Adaptive Beamforming Structure with STBC for IEEE 802.11n WLAN Systems

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***Abstract* – This paper proposes a structure of adaptive beamforming system especially tailored for IEEE 802.11n compliant WLAN operating in multiple input-multiple output (MIMO) orthogonal frequency division multiplexing (OFDM) mode. The proposal defines beamforming system for 802.11n transceiver exploiting space time block coding (STBC) of MIMO technology. The proposed structure is based on adaptive computation of complex beamforming matrices at transmitter and receiver side for every OFDM subcarrier. For proposed structure, single-link single-user system model with detailed hardware architecture of 4x4 802.11n transceiver is presented using matrix algebra. In addition, solutions related to adaptive beamforming for proposed MIMO-OFDM system with variable number of transmitted spatial streams are shown in this paper.**

***Index terms* - beamforming, IEEE 802.11n, MIMO-OFDM, WLAN, STBC, 4x4 transceiver**

1. INTRODUCTION

Emerging 802.11n standard will incorporate both MAC and PHY layer enhancements [1]. Major PHY throughput enhancements that new standard will include: wider channel bandwidth (40MHz channels in 5 GHz band), combination of orthogonal frequency division multiplexing (OFDM) and multiple input multiple output (MIMO) transmission as the most promising techniques to support high data rate and high performance. OFDM is essentially a discrete implementation of multicarrier modulation, which divides the transmitted bitstream into many different substreams and sends them over many different subchannels (subcarriers). Furthermore, MIMO wireless communication refers to the transmissions over wireless links formed by multiple antennas at both the transmitter and receiver side. In 802.11n, MIMO takes advantage of multipath propagation to simultaneously increase: throughput obtained through *spatial multiplexing* (SM), range obtained through transmit/receive *beamforming*, and reliability obtained through *diversity*.

SM spatially multiplexes multiple independent data streams, transferred simultaneously within one spectral channel of bandwidth. Thus, MIMO can significantly increase data throughput as the number of resolved spatial streams (SSs) is increased (up to 4 SS in 802.11n). Adaptive transmit beamforming (beam steering) is technique that concentrates radio signal (energy) directly on target antenna. Such concentrated radio signal (beam) will improve range (indirectly improving throughput) because all of radiated radio waves can be focused in the one direction of interest.

In MIMO wireless systems three types of diversity exist, and can be defined as: *space* (spatial), *time* (temporal) and *frequency* diversity. Spatial diversity is exploited when the same information will be transmitted from multiple transmit antennas and received at multiple receive antennas simultaneously. Apart from the spatial diversity, other forms of diversity are commonly available, namely, time diversity and frequency diversity, if the replicas of the faded signals are received in the form of redundancy in the temporal and frequency domains, respectively. Combinations of diversities such as: space-time (ST), space-frequency (SF), and space-time-frequency (STF) are used to accomplish higher transmit (Tx)/receive (Rx) diversity gains and/or coding gains [6]. In this paper, ST diversity is exploited.

Considerable work has been done in research on adaptive transmit beamforming in frequency domain for MIMO-OFDM systems which utilize space diversity for transmission of only single spatial stream across multiple antennas [11]-[15]. Also, accomplishment of higher diversity and coding gains for ST coding, but again for transmission of single spatial stream in MIMO systems has been in focus of researchers interest [16],[17],[19],[20]. Beamforming in combination with STBC is analyzed in [2]-[5]. On the other hand, multi stream transmission with fixed number of concurrently transmitted SS in MIMO-OFDM systems has been investigated in [7],[9],[10]. Combination of beamforming scheme and spatial multiplexing scheme in downlink communication systems is shown in [8].

In 802.11n system AP or BS will encounter other 802.11n devices and depending on number of antennas (separate RF chains), number of transmitted SS between 802.11n devices can differ. Thus, number of SSs that single 802.11n device transmits during communication with other devices can be dynamically and randomly changed in time. This imposes that every 802.11n device must be capable of dynamic adaptation to the different number of SS ranging from single to several (up to 4) SSs, in order to accomplish communication with various 802.11n devices. Instead of MIMO communication with fixed number of transmitted SS at all times, varying number of SS introduces new challenges in MIMO-OFDM systems with adaptive beamforming [18]. In such MIMO-OFDM systems adaptive beamforming has not yet been deeply investigated, motivating us to propose adaptive beamfroming transceiver structure for 802.11n system with four Tx and Rx antennas (4x4). Since in proposed system transmission between one and 4 SS can be realized, analyses of such system with beamforming capabilities has been performed for all transmissions of up to 4 SS.

Main contribution of this paper is proposal of beamforming system for 802.11n 4x4 transceiver exploiting ST diversity in form of space time block coding (STBC). Proposed structure is based on adaptive changes of complex beamforming matrices for every corresponding OFDM subcarrier at Tx and Rx side. Therefore, beamforming will be accomplished for each OFDM subcarrier, and it will be performed (on Tx side) before inverse

Number of simultaneously transmitted streams	Total no. of possible combinations	Ordinal (number) of spatial stream/total number of used Tx chains	Possible combination of Tx chains used for transmission					
Parallel transmission of 1 spatial stream $P=1$	$M_{Tx}!/P!(M_{Tx}-P)!= =4!/1!3!=4$	First stream ($p=1$)	1*	2	3	**4**	n/a	n/a
		M_{Tx}-Total number of used Tx chains	1*	2	3	**4**	n/a	n/a
Parallel transmission of 2 independent spatial streams $P=2$	$M_{Tx}!/P!(M_{Tx}-P)!= =4!/2!2!=6$	First stream ($p=1$)	1*	2	1	**2**	3	1
		Second stream ($p=2$)	1*	1	2	**2**	1	3
		M_{Tx}-Total number of used Tx chains	2*	3	3	**4**	4	4
Parallel transmission of 3 independent spatial streams $P=3$	$M_{Tx}!/P!(M_{Tx}-P)!= =4!/3!1!=4$	First stream ($p=1$)	1*	2	**1**	1	n/a	n/a
		Second stream ($p=2$)	1*	1	**2**	1	n/a	n/a
		Third stream ($p=3$)	1*	1	**1**	2	n/a	n/a
		M_{Tx}-Total number of used Tx chains	3*	4	**4**	4	n/a	n/a
Parallel transmission of 4 independent spatial streams $P=4$	$M_{Tx}!/P!(M_{Tx}-P)!= =4!/4!0!=1$	First stream ($p=1$)	**1***	n/a	n/a	n/a	n/a	n/a
		Second stream ($p=2$)	**1***	n/a	n/a	n/a	n/a	n/a
		Third stream ($p=3$)	**1***	n/a	n/a	n/a	n/a	n/a
		Forth stream ($p=4$)	**1***	n/a	n/a	n/a	n/a	n/a
		M_{Tx}-Total number of used Tx chains	**4***	n/a	n/a	n/a	n/a	n/a

Table 1- Possible 802.11n transmit combinations of up to 4 SSs across up to 4 Tx RF chains (antennas)

discrete Fourier transform (IDFT) in frequency domain. Single-link single-user transceiver structure in downstream direction from base station (BS) or access point (AP) to mobile station (MS) is analyzed.

The rest of this paper is organized as follows: in Section 2, transmission principles used by proposed 802.11n transceiver are described. Section 3 shows architecture of proposed 802.11n transceiver. STBC and spatial multiplexing principles implemented in such system are presented in Section 4. Adaptive beamforming structure and system model for 802.11n transceiver based on STBC are discussed in Section 5. Finally, some concluding remarks are given in Section 6.

2. TRANSMISSION PRINCIPLES

Data payload can be broken up and simultaneously transmitted (multiplexed) across multiple spatial streams (SSs), which are reassembled at the receiver. In proposed 802.11n transceiver structure each RF chain and its corresponding antenna are responsible for transmitting a SS. The maximal number of SSs available on the MIMO link between a transmitting station (STA) with M_{Tx} antennas and a receiving STA with M_{Rx} antennas is $N_{SS}=min(M_{Tx}, M_{Rx})$. As defined in 802.11n draft, maximal number of SS between 802.11n STA in optional modes will be up to 4 and support for at least two SS will be mandatory. Thus, basic 802.11n devices will support 2x2 structures in mandatory mode and in optional mode will support up to 4x4 structures, resulting in 4 independent Tx or Rx chains and corresponding antennas. Since 802.11n standard will be compatible with older a/b/g standards, and new standard will also introduced different RF Tx/Rx structures, it is possible that WLAN devices during operation encounter other devices built with a different number of Tx/Rx chains (antennas).

Therefore, our analysis will be carried out on the most complex Tx/Rx 802.11n structure that will include 4 antennas (RF chains) on both sides for transmission of all possible combinations of up to 4 SSs. Advantage of that approach is in the fact that the obtained results can be extended to simpler structures containing combinations with less number of Tx/Rx antennas and consequently less number of SSs. Accordingly, Table 1 presents all possible combinations for transmission of up to 4 spatial streams over 4 different Tx RF chains. The same logic can be applied on receiver side with 4 Rx RF chains. When the number of SS is less then the number of Tx chains, different SS/Tx chains combinations arise as shown in Table 1. On the other hand, when number of SS is equal to the number of Tx chains ($N_{SS}=M_{Tx}=4$) only one SS/Tx combination is possible requiring transmission of every single SS over only one Tx chain (last row of Table 1).

For any number P of different SS that need to be transmitted, most interesting combinations are the ones that maximize spatial diversity (shadowed in the Table 1). Among combinations that maximize diversity, the ones expressed with bold numbers in Table 1 are used for consideration in further analysis. Basic idea for maximizing spatial diversity was in exploration of every disposal RF Tx chain in situations when number of SSs are less then number of RF chains. For example, transmission of 2 SS will be accomplished through maximal number of 4 RF chains on Tx side, and received through 2, 3 or 4 RF chains, depending on the number of RF chains at the Rx side. Thus multiple copies of the same signal (SS) will be received on antennas at the Rx side enabling space diversity as one of the most important features of MIMO systems. Minimum diversity effects can be expect in 4x4 systems where 4 SSs are transmitted over 4 RF Tx chains and received over 4 RF Rx chains.

Important conclusions can be made if we express relationship between number of SS and number of Tx chains used for transmission (shown in Table 1) in matrix form. Let columns of the matrix represents ordinal (number) of Tx chain (up to 4) while rows of the matrix represent ordinal (number) of SS (up to 4) transmitted over that Tx chain. Let $\mathbf{S}_{M_{Tx}}^{P}$ defines parallel transmission of P $(1\leq P\leq 4)$ independent SS over M_{Tx} $(1\leq M_{Tx}\leq 4)$ available RF chains (antennas). Then maximum spatial diversity combinations will be accomplished if all four Tx RF chains ($M_{Tx}=4$) are used (bold combinations in Table 1.) which can be expressed in matrix form as:

$$\mathbf{S}^{P=1}_{M_{Tx}=4}=\begin{bmatrix} s_1^1 & s_2^1 & s_3^1 & s_4^1 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix} \qquad \mathbf{S}^{P=2}_{M_{Tx}=4}=\begin{bmatrix} s_1^1 & s_2^1 & 0 & 0 \\ 0 & 0 & s_3^2 & s_4^2 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix}$$

$$s_1^1 = s_2^1 = s_3^1 = s_4^1 \qquad s_1^1 = s_2^1 \neq s_3^2 = s_4^2$$

$$\mathbf{S}^{P=3}_{M_{Tx}=4}=\begin{bmatrix} s_1^1 & 0 & 0 & 0 \\ 0 & s_2^2 & s_3^2 & 0 \\ 0 & 0 & 0 & s_3^3 \\ 0 & 0 & 0 & 0 \end{bmatrix} \qquad \mathbf{S}^{P=4}_{M_{Tx}=4}=\begin{bmatrix} s_1^1 & 0 & 0 & 0 \\ 0 & s_2^2 & 0 & 0 \\ 0 & 0 & s_3^3 & 0 \\ 0 & 0 & 0 & s_4^4 \end{bmatrix}$$

$$s_1^1 \neq s_2^2 = s_3^2 \neq s_4^3 \qquad s_1^1 \neq s_2^2 \neq s_3^3 \neq s_4^4$$

where s_i^p represents *p-th* SS transmitted over *i-th* Tx RF chain.

For example, if we transmit single SS over all 4 TX RF chains (matrix $\mathbf{S}^{P=1}_{M_{Tx}=4}$), second copy of single SS transmitted over second Tx chain will be expressed as s_2^1. In such situation, all SSs that are transmitted over 4 different Tx chains belongs to the same SS $(s_1^1 = ... = s_4^1)$. On the other hand, if we transmit 4 different SS across 4 Tx RF chains ($\mathbf{S}^{P=4}_{M_{Tx}=4}$), all transmitted SS will be different $(s_1^1 \neq ... \neq s_4^1)$. Although parallel transmission of *P=2* and *P=3* SSs over $M_{Tx}=4$ Tx chains can be expressed using different SS/Tx chain combinations (shadowed in Table 1), all of them results with the same diversity effect. Among these combinations the ones ($\mathbf{S}^{P=2}_{M_{Tx}=4}$ and $\mathbf{S}^{P=3}_{M_{Tx}=4}$) defined in previous matrix form will be used for further analysis. It is noticeable that we comprise all possible combinations for transmission of up to 4 SS over 4 Tx RF chains simply using derived matrix forms $(\mathbf{S}^{P}_{M_{Tx}})$.

3. STRUCTURE OF 802.11N TRANSCEIVER

Proposed 802.11n MIMO-OFDM transceiver structure with STBC and adaptive beamforming is shown on Figure 1. The SS parser is responsible for dividing the unified bit stream into subsidiary streams (N_{SS}) for transmission. Each of N_{SS} spatial streams is punctured up to the desired rate. Now each SS consists of sequence of coded bits, ready for mapping on to OFDM subcarriers by the interleaver. After the interleaver, each block of bits in each SS can be mapped on to a single symbol by the constellation mapper. In STBC encoder, constellation points from N_{SS} spatial streams (SS) are spread into N_{STS} space time streams (STS) using space time block code, whereby $N_{SS} \leq N_{STS} = N_{Tx} = 4$. Thus, for this transceiver proposal, number of transmitted STS will always be equal to the number of used Tx RF chains for any number of SSs transmitted (Table 2). Special case is transmission of 4 SSs across 4 Tx chains (last row in Table 2), where STBC can not be exploited since number of STSs is equal to the number of Tx chains ($N_{SS}=N_{STS}=N_{Tx}=4$). Each symbol belonging to the corresponding STS is processed by single Tx chain. Thus, one to one interface exist between STS processors and the rest of RF transmit chain. Spatial steering matrix is responsible for one to one mapping,

Tx parameters for beamforming transceiver with STBC		
p/SS/STS/ /M_{Tx} Number	Spatial mapping matrix ($N_{SS} \leq N_{STS}$) [N_{Tx}xN_{SS}];	Beamsteering matrix ($N_{SS} \neq N_{STS}$) [N_{Tx}xN_{STS}]
p=1 N_{SS}=1 N_{STS}=P=4 M_{Tx}=4	$\mathbf{s}_i^p(k)=\begin{bmatrix}1\\1\\1\\1\end{bmatrix}$	$\mathbf{V}_{i,k}^P=\begin{bmatrix} v_{1,k}^1 & 0 & 0 & 0 \\ 0 & v_{2,k}^1 & 0 & 0 \\ 0 & 0 & v_{3,k}^1 & 0 \\ 0 & 0 & 0 & v_{4,k}^1 \end{bmatrix}$
p=1,2 N_{SS}=2 N_{STS}=P=4 M_{Tx}=4	$\mathbf{S}_i^p(k)=\begin{bmatrix}1 & 0\\1 & 0\\0 & 1\\0 & 1\end{bmatrix}$	$\mathbf{V}_{i,k}^P=\begin{bmatrix} v_{1,k}^1 & 0 & 0 & 0 \\ 0 & v_{2,k}^1 & 0 & 0 \\ 0 & 0 & v_{3,k}^2 & 0 \\ 0 & 0 & 0 & v_{4,k}^2 \end{bmatrix}$
p=1,2,3 N_{SS}=3 N_{STS}=P=4 M_{Tx}=4	$\mathbf{S}_i^p(k)=\begin{bmatrix}1 & 0 & 0\\0 & 1 & 0\\0 & 1 & 0\\0 & 0 & 1\end{bmatrix}$	$\mathbf{V}_{i,k}^P=\begin{bmatrix} v_{1,k}^1 & 0 & 0 & 0 \\ 0 & v_{2,k}^2 & 0 & 0 \\ 0 & 0 & v_{3,k}^2 & 0 \\ 0 & 0 & 0 & v_{4,k}^3 \end{bmatrix}$
p=1,2,3,4 N_{SS}=4 N_{STS}=P=4 M_{Tx}=4	$\mathbf{S}_i^p(k)=\begin{bmatrix}1 & 0 & 0 & 0\\0 & 1 & 0 & 0\\0 & 0 & 1 & 0\\0 & 0 & 0 & 1\end{bmatrix}$	$\mathbf{V}_{i,k}^P=\begin{bmatrix} v_{1,k}^1 & 0 & 0 & 0 \\ 0 & v_{2,k}^2 & 0 & 0 \\ 0 & 0 & v_{3,k}^3 & 0 \\ 0 & 0 & 0 & v_{4,k}^4 \end{bmatrix}$

Table 2 - Transmit parameters of beamforming system with STBC

assigning each SS and its corresponding symbol to the appropriate RF Tx chain. Depending on the number of SS (STS) that must be simultaneously transmitted (*P=1,2,3,4*), one of previously defined matrices ($\mathbf{S}^{P}_{M_{Tx}}$) will be used in process of spatial steering. Adaptive changes of weighted beamforming matrices for every OFDM subcarrier are performed in *pre-adaptive* beamforming block shown on Figures 1 and 2.

Finally, after IDFT and analog to digital conversion (ADC), RF circuit is used to up convert signals from baseband frequency to 2.4 GHz or 5 GHz band for transmission over corresponding antennas. The receiver (Rx) then down converts the RF signals to the baseband and performs the reverse process from the one performed at transmitter.

Detailed architecture of Tx (pre) beamformer and Rx (post) beamformer blocks of 802.11n system at Tx and Rx side are shown in Figure 2. Potential number of possible SSs that must be bind with every IDFT transformer directly impacts complexity of adaptive beamforming block and overall beamforming steering (beamsteering) structure.

We must cover all possible transmit combinations of up to 4 SS over up to 4 Tx chains shown in Table 1. From matrices derived in Section 2, we can determine exact number of potential SS that must be led to each IDFT transformer in order to obtain full spatial diversity for any number of transmitted SSs.

Relationship between potential number of necessary SSs per Tx chain can be observed if we analyze only the same columns of all 4 matrices simultaneously. Results of analysis are presented in Figure 2 in a form of different number of SSs led to each IDFT transformer (RF chain).

In practice, for any number of transmitted SS always one SS will be led to corresponding IDFT. Which of potential SS shown on Figure 2 will be led to related IDFT depends on

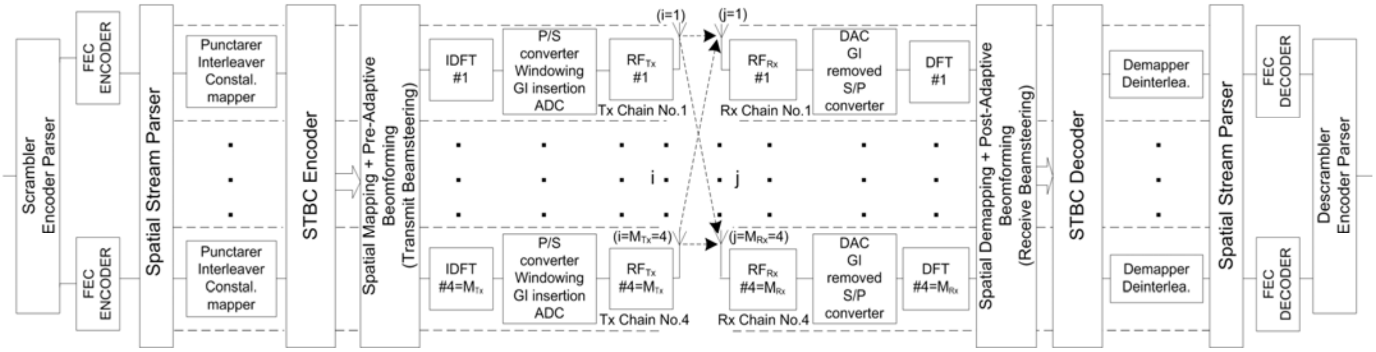

Figure 1 - Block diagram of proposed adaptive beamforming MIMO-OFDM 802.11n WLAN transceiver with STBC

beamsteering matrices shown in Table 2. According to beamsteering matrix, assignment of SS to corresponding Tx chain and beamforming is preformed in Tx beamsteering block. Every subcarrier of each SS (OFDM symbol) is multiplied with corresponding beamforming weight at Tx or Rx side in beamforming blocks (Figure 2). Overall number of multiplication weights depends on number of subcarriers of corresponding SS (symbols) that must be lead to IDFT transformer.

We will define few assumptions that will be used in further study:

- the analyses will be focused onto a single subcarrier k and then results can be extended to all other subcarriers of the same symbol (SS). Maximal number of OFDM subcarriers for 40 MHz channels will be twice larger then number of OFDM subcarriers for 20 MHz channels. Number of OFDM subcarriers per OFDM symbol (SS) can be

$$1 \le k \le K$$

with K denoting maximal number of subcarriers per transmitted symbol (Figure 2).

- number of Tx antennas is equal to the number of Tx RF chains. Number of Rx antennas is equal to the number of Rx RF chains. Number of TX or Rx antennas used for transmission can be

$$1 \le i \le 4 = M_{Tx},\ 1 \le j \le 4 = M_{Rx}$$

with M_{Tx} denoting maximal number of Tx antennas used for transmission and M_{Rx} denoting maximal number of Rx antennas used for reception respectively (Figure 1 and 2).

- One SS carries one OFDM symbol in moment of transmission of each SS. Thus, during one OFDM time period only one complex data symbol per subcarrier of each SS (OFDM symbol) is transmitted. For simplicity each stream can be regarded as a symbol. Number of SSs (symbols) simultaneously transmitted can be

$$1 \le p \le 4 = P$$

with P denoting maximal number of SSs that are simultaneously transmitted. This assumption includes all possible combinations of SS transmissions shown in Table 1.

- OFDM symbols of each SS are transmitted in time blocks, where number of blocks is defined as $1,2,\ldots n,\ n+1,\ldots,N$. We will assume that all further analyses are performed for transmissions of OFDM symbol of every SS during *n-th* OFDM symbol time (period).

4. STBC AND SPATIAL MULTIPLEXING PRINCIPLES

Space–time block coding (STBC) is a technique used in wireless communications to transmit multiple copies of a data stream across a number of antennas and to exploit the various received versions of the data to improve the reliability of data-transfer. For transmission of less then 4 SSs, application of two well known types of STBCs is proposed for this transceiver structure. Among different types of STBCs, implementation of orthogonal ST block code (OSTBC) is envisioned in this paper, also proposed by IEEE TGn in 802.11n draft [1].

According to OSTBC design, sometimes referred to as Alamouti code, two information symbols are transmitted on the same subcarrier k in a different order from two transmit antennas with some modification (conjugate and sign), within two OFDM symbol times t ($n,\ n+1$). Due to the orthogonallity of the code matrix, the Alamouti code has fast linear optimal maximum-likelihood (ML) decoding property which allows simple single-symbol ML detection. Also, the Alamouti (OSTBC) code can provide the full diversity of 2 for two transmit antennas with a coding rate of 1.

We will exploit these significant properties by employing OSTBC during transfer of two and three SSs, resulting in ultimate transmission of 4 STSs. Furthermore, OSTBC will be implemented in combination with spatial multiplexing (SM) [7], constituting hybrid (OSTBC/SM) scheme for transmission of 2 and 3 SSs in form of 4 STSs across 4 Tx antennas as presented in Table 3. For transmission of 2 SSs, this is accomplished by dividing the $N_{Tx}=4$ transmit antennas (RF chains) into two groups comprised of 2 Tx antennas (RF chains), where each group employs an OSTBC (Table 3). In the following description, the *m-th* $(1 \le m \le M)$ complex-valued modulation data at the output of the STBC encoder, transmitted in subcarrier k $(1 \le k \le K)$ of *p-th* $(1 \le p \le P=4)$ SS during one OFDM timeslot t $(n \le t \le n+(M-1)=T)$ is denoted as $d_{k,m}^{p}$. As presented in Table 3 for transmission of 2 SSs, two complex data symbols ($m=1,2$) of each SS ($p=1,2$) are transmitted in two ($T=M=2$) time slots ($t=n,\ n+1$) using same subcarrier k from 4 antennas in form of 4 STSs. In addition, for transmission of 3 SSs, $N_{Tx}=4$ transmit antennas are allocated into three groups, with two groups with

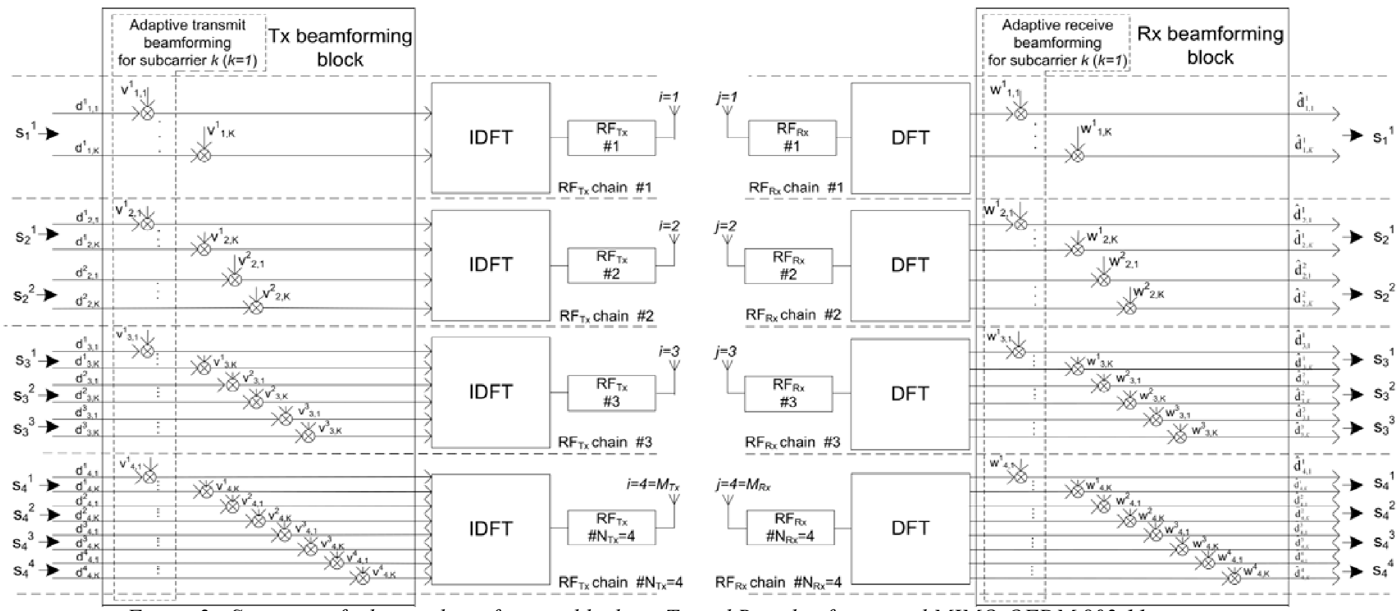

Figure 2 - Structure of adaptive beamforming blocks at Tx and Rx side of proposed MIMO-OFDM 802.11n transceivers

1 Tx RF chain and one group with 2 Tx RF chains employing an OSTBC. Thus, hybrid OSTBC/SM approach is applied in both cases since multiple SSs are spatially multiplex and orthogonal STB coding is implemented on one SS (or both in case of 2 SS transmission) in order to form 4 STSs.

Although OSTBC exploits MIMO communication systems to obtain full diversity and therefore high link reliability, unfortunately, it is not possible to construct OSTBC with a coding rate equal to one for more than two transmit antennas. It is shown in [16], [17] that it is possible to achieve the full diversity as in the case of OSTBC by using Quasi-orthogonal STBC (QSTBC) with a coding gain equal to one, by only a small increase in the complexity of the optimal detector. Thus, QSTBC can accomplish full diversity and full coding gain for 2^n(n=1,2,…) Tx antennas and arbitrary number of receive antennas.

In this paper, we use QSTBC for transmission of single SS dispersed into 4 STSs across 4 Tx RF chains (antennas) as presented in first row of Table 3. Hence, 4 complex data symbols (*m=1,2,3,4*) of one SS are transmitted in *T=M=4* time slots *t* (*n, n+1, n+2, n+3*) using single subcarrier *k* from 4 Tx RF chains (antennas) resulting in coding rate equal to 1. Thus, when QSTBC is implemented, block length of modulation matrix *T* is equal to the number of transmitted complex data symbols *M* (*T=M*). When OSTBC/SM and only SM are used for transmission of two/three and four SSs respectively, number of complex data symbols are higher then the number of time slots used for their transmission (*T<M*).

5. BEAMFORMING MODEL WITH STBC

We consider a system with $i=M_{Tx}=4$ transmit and $j=M_{Rx}=4$ receive antennas, although results obtained for 4 Rx antennas can be extended to any number of receive antennas from 1 to 3. If *T* $(1\le t\le T)$ is block length of modulation matrix (STBC) and *P* defines number of SS transmitted on subcarrier *k*, our system model can be expressed by

$$\underset{[TXM_{Rx}]}{\mathbf{X}^{P}_{j,k}} = \underset{[TXM_{Tx}]}{\mathbf{G}^{P}_{i,k}}\;\underset{[M_{Tx}XM_{Tx}]}{\mathbf{V}^{P}_{i,k}}\;\underset{[M_{Tx}XM_{Rx}]}{\mathbf{H}^{P}_{i,j,k}} + \underset{[TXM_{Rx}]}{\mathbf{N}^{P}_{j,k}} \qquad (1)$$

where $\mathbf{G}^{P}_{i,k}$ denotes the transmit matrix, $\mathbf{X}^{P}_{j,k}$ matrix of receive signal, $\mathbf{H}^{P}_{i,j,k}$ channel matrix, $\mathbf{V}^{P}_{i,k}$ beamforming matrix, and $\mathbf{N}^{P}_{j,k}$ complex white Gaussian noise (AWGN) matrix, respectively. Since $\mathbf{H}^{P}_{i,j,k}$ actually represents the frequency domain MIMO channel matrix evaluated for the *k-th* subcarrier frequency during transmission of *P* SSs, sent between transmitter with $i=M_{Tx}$ RF chains and receiver with $j=M_{Rx}$ RF chains it can be expressed as

$$\mathbf{H}^{P}_{i,j,k} = \begin{bmatrix} h^{p}_{1,1,k} & . & h^{p}_{1,M_{Rx},k} \\ . & . & . \\ h^{p}_{i,1,k} & h^{p}_{i,j,k} & h^{p}_{i,M_{Rx},k} \\ . & . & . \\ h^{p}_{M_{Tx},1,k} & . & h^{p}_{M_{Tx},M_{Rx},k} \end{bmatrix}^{T} \qquad (2)$$

and *T* denotes transponse matrix operation.

Instead of analyzing system during all *T* OFDM timeslots, we will restrict our analyses on single timeslot *t,* while obtained results can be extended to other timeslots in cases when QSTBC or OSTBC/SM are implemented. Accordingly, transmit matrix $\mathbf{G}^{P}_{i,k}$ in relation (1) can be presented as set of *T* transmit complex data vectors $\mathbf{d}^{P}_{i,k}(t)$ as shown in Table 3, where *P* denotes overall number of SSs transmitted on *k-th* subcarrier during *t-th* OFDM symbol time. Thus, transmit data complex vector within single timeslot *t,* where number of timeslots can vary depending on number of transmitted SS (from *t=n* to *t=n , n+1, n+2, n+3*) as shown in Table 3, can be expressed as

p,SS,STS,M_{Tx} Number/ /CODING	OFDM Symbol Time t	Transmit matrices for single OFDM symbol period $[1XM_{Tx}]=[1X4]$
p=1 N_{SS}=1 N_{STS}=P=4 M_{Tx}=4 /QOSTBC	t=n	$\mathbf{d}^1_{i,k}(t)=\left[d^1_{k,1} \quad d^1_{k,2} \quad d^1_{k,3} \quad d^1_{k,4}\right]^T$
	t=n+1	$\mathbf{d}^1_{i,k}(t)=\left[-d^{*1}_{k,2} \quad d^{*1}_{k,1} \quad -d^{*1}_{k,4} \quad d^{*1}_{k,3}\right]^T$
	t=n+2	$\mathbf{d}^1_{i,k}(t)=\left[-d^{*1}_{k,3} \quad -d^{*1}_{k,4} \quad d^{*1}_{k,1} \quad d^{*1}_{k,2}\right]^T$
	t=n+3= =T	$\mathbf{d}^1_{i,k}(t)=\left[d^{*1}_{k,4} \quad -d^{*1}_{k,3} \quad -d^{*1}_{k,2} \quad d^{*1}_{k,1}\right]^T$
p=1,2 N_{SS}=2 N_{STS}=P=4 M_{Tx}=4/ OSTBC/SM	t=n	$\mathbf{d}^2_{i,k}(t)=\left[d^1_{k,1} \quad d^1_{k,2} \quad d^2_{k,1} \quad d^2_{k,2}\right]^T$
	t=n+1= =T	$\mathbf{d}^2_{i,k}(t)=\left[-d^{*1}_{k,2} \quad d^{*1}_{k,1} \quad -d^{*2}_{k,2} \quad d^{*2}_{k,1}\right]^T$
p=1,2,3 N_{SS}=3 N_{STS}=P=4 M_{Tx}=4/ OSTBC/SM	t=n	$\mathbf{d}^3_{i,k}(t)=\left[d^1_{k,1} \quad d^2_{k,1} \quad d^2_{k,2} \quad d^3_{k,1}\right]^T$
	t=n+1= =T	$\mathbf{d}^3_{i,k}(t)=\left[d^{*1}_{k,2} \quad -d^{*2}_{k,2} \quad d^{*2}_{k,1} \quad d^{*3}_{k,2}\right]^T$
p=1,2,3,4 N_{SS}=4 N_{STS}=P=4 M_{Tx}=4/ SM	t=n=T	$\mathbf{d}^1_{i,k}(t)=\left[d^1_{k,1} \quad d^2_{k,1} \quad d^3_{k,1} \quad d^4_{k,1}\right]^T$

Table 3 - Types of STBC coding shames for transmission of different number of SSs

$$\mathbf{d}^P_{i,k}(t) \in C^{4X1} \quad \forall P = 1,2,3,4 \tag{3}$$

where elements of each column vector are complex data at the output of STBC encoder during *t-th* timeslot while * defines complex conjugate operation. By implementing QSTBC or OSTBC/SM, transmission of up to 3 SS will be spread into 4 STSs, where each STS is directly mapped to corresponding Tx RF chain (Table 2 and 3). Since STBC will not be applied for transmission of 4 SSs, this also results in direct mapping of 4 STSs to the corresponding Tx RF chain (antenna). Thus, it is noticeable that independently on number of SSs transmitted, 4 STSs are always transmitted across 4 corresponding Tx RF chains. This explains why dimension of transmitted data vector (3) will not depend on number of transmitted SSs and will always be equal to the number of transmitted STSs which is 4.

Now, instead of presenting system model as shown in relation (1), we will present system model for transmission of *P* SSs emitted on subcarrier *k* during single OFDM timeslot *t* across *i*=M_{TX}=4 antennas as

$$\underset{[M_{Rx}X1]}{\mathbf{x}^P_{j,k}} = \underset{[M_{Rx}XM_{Tx}]}{\mathbf{H}^P_{i,j,k}} \; \underset{[M_{Tx}XN_{STS}]}{\mathbf{V}^P_{i,k}} \; \underset{[N_{STS}X1]}{\mathbf{d}^P_{i,k}} + \underset{[M_{Rx}X1]}{\mathbf{n}^P_{j,k}} \tag{4}$$

while results obtained from presented system model can be applied on other subcarriers $(1 \le k \le K)$. In previous relation, $\mathbf{x}^P_{j,k}$ is column vector (M_{Rx}x1) of received signal when *P* SSs are transmitted, which can also be expressed as

$$\underset{[M_{Rx}X1]}{\mathbf{x}^P_{j,k}} = \underset{[M_{Rx}XM_{Tx}]}{\mathbf{H}^P_{i,j,k}} \; \underset{[M_{Tx}X1]}{\mathbf{z}^P_{i,k}} + \underset{[M_{Rx}X1]}{\mathbf{n}^P_{j,k}} \tag{4a}$$

where $\mathbf{z}^P_{i,k}$ is a column vector of transmit (data) signal with size equal to (M_{Tx}x1) for any number *P* of transmitted SSs on single subcarrier *k*. Furthermore, in relation (4) $\mathbf{n}^P_{j,k}$ is additive white Gaussian (AWG) noise vector affecting the *k-th* subcarrier within *p-th* OFDM symbol received on *j-th* Rx chain. Noise vector $\mathbf{n}^P_{j,k}$ entries have the independent and identically distributed (i.i.d.) complex Gaussian distribution with zero mean and variance σ^2_n. We can express column vectors $\mathbf{x}^P_{j,k}$ and $\mathbf{z}^P_{i,k}$ as

$$\mathbf{x}^P_{j,k} \in C^{4X1} \quad \forall P = 1,2,3,4 \tag{5}$$

$$\mathbf{z}^P_{i,k} \in C^{4X1} \quad \forall P = 1,2,3,4 \tag{6}$$

in case when *P* SSs are transmitted across *i=4* Tx RF chains and received on *j=4* Rx RF chains at receiver side.

Hence, for 802.11n transmitter with STBC encoder, global expression for the signal vector of transmitted data will be

$$\underset{[M_{Tx}X1]}{\mathbf{z}^P_{i,k}} = \underset{[M_{Tx}XN_{STS}]}{\mathbf{V}^P_{i,k}} \; \underset{[N_{STS}X1]}{\mathbf{d}^P_{i,k}} \tag{7}$$

where $\mathbf{V}^P_{i,k}$ is the beamsteering matrix used for transmission of *P* (up to 4) different SS across *i=M_{TX} =4* Tx RF chains on subcarrier *k* (Table 2). Thus, each vector of constellation points taken from output of STBC encoder during single timeslot *t* is multiplied by matrix of steering vectors called beamsteering matrix to produce the input to the transmit chains. Beamsteering matrix is formed in beamsteering section which is consisted of spatial mapper and pre-adaptive beamforming section (Figure 1). Spatial mapper takes complex data at the output of STBC encoder and performs direct mapping to the corresponding Tx RF chain. Direct mapping is achieved according to matrices $\mathbf{S}^{P=1}_{M_{Tx}=4}$ - $\mathbf{S}^{P=4}_{M_{Tx}=4}$ or differently expressed (for single subcarrier *k*) according to matrices $\mathbf{S}^p_i(k)$ shown in Table 2. Thus, transmit beamsteering matrices for transmission of up to 4 SS can be expressed as diagonal matrices with complex valued diagonal entries

$$\begin{aligned}
\mathbf{V}^P_{i,k} &= diag(v^1_{1,k}, v^1_{2,k}, v^1_{3,k} v^1_{4,k}) \in C^{4X4} \quad \vee P = 1 \\
\mathbf{V}^P_{i,k} &= diag(v^1_{1,k}, v^1_{2,k}, v^2_{3,k} v^2_{4,k}) \in C^{4X4} \quad \vee P = 2 \\
\mathbf{V}^P_{i,k} &= diag(v^1_{1,k}, v^2_{2,k}, v^2_{3,k} v^3_{4,k}) \in C^{4X4} \quad \vee P = 3 \\
\mathbf{V}^P_{i,k} &= diag(v^1_{1,k}, v^2_{2,k}, v^3_{3,k} v^4_{4,k}) \in C^{4X4} \quad \vee P = 4
\end{aligned} \tag{8}$$

where $v^p_{i,k}$ denotes transmit controllable complex (beamforming) weight related to *k-th* subcarrier multiplied with complex data of *p-th* SS transmitted over *i-th* T_X RF chain (Figure 2). Transmitter with STBC encoding is constructed in such a way that independently on number of concurrently transmitted SSs (N_{SS}), 4 STS (N_{STS} =4) are always transmitted across 4 Tx RF chains. This determines fixed size $(M_{Tx}XN_{STS} = 4X4)$ of beamsteering matrix for any number of transmitted SS as presented in relations (7,8) and Table 2.

On the receiver side, relations that describe complex data vector at the input of STBC decoder, for reception of *P* SSs transmitted in *k-th* subcarrier during single timeslot t can be expressed as:

$$\hat{\mathbf{d}}_{j,k}^{P} = \left[\mathbf{W}_{j,k}^{P}\right]^{H} \mathbf{x}_{j,k}^{P} \qquad (9)$$

$$\left[N_{STS} X 1\right] = \left[N_{STS} X M_{Rx}\right]\left[N_{Rx} X 1\right]$$

Since number of Tx and Rx chains in our analyses is $4=N_{TX}=N_{Rx}$, we can omit these information's in further analysis as presented in next relation

$$\hat{\mathbf{d}}_{k}^{P} = \left[\mathbf{W}_{k}^{P}\right]^{H} \mathbf{x}_{k}^{P} = \left[\mathbf{W}_{k}^{P}\right]^{H} \mathbf{H}_{k}^{P}\mathbf{z}_{k}^{P} + \left[\mathbf{W}_{k}^{P}\right]^{H} \mathbf{n}_{k}^{P} \qquad (9a)$$

where $\left[\mathbf{W}_{j,k}^{P}\right]^{H}$ denotes controllable complex receive beamsteering matrix relative to the *k-th* subcarrier of *p-th* symbol (SS) received over *j-th* Rx chain, and H stands for Hermitian matrix. Like transmit beamsteering matrix presented in (8), a receive beamsteering matrix for any number of transmitted SS P is also square diagonal matrix, and can be defined as

$$\left[\mathbf{W}_{j,k}^{P}\right]^{H} (\mathrm{N_{STS}xM_{Rx}}) = diag(w_{1,k}^{1},\dots,w_{4,k}^{p}) \in C^{4X4} \quad \forall P \qquad (10)$$

where $w_{j,k}^{p}$ denotes receive controllable (beamforming) weight related to *k-th* subcarrier of *p-th* SS received over *j-th* T_X RF chain.

One can notice that for any number of SSs transmitted, complex data receive vectors $\hat{\mathbf{d}}_{k}^{P}$ at the input of STBC decoder (9) have same dimensions as complex data transmit vectors $\mathbf{d}_{k}^{P}$ defined in relation (3) and presented in Table 3. Similar equations to the one defined in relations (1)-(10) can be written for all subcarriers (tones).

6. CONCLUSION

Adaptive beamforming system embedded in 802.11n transceiver structure with STBC is proposed. Analyzes has been performed for all transmissions of up to 4 SSs using single-link single-user 4x4 802.11n system with adaptive beamforming for every OFDM subcarrier in frequency domain. In such a system, single stream transmission across 4 Tx antennas is accomplished by QSTBC. For transmission of two and three spatial streams, OSTBC in combination with spatial multiplexing (OSTBC/SM) is envisioned. Transmission of 4 SSs is performed using direct mapping of every SS to corresponding RF chain exploiting spatial multiplexing principles of MIMO technology. Thus, we present adaptive beamforming solution for 802.11n system whose number of transmitted SSs varies during communication. Detailed architecture of proposed 4x4 802.11n structures with adaptive beamformers at Tx and Rx side are described and system models for proposed transceiver are explained using matrix algebra. Size and structure of Tx or Rx beamsteering matrices for all transmissions of up to 4 SS in proposed system model are derived. Obtained results for proposed beamforming system with STBC can be useful in development of future 802.11n beamforming transceiver structures. Further steps should include development of adequate adaptive beamforming algorithms for such systems.

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