Non-Linear Detection for Joint Space-Frequency Block Coding and Spatial Multiplexing in OFDM-MIMO Systems

Muhammad Imadur Rahman, Nicola Marchetti, Frank Fitzek, Ramjee Prasad
Center for TeleInFrastruktur (CTiF), Aalborg University, Denmark
e-mail: *imr|nm|ff|prasad@kom.aau.dk*; ph: +45 9635 8688

***Abstract*— In this work, we have analyzed a joint spatial diversity and multiplexing transmission structure for MIMO-OFDM system, where Orthogonal Space-Frequency Block Coding (OSFBC) is used across all spatial multiplexing branches. We have derived a BLAST-like non-linear Successive Interference Cancellation (SIC) receiver where the detection is done on sub-carrier by sub-carrier basis based on both Zero Forcing (ZF) and Minimum Mean Square Error (MMSE) nulling criterion for the system. In terms of Frame Error Rate (FER), MMSE based SIC receiver performs better than all other receivers compared in this paper. We have found that a linear two-stage receiver for the proposed system [1] performs very close to the non-linear receiver studied in this work. Finally, we compared the system performance in spatially correlated scenario. It is found that higher amount of spatial correlation at the transmitter can be tolerated, whereas higher receive spatial correlation is detrimental to the system.**

I. Introduction

Multiple antennas will be an integral part of all future generations of wireless systems. Multiple Input Multiple Output (MIMO) systems can be divided into two broad categories: Space Diversity (SD) systems and Spatial Multiplexing (SM) systems. SD-MIMO can provide higher reliability in the system, whereas SM schemes guarantee higher spectral efficiency without increasing the bandwidth requirement. All of these MIMO algorithms perform well in frequency flat scenario. Thus, Orthogonal Frequency Division Multiplexing (OFDM) can be put together with MIMO and the processing can be done on OFDM sub-carrier basis. In this way, the MIMO benefits can be obtained also in wideband systems.

In recent years, there is an effort to derive MIMO schemes, where both SD and SM benefits are achievable. We term such schemes as Joint Diversity and Multiplexing (JDM)-MIMO schemes. [2] proposed a JDM scheme, and derived a spatial whitening matched filter. Later [3] derived a linear two-stage receiver for a JDM system, where SM and Space-Time Block Code (STBC) are combined at the transmitter. In this receiver, the SM branches are first separated based on Least-Square (LS) principle and then the particular STBC branches are detected. We have extended this linear receiver for Spatially-Multiplexed Orthogonal Space-Frequency Block Coded Orthogonal Frequency Division Multiplexing (SM-OSFBC-OFDM) system in [1]. We have combined Orthogonal Space-Frequency Block Code (OSFBC) and SM in one structure, where OSFBC is realized using well-known Alamouti orthogonal coding [4] across neighboring sub-carriers. The receiver takes both ZF and MMSE criterion for two-stage nulling procedure.

In this work, we have derived an Ordered Successive Interference Cancellation (OSIC) receiver for the above mentioned SM-OSFBC-OFDM system, where layer by layer decoding is performed for each sub-carrier. The layer with the strongest Signal to Noise Ratio (SNR) is first determined based on ZF or MMSE criterion and then detected. At this point the effect of the first detected branch is subtracted and the next strongest layer is detected. This procedure is continued until all the spatial channels are recovered. This kind of OSIC technique is very similar to the original Vertical - Bell Labs LAyered Space-Time Architecture (VBLAST) receiver, that was proposed in [5] for SM systems.

In the present work one compares, in terms of FER in indoor and outdoor scenarios, a non-linear receiver and the linear receiver previously studied by the Authors [1]. As a reliability analysis, we have compared the 10% outage spectral efficiency of the systems. We have also studied the performance of the systems in terms of varying spatial correlation at the transmitter and the receiver antennas. For comparison purposes, the original VBLAST system is also studied in this paper.

The rest of this paper is organized as follows. The system model is presented in Section II. Outage capacity analysis, simulations and discussions are provided in Section III. Finally, conclusions on the presented work are drawn in Section IV.

II. System Model

A. Joint Diversity and Multiplexing based Transmitter

We denote the number of SM branches at the transmitter side and number of receive antennas as P and Q respectively. We have N number of sub-carriers in the system.

Figure 1 explains the basic transceiver architecture. At first the source bits are Forward Error Correction (FEC) coded and bit interleaved. The interleaved bit stream is baseband modulated using an appropriate constellation diagram, such as Binary Phase Shift Keying (BPSK), Quadrature Amplitude Modulation (QAM) etc. We denote this baseband modulated symbols as m_k. The sequences of m_k is demultiplexed into $\mathbf{m}_1, \dots, \mathbf{m}_P$ vectors. $\mathbf{m}_p$ is transmitted via p^{th} spatial channel.

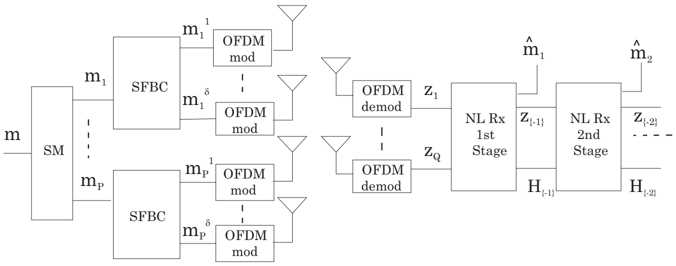

Fig. 1. Simplified System Model for SM-SFBC-OFDM Transmission Scheme with Non-Linear Receiver

For every p^{th} SM branch, we implement a block coding across the sub-carriers, thus OSFBC is included in the system. For p^{th} SM branch, we have Δ_p number of antennas where Space-Frequency Block Code (SFBC) can be implemented. When $\Delta_p = \Delta$, $\forall p$, then we have $\Delta * P$ number of transmit antennas at the transmission side. When $\Delta = 2$, we can use well-known Alamouti coding [4] across the sub-carriers.

For the p^{th} SM branch, $\mathbf{m}_p$ is coded into two vectors, $\mathbf{m}_p^{(\delta)}$; $\delta = 1, 2$. Thus, the output of the SFBC encoder block of the p^{th} SM branch will be

$$\mathbf{m}_p^{(1)} = \begin{bmatrix} m_{p,1} & -m_{p,2}^* & \ldots & m_{p,N-1} & -m_{p,N}^* \end{bmatrix} \quad (1)$$

$$\mathbf{m}_p^{(2)} = \begin{bmatrix} m_{p,2} & m_{p,1}^* & \ldots & m_{p,N} & m_{p,N-1}^* \end{bmatrix} \quad (2)$$

Following this, we define

$$\mathbf{m}_{p,o} = \begin{bmatrix} m_{p,1} & m_{p,3} & \ldots & m_{p,N-3} & m_{p,N-1} \end{bmatrix} \quad (3)$$

$$\mathbf{m}_{p,e} = \begin{bmatrix} m_{p,2} & m_{p,4} & \ldots & m_{p,N-2} & m_{p,N} \end{bmatrix} \quad (4)$$

Using these equations, we can write that

$$\mathbf{m}_{p,o}^{(1)} = \mathbf{m}_{p,o}; \qquad \mathbf{m}_{p,e}^{(1)} = -\mathbf{m}_{p,e}^* \quad (5)$$

$$\mathbf{m}_{p,o}^{(2)} = \mathbf{m}_{p,e}; \qquad \mathbf{m}_{p,e}^{(2)} = \mathbf{m}_{p,o}^* \quad (6)$$

After SM and OSFBC operations, IFFT modulation is performed and Cyclic Prefix (CP) is added before transmission via the respective transmit antenna. Transmitted time domain samples, $\mathbf{x}_p^{(\delta)}$, can be related to $\mathbf{m}_p^{(\delta)}$ as, $\mathbf{x}_p^{(\delta)} = \mathbb{F}^H\{\mathbf{m}_p^{(\delta)}\}$.

B. OSIC-based Non-Linear Receiver

The key idea of the non-linear receiver is to decode the symbol streams successively and strip the streams away layer by layer. At the beginning of each stage, the stream with highest SNR is chosen using ZF or MMSE detection for peeling. Once one particular layer is decoded, then the effect the detected layer is subtracted from the received signal and the next branch in terms of SNR strength is chosen. This is continued until the last layer is decoded. This kind of non-linear detection is called OSIC. OSIC is performed on sub-carrier by sub-carrier basis. On each sub-carrier, the detection scheme appears to be very similar to VBLAST detection, as derived in [5]. OSIC improves the detection quality compared to detection without ordering and is shown to be optimal for SIC approach [6]. In [7] a non-linear receiver for an hybrid scheme combining SM and Transmit Diversity (TD) is proposed. In this work, we adopt a similar receiver structure for our SM-SFBC-OFDM system.

We consider $P = 2$, $\Delta = 2$ and $Q = 2$. We assume that the length of CP in time is longer than the maximum durations of Channel Impulse Response (CIR), thus, no inter-OFDM-symbol interference occurs. In this case, we can consider the whole system in the frequency domain, so it can be written

$$\begin{aligned}\mathbf{z}_k &= \mathbf{H}_k\mathbf{m}_k + \mathbf{n}_k \\ &= \begin{bmatrix} h_{11,o}^{(1)} & h_{11,o}^{(2)} & h_{12,o}^{(1)} & h_{12,o}^{(2)} \\ h_{11,e}^{(2)*} & -h_{11,e}^{(1)*} & h_{12,e}^{(2)*} & -h_{12,e}^{(1)*} \\ h_{21,o}^{(1)} & h_{21,o}^{(2)} & h_{22,o}^{(1)} & h_{22,o}^{(2)} \\ h_{21,e}^{(2)*} & -h_{21,e}^{(1)*} & h_{22,e}^{(2)*} & -h_{22,e}^{(1)*} \end{bmatrix}_k \mathbf{m}_k + \mathbf{n}_k\end{aligned} \quad (7)$$

where $k \in [1, \ldots, \frac{N}{2}]$, $\mathbf{z}_k = \begin{bmatrix} z_{1,o} & z_{1,e}^* & z_{2,o} & z_{2,e}^* \end{bmatrix}_k^T$, $\mathbf{m}_k = \begin{bmatrix} m_{1,o} & m_{1,e} & m_{2,o} & m_{2,e} \end{bmatrix}_k^T$ and $\mathbf{n}_k = \begin{bmatrix} n_{1,o} & n_{1,e}^* & n_{2,o} & n_{2,e}^* \end{bmatrix}_k^T$. We denote the equivalent channel in (7) as $\mathbf{H}_k$.

As well known OSIC based Bell labs LAyered Space Time (BLAST) receiver consists of two steps: nulling and cancellation. Nulling is used to separate the strongest received branch. We consider two techniques for nulling purposes, namely ZF and MMSE.

For ZF, we calculate the Moore-Penrose pseudo-inverse of the Channel Transfer Function (CTF) as

$$\mathbf{G}_k = [\mathbf{g}_1\ \mathbf{g}_2\ \mathbf{g}_3\ \mathbf{g}_4]_k = \{\mathbf{H}_k^H\mathbf{H}_k\}^{-1}\mathbf{H}_k^H \quad (8)$$

while for the MMSE, a kind of pseudo-inverse that also considers the noise variance, is used

$$\mathbf{G}_k = [\mathbf{g}_1\ \mathbf{g}_2\ \mathbf{g}_3\ \mathbf{g}_4]_k = \{\mathbf{H}_k^H\mathbf{H}_k + \sigma^2\mathbf{I}_4\}^{-1}\mathbf{H}_k^H \quad (9)$$

where $[\mathbf{g}_i]_k$ is the i^{th} column of $\mathbf{G}_k$, σ^2 is the total noise variance and $\mathbf{I}_4$ is the 4×4 identity matrix. At this stage , we have to decide whether the first or second stream has the strongest received SNR. For this purpose, we calculate the metric:

$$l = arg\min_l\{d_1, d_2\} \quad (10)$$

where $d_1 = \mathbf{c}(1) + \mathbf{c}(3),\ d_2 = \mathbf{c}(2) + \mathbf{c}(4)$.

For ZF nulling, the vector $\mathbf{c}$ can be expressed as

$$\mathbf{c} = diag(\{\mathbf{H}_k^H\mathbf{H}_k\}^{-1}) \quad (11)$$

and for MMSE the vector $\mathbf{c}$ is

$$\mathbf{c} = diag(\{\mathbf{H}_k^H\mathbf{H}_k + \sigma^2\mathbf{I}_4\}^{-1}) \quad (12)$$

If $l = arg\min_l\{d_1, d_2\} = 1$ then we first decode the stream associated to $p = 1$ by doing

$$\widehat{\mathbf{m}}_{1,k} = \begin{bmatrix} \widehat{\mathbf{m}}_{1,o} \\ \widehat{\mathbf{m}}_{1,e} \end{bmatrix}_k = \begin{bmatrix} \mathbf{g}_1^H \\ \mathbf{g}_2^H \end{bmatrix}_k \mathbf{z}_k \quad (13)$$

TABLE I

OFDM SIMULATION PARAMETERS

Parameters	Indoor	Outdoor
System bandwidth, B	20MHz	
Carrier frequency, f_c	5.4 GHz	
User mobility,v	3 kmph	200 kmph
OFDM sub-carriers, N	64	256
Subcarrier spacing, $\Delta f = B/N$	312.5 kHz	78.13 kHz
CP length, N_{CP}	16	100
Total samples in OFDM Symbol with CP, $N_s = N + N_{CP}$	80	356
Symbol duration, $T_s = T_u + T_{CP}$	4.0 μs	17.8 μs
OFDM symbols/frame, N_f	16	
Frame duration, $T_f = N_f T_s$	64.0 μs	284.8 μs
Data Symbol mapping	QPSK	
Channel coding scheme	$\frac{1}{2}$-rate convolutional coding	

and the second stream by doing the following steps (in (14) the cancellation operation is performed)

$$\mathbf{z}_k^{'} = \mathbf{z}_k - [\mathbf{h}_1 \ \mathbf{h}_2]_k \left[\begin{array}{c} \widehat{\mathbf{m}}_{1,o} \\ \widehat{\mathbf{m}}_{1,e} \end{array} \right]_k \quad (14)$$

$$\mathbf{H}_k^{'} = [\mathbf{h}_3 \ \mathbf{h}_4]_k \quad (15)$$

$$\mathbf{H}_k^{'H}\mathbf{H}_k^{'} = \frac{1}{\alpha}\mathbf{I}_2 \quad (16)$$

$$\widehat{\mathbf{m}}_{2,k} = \left[\begin{array}{c} \widehat{\mathbf{m}}_{2,o} \\ \widehat{\mathbf{m}}_{2,e} \end{array} \right]_k = \frac{1}{\alpha}\mathbf{H}_k^{'H}\mathbf{z}_k^{'} \quad (17)$$

where $\alpha = \mid \mathbf{h}_{12,o}^{(1)} \mid^2 + \mid \mathbf{h}_{12,o}^{(2)} \mid^2 + \mid \mathbf{h}_{22,o}^{(1)} \mid^2 + \mid \mathbf{h}_{22,o}^{(2)} \mid^2$, $[\mathbf{h}_i]_k$ is the i^{th} column of $\mathbf{H}_k$ and $\mathbf{I}_2$ is the 2×2 identity matrix.

Exactly the dual procedure of (13)-(17) has to be applied if $l = arg \ \min_l\{d_1, d_2\} = 2$. In that case, first we decode the second SM branch and then we detect the first branch.

III. ANALYSIS, SIMULATIONS AND DISCUSSIONS

A. System Parameters

We have used two simulation scenarios as explained in Table I. For all our analysis and simulations, we have confined ourselves to the case of 2 or 4 antennas on transmit side and dual antennas on receiver side. For MIMO multiplexing, 2 SM branches are simulated (i.e. $Q = 2, \ P = 2$ and $\Delta = 2$). We assume that perfect time and frequency synchronization is established. We also assume that perfect channel estimation values for each sub-carrier for both the spatial channels are available at the receiver. We use the exponential channel model to generate the corresponding CIR and CTF of the channel. In our exponential model, the power delay profile of the channel is exponentially distributed with decay between the first and the last impulse as -40dB.

B. FER Analysis

Figures 2 and 3 show the Frame Error Rate (FER) performance of the combining schemes in indoor and outdoor scenario respectively. In indoor scenario, a frame consists of $N * L_f * M * P * R_c = 64 * 16 * 2 * 2 * 0.5 = 2048$ source bits, while in outdoor scenario, it is $256 * 16 * 2 * 2 * 0.5 = 8192$ source bits in one frame. All the transmission schemes use Quadrature Phase Shift Keying (QPSK). Total transmitted power is always kept constant, so that comparison is done on equal footing. So the power transmitted via any branch is always $\frac{P_T}{P*\Delta}$ and $\frac{P_T}{P}$ for all JDM and SM schemes respectively, where P_T is the total transmitted power. As a reference, *ML* is plotted along with the other schemes, so that the benefit out of the optimal receiver is also compared.

As it is seen, for both indoor and outdoor scenario, *SM-OSFBC-MMSE-OSIC* performs better than all other schemes. This is due to the fact that two added antennas at the transmitter provide a form of SNR boost for the system and also the SIC receiver provides better detection. Compared to this, *SM-OSFBC-MMSE-Lin* system performs quite close to *SM-OSFBC-ZF-OSIC*. Both the linear receiver schemes approaches to MMSE non-linear schemes by 2dB and 3 db respectively at an FER of 10^{-2} for indoor scenario. This is significant considering the fact that linear receiver is simpler to implement compared to non-linear receiver. It is generally noted that JDM schemes performs much better compared to simple SM schemes. This is achieved at the cost of the increased system complexity, as the transmitter will require more antennas.

Similar trend is also noted in outdoor scenario. Including more antennas for transmitter OSFBC offers immense benefit. But, of course, it is clear that outdoor channel is more frequency selective, thus all the systems require more SNR compared to indoor scenario for any FER reference point.

C. 10% Channel Outage Capacity and Average Spectral Efficiency

Outage analysis is a form of reliability analysis. We define 10% outage channel capacity as the information rate that is guaranteed for 90% of the channel realizations, such that the probability that outage rate falls below the certain threshold rate is at most 10% [6]. The 10% outage channel capacities for Spatial Multiplexed Orthogonal Frequency Division Multiplexing (SM-OFDM) and SM-OSFBC-OFDM are given in Figure 4. Here the channel responses are simulated for indoor environment and then the outage capacity is calculated. For reference purpose, *2x1 OSFBC* outage channel capacity is plotted in the figure. *4x2 SM-OFDM* shows the optimum achievable outage channel capacity derived from Shannon limit. We can see that upper bound in outage channel capacity of our scheme (i.e. *4x2 SM-OSFBC-OFDM*) approaches very close to the above mentioned limit. As expected, the difference in 10% outage channel capacity of SM and JDM scheme is 3 bps/Hz at comparatively low SNR (i.e. at 4dB of SNR) and is more than 5 bps/Hz at comparatively high SNR (i.e. at 16dB of SNR).

Figure 5 shows us the average spectral efficiency of the studied systems in indoor scenario. The maximum rate with 1/2-rate convolutional coding, QPSK modulation and two spatially-multiplexed branches is, $R_b = \frac{Numberofbitsperframe}{frameduration} = \frac{NMPR_cN_f}{N_fT_s} = \frac{64*2*2*0.5*16}{16*(4*10^{-6})}$ bps = 32Mbps, thus, a spectral efficiency of 1.6 bps/Hz at 20MHz system bandwidth. We define, the practical spectral efficiency as $SE = R_b(1 - FER)$. Thus, at the best case with current modulation and coding level along with MIMO rate, the maximum spectral efficiency can be 1.6 bps/Hz. It can be seen that the average spectral efficiency of the JDM schemes is much higher than the 2×2 SM schemes at comparatively low SNR. As the SNR increases, the average spectral efficiency approaches to the maximum value (i.e. 1.6 bps/Hz) for all the schemes. It is noticed that for JDM schemes, maximum achievable spectral efficiency is obtained faster than other schemes when compared to increment in SNR. As expected, *SM-OSFBC-MMSE-SIC* performs better than others in terms of average spectral efficiency, which is supported by its better FER performances seen in Figures 2 and 3.

Outage spectral efficiency results via simulations may offer more insights into the practical outage scenario, when all the mentioned schemes are compared. It is an issue that is under investigation at the moment.

D. Effect of Transmit and Receive Correlation

We model the spatial correlation in $\mathbf{H}$ based on the inter-element distances in the transmit and receive antenna arrays, as it is done in [8]. We can model the spatial correlation across all sub-carriers as

$$\mathbf{H}_k = \sqrt{\mathbf{R}_{k,rx}}\mathbf{H}_{w,k}\sqrt{\mathbf{R}_{k,tx}} \tag{18}$$

where $\mathbf{R}_{k,tx}$, $\mathbf{R}_{k,rx}$ and $\mathbf{H}_{w,k}$ are transmit correlation matrix, receive correlation matrix and uncorrelated channel matrix respectively. The correlation coefficient between between p_1 and p_2 transmit antennas can be written as

$$[\mathbf{R}_{k,tx}]_{p_1,p_2} = \mathcal{J}_0\left(\frac{2\pi(p_1 - p_2)d}{\lambda}\right) \tag{19}$$

where $p_1, p_2 \in [1, \ldots, P]$. $\mathcal{J}_0$ denotes the 0^{th} order Bessel function of 1^{st} kind, d is the distance between the elements and λ is the wavelength corresponding to the carrier frequency. Similar spatial correlation can be defined for receiver also.

In Figures 6 and 7, we produce the FER results of all the schemes. These results are obtained for indoor wireless channel parameters as mentioned in Table I. We have modelled the correlation values for different antenna spacing and we have plotted the correlation values in the figure. For Figure 6, we varied the transmit correlation and fixed the receive correlation to 0.3, and the opposite is done for Figure 7. The results are obtained for a particular SNR value, i.e. 12dB. One interesting conclusion that can be drawn from the figures is that receive correlation affects these systems much more than transmit correlation. This is because of the fact that no extra diversity measures are taken in the receiver. From Figure 7, we see that the FERs start to increase very fast when the correlation increases more than 0.3, that corresponds to separation between receive antenna elements of at least 1.67 cm. This is true for all *SM-OSFBC* systems. For increasing transmit correlation with a fixed receive correlation, the degradation in JDM schemes is gradual. Up to 60% of spatial correlation between the transmit antennas, the JDM schemes perform quite consistently, it worsens only when the spatial correlation is increased more than this. Thus, as long as the transmit elements are separated by a spacing of at least 1.17 cm for our system, the effect of spatial correlation in FER performance is not quite significant for JDM systems. For transmit correlation values up to 50%, only *SM-OSFBC-MMSE-SIC* provides FER below 10^{-2} at 12dB of SNR.

For both cases, *ZF-BLAST* and *MMSE-BLAST* performs quite badly, when the spatial correlation is increased more than 0.3. Thus, it is evident that original VBLAST systems are not so robust in spatially correlated scenario as it was previously reported in [6].

It should be kept in mind that our correlation model only takes into account the inter-element distance at both locations of transmission link as the contributing factor for defining the spatial correlation. There are a number of other factors that can also increase the spatial correlation across co-located antenna elements, such as presence of Line of Sight (LOS) components that causes Ricean fading, insufficient scattering in the environment, use of polarized antennas which leads to gain imbalances etc.

IV. Conclusion

Non-linear receivers for JDM scheme are derived and analyzed in this paper. The studied schemes are compared with linear two-stage receivers [1] and original VBLAST systems [5]. It is found that non-linear JDM schemes performs very well in terms of FER in both indoor and outdoor scenario. Due to the advantages obtained from additional transmit antennas, JDM schemes are also very robust to transmit spatial correlation. In line with their better FER characteristics, these schemes also outperform other schemes compared in this paper in terms of average spectral efficiency.

Performances of the analyzed non-linear JDM schemes in more practical scenario, such as presence of LOS component, lack of rich scattering environment, etc., can be interesting issues for further studies.

References

[1] M.I. Rahman, N. Marchetti et al., "Combining Orthogonal Space-Frequency Block Coding and Spatial Multiplexing in MIMO-OFDM System," in *International OFDM Workshop*, Hamburg, Germany, September 2005.

[2] Y. Li et al., "MIMO-OFDM for Wireless Communications: Signal Detection with Enhanced Channel Estimation," *IEEE Trans. Comm.*, vol. 50, no. 9, September 2002.

[3] X. Zhuang et al., "Transmit Diversity and Spatial Multiplexing in Four-Transmit-Antenna OFDM," in *Proc. of ICC*, vol. 4, May 2003, pp. 2316 – 2320.

[4] S. M. Alamouti, "A Simple Transmit Diversity Technique for Wireless Communications," *IEEE JSAC*, vol. 16, no. 8, October 1998.

[5] P.W. Wolniansky et al., "V-BLAST: An Architecture for Realizing Very High Data Rates Over the Rich-Scattering Wireless Channel," in *Proc. IEEE-URSI International Symposium on Signals, Systems and Electronics*, Pisa, Italy, May 1998.

[6] A.J. Paulraj, R. Nabar & D. Gore, *Introduction to Space-Time Wireless Communications*, 1st ed. Cambridge University Press, September 2003.

[7] C.-B. Chae et al., "Adaptive Spatial Modulation for MIMO-OFDM," in *Proc. of WCNC*, vol. 1, March 2004, pp. 87 – 92.

[8] H. Skjevling, D. Gesbert & N. Christophersen, "Combining Space-Time Codes and Multiplexing in Correlated MIMO Channels: An Antenna Assignment Strategy," in *Nordic Signal Processing Conference*, June 2003.

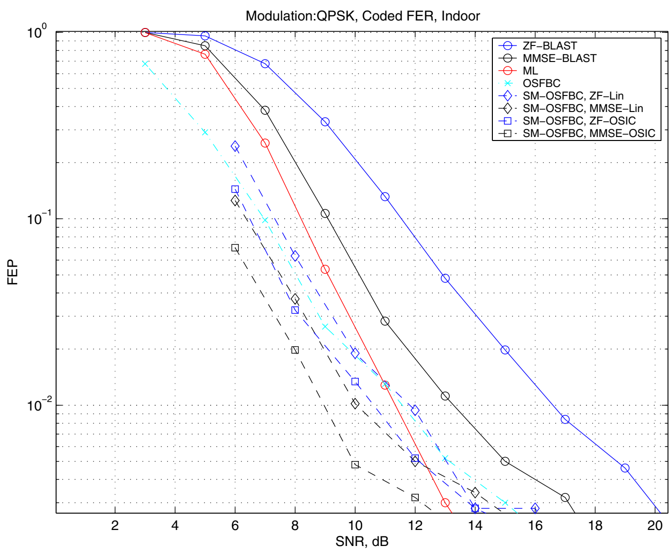

Fig. 2. FER performance in indoor scenario

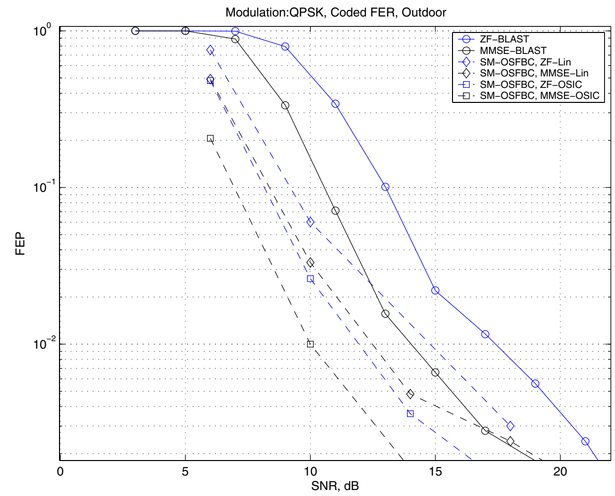

Fig. 3. FER performance in outdoor scenario

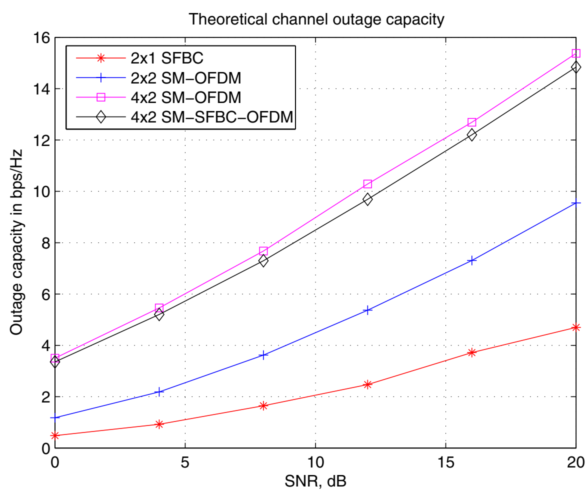

Fig. 4. 10% channel outage capacity for reference systems

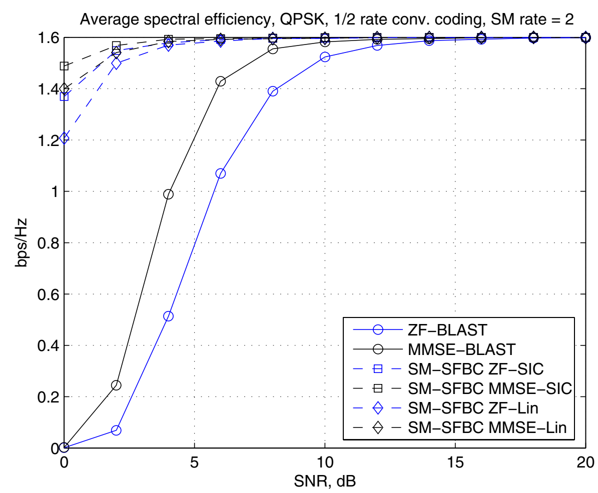

Fig. 5. Average spectral efficiency for reference systems

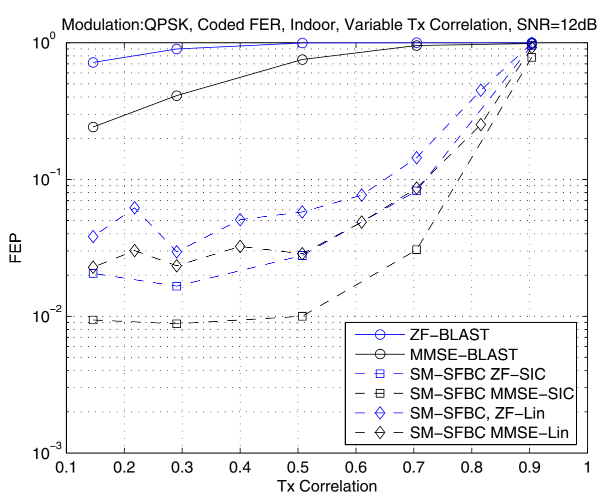

Fig. 6. FER performance for variable spatial correlation at the transmitter side

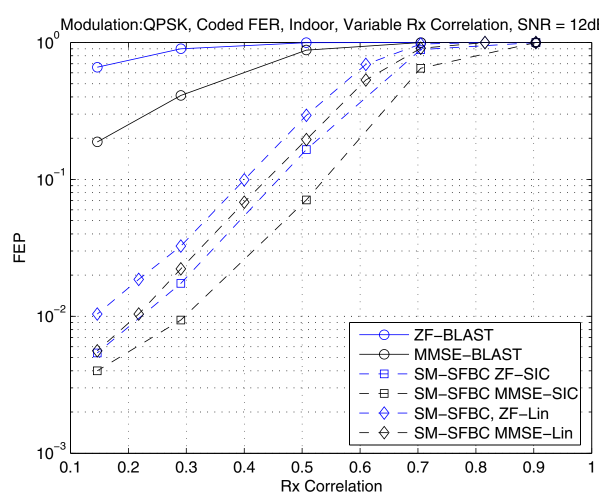

Fig. 7. FER performance for variable spatial correlation at the receiver side