N$ Alamouti space-time coding matrix. The authors in [20] utilize a base station equipped with one array of M transmit antennas to transmit data to users with two receive antennas each. In particular, during the uplink transmission, the user utilizes space-time coding for communicating with the base station. In [21], the authors discuss a hybrid analog-

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digital architecture for the base station and an analog-only architecture for the users, both utilizing a massive MIMO antenna configuration with a large number of antennas in a single antenna array at both the base station and receiver. Like the previous works, the signal is space-time coded at the transmitter, before receiving massive MIMO pre-coding for transmission. In [22], the authors propose a massive MIMO system in which the base station is equipped with a single array of M transmit antennas and the receiver is equipped with two antennas. At the base station, the Golden Code is applied to signal. This, like the other techniques discuss above, allows their proposed system to achieve diversity in some form while using a massive MIMO configuration of a transmit antenna array of M transmit antennas.

In this paper, we propose a generalization of STCM-MIMO where the system uses space-time coding and transmit antenna array configurations to increase the symbol diversity of the system while simultaneously taking advantage of the interference cancellation and bandwidth efficiency of massive MIMO. This scheme was introduced in [23], where the authors explored a system with two transmit antenna arrays, at the base station, to transmit two space-time coded symbols to a user with one receive antenna. In the proposed STCM-MIMO configuration, we consider M transmit antennas and N_r receive antennas. We group $N = \frac{M}{N_t}$ transmit antennas in each array, where N_t is the number of transmit antenna arrays and M is the total number of transmit antennas at the base station. By using this configuration, the diversity, and therefore the system reliability, increases as N_t and N_r increases. We demonstrate that the proposed STCM-MIMO system significantly outperforms traditional massive MIMO systems, in the case of having M much greater than $N_t \times N_r$.

II. Generalized Space-Time Codes

Space-time codes are used in wireless communications systems for their system reliability which is a direct result of the symbol diversity that they create for the system. This technique was pioneered by [1] who explored a space-time coded configuration with two transmit antennas and N_r receive antennas, and it was later generalized by [3] who expanded the system to be configured with N_t transmit antennas and N_r receive antennas. The authors in [3] expand Alamouti's space-time encoding from a 2×2 encoder to a $N_t \times t$ space-time encoder that corresponds to the number of transmit antennas and the number of time slots used in the desired space-time code configuration.

The generalized received signal, discussed in [3], takes into account the N_t transmit antennas and N_r receive antennas, and can be expressed in Equation 1,

$$r_{t,p} = \sum_{j=0}^{N_t-1} h_{p,j} x_{t,j} + n_{t,p} \qquad (1)$$

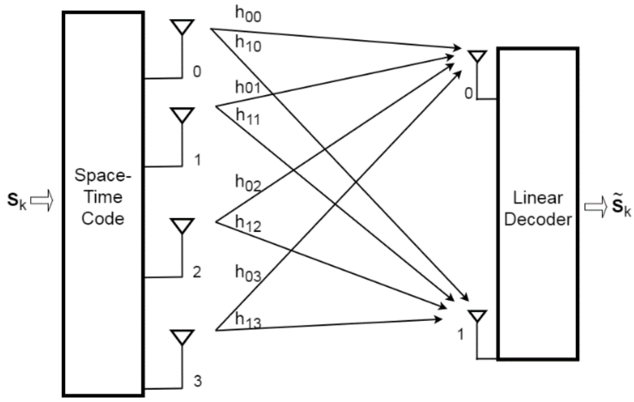

Fig. 1. Space-Time Coded 4 x 2 configuration

where $r_{t,p}$ is the received signal at time t and receive antenna p, N_t is the total number of transmit antennas, $h_{p,j}$ is the channel between receive antenna p and transmit antenna j, and $n_{t,p}$ is the AWGN. The signal $x_{t,j}$ is the specific symbol at time t from transmit antenna j corresponding to the **X** space-time coded matrix in Equation 2. As explained in [3], the specific symbols $x_{t,j}$, $j = 1,2,...,N_t$ are transmitted simultaneously at time t from transmit antennas 1 through N_t.

Let us consider a system with 4 transmit antennas and 2 receive antennas, in order to encode the symbols from space-time code matrix **X** at the transmitter, (see Figure 1). In Figure 1, $\boldsymbol{S_k}$ (the data for user k) is encoded by matrix **X**, and the corresponding symbols are transmitted from the base station to the receiver, where $\tilde{\boldsymbol{S}}_k$ is the estimated data for user k.

$$\mathbf{X} = \begin{pmatrix} s_0 & s_1 & \frac{s_2}{\sqrt{2}} & \frac{s_2}{\sqrt{2}} \\ -s_1^* & s_0^* & \frac{s_2}{\sqrt{2}} & -\frac{s_2}{\sqrt{2}} \\ \frac{s_2^*}{\sqrt{2}} & \frac{s_2^*}{\sqrt{2}} & \frac{(-s_0 - s_0^* + s_1 - s_1^*)}{2} & \frac{(-s_1 - s_1^* + s_0 - s_0^*)}{2} \\ \frac{s_2^*}{\sqrt{2}} & -\frac{s_2^*}{\sqrt{2}} & \frac{(s_1 + s_1^* + s_0 - s_0^*)}{2} & -\frac{(s_0 + s_0^* + s_1 - s_1^*)}{2} \end{pmatrix} \qquad (2)$$

Matrix **X** shows three symbols are being transmitted over four transmit antennas–this is to allow a higher data rate than the transmission of four symbols, due to the smaller amount of time blocks necessary to achieve orthogonality. This code has a rate of $\frac{3}{4}$, derived from three symbols being transmitted through four time blocks [3].

Once the received signal is detected, the appropriate $\frac{3}{4}$ rate decoder can be implemented at the receiver, to estimate the transmitted signal. The appropriate decoding formulas, corresponding to the space-time code matrix **X**, can be expressed as Equation 3 [3]. Where $\tilde{s}_0$, $\tilde{s}_1$, and $\tilde{s}_2$ are the estimated symbols of s_0, s_1, and s_2 respectively.

We will use this code to demonstrate how to develop a STCM-MIMO structure with high dimension MIMO configurations and space-time codes.

$$\tilde{s}_0 = \sum_{j=0}^{N_{r-1}} r_{0,j}h_{0,j}^* + (r_{1,j})^* h_{1,j} + \frac{(r_{3,j}-r_{2,j})(h_{2,j}^*-h_{3,j}^*)}{2} - \frac{(r_{2,j}+r_{3,j})^*(h_{2,j}+h_{3,j})}{2} \tag{3a}$$

$$\tilde{s}_1 = \sum_{j=0}^{N_{r-1}} r_{0,j}h_{1,j}^* - (r_{1,j})^* h_{0,j} + \frac{(r_{3,j}+r_{2,j})(h_{2,j}^*-h_{3,j}^*)}{2} + \frac{(-r_{2,j}+r_{3,j})^*(h_{2,j}+h_{3,j})}{2} \tag{3b}$$

$$\tilde{s}_2 = \sum_{j=0}^{N_{r-1}} \frac{(r_{0,j}+r_{1,j})(h_{2,j}^*)}{\sqrt{2}} + \frac{(r_{0,j}-r_{1,j})h_{3,j}^*}{\sqrt{2}} + \frac{(r_{2,j})^*(h_{0,j}+h_{1,j})}{\sqrt{2}} + \frac{(r_{3,j})^*(h_{0,j}-h_{1,j})}{\sqrt{2}} \tag{3c}$$

III. Generalized Space-Time Coded Massive MIMO

A. Simple $2N \times 1$ STCM-MIMO System

A $2N \times 1$ STCM-MIMO system takes advantage of the space-time encoding scheme discussed in [1] and exploits the interference cancellation provided from the massive MIMO pre-coding. Each transmit antenna array, N_t, has N transmit antennas where $N = \frac{M}{N_t}$ antennas. Fig. 2 depicts a model of a $2N \times 1$ STCM-MIMO system, where two symbols are transmitted from two transmit antenna arrays. This model utilizes the full rate symbol encoding scheme proposed by [1], with two transmit antennas and two time slots for transmission. The received signal at the receiver can be expressed as [23]:

$$\tilde{r}_0 = \tilde{r}(t) = \boldsymbol{w}_0^H \boldsymbol{h}_0 s_0 + \boldsymbol{w}_1^H \boldsymbol{h}_1 s_1 + \sum_{j\neq 0}^{K-1} (\boldsymbol{w}_{2j}^H \boldsymbol{h}_0 s_{2j} + \boldsymbol{w}_{(2j+1)}^H \boldsymbol{h}_1 s_{(2j+1)} + \tilde{n}_0 \tag{4a}$$

$$\tilde{r}_1 = \tilde{r}(t+T) = -\boldsymbol{w}_0^H \boldsymbol{h}_0 s_1^* + \boldsymbol{w}_1^H \boldsymbol{h}_1 s_0^* + \sum_{j\neq 0}^{K-1} (-\boldsymbol{w}_{2j}^H \boldsymbol{h}_0 s_{(2j+1)}^* + \boldsymbol{w}_{(2j+1)}^H \boldsymbol{h}_1 s_{2j}^*) + \tilde{n}_1 \tag{4b}$$

where $\tilde{r}_0$ is the received signal at time slot t, $\tilde{r}_1$ is the received signal at time slot $t+T$, $\mathbf{w}_j$ is the massive MIMO pre-coding parameter equal to $\frac{1}{N}\mathbf{h}_j$, and K is the number of users with one receive antenna each.

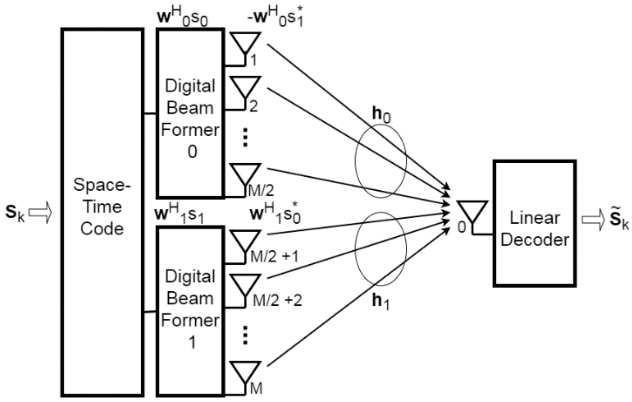

Fig. 2. STCM-MIMO 2N x 1

B. Generalized $(N_t)N \times N_r$ STCM-MIMO System

A generalized STCM-MIMO system can be considered where N_t is dependent on the space-time encoder being used, and N_r is dependent on the desired diversity for the system. In the case of the $\frac{3}{4}$ rate encoder from space-time code **X**, there are four columns in the encoder matrix, which correspond to $N_t = 4$ arrays of $N = \frac{M}{N_t}$ transmit antennas each, for a total of M transmit antennas for the system. The coded symbol from each column, in matrix **X**, are transmitted from the corresponding array of $N = \frac{M}{4}$ transmit antennas to the receiver. Let us consider a $4N \times 1$ configuration, so the system only utilizes 1 receive antenna. The system takes into account the diversity gain from four channel vectors being used from the four transmit antenna arrays to the one receive antenna. If greater diversity is required, more receive antennas can be implemented to create more channels from transmitter to receiver. In the case of a $4N \times 2$ system, two receive antennas are used, and the diversity of the system will be evaluated over eight channel vectors from transmitter to receiver.

Through combining Equation 1 and Equation 4, Equation 5 can be derived, which is generalized to use any space-time encoding scheme desired for STCM-MIMO:

$$r_{t,p}^k = \sum_{i=0}^{N_t-1} (\boldsymbol{w}_{p,i}^k)^H \boldsymbol{h}_{p,i}^k x_{t,i}^k + \sum_{n\neq p}^{N_r-1} \sum_{j=0}^{N_t-1} (\boldsymbol{w}_{n,j}^k)^H \boldsymbol{h}_{p,j}^k x_{t,j}^k + \sum_{q\neq k}^{K-1} \sum_{v=0}^{N_r-1} \sum_{l=0}^{N_t-1} (\boldsymbol{w}_{v,l}^q)^H \boldsymbol{h}_{p,l}^k x_{t,l}^q + \tilde{n}_{t,p}^k \tag{5}$$

where $r_{t,p}^k$ is the received signal at time t, at receive antenna p, for user k; $(\boldsymbol{w}_{p,i}^k)^H$ is the pre-code vector parameter corresponding to the channel from transmit antenna i to receive antenna p, at user k; N_t is the total number of transmit antenna arrays in the system; N_r is the total number of receive antennas; K is the total number of users; $x_{t,i}^k$ is the specific symbol at time t from transmit antenna i for user k, which corresponds to the coded symbols of space-time code $\mathbf{X}$; $\tilde{n}_{t,p}^k$ is the AWGN. The first term of Equation 5 is the desired part of the received signal in which the transmitted symbols are preserved. The second term of Equation 5 is the auto-interference of the system, stemming from each additional pre-coded vector parameter which corresponds to each additional receive antenna at the user. The third term of Equation 5 is the interference from the addition of other users. When M transmit antennas is large, the second and third term of this equation are essentially cancelled due to the interference cancelling properties of the massive MIMO portion of the system's configuration–leaving the first term to be evaluated at the space-time decoder.

This configuration allows the STCM-MIMO system to incorporate any combination of transmit antenna arrays and receive antennas. The estimated signals can be found through the techniques described by [3], where the space-time coded symbols can be simply linearly decoded. For example, a $4N \times 4$ spacetime encoder, such as $\mathbf{X}$, can be used within this STCM-MIMO system. Using this $\frac{3}{4}$ rate space-time encoder, the STCM-MIMO received signals can subsequently be decoded as seen in the $\frac{3}{4}$ rate combiner shown in Equation 6, which is derived from [3] where in Equation 6 $\tilde{s}_0$, $\tilde{s}_1$, and $\tilde{s}_2$ are the estimated symbols of s_0, s_1, and s_2 respectively. Here the system is taking advantage of the space-time code's diversity, while already having benefited from the interference cancellation due to the massive MIMO linear pre-coding.

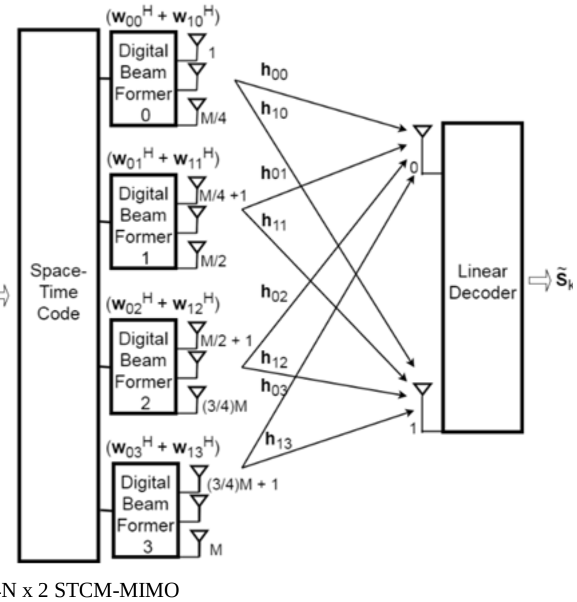

Fig. 3. 4N x 2 STCM-MIMO

Fig. 3 models a $4N \times 2$ STCM-MIMO system, where each antenna array is composed of $N = \frac{M}{4}$ transmit antennas of the total M transmit antennas. Three symbols, s_0, s_1, and s_2 are encoded and then transmitted from the four transmit antenna arrays across eight channels, using the $\frac{3}{4}$ rate space-time encoding from $\mathbf{X}$. Generally, the transmitted symbol, from the corresponding transmit antenna array, is pre-coded with a sum of N_r pre-code vector parameters due to each channel created from that transmit antenna array to the receive antennas. In the case of Fig. 3, two pre-code vector parameters are used at each array to correspond to the two wireless channels created from each transmit antenna array to the two receive antennas. Without the sum of the corresponding pre-code vector parameters, the transmit symbol would be lost at the additional receive antennas, due to the interference cancellation property of the system, and ultimately no additional diversity would be achieved.

IV. Computer Experiment Results

The following computer experiments demonstrate the Bit Error Rate (BER) efficiency of the proposed generalized STCM-MIMO system with N_t = 4 transmit antenna arrays in each of the STCM-MIMO system, with each transmit

$$\tilde{s}_0 = \sum_{j=0}^{N_{r-1}} r_{0,j}^k \left\|h_{0,j}^k\right\|^2 + (r_{1,j}^k)^* \left\|h_{1,j}^k\right\|^2 \tag{6a}$$

$$+ \frac{(r_{3,j}^k - r_{2,j}^k)(\left\|h_{2,j}^k\right\|^2 - \left\|h_{3,j}^k\right\|^2)}{2}$$

$$- \frac{(r_{2,j}^k + r_{3,j}^k)^*(\left\|h_{2,j}^k\right\|^2 + \left\|h_{3,j}^k\right\|^2)}{2}$$

$$\tilde{s}_1 = \sum_{j=0}^{N_{r-1}} r_{0,j}^k \left\|h_{1,j}^k\right\|^2 - (r_{1,j}^k)^* \left\|h_{0,j}^k\right\|^2 \tag{6b}$$

$$+ \frac{(r_{3,j}^k + r_{2,j}^k)(\left\|h_{2,j}^k\right\|^2 - \left\|h_{3,j}^k\right\|^2)}{2}$$

$$+ \frac{(-r_{2,j}^k + r_{3,j}^k)^*(\left\|h_{2,j}^k\right\|^2 + \left\|h_{3,j}^k\right\|^2)}{2}$$

$$\tilde{s}_2 = \sum_{j=0}^{N_{r-1}} \frac{(r_{0,j}^k + r_{1,j}^k)(\left\|h_{2,j}^k\right\|^2)}{\sqrt{2}} + \frac{(r_{0,j}^k - r_{1,j}^k)\left\|h_{3,j}^k\right\|^2}{\sqrt{2}} \tag{6c}$$

$$+ \frac{(r_{2,j}^k)^*(\left\|h_{0,j}^k\right\|^2 + \left\|h_{1,j}^k\right\|^2)}{\sqrt{2}}$$

$$+ \frac{(r_{3,j}^k)^*(\left\|h_{0,j}^k\right\|^2 - \left\|h_{1,j}^k\right\|^2)}{\sqrt{2}}$$

antenna array having $N = \frac{M}{N_t}$ antennas. Fig. 4 demonstrates STCM-MIMO systems with $4N \times 1$, $4N \times 2$, and 4N × 4 antenna configurations while utilizing the $\frac{3}{4}$ rate space-time encoding from matrix **X** in comparison to a massive MIMO system of M transmit antennas and one receive antenna. Both of the STCM-MIMO simulations and the massive MIMO simulation have their base stations composed of M = 500 total transmit antennas, each normalized in power to be equal to the four transmit antennas of the space-time coded configurations. Each simulation also considers the interference created by having three users in each scheme.

The 4N × 1 STCM-MIMO configuration reached a BER of 10^{-5} at an SNR of 4 dB, performing 2.5 dB better than the massive MIMO simulation, where it reached a BER of 10^{-5} at an SNR of 6.5 dB. While the 4N × 2 STCM-MIMO configuration reached a BER of 10^{-5} at an SNR of 3 dB, performing 1 dB better than the 4N × 1 STCM-MIMO simulation, and 3.5 dB better than the massive MIMO simulation. Ultimately, the 4N × 4 STCM-MIMO simulation reached a BER of 10^{-5} at an SNR of 1.5 dB, which performed 1.5 dB better than the 4N × 2 STCM-MIMO, 2.5 dB better than the 4N × 1 STCM-MIMO simulation, and 5 dB better than the massive MIMO simulation.

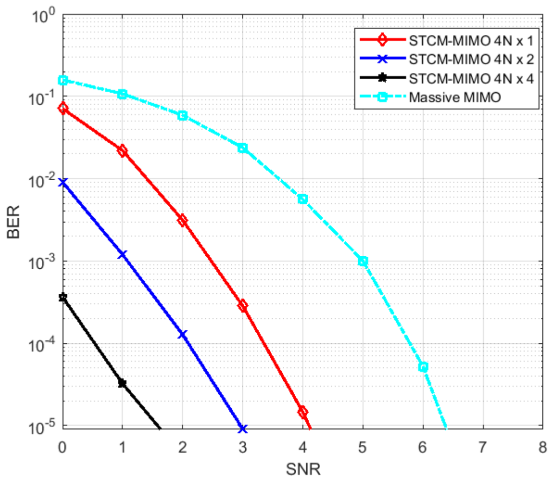

Fig. 4. $\frac{3}{4}$ Rate Coding with 500 TX Antennas

Fig. 5 demonstrates the systems' BER as M transmit antennas increases for a 4N × 4 and a 4N × 2 STCM-MIMO system, and a traditional massive MIMO system. The static SNR in this simulation was set to 2 dB to observe the BER trends of the three different configurations. Similar to Fig. 4, Fig. 5 also has the power of the overall system normalized, and three users are considered for each system to introduce interference so the interference cancelling properties of the massive MIMO portion of the systems can be utilized.

The massive MIMO simulation did not vary with any additional antennas at an SNR of 2 dB, due to the system's lack of diversity gain, so it stayed consistent at a BER of 10^{-1}. The 4N ×2 STCM-MIMO configuration shows great improvement in BER from 10^{-1} to 10^{-4} by increasing to 400 total transmit antennas for the system. The 4N × 4 STCM-MIMO configuration demonstrates a more rapid improvement of the system when the M transmit antennas increases. The simulation shows that the 4N × 4 STCM-MIMO system improves its BER from $10^{-.5}$ to $10^{-5.5}$ by 400 total transmit antennas. It shows improvement over both other configurations when M is 50 total transmit antennas.

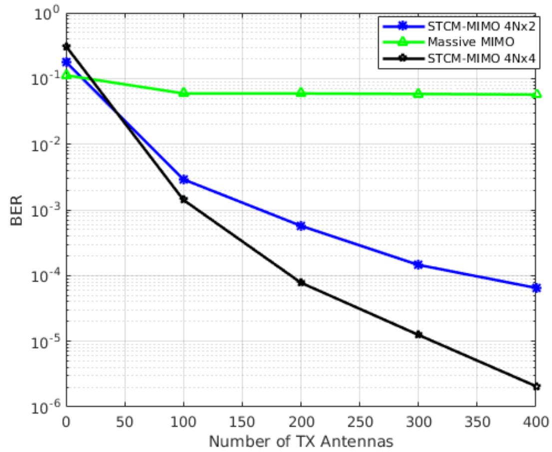

Fig. 5. BER Performance at 2 dB SNR

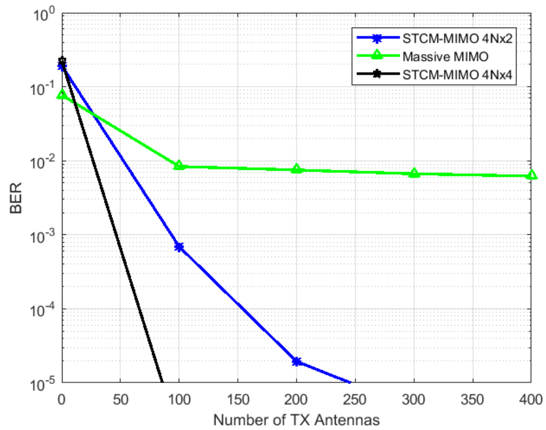

Fig. 6. BER Performance at 4 dB SNR

Fig. 6 similarly demonstrates the BER performance of the 4N ×4 and 4N ×2 STCM-MIMO systems and a massive MIMO system, while the number of total transmit antennas increase at a static SNR of 4 dB. While these systems are being evaluated over an SNR of 4 dB, a similar trend followed from the results demonstrated in Fig. 5. In Fig. 6, the massive MIMO system began at a BER of 10^{-1} and decreased to a BER of 10^{-2} at M = 100 total transmit antennas, and continued to stay static at a BER of 10^{-2}, regardless of how many more transmit antennas were added to the system. The 4N × 2 STCM-MIMO system began at a BER of $10^{-.5}$ and reached a BER of 10^{-5} when the system reached 250 transmit antennas. The most rapid improvement of all the systems occurred when the 4N × 4 STCM-MIMO system reached a BER of 10^{-5} at an SNR of 4 dB, when M was approximately 80 total transmit antennas for the system.

From these simulations, when $M >> (N_t \times N_r)$ the systems are able to take advantage of both the diversity provided by the space time codes and the interference cancellation of the massive MIMO technique. When $N_t = 4$ and $M = 500$ the total number of transmit antennas for each transmit antenna array in the system is $N = 125$, which remains sufficient to maintain said diversity and interference cancellation for all four STCM-MIMO systems in the computer simulation.

As N_r receive antennas increases, so does the number of pre-coding vector parameters that are needed at the transmitter. The number of pre-coding vector parameters is equal to N_r. The system then creates auto-interference while transmitting across its multiple channels due to having to assess the redundant pre-coding parameter coefficients to ensure that diversity is preserved throughout the system. The system also experiences interference from the signals over $N_t \times N_r$ number of channels from each other user. Figures 4-6 demonstrated that when the $M >> (N_t \times N_r)$ then the STCM-MIMO system will cancel the additional interference and still take advantage of the diversity provided by the space-time coding.

V. Conclusions

The study in this research has shown that the generalized STCM-MIMO performs more efficiently than massive MIMO alone. Generalized STCM-MIMO was shown to be able to take advantage of all the generalized space-time coding techniques to obtain diversity of the system, while maintaining the interference cancelling properties provided by massive MIMO antenna arrays. For STCM-MIMO systems with large N_t and large N_r, if M remains much larger than $N_t \times N_r$ the system will maintain both diversity gain and interference cancellation capability.

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