

Generalized Space-Time Coded Massive MIMO System

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Abstract—This paper serves as a generalization of a wireless communications technique called space-time coded massive (STCM) multiple-input multiple-output (MIMO). This generalized STCM-MIMO technique can use N_t number of transmit antennas 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 space-time coded MIMO and 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 further demonstrated that the diversity of the system increases significantly as the number of transmit and receive antennas increases. Although the space-time 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 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 explained 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, where [18] discussed omnidirectional STCM-MIMO systems by pre-coding a massive MIMO system with a coefficient at the transmitter, and encoding the signal with the technique introduced in [1]. In [19–21] STCM-MIMO is discussed by creating diversity while using M transmit antennas at the base station and two receive antennas at the user. In [19], [21], the authors utilize the golden code for their symbol encoding for the system. In above mentioned works, the base station is equipped with a single array of M transmit antennas, where diversity, through space-time coding, comes from pre-coding the transmit symbols and equipping the receiver with multiple 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 [22], 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 $\frac{M}{N_t}$ transmit antennas in each array resulting in N_t transmit antenna arrays and a total of M transmit antennas. 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 space-time coded

MIMO systems as well as uncoded 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. [3] was able to 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,

$$r_t^p = \sum_{j=0}^{N_t-1} h_{p,j} x_t^j + n_t^p \quad (1)$$

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 Table I. As explained in [3], the specific symbols $x_t^j, j = 1, 2, \dots, N_t$ 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 the symbols from Table I at the transmitter, (see Figure 1).

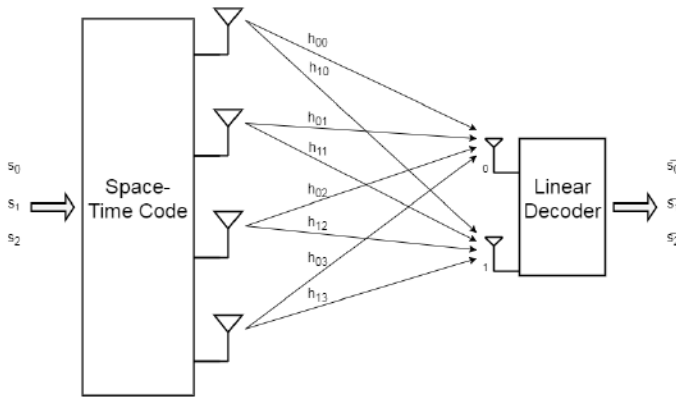


Fig. 1: Space-Time Coded 4×2 Configuration

This table 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

TABLE I: $\frac{3}{4}$ Rate Space-Time Encoder

	Antenna 0	Antenna 1	Antenna 2	Antenna 3
Time t	s_0	s_1	$\frac{s_2}{\sqrt{2}}$	$\frac{s_2}{\sqrt{2}}$
Time $t+T$	s_1^*	s_0^*	$\frac{s_2}{\sqrt{2}}$	$\frac{s_2}{\sqrt{2}}$
Time $t+2T$	$\frac{s_2^*}{\sqrt{2}}$	$\frac{s_2^*}{\sqrt{2}}$	$\frac{(-s_0 - s_0^* + s_1 - s_1^*)}{2}$	$\frac{(-s_1 - s_1^* + s_0 - s_0^*)}{2}$
Time $t+3T$	$\frac{s_2^*}{\sqrt{2}}$	$\frac{s_2^*}{\sqrt{2}}$	$\frac{(s_1 + s_1^* + s_0 - s_0^*)}{2}$	$\frac{(s_0 + s_0^* + s_1 - s_1^*)}{2}$

the transmitted signal. The appropriate decoding formulas, corresponding to the encoder of Table I, can be expressed as Equation 2 [3]. Where $\tilde{s}_0$, $\tilde{s}_1$, and $\tilde{s}_2$ are the estimated signals 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.

$$\tilde{s}_0 = \sum_{j=0}^{N_r-1} r_0^j h_{0,j}^* + (r_1^j)^* h_{1,j} + \frac{(r_2^j - r_2^j)(h_{2,j}^* - h_{3,j}^*)}{2} - \frac{(r_2^j + r_2^j)^*(h_{2,j} + h_{3,j})}{2} \quad (2a)$$

$$\tilde{s}_1 = \sum_{j=0}^{N_r-1} r_0^j h_{1,j}^* - (r_1^j)^* h_{0,j} + \frac{(r_2^j + r_2^j)(h_{2,j}^* - h_{3,j}^*)}{2} + \frac{(-r_2^j + r_2^j)^*(h_{2,j} + h_{3,j})}{2} \quad (2b)$$

$$\tilde{s}_2 = \sum_{j=0}^{N_r-1} \frac{(r_0^j + r_1^j)(h_{2,j}^*)}{\sqrt{2}} + \frac{(r_0^j - r_1^j)h_{3,j}^*}{\sqrt{2}} + \frac{(r_2^j)^*(h_{0,j} + h_{1,j})}{\sqrt{2}} + \frac{(r_3^j)^*(h_{0,j} - h_{1,j})}{\sqrt{2}} \quad (2c)$$

III. GENERALIZED SPACE-TIME CODED MASSIVE MIMO

A. Simple 2×1 STCM-MIMO System

A 2×1 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. Figure 2 depicts a model of a 2×1 STCM-MIMO system, where two symbols are transmitted from two transmit antenna arrays of $\frac{M}{2}$ antennas each. 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 [22]:

$$\tilde{r}_0 = \tilde{r}(t) = \mathbf{w}_0^H \mathbf{h}_0 s_0 + \mathbf{w}_1^H \mathbf{h}_1 s_1 + \sum_{j \neq 0}^{K-1} (\mathbf{w}_{2j}^H \mathbf{h}_0 s_{2j} + \mathbf{w}_{(2j+1)}^H \mathbf{h}_1 s_{(2j+1)}) + \tilde{n}_0 \quad (3a)$$

$$\tilde{r}_1 = \tilde{r}(t+T) = -\mathbf{w}_0^H \mathbf{h}_0 s_1^* + \mathbf{w}_1^H \mathbf{h}_1 s_0^* + \sum_{j \neq 0}^{K-1} (-\mathbf{w}_{2j}^H \mathbf{h}_0 s_{(2j+1)}^* + \mathbf{w}_{(2j+1)}^H \mathbf{h}_1 s_{2j}^*) + \tilde{n}_1 \quad (3b)$$

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 $\frac{N_t}{M} \mathbf{h}_j$, and K is the number of users with one receive antenna each.

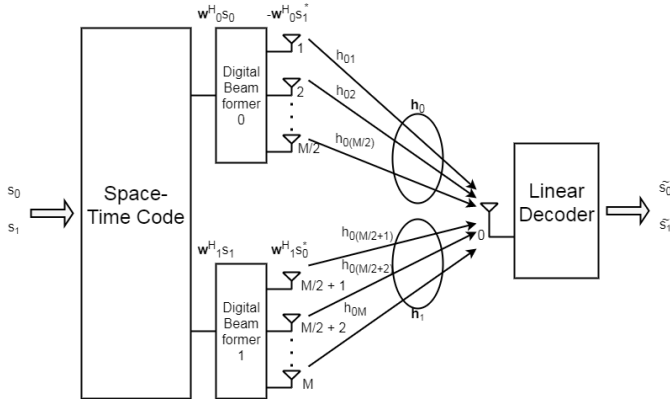


Fig. 2: STCM-MIMO 2×1

B. Generalized $(N_t \times N_r)$ 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 Table I, there are four columns in the encoder matrix, which correspond to $N_t = 4$ arrays of $\frac{M}{N_t}$ transmit antennas each, for a total of M transmit antennas for the system. The coded symbol from each column in Table I, are transmitted from the corresponding array of $\frac{M}{N_t}$ transmit antennas to the receiver. Let us consider a 4×1 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 utilized to create more channels from transmitter to receiver. In the case of a 4×2 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 3, Equation 4 can be easily derived, which is generalized to use any encoding scheme desired for STCM-MIMO:

$$r_t^p = \sum_{i=0}^{N_t-1} \mathbf{w}_{p,i}^H \mathbf{h}_{p,i} x_t^i + \sum_{j=0}^{K(N_t-1)} \mathbf{w}_{n,j}^H \mathbf{h}_{p,j} x_t^j + \tilde{n}_t^p \quad (4)$$

where r_t^p is the received signal at time t and receive antenna p , $\mathbf{w}_{n,j}^H$ is the pre-code vector parameter corresponding to the channel from transmit antenna j and to receive antenna n , where $n \neq p$, K is the number of users, N_t is the total number of transmit antenna arrays in the system, x_t^i is the specific symbol at time t and from transmit antenna i corresponding to the coded symbols of Table I, and $\tilde{n}_t^p$ is the AWGN.

This configuration allows the STCM-MIMO system to utilize any combination of transmit antennas and receive antennas. The estimated signals can be found through the techniques described by [3], where the space-time coded symbols used can be simply linearly decoded. For example, a 4×4 space-time encoder, located in Table I 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 5 derived from [3]

$$\tilde{s}_0 = \sum_{j=0}^{N_r-1} r_0^j \|\mathbf{h}_{0,j}\|^2 + (r_1^j)^* \|\mathbf{h}_{1,j}\|^2 + \frac{(r_3^j - r_2^j)(\|\mathbf{h}_{2,j}\|^2 - \|\mathbf{h}_{3,j}\|^2)}{2} - \frac{(r_2^j + r_3^j)^*(\|\mathbf{h}_{2,j}\|^2 + \|\mathbf{h}_{3,j}\|^2)}{2} \quad (5a)$$

$$\tilde{s}_1 = \sum_{j=0}^{N_r-1} r_0^j \|\mathbf{h}_{1,j}\|^2 - (r_1^j)^* \|\mathbf{h}_{0,j}\|^2 + \frac{(r_3^j + r_2^j)(\|\mathbf{h}_{2,j}\|^2 - \|\mathbf{h}_{3,j}\|^2)}{2} + \frac{(-r_2^j + r_3^j)^*(\|\mathbf{h}_{2,j}\|^2 + \|\mathbf{h}_{3,j}\|^2)}{2} \quad (5b)$$

$$\tilde{s}_2 = \sum_{j=0}^{N_r-1} \frac{(r_0^j + r_1^j)(\|\mathbf{h}_{2,j}\|^2)}{\sqrt{2}} + \frac{(r_0^j - r_1^j)\|\mathbf{h}_{3,j}\|^2}{\sqrt{2}} + \frac{(r_2^j)^*(\|\mathbf{h}_{0,j}\|^2 + \|\mathbf{h}_{1,j}\|^2)}{\sqrt{2}} + \frac{(r_3^j)^*(\|\mathbf{h}_{0,j}\|^2 - \|\mathbf{h}_{1,j}\|^2)}{\sqrt{2}} \quad (5c)$$

where in Equation 5 $\tilde{s}_0$, $\tilde{s}_1$, 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.

Figure 3 models a 4×2 STCM-MIMO system, where each antenna array is composed of $\frac{M}{4}$ 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 Table I. 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 Figure 3, two pre-code

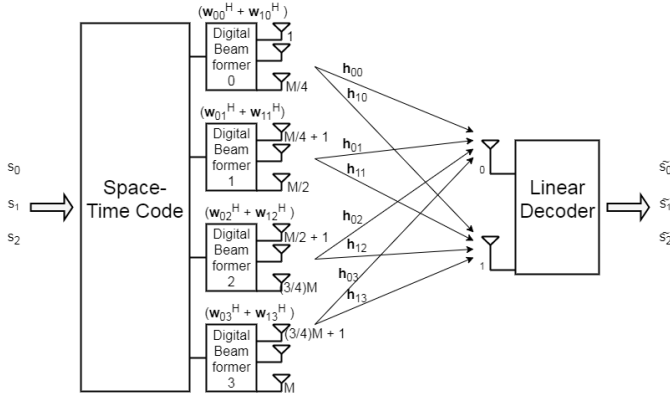


Fig. 3: 4×2 STCM-MIMO

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 antenna array having $\frac{M}{N_t}$ transmission antennas. Figure 4 demonstrates STCM-MIMO systems with 4×1 , a 4×2 , and 4×4 antenna configurations while utilizing the $\frac{3}{4}$ rate space-time encoding from Table I in comparison to a space-time coded only system of the same configurations and symbol matrix, and 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.

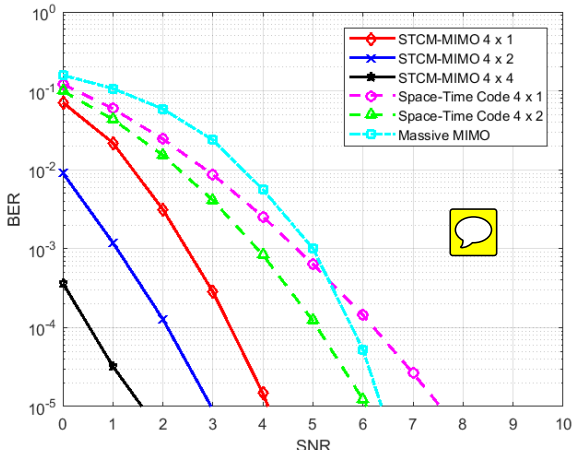


Fig. 4: $\frac{3}{4}$ Rate Coding with 500 TX Antennas

The 4×1 STCM-MIMO configuration reached a BER of 10^{-5} at an SNR of 4 dB, performing 3.5 dB better than the

4×1 space-time coded simulation which reached a BER of 10^{-5} at an SNR of 7.5 dB, and 2 dB better than the 4×2 space-time coded and 2.5 dB better than the massive MIMO simulations, where they both reached a BER of 10^{-5} at an SNR of 6 dB and 6.5 dB respectively. While the 4×2 STCM-MIMO configuration reached a BER of 10^{-5} at an SNR of 3 dB, performing 1 dB better than the 4×1 STCM-MIMO simulation, 4.5 dB better than the 4×1 space-time coded signal, 3 dB better than the 4×2 space-time coded signal, 3.5 dB better than the massive MIMO simulation. Ultimately, the 4×4 STCM-MIMO simulation reached a BER of 10^{-5} at an SNR of 1.5 dB, which was significantly better than all the of the other simulations mentioned above, even outperforming the 4×2 STCM-MIMO simulation by 1.5 dB.

From this simulation, it is clear that when $M \gg (N_t \times N_r)$ 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 $\frac{M}{N_t} = 125$, 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. Figure 4 demonstrated that when the $M \gg (N_t \times N_r)$ then the STCM-MIMO system will cancel the additional interference and still take advantage of the diversity provided by the space-time coding.

V. CONCLUSION

The study in this research has shown that the generalized STCM-MIMO performs more efficiently than massive MIMO and space-time codes 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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