Space-Time Coded Massive MIMO for Next Generation Wireless Systems

Jeremy J. Ice, Reza Abdolee, and Vida Vakilian

Dept. of Computer and Electrical Engineering, California State University, Bakersfield, California

***Abstract*—This paper serves as an evaluation of an experimental wireless communications technique called space-time coded massive (STCM) multiple-input multiple-output (MIMO). The STCM-MIMO system utilizes two massive MIMO antenna arrays which transmit data over two channel vectors to a user with one receive antenna. This configuration permits the system to use the asymptotic orthogonal qualities of massive MIMO pre-coding to eliminate the interference from other users' channel vectors and signals. The system also maintains the diversity of space-time codes to recover lost data through treating each transmitting massive MIMO array similarly to how a 2×1 Alamouti space-time code would treat each transmitting antenna. Our results show that a wireless system with the proposed STCM-MIMO technology can significantly outperform those with space-time coding techniques.**

***Index Terms*—Massive MIMO, Space-Time Coding, Wireless Systems, Reliability, Interference Cancellation, Multi-Users**

1 Introduction

THE primary objective of future wireless communication systems is to fulfill the demands of emerging bandwidth-hungry multimedia applications and to serve the rapidly growing density of wireless users. Current wireless communication technologies may fail to meet such growing demands. Consequently, new techniques need to be explored to discover a reliable and capable system to be used for future wireless cellular networks.

The space-time coding technique is one of the promising wireless technologies that can enhance the reliability and capacity of wireless networks. They operate efficiently through an effect called diversity. Past works from [1], [2] have discussed that diversity is measured off the number of antennas used and thus how many channels are created between the base station and the mobile terminal. The space-time diversity effect allows for greater signal clarity, because multiple copies of the symbols are transmitted over the channels to recover faded data. A very efficient space-time coding system, which permits full diversity while maintaining the data rate of the system, was reported in [3]. Both [3] and [4] have analyzed how the orthogonal qualities of the system allow for simple linear processing at the receiver. Although the space-time codes are powerful and capable of enhancing the data rate and reliability of wireless systems, they may fail to efficiently accommodate the growing density in multi-user wireless systems.

Massive multiple-input multiple-output (MIMO) is an emerging technology that can solve the limited bandwidth issue, of wireless communication systems, to accommodate a larger density of users. The main idea of massive MIMO is to use a large number of transmit antennas at a base station with linear pre-coding and combining, respectively, to eliminate interfering signals at the mobile station [5]. The signal clarity and efficient bandwidth usage of massive MIMO are further discussed at great lengths by [6–14] with regard to the linear pre-coding. Linear pre-coding involves the exploitation of the asymptotic orthogonal qualities of the system's channel vectors. With a base station composed of a large number of transmit antennas, Hermitian pre-coding can be implemented. Hermitian pre-coding was proposed in [15], which involves applying the complex-transpose of the channel vectors to estimate the signal.

In this paper, we propose a new wireless technology that uses the advantages of the space-time codes and massive MIMO systems, and we therefore call it space-time coded massive (STCM)-MIMO. The proposed system benefits from the diversity feature of space-time codes, and the interference cancellation capability of massive MIMO systems. The diversity of space-time codes will be preserved in the proposed system by treating multiple arrays of massive MIMO transmit antenna elements, similarly to how a space-time code would treat its individual transmit antennas. This arrangement will allow an antenna array to transmit data over a channel vector to the receiver, while each additional antenna array does the same over other channel vectors.

When the number of transmit antennas are much larger than the number of receive antennas, [16–18] explain that the law of large numbers permits massive MIMO systems to treat the channels as being orthogonal, which allows for an approximate elimination the other signals' and channels' interference to the desired signal. This concept will be combined in the proposed STCM-MIMO system as two separate massive MIMO systems working in tandem at a base station in order to eliminate the interference of the signals and channels not directed at the desired users. Our results show that a wireless system with the proposed STCM-MIMO technology can significantly outperform ones with space-time coding techniques.

2 Space-Time Codes

Space-time codes diversify a transmitted signal through both the space and time domains. The space domain is represented by the number of transmit antennas being utilized at the base station, which allows data to be transmitted simultaneously to the receiver. The time domain is represented by multiple time blocks that the signal is transmitted over. For example, in the Alamouti scheme [3] a base station transmits a signal with two transmit antennas to the wireless user. In particular, the base station transmits symbols s_0 and s_1 simultaneously from the two antennas at the first time block, at time t. Then symbols $-s_1^*$ and s_0^* are transmitted from the same two antennas at the second time block, at time $t+T$ (see Table I).

TABLE I: Space-Time Alamouti Code Matrix

	Antenna 0	Antenna 1
Time t	s_0	s_1
Time t+T	s_1^*	s_0^*

The Alamouti Code takes advantage of this linear system and makes use of the orthogonal qualities of the transmit signal to accurately estimate the signal at the receiver. For an Alamouti transmit system, consisting of two transmit antennas and one receive antenna, the received signals can be written as [3]

$$\begin{aligned} r_0 &= r(t) = h_0 s_0 + h_1 s_1 + n_0 \\ r_1 &= r(t+T) = -h_0 s_1^* + h_1 s_0^* + n_1 \end{aligned} \tag{1}$$

where r_0 and r_1 are the received signals at time t and $t+T$ respectively, h_0 is the channel over which symbol s_0 at time t and symbol $-s_1^*$ at time $t+T$ are sent, h_1 is the channel utilized to send symbol s_1 at time t and symbol s_0^* at time $t+T$, and n_0 and n_1 are the additive white Gaussian noise (AWGN) the signal encounters during transmission. Both h_0 and h_1 are represented by fading coefficients which are generalized as $\alpha_0 e^{j\theta_0}$ and $\alpha_1 e^{j\theta_1}$ respectively [3]. The received signals are then linearly combined at the receiver where the Alamouti Code exploits the orthogonal qualities of the system. The combined signals can be represented by

$$\begin{aligned} \tilde{s}_0 &= h_0^* r_0 + h_1 r_1^* \\ \tilde{s}_1 &= h_1^* r_0 - h_0 r_1^* \end{aligned} \tag{2}$$

where $\tilde{s}_0$ and $\tilde{s}_1$ are sent to the likelihood detector to estimate s_0 and s_1 respectively. By utilizing this method, the redundancy of the transmitted symbols allows the system to recover data that may have been lost or heavily distorted during transmission. This is a product of the diversity that space-time codes enable in their utilization in wireless communication systems. A model of the 2×1 Alamouti system can be seen in Figure 1 for reference.

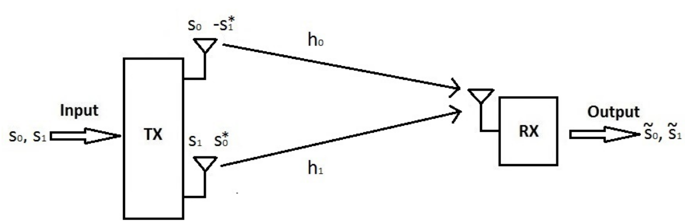

Fig. 1: 2×1 Alamouti Model

Diversity is the desirable product of space-time codes that will be used in the new proposed system in the space-time coded massive MIMO section of this report.

3 Massive MIMO

Massive MIMO applies a concept of pre-coding that enables a signal to be estimated very efficiently at the receiver. The theory behind the massive MIMO pre-coding is that with a large number of transmit antennas, a signal can be transmitted to a specific user and transmit data over the same bandwidth occupied by many other users [11]. Figure 2 is a massive MIMO model, with one user, visually depicting how the channel vector is exploited by the signal pre-coding.

This technique works due to the asymptotic orthogonal nature of the channels with respect to the number of transmitting antennas. The signal is pre-coded at the transmitter with the Hermitian of the channel vector, whose length is equal to the number of transmit antennas used in the system. The massive MIMO linear processing can be represented as [7], [8]:

$$y_0 = \mathbf{w}_0^H \mathbf{h}_0 s_0 + \sum_{j\neq0}^{K} \mathbf{w}_j^H \mathbf{h}_0 s_j + n \tag{3}$$

where y_0 is the received signal, $\mathbf{w}_0$ is the pre-coding vector parameter, $\mathbf{h}_0$ is the channel vector composed of all the fading constant values of the channels from each transmitting antenna to the receive antenna, K is the number of mobile users, and $\mathbf{w}_j$ are the pre-coded channel vectors utilized to transmit to additional users. In Equation 3 $\mathbf{w}_j$ and s_j are interference at the desired user's receiver. The pre-coding vector parameter is defined as:

$$\mathbf{w}_0 = \frac{1}{M}\mathbf{h}_0 \tag{4}$$

where $\mathbf{w}_0$ corresponds to channel $\mathbf{h}_0$ and M is the number of transmit antennas. The asymptotic orthogonal property allows the interference of the signal to be greatly reduced, as long as the number of transmit antennas is much greater than the number of receive antennas [7], [8].

$$\begin{aligned} \mathbf{w}_0^H \mathbf{h}_0 &= \frac{1}{M}\|\mathbf{h}_0\|^2 \Rightarrow \lim_{M\to\infty} \frac{1}{M}\|\mathbf{h}_0\|^2 = 1 \\ \mathbf{w}_0^H \mathbf{h}_1 &= \frac{1}{M}\mathbf{h}_0^H \mathbf{h}_1 \Rightarrow \lim_{M\to\infty} \frac{1}{M}\mathbf{h}_0^H \mathbf{h}_1 = 0 \end{aligned} \tag{5}$$

Equation 5 depicts the asymptotic orthogonal properties of the channel vectors when the two channels are mismatched. As M goes to infinity, the value of the asymptotic orthogonal channel vectors' product, goes to zero. When the channel vectors are matched and M goes to infinity, their squared magnitude approaches the value of M, allowing their product to go to one. Equation 5 further implies the larger number of transmit antennas that are used at the base station, the less the signal interference is, with minimal error in the process of transmission. For example, if Equation 3 is evaluated with a large value of M, the equation ideally becomes $y_0 = s_0 + 0 + n$, leaving the original signal and the AWGN.

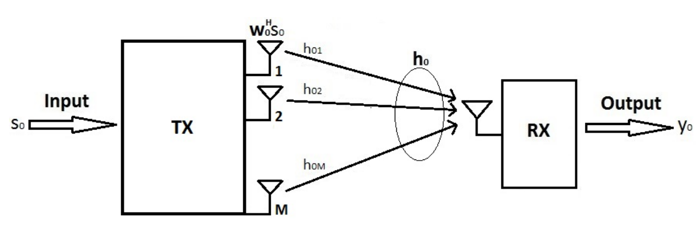

Fig. 2: Traditional Massive MIMO.

Adding additional users to the massive MIMO system allows their pre-coded signals to be evaluated across the channel vector of the desired user. The other users' pre-coded channel vectors are orthogonal to the desired user's channel vector, so the value of their interference approaches zero.

4 Space-Time Coded Massive MIMO

The proposed technique of this paper, for developing a viable next generation wireless communication system, utilizes the diversity of space-time codes and the pre-coding of massive MIMO. To accomplish this goal, a base station with two arrays of M number of transmit antennas transmitting to users with one receive antenna are considered. A model of this STCM-MIMO system can be viewed in Figure 3.

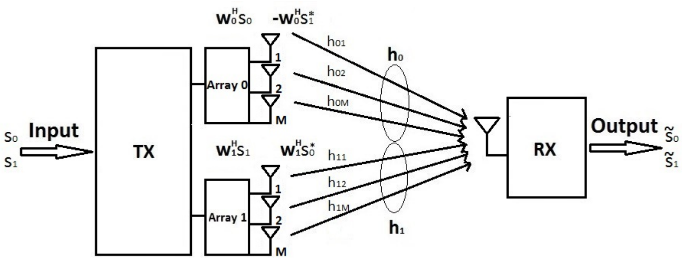

Fig. 3: Space-Time Coded Massive MIMO.

In so doing, the orthogonal channel vectors eliminate most of the interference from other peripheral signals. With the massive MIMO portion of the system implemented, the Alamouti space-time matrix can be utilized, which can be seen in Table I. The symbols, in the corresponding time block, are transmitted from the two massive MIMO arrays in the space dimension of the matrix, from Array 0 and Array 1. The Alamouti space-time matrix permits the system to transmit multiple copies of the original signals in a subsequent time slot, allowing for signal diversity and clarity. Equation 6 can now be be applied to ideally exploit both the space-time coding and massive MIMO systems in the combined scheme.

$$\begin{aligned}\tilde{r}_0 = \tilde{r}(t) &= \mathbf{w}_0^H \mathbf{h}_0 s_0 + \mathbf{w}_1^H \mathbf{h}_1 s_1 \\ &+ \sum_{j \neq 0}^{K-1} (\mathbf{w}_{2j}^H \mathbf{h}_0 s_{2j} + \mathbf{w}_{(2j+1)}^H \mathbf{h}_1 s_{(2j+1)}) + \tilde{n}_0 \end{aligned} \quad (6)$$

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

When the signals are received, they are now able to follow the linear combination of the Alamouti Code and take advantage of its diversity. The combined signals can be expressed as Equation 7

$$\begin{aligned}\tilde{s}_0 &= \|\mathbf{h}_0\|^2 \tilde{r}_0 + \|\mathbf{h}_1\|^2 \tilde{r}_1^* \\ \tilde{s}_1 &= \|\mathbf{h}_1\|^2 \tilde{r}_0 - \|\mathbf{h}_0\|^2 \tilde{r}_1^* \end{aligned} \quad (7)$$

where $\tilde{s}_0$ and $\tilde{s}_1$ are then sent to the likelihood detector to estimate s_0 and s_1. In order to evaluate this system fairly, the power of the transmit signals in both STCM-MIMO and Alamouti scheme are normalized to one. This allows for the STCM-MIMO system to be evaluated at the same overall power that the Alamouti system radiates with two antennas.

Through this process, the signal undergoes the pre-coding techniques of a massive MIMO system, which eliminated most of the interference from other users and other channels, and also undergoes the Alamouti space-time diversity scheme, which allowed signals that were distorted by AWGN, to be reevaluated and recovered from the redundancy of the space-time aspect of the system.

5 Computer Experiment Results

Figure 4 demonstrates the bit error rate (BER) efficiency of the proposed STCM-MIMO system with a comparison to the Alamouti space-time code. The proposed STCM-MIMO system utilizes two massive MIMO transmit antenna arrays of 100 antennas each and a user with one receive antenna, while the Alamouti space-time code is using the 2×1 configuration. The STCM-MIMO and Alamouti simulations also take into account the interference of two other users by introducing the interfering users' signals and channels to the individual simulations–this is done to demonstrate the interference canceling abilities of the massive MIMO portion of the proposed system, and to maintain equal conditions for both simulations.

Both the STCM-MIMO and Alamouti Code are similar in their signal combining at the receiver and signal estimation, and both have their signal power normalized. In the simulations, we consider Rayleigh fading wireless channels and AWGN. The STCM-MIMO simulation performed with significantly improved efficiency over the Alamouti 2×1 simulation.

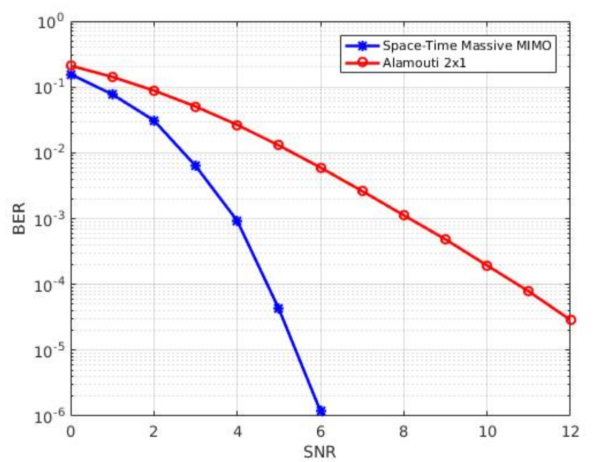

Fig. 4: Space-Time Massive MIMO Vs. Alamouti 2x1

The STCM-MIMO simulation reaches a BER of 10^{-3} at a signal to noise ratio (SNR) of 4 dB, which is 4 dB better than the Alamouti simulation, where it reached a BER of 10^{-3} at an SNR of 8 dB. As SNR becomes higher, the STCM-MIMO simulation produces a BER of 10^{-4} at an SNR of 5 dB, whereas, the Alamouti simulation reaches a BER of 10^{-4} at an SNR of 11 dB, a 6 dB difference.

Figure 5 demonstrates the effect that increased user density has on the STCM-MIMO system. In the simulation, 100 transmitting antennas per array are utilized to evaluate 5, 10, and 20 users. As the ratio of transmit antennas to number of users gets smaller, the interference becomes more noticeable and can affect the clarity of the signal to the desired user.

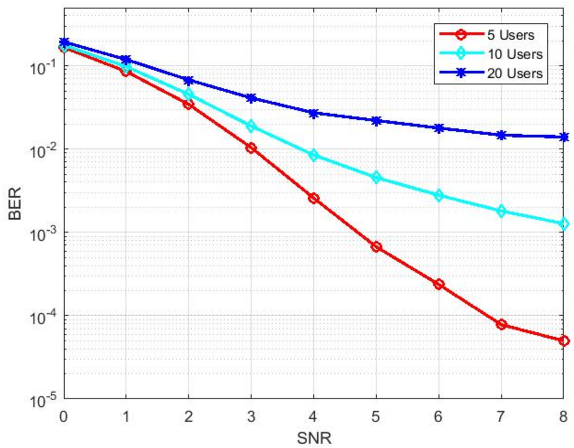

Fig. 5: 100 TX Antennas with Varying User Density

The simulation demonstrates that at 100 transmit antennas and 5 users, the BER approaches 10^{-5} at an SNR of 8 dB, but appears to be leveling out where it converges with the value of the interference of the five users. At 10 users, the BER converges to 10^{-3} at an SNR of 8 dB, and at 20 users, the BER converges at 10^{-2} at an approximate SNR of 6 dB. This BER convergence can be reduced to much smaller values for increased reliability performance by introducing more transmit antennas.

Figure 6 demonstrates the STCM-MIMO performance with 5, 10, and 20 users, but with 600 transmit antennas per antenna array. The BER convergence is significantly smaller and the reliability is not nearly as affected as it was in the simulation in Figure 5.

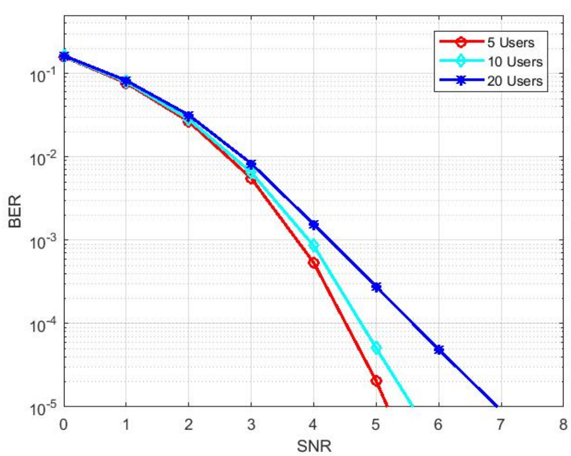

Fig. 6: 600 TX Antennas with Varying User Density

The simulation produced a BER of 10^{-5} at an SNR of 5 dB with 5 users, which performed only 0.5 dB better than when 10 users were simulated. When 20 users were simulated, the BER of 10^{-5} was reached at an SNR of 7dB, approximately 2 dB worse than when five users were simulated. Figure 6 shows that by adding additional transmit antennas, the signal can remain very reliable for a growing user density.

6 Conclusion

The study in this research has shown that the proposed space-time coded massive MIMO performs more efficiently than the Alamouti coding scheme. Space-time codes provide transmit diversity, which allow the signal an opportunity to retain their data if a symbol is lost during the transmission. Massive MIMO systems enable a spectrum efficient multi-user wireless communication system. By combining the space-time coding techniques with a massive MIMO system, a space-time coded massive MIMO system can be created that offers the benefits of both technologies.

References

[1] Vahid Tarokh, Hamid Jafarkhani, A. Robert Calderbank *"Space-Time Block Coding for Wireless Communications: Performance Results"*. IEEE Journal on Selected Areas in Communications, Vol. 17, No. 3, March 1999.

[2] Namita Agarwal, Shikha Nema *"Space Time Coding Techniques: A Review"*. International Journal of Engineering Research & Technology (IJERT), Vol. 1, Issue 6, August 2012.

[3] Siavish M. Alamouti *"A Simple Transmit Diversity Technique for Wireless communications"*. IEEE Journal on Select Areas in Communications, Vol. 16, No. 8, October 1998.

[4] Anastasios Stamoulis, Naofal Al-Dhahir, and A. Robert Calderbank *"Further Results on Interference Cancellation and Space-Time Block Codes"*. Signals, Systems and Computers. Thirty-Fifth Asilomar Conference, Pacific Grove, CA, November 2001.

[5] Thomas L. Marzetta *"Noncooperative Cellular Wireless with Unlimited Numbers of Base Station Antennas"*. IEEE Transactions on Wireless Communications, Vol. 9, No. 11, November 2010.

[6] Zhou Ge and Wu Haiyan *"Linear Precoding Design for Massive MIMO Based on the Minimum Mean Square Error Algorithm"*. EURASIP Journal on Embedded Systems, January 2017.

[7] Axel Mueller, Abla Kammoun, Emil Bjornson and Merouane Debbah *"Linear Precoding Based on Polynomial Expansion: Reducing Complexity in Massive MIMO"*. EURASIP Journal on Wireless Communications and Networking, February 2016.

[8] Emil Bjornson *"Massive MIMO Bringing the Magic of Asymptotic Analysis to Wireless Networks"*. International Workshop on Computer-Aided Modeling Analysis and Design of Communication Links and Networks (CAMAD), December, 2004.

[9] Samuele Zoppi, Michael Joham, David Neumann, and Wolfgang Utschick *"Pilot Coordination in CDI Precoded Massive MIMO Systems"*. Workshop on Smart Antennas (WSA), Munich, Germany, March 2016.

[10] Emil Bjornson, Marios Kountouris, and Mérouane Debbah *"Massive MIMO and Small Cells: Improving Energy Efficiency by Optimal Soft-Cell Coordination"*. Telecommunications (ICT), 20th International Conference, Casablanca, Morocco, May 2013

[11] Hien Quoc Ngo *"Massive MIMO: Fundamentals and System Designs"*. Linkoping Studies in Science and Technology Dissertations, No. 1642, Linkoping, Sweden, 2015.

[12] Kaifeng Guo, Yan Guo, Gabor Fodor, and Gerd Ascheid *"Uplink Power Control with MMSE Receiver in Multi-Cell MU-Massive-MIMO Systems"*. IEEE ICC Wireless Communications Symposium, 2014.

[13] Haralabos Papadopoulos, Chenwei Wang, Ozgun Bursalioglu, Xiaolin Hou, and Yoshihisa Kishiyama *"Massive MIMO Technologies and Challenges towards 5G"*. IEICE Trans. Commun., Vol. E99-B, No. 3, March 2016.

[14] Lu Lu, Geoffrey Ye Li, A. Lee Swindlehurst, Alexi Ashikhmin, and Rui Zhang *"An Overview of Massive MIMO: Benefits and Challenges"*. IEEE Journal of Selected Topics in Signal Processing, Vol. 8, No. 5, October 2014.

[15] Jianwen Zhang, Xiojun Yuan, and Li Ping *"Hermitian Precoding for Distributed MIMO Systems with Individual Channel State Information"*. IEEE Journal on Selected Areas in Communications, Vol. 31, No. 2, February 2013.

[16] David Neumann, Michael Joham, Wolfgang Utschick *"Channel Estimation in Massive MIMO Systems"*. Technische Universität München, 80290 Munich, Germany, March, 2015.

[17] Erik G. Larsson *"Massive MIMO for Next Generation Wireless Systems"*. IEEE Communications Magazine, February 2014.

[18] Fredrik Rusek, Daniel Persson, Buon Kiong Lau, Erik G. Larsson, Thomas L. Marzetta, Ove Edfors, and Fredrik Tufvesson *"Scaling up MIMO: Opportunities and Challenges with Very Large Arrays"*. IEEE Signal Processing Magazine, Vol. 30, No. 1, January 2013.