Super-Orthogonal Space-Time Trellis Codes for Virtual Antenna Arrays

Oludare Sokoya[1], Hongjun Xu[2] and Fambirai Takawira[3], *Member IEEE*
1. Meraka Institute, CSIR Pretoria. dsokoya@csir.co.za.
2 & 3. School of Electrical, Electronic and Computer Engineering
University of KwaZulu-Natal
Durban 4041, South Africa
{Xuh, ftakaw}@ukzn.ac.za

Abstract—This paper investigates the performance of super-orthogonal space time trellis codes when Virtual Antenna Arrays (VAA) are employed. The concept of virtual antenna arrays was developed to emulate Multiple-Input Multiple-Output (MIMO) schemes with limited number of antennas. The emulated MIMO systems drastically increase data throughput in terms of the bit error rate (BER) and the frame error rate (FER) when compared with MIMO schemes where VAA is not employed.

Index Terms— super orthogonal codes, antenna arrays, co-operative diversity, space time codes, error rate, fading channel.

I. INTRODUCTION

Wireless systems which communicate over Single-Input Single-Output (SISO) wireless channel have limited capacities in fading channels when compared to transmission over MIMO wireless channels. Telatar [1] and Foschini et al [2] have shown that not only can MIMO overcome the limitation of SISO systems, but the average capacity of a $N_t \times N_r$ MIMO Gaussian channel grows linearly with $\min(N_t, N_r)$.

The work in [1] and [2] assume that the fading between pairs of transmit-receive antenna elements are independent and identically Rayleigh for the MIMO (or multielement antenna) systems to achieve their large capacity. However, in real propagation environments, the fading is not independent, due mainly to the insufficient spacing between antenna elements especially at the receiver side. It has been observed [3] that when the fading is correlated, the channel capacity can be significantly smaller than when the fades are independently identically distributed. This inherent challenge of MIMO schemes limits the number of antenna elements that can be deployed at various ends of a MIMO system i.e. the transmit and the receive end.

For a cellular network, the deployment of multiple antennas might be possible at the Base Station (Transmit end), but it might not be possible to have more than one antenna at the Mobile station (MS) due to the compact nature of mobile devices.

Virtual antenna arrays [4] were recently introduced to allow the application of MIMO capacity enhancement techniques, to mobile terminals with a limited number of antenna elements.

Naturally, the deployment of MIMO techniques seems to be impossible where the number of antennas at the receiver is a limiting factor. However, one could view a cell not as a system of single point communication links, but rather as a network with certain number of antenna elements available in it, which then allow it to communicate among each other. With appropriate precautions, such deployment could emulate MIMO systems. The difference to the traditional MIMO antenna array is that the antenna elements are connected through a wireless link. The configuration of a Virtual antenna array MIMO scheme is depicted in Figure 1.

The paper is organized as follows. In Section II, the concept of VAA is presented. In Section III, a brief review of space time coding schemes is given with emphasis on the SOSTTC scheme. Section IV, the general transmission model of the SOSTTC is given and later on the emulated MIMO scheme is expressed. Simulation results are later presented in Section V. Finally, conclusions are drawn in Section VI

II. CONCEPT OF VIRTUAL ANTENNA ARRAYS

Dohler [4] summarized the concept of Virtual Antenna Arrays as: "*Let a sufficient number of users within a communication system communicate with the base station and directly with each other such that a trade-off is found between current technological limits*

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and required capacity increased". From that simple design criterion various technical implications follow.

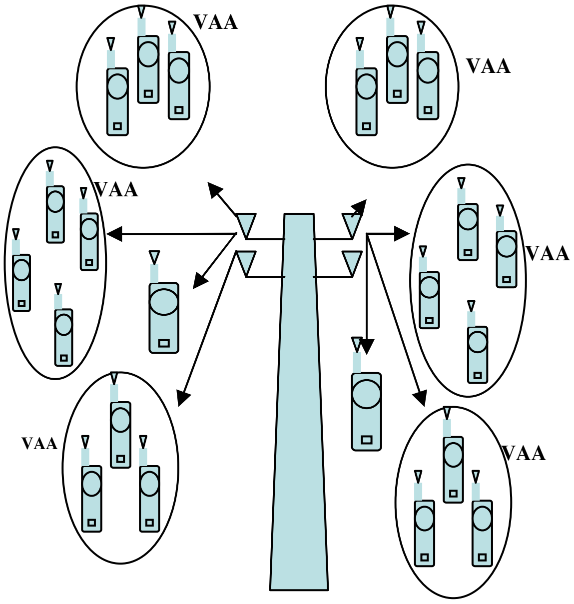

Figure 1: A Virtual Antenna MIMO Scheme

The number of communicating antenna elements will dictate the maximum achievable capacity. This number will depend on the actual number of available antenna elements willing to communicate and the general technology limit. Once the number of mutually communicating antennas are established, technical realizations have to be found to come close to the theoretical capacity bound. The realization of a VAA scheme will largely depend on the following;

- Access scheme (FDMA, TDMA and CDMA)
- Choice of main link technology (GSM, UMTS)
- Choice of relaying technology (Fixed, Selective and Incremental Relaying)
- Transceiver Complexity
- Number of antennas within a given geographical area
- Synchronization

To embed VAA into an existing technology, such as GSM, the direct link between the base station and the mobile station can be chosen to be based on 3G UMTS W-CDMA technology and the relaying link can use a technology that is capable of direct mode communication e.g. HiperLAN2. A VAA can be formed with mobile terminals that are close geographically to each other and which require a better QoS in that they start supporting each other via mutual communication. For example, the mobile terminals can communicate with the base station using the W-CDMA link and at the same time they relay further captured information to other mobile terminals within the same VAA group using HiperLAN2 technology.

Conceptual rules for forming a VAA can be summarized as follows:

- Base stations and mobile terminals should be able to support a VAA scheme; for the mobile terminal this means it must be able to support both the main link with the base station and also the relaying link to other terminals and for the Base station this means it must be able to encode data-streams such as if it is communicating to each mobile terminal through a MIMO system.
- Upon registering into a network each mobile terminal must inform the base station of its ability to support VAA with its technological realization and limitations.
- The mobile station should be able to track each mobile station to determine its position within the network.
- Whenever two or more mobile stations get close spatially together to form a VAA, the base station should inform the mobile station about such possibility.
- Depending on the previously negotiated agreement, the network initiates the formation of a VAA among these mobile terminals.
- When the condition of a relaying link deteriorates, the network should initiate a detachment of the mobile terminal or terminate the entire VAA group.

III SPACE TIME CODING

The use of channel coding in combination with a MIMO scheme achieves diversity, but the drawback is loss in bandwidth efficiency. Diversity can be achieved without any sacrifice in bandwidth efficiency if the channel codes are specifically designed for multi-antenna transmission scheme. Space time coding is a bandwidth and power efficient method of communicating over fading channels. It combines the design of channel coding, modulation, transmit diversity, and receive diversity. Space time codes provide better performance compared to an uncoded system. Some of the basic techniques of space time code are reviewed below

A. *Layered Space Time Code*

Layered space time (LST) codes are channel codes that are designed according to the layered architecture proposed by Foschini in [6]. The construction of the

LST codes for an $N_t \times N_r$ system whose capacity is linearly scaled with N_t is based on an N_t separately coded one-dimensional (1-D) subsystems of equal capacity. The LST architecture demultiplexes a stream of data into N_t layers and each layered data is then 1-D convolutionally encoded by the N_t encoders and then transmitted by N_t antennas. The above described layered space time architecture is formally known as the horizontally layered space time (HLST) architecture. Data can be rearranged amongst the layers such that the coded data are transmitted by N_t transmit antennas forming a diagonally layered space time architecture (DSLT) [7].

B Space Time Block Code

Space time block codes were first presented by Alamouti [8] as a simple transmit diversity technique. Tarokh et al [9], [10] generalized Alamouti's scheme by using the theory of orthogonal design and also extended it to two or more transmit antennas.

The orthogonal design allows for the use of a simple maximum-likelihood decoding algorithm based on linear combining at the receiver. There are two classes of space time block codes generated from orthogonal designs. The first class consists of those from real orthogonal designs for real constellation such as Pulse Amplitude Modulation (PAM) and the second consist of those from complex orthogonal designs for complex constellations such as Phase Shift Keying (PSK) and Qudrature Amplitude Modulation (QAM).

The existence of real orthogonal designs for different value of N_t is known as the Hurwitz-Radon problem in mathematics [11]. From the Hurwitz-radon theory, a full rate real orthogonal design exist only when N_t =2, 4 or 8.

The proposed scheme of Alamouti in [8] was later shown in [9] as a space time block code from complex orthogonal design of rate 1 for N_t =2.

C Space Time Trellis Code

Space time trellis coding was introduced by Tarokh et al [12] as a means of combining signal processing and multiple transmit antenna producing a system with significant gain over the earlier transmit diversity schemes.

Space time trellis codes operates on a one input symbol at a time and then produce a sequence of vector symbols whose length represent the number of transmit antennas.

In [13], optimum space time trellis codes were proposed using generator matrices, which provide maximum diversity and coding gain for various numbers of states and antenna with PSK modulation. It can be shown that the space time trellis codes presented by Tarokh in [12] provide the best tradeoff between constellation size, data rate, diversity advantage and trellis complexity when compared with other codes [13], [14].

D Super-Orthogonal Space Time Trellis Code

A new class of space time codes called super orthogonal space time trellis codes (SOSTTC), was introduces in [15]. These codes combine set partitioning and a super set of orthogonal space time block codes in a systematic way to provide full diversity and improved coding gain when compared with earlier space time trellis constructions [12], [13] and [14]. SOSTTC not only provide a scheme that is an improvement in coding gain when compared with earlier constructions, but it also answers the question of a systematic design for any rate, number of states and the maximization of coding gain.

The orthogonal transmission matrix used in the design of SOSTTC is given in (1).

$$\mathrm{A}\left(x_1, x_2, \theta\right) = \begin{pmatrix} x_1 e^{j\theta} & x_2 \\ -x_2^* e^{j\theta} & x_1^* \end{pmatrix} \qquad (1)$$

For an M-PSK modulation with constellation signal represented by $x_i \in e^{j\frac{2\pi a}{\mathrm{M}}}$, i =1,2. , a= 0,1, …, M-1, one can pick θ = 2πá/M, where á = 0,1,…, M-1.

In this case, the resulting transmitted signals of (1) are also member of the M-PSK constellation and, therefore do not expand the constellation signals. Since the transmitted signals are from a PSK constellation, the peak-to-average power ratio of transmitted signals is equal to one. The choice of θ = 0, π for Binary PSK (BPSK) and θ = 0, π/2, π, 3π/2 for Quaternary PSK (QPSK).

It should be noted that when θ = 0, (1) becomes the code presented in [8].

The construction of the SOSTTC is based on the expansion of the orthogonal transmission matrices and standard set partitioning method [16]. In [15], the set partitioning for the SOSTTCs is shown and also the way the code maximize coding gain, without sacrificing rate, in more details.

IV System Model

A transmission system of N_t transmit antennas and N_r receive antennas is considered. The input binary data streams are first fed into an outer trellis code modulation encode to generate a sequence of complex modulated symbols. The complex modulated symbols x_i (i =1, 2, …, N_t) are then fed into an inner space time block encoder to generate the orthogonal transmitted code matrix (1). $x_i^{(n)}$ is define as the complex value of the modulated symbol transmitted from the N_tth transmit antenna in the nth signaling interval and $h_{ij}^{(n)}$ is the channel coefficient from the ith transmit antenna to the jth receive antenna at the same signaling interval, $i \in (1,2, \ldots, N_t)$ and $j \in (1,2, \ldots, N_r)$. Assuming that the channel state information is know

$$\begin{aligned} r_l^{(n)} &= h_{l1}^{(n)} x_1^{(n)} e^{j\theta^{(n)}} + h_{l2}^{(n)} x_2^{(n)} + \eta_l^{(n)} \\ r_{l+N_r}^{(n)} &= h_{l1}^{(n)} \left(-x_2^{(n)}\right)^* e^{j\theta^{(n)}} + h_{l2}^{(n)} \left(x_1^{(n)}\right)^* + \eta_{l+N_r}^{(n)} \end{aligned} \qquad (2)$$

at the receiver, the corresponding set of successive signal sample at two output time is given by: where $l = 1, 2, \ldots, N_r$ and $\eta_l^{(n)}$ are independently identical distributed complex zero mean Gaussian noise samples, each sample with $\sigma^2/2$ per dimension. It is assume that the channel elements undergo Rayleigh Fading.

A EMULATION OF (N_t=2, N_r=2) SOSTTC WITH VAA

In [15], Hamid et al. presented various example of the SOSTTC scheme with more than one antenna at the receiver and various states of the trellis. Our interest in this section of the paper is the scheme with two transmit antennas and two receive antennas. The combined signals from the two receive antennas are a simple addition of the combined signal, which could have been made at each receive antenna. It can hence be concluded that if signals received at each antenna are independent and if the combining is performed at each antenna, the same results should be obtained by adding the two signals. The (2, 2) SOSTTC scheme can be applied to a single antenna mobile terminal. The main idea is to use the other (supporting) mobile terminal as a transparent relay. This latter one acts as a second receiving antenna for the target mobile terminal. The scheme is depicted in Figure 2.

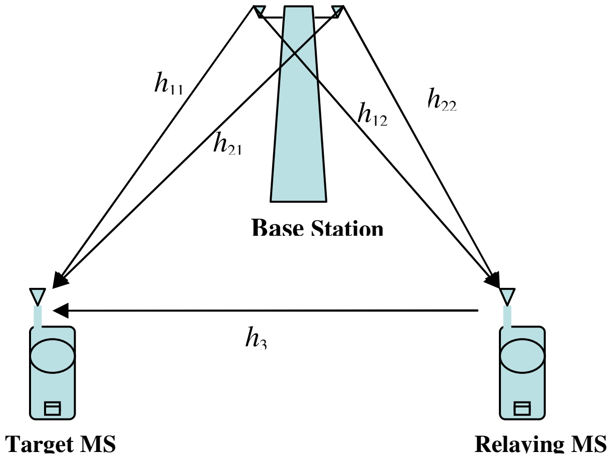

Figure 2: 2 Base Station Antennas (Tx) and One Relaying MS emulation the (2, 2) SOSTTC scheme.

This scheme yield a diversity gain of 4 under perfect condition with respect to non-diversity scheme. The idea is to send both orthogonal transmission matrix intended for the target mobile station (MS) from the two transmit antenna at the base station (BS). Both these streams are received by the relaying MS and the target MS, through different channels h_{11}, h_{12}, h_{21}, h_{22}. The relaying MS retransmits its received double stream to the target MS using channel h_3, acting as a transparent transceiver. It should be noted that the target MS receives two sets of orthogonal transmitted signals i.e. the received signals as a result of the BS /Target MS link and also the received signal as a result of the Relaying MS/Target MS link.

The technological realization of separability is not straightforward and severely dependent on the underlying system assumptions and access technology. It should be noted, however that the separation is technically feasible and accomplished as noted in [17]. Since the two signal streams are separable, the combining takes place in the target MS.

The target MS receives (3):

$$\begin{aligned} r_1^{(n)} &= h_{11}^{(n)} x_1^{(n)} e^{j\theta^{(n)}} + h_{21}^{(n)} x_2^{(n)} + \eta_1^{(n)} \\ r_2^{(n)} &= h_{11}^{(n)} \left(-x_2^{(n)}\right)^* e^{j\theta^{(n)}} + h_{21}^{(n)} \left(x_1^{(n)}\right)^* + \eta_2^{(n)} \end{aligned} \qquad (3)$$

at the nth signaling interval from the base station and the relaying MS receives (4):

$$\begin{aligned} r_3^{(n)} &= h_{12}^{(n)} x_1^{(n)} e^{j\theta^{(n)}} + h_{22}^{(n)} x_2^{(n)} + \eta_3^{(n)} \\ r_4^{(n)} &= h_{12}^{(n)} \left(-x_2^{(n)}\right)^* e^{j\theta^{(n)}} + h_{22}^{(n)} \left(x_1^{(n)}\right)^* + \eta_4^{(n)} \end{aligned} \qquad (4)$$

The relaying MS retransmits the received double stream through channel h_3. Thus, the target MS receives finally:

$$\begin{aligned} r_5^{(n)} &= h_3^{(n)} r_3^{(n)} + \eta_5^{(n)} \\ r_5^{(n)} &= h_3^{(n)} h_{12}^{(n)} x_1^{(n)} e^{j\theta^{(n)}} + h_3^{(n)} h_{22}^{(n)} x_2^{(n)} + h_3^{(n)} \eta_3^{(n)} + \eta_5^{(n)} \\ r_6^{(n)} &= h_3^{(n)} r_4^{(n)} + \eta_6^{(n)} \\ r_6^{(n)} &= h_3^{(n)} h_{12}^{(n)} \left(-x_2^{(n)}\right)^* e^{j\theta^{(n)}} + h_3^{(n)} h_{22}^{(n)} \left(x_1^{(n)}\right)^* + h_3^{(n)} \eta_4^{(n)} + \eta_6^{(n)} \end{aligned} \qquad (5)$$

At the branch of the trellis of the SOSTTC scheme, the decoder computes an estimate of signals for both the direct base station/target MS link and the relaying/ MS link using the maximum likelihood technique.

Once the branch metrics are computed the Viterbi Algorithm [5] is applied to search for the path with the lowest accumulated metric.

V SIMULATION RESULTS

The simulation results shown in Figure 3-6 were based on the following assumptions. The entire wireless channels involved are quasi-static non-frequency selective Rayleigh channels with average power of unity. The total power of the transmitted coded symbol was normalize to unity. The receiver is assumed to have perfect knowledge of the channels. For the SOSTTC results, each frame consists of 256 bits while for the STBC results, each frame consist of 4 bits.

Figures 3 and 4 shows the bit error rate and the frame error rate of a 4-state SOSTTC for a VAA and non-VAA systems with QPSK modulation respectively, while Figure 5 and 6 shows the bit error rate and the frame error rate of a STBC scheme for a VAA and non-VAA systems with QPSK modulation respectively. From the four figures, one can see that the emulated (2, 2) VAA scheme performs worse that the traditional (2, 2) MIMO schemes i.e. STBC and SOSTTC, however better that the (2, 1) MIMO schemes. The performance degradation with respect to the (2, 2) MIMO schemes is due to the additional noise in the relaying mobile station.

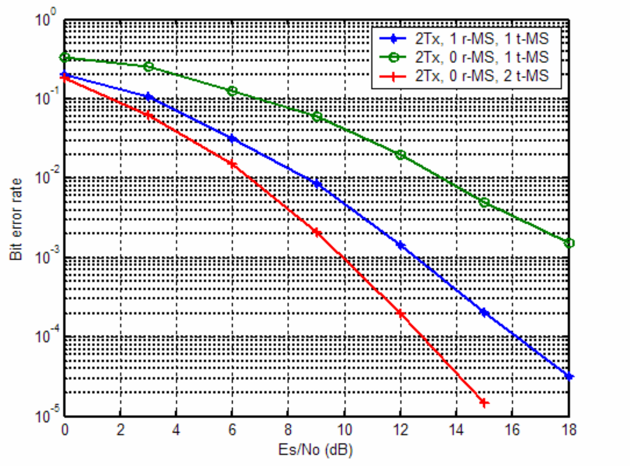

Figure 3: BER of 4-State SOSTTC scheme with QPSK, VAA and non -VAA for a varying number of transmit, relaying and target mobile station

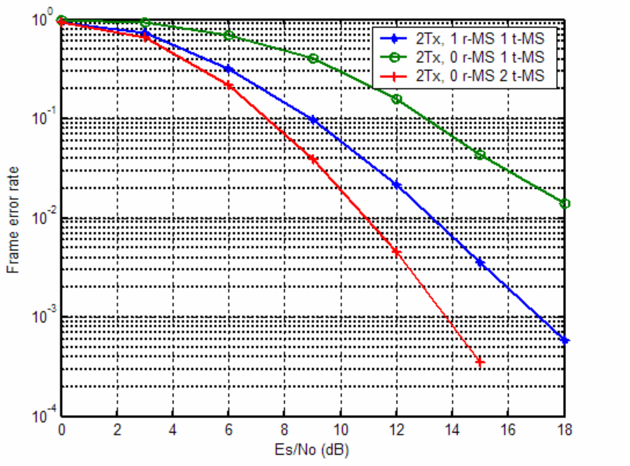

Figure 4: FER of 4-State SOSTTC scheme with QPSK, VAA and non -VAA for a varying number of transmit, relaying and target mobile station

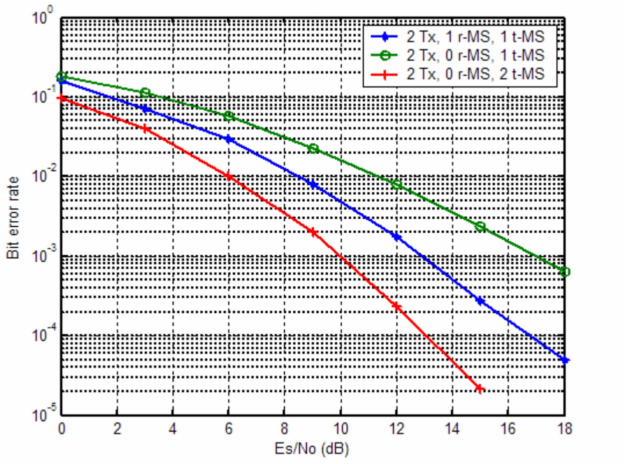

Figure 5: BER of STBC scheme with QPSK, VAA and non -VAA for a varying number of transmit, relaying and target mobile station

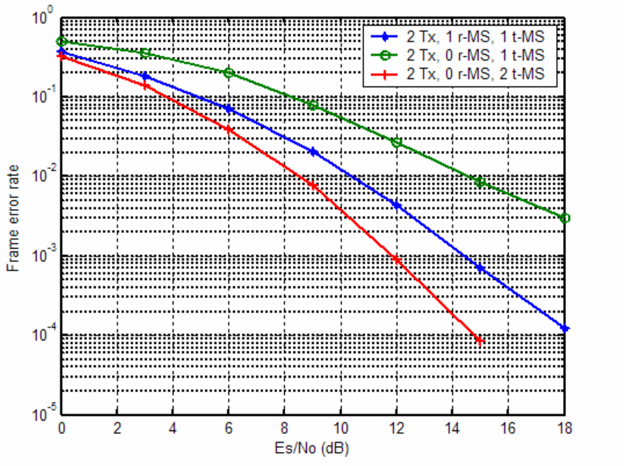

Figure 6: FER of STBC scheme with QPSK, VAA and non -VAA for a varying number of transmit, relaying and target mobile station

VI CONCLUSION

This paper dealt primarily with the performance of 4-state SOSTTC scheme with systems with deployed Virtual Antenna Arrays. It could be shown that VAA successfully emulates a traditional MIMO system by letting adjacent mobile station communicate among each other. Simulations results show clearly that a VAA deployment clearly outperforms a system without VAA by several dB, which justifies the increase in complexity due to the required relaying procedure.

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Oludare A. Sokoya completed his BSc. Eng degree in August 2001 in the School of Electronic and Electrical Engineering at the Obafemi Awolowo University, Ile-Ife, Nigeria and M.Eng from University of KwaZulu Natal in 2005. He worked with Philips Project Centre, Nigeria from 2002 to late 2003 as a Telecommunication Engineer. He is currently with Meraka Institute as a student with the Wireless Africa group.

Dr. Hong-Jun Xu received the BSc degree in 1984 from the University of Guilin Technology and the M Sc degree from the Institute of Telecontrol and Telemeasure in Shi Jian Zhuang, 1989, and the PhD degree from the Beijing University of Aeronautics and Astronautics in 1995. His research interests are in the area of digital and wireless communications and digital systems.

Professor Fambirai Takawira is head of the School of Electrical, Electronic and Computer Engineering at the University of KwaZulu-Natal. His research interests are in the general areas of adaptive signal processing, digital communications and data networks