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An ESPAR antenna for beamspace-MIMO systems using PSK modulation schemes

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Abstract— **In this paper the use of electronically steerable passive array radiator (ESPAR) antennas is introduced for achieving increased spectral efficiency characteristics in multiple-input, multiple-output (MIMO) systems using a single active element, and compact antennas. The proposed ESPAR antenna is capable of mapping phase-shift-keying (PSK) modulated symbols to be transmitted onto orthogonal basis functions on the wavevector domain of the multi-element antenna (MEA), instead of the traditional approach of sending different symbol streams in different locations on the antenna domain. In this way, different symbols are transmitted simultaneously towards different angles of departure at the transmitter side. We show that the proposed system, called beamspace-MIMO (BS-MIMO) can achieve performance characteristics comparable to traditional MIMO systems while using a single radio-frequency (RF) front-end and ESPAR antenna arrays of total length equal to λ/8, for popular PSK modulation schemes such as binary-PSK (BPSK), quaternary-PSK (QPSK), as well as for their offset-PSK and differential-PSK variations.**

Keywords- MIMO, ESPAR antennas, radiation patterns, virtual channels, wavevector domain, PSK modulation, beamspace domain

I. INTRODUCTION

Multiple-Input Multiple-Output (MIMO) wireless communication architectures utilising Multiple Element Antennas (MEA) are known to increase the spectral efficiency of the wireless link almost linearly with respect to the number of transmit and receive antennas [1], [2]. Such architectures have evolved into feasible implementations and have been included in communications standards such as IEEE 802.11n and 3GPP. However, traditional approaches require that MIMO antenna arrays utilise multiple IF/RF front ends in order for the signal transmitted or received from each antenna element to be weighted independently. Using such multiple front-ends is expensive in terms of both hardware cost and physical size, thereby making MIMO systems hard to integrate in cost, size and power-sensitive applications such as mobile telephony and computing. In order for MIMO systems to be able to meet the stringent requirements of such applications, minimizing the number of required RF front ends and reducing the size of the antenna arrays without compromising on the total performance of the wireless communication system is critical.

This work builds upon the theoretic framework introduced in [3] and the implementation approach presented in [4] to show that uplink MIMO communications can be achieved using a single RF front end and compact arrays in the mobile terminal. According to this, instead of the traditional approach of sending different symbol streams in different elements of the MEA, symbols to be transmitted are mapped into the wavevector domain of the antenna array using multiple sectored beams both at the transmitter and receiver side of the communication link. The concept, which extends the findings of Teletar [1], Foschini and Gans [2] in the wavevector domain, is demonstrated using a 2x2 system example with switched parasitic arrays using on-off-keying (OOK) modulation, and achieves capacity gains equivalent to those of traditional MIMO systems.

In this paper a new electronically steerable passive array radiator (ESPAR) antenna is used for implementing "beamspace-MIMO" systems with a single active element and compact dimensions, following the method described in [4], for PSK modulation schemes that have not been considered hitherto. The proposed system uses a 3-element ESPAR antenna designed specifically for the purpose of transmitting different symbol pairs simultaneously towards different angles of departure, and more specifically towards the channel's virtual angles described in [5]. We illustrate the performance gains that are achieved by the proposed system using a 2x2 MIMO example and we show through simulation results that by using the proposed scheme in rich scattering environments we are able to achieve a performance that is comparable to that of traditional MIMO systems, using a single RF front end and compact antennas.

The paper is divided into the following sections: in Section II the method of building MIMO systems with a single active antenna element is reviewed, while in Section III the ESPAR antenna architecture is presented; Section IV gives simulation results of a system example that implements the proposed architecture using a single active antenna element, and the paper concludes with a summary of our results.

II. BEAMSPACE MIMO SYSTEMS

In [3] and [4] it was described how the performance metrics of MIMO systems like capacity and diversity can be disassociated from the input vector that feeds the elements of

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the transmit array, and how they can be associated with the far field characteristics of the transmitting and receiving antenna arrays. In both papers the analysis in [5] was used to describe the channel with a channel matrix $\mathbf{H}_V$ corresponding to uniform transmit and receive angles (called "virtual angles"), that is related to the channel matrix in the antenna domain through the equation,

$$\mathbf{H} = \mathbf{A}_R(\hat{\boldsymbol{\theta}}_R)\mathbf{H}_b\mathbf{A}_T^H(\hat{\boldsymbol{\theta}}_T) = \tilde{\mathbf{A}}_R\mathbf{H}_V\tilde{\mathbf{A}}_T^H \tag{1}$$

where $\mathbf{A}_R(\hat{\boldsymbol{\theta}}_R)$ and $\mathbf{A}_T(\hat{\boldsymbol{\theta}}_T)$ are the transmit and receive steering matrices, $\tilde{\mathbf{A}}_R, \tilde{\mathbf{A}}_T$ are the full rank square steering matrices corresponding to the virtual transmit and receive directions respectively, $\hat{\boldsymbol{\theta}}_R, \hat{\boldsymbol{\theta}}_T$ are the direction vectors of the AoA and AoD respectively, and $\mathbf{H}_b$ is a diagonal $L \times L$ matrix whose entries are the complex gains of each path. Using this approach the capacity of a linear multiple antenna wireless system with N_t transmit and N_r receive antennas can be described by the same capacity expressions as in [2] for full rank $\mathbf{H}$ and $\mathbf{H}_V$ matrices [5]:

$$C \approx \log_2\left[\det(\mathbf{I}_{Nr} + \frac{\rho}{N_t}\mathbf{H}_V\mathbf{H}_V^H)\right] \text{ bits/s/Hz} \tag{2}$$

In [4] the aforementioned analysis was used to show that it is feasible to achieve increased spectral efficiency using systems with a single transceiver. Rather than being concerned with the inputs of the diverse antenna elements, the idea of mapping symbols directly in the wavevector domain of the antenna array is investigated. Following Teletar [1] in the concept that maximum capacity in a MIMO system is achieved when signals are fed onto a set of orthogonal functions in the antenna domain, these findings are extended by using a set of orthogonal functions in the wavevector domain to send symbol streams towards the virtual channel angles. This is implemented *by mapping the input vector* $\mathbf{x}_{bs}$ *on radiation patterns that are considered to be orthogonal basis functions in the beamspace domain.* The transmitted symbols $\mathbf{x}_{bs}$ and the received symbols $\mathbf{y}_{bs}$, are related to the inputs of the antenna elements in the following way:

$$\mathbf{y}_{bs} = \mathbf{B}_{bsRx}^H\mathbf{y} = \tilde{\mathbf{A}}_R^H\mathbf{y}, \quad \mathbf{x}_{bs} = \mathbf{B}_{bsTx}^H\mathbf{x} = \tilde{\mathbf{A}}_T^H\mathbf{x} \tag{3}$$

where $\mathbf{B}_{bsTx}^H = \tilde{\mathbf{A}}_T^H$ and $\mathbf{B}_{bsRx}^H = \tilde{\mathbf{A}}_R^H$ are the Butler matrices of the transmitting and receiving arrays respectively which are unitary Discrete Fourier Transform (DFT) matrices for uniform linear arrays (ULA). Therefore, for a full dimension beam-space the outputs of an N-element standard linear array may be processed to produce N orthogonal beams. The beam pattern, e.g. at the transmitter, is

$$B_{\theta_T}(\theta_T) = \mathbf{w}^H\mathbf{a}_T(\theta_T) = \sum_{k=0}^{N-1} w_k^* e^{-j2\pi k\theta_T} \tag{4}$$

where $\mathbf{a}_T(\theta_T)$ is the steering vector of the transmitting array, and $\mathbf{w}$ is the complex weight vector of the transmitting antenna. For $\mathbf{w}^H(i) = \mathbf{a}_T^H(\tilde{\theta}_{T,i})$, where $\tilde{\theta}_{T,i}$ are the virtual angles of departure, the main response axis for the i^{th} beam occurs at angle i/N. All the other beams have nulls at that point. This is due to the orthogonality of the weight vectors, and it ensures that uncorrelated symbols are transmitted simultaneously towards the virtual angles of departure.

The radiation pattern of the transmitting antenna on each symbol period can therefore be described as a linear combination of the symbols with the respective orthogonal functions. Assume for example that the symbol vector $\mathbf{x}_{bs} = [s_0 \quad s_\pi]^T$ is to be transmitted using a set of orthogonal functions in the beamspace domain $\{B_{T,i}(\theta)\}$, where s_0 is the symbol to be transmitted towards 0 degrees, and s_π is the symbol to be transmitted towards 180 degrees. The radiation pattern on each symbol period using this approach will be

$$\mathbf{B}_{bsTx}(\theta)\mathbf{x}_{bs} = s_0 B_{T,1}(\theta) + s_\pi B_{T,2}(\theta) \tag{5}$$

and the symbols of the symbol vector will be transmitted simultaneously through the air. The signals transmitted towards the AoD of the channel scatterers will therefore be

$$\mathbf{B}_{bsTx}(\hat{\boldsymbol{\theta}})\mathbf{x}_{bs} = s_0 B_{T,1}(\hat{\boldsymbol{\theta}}) + s_\pi B_{T,2}(\hat{\boldsymbol{\theta}}) \tag{6}$$

Consequently, if the transmitting array is able to form radiation patterns that are linear combinations of a set of orthogonal basis radiation patterns convolved with the input symbol vector towards the virtual angles of departure, then due to (1), (3) and (6) the received signal will be of the form,

$$\mathbf{y}_{bs} = \mathbf{H}_V\mathbf{x}_{bs} + \mathbf{n}_{bs} \tag{7}$$

and the capacity of the system will be given by (2), where the channel matrix coefficients $\{H_V(i,j)\}$ describe the coupling between the j^{th} orthogonal basis radiation pattern of the transmit antenna and the i^{th} orthogonal basis radiation pattern of the receive antenna, as in every MIMO system representation. The performance of the "beam-space MIMO" systems has been evaluated for a number of orthogonal basis functions including perfect sectors, cardioids and sine/cosine patterns.

Although the scheme proposed in [4] presents a significant advancement in the field of low-cost, compact MIMO systems for mobile terminals, popular modulation types such as BPSK and QPSK modulation schemes have not been considered so far. In this work we address this issue by using the analysis reviewed in this paragraph and by introducing the use of

ESPAR antennas, instead of the switched parasitic arrays (SPA) described in [4].

III. ESPAR Antenna Design

ESPAR antenna architectures have been introduced since 2000 by the ATR laboratory in Japan [6]. They are smart antenna systems that present a significant advantage over their predecessors: they are able to control their beam patterns as any smart antenna system, while being implemented using a single active antenna element and a number of parasitic elements placed on a circle around the active element. The parasitic elements are short-circuited and loaded with variable reactors (varactors) that control the imaginary part of the parasitic elements' input impedances. By adjusting the varactors' response, the radiation pattern of the ESPAR antenna system can be controlled to direct its beams and nulls towards certain directions in an adaptive or predefined fashion. ESPAR antennas have already been used at the receiver for adaptive beamforming applications [7] and receive diversity schemes [8], where the antenna is controlled to maximize the received signal-to-noise-ratio (SNR) and the signal-to-noise-and-interference-ratio (SNIR). In this work we focus on using ESPAR antennas for implementing MIMO systems using a single active element at the transmitter.

As described in section II, we are concerned with sending diverse symbol streams towards the virtual angles of departure. When OOK modulation is used in a 2x2 MIMO system example, this can be achieved by creating radiation patterns with a maximum towards the one virtual angle, and a null towards the other, a configuration that can be easily created using an SPA. However, in many mobile communication systems BPSK and QPSK modulation types are more popular than the simple OOK scheme. This has implications on the antenna design, discussed in this paragraph.

Our goal is to create radiation patterns that will satisfy (5) for all the aforementioned modulation types, using the appropriate set of basis functions $\{B_{T,i}(\theta)\}$. We consider a 3-element ESPAR antenna configuration as described in Fig. 1, to achieve this goal. The inter-element spacing, d, of the dipoles was considered as a parameter of the system and was tested for a number of values including λ/2, λ/4, λ/8, and λ/16. The radiation pattern of the ESPAR antenna configuration [5] is given by

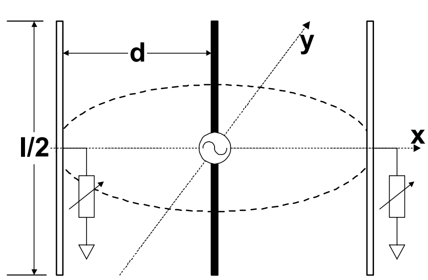

Figure 1. A 3-element ESPAR antenna architecture

$$A(\theta) = \mathbf{i}^T \mathbf{a}(\theta) \tag{8}$$

where $\mathbf{i}$ is the complex current vector on the antenna elements and $\mathbf{a}(\theta)$ is the steering vector of the array. Following the notation of ESPAR antennas, the first element of the steering vector corresponds to the central active antenna of the array, while the rest of the elements correspond to the parasitic antennas of the array. When we feed only the central element of the array, the current vector $\mathbf{i}$ is given by

$$\mathbf{i} = \frac{1}{C}[\mathbf{I} + \mathbf{YX}]^{-1} \mathbf{y}_0 \tag{9}$$

where for the 3-element ESPAR, $\mathbf{y}_0 = \begin{bmatrix} y_{00} & y_{10} & y_{10} \end{bmatrix}^T$,

$$\mathbf{Y} = \begin{pmatrix} y_{00} & y_{10} & y_{10} \\ y_{10} & y_{11} & y_{21} \\ y_{10} & y_{21} & y_{11} \end{pmatrix}, \text{ and } \mathbf{X} = \begin{pmatrix} R_0 & 0 & 0 \\ 0 & jx_1 & 0 \\ 0 & 0 & jx_2 \end{pmatrix} \tag{10}$$

where $\mathbf{Y}$ is the admittance matrix that expresses the mutual coupling between the elements, $\mathbf{X}$ is the reactance matrix that adjusts the pattern of the antenna, and $C = 2R_0\sqrt{D}, D = 1.64$, R_0=50ohm, for dipoles.

The response of the arrays is controlled by setting the reactive weights $x_1, \ldots, x_n$ so that equation (5) is satisfied for all transmitted symbol pairs, where,

$$\begin{aligned} B_{T,1}(\theta) &= (1+\cos\theta)/\sqrt{2} \\ B_{T,2}(\theta) &= (1-\cos\theta)/\sqrt{2} \end{aligned} \tag{11}$$

This requires the solution of the aforementioned equations in order to find the unknown weights. Since these are non-linear equations, this is not a trivial task. Pre-coding the transmission vector requires the antenna array to be controlled adaptively. Fortunately, since the constellation of all the possible symbol combinations is finite, we need not rely on numerical methods as in [7] where the antenna is used at the receiver. The array factor for the ESPAR antenna is computed for all possible loading combinations within a range of –j500 to j500 ohm, with a step of 1 ohm, and a look-up table is created such that given the desired complex gain for each sampled direction of the channel the closest possible match can be found. The closest match is computed by taking the Euclidean distance between the desired response towards the channel's virtual angles, taken from (5) and (11) and all possible responses in the look-up table. The result of this is the actual field pattern response achievable, along with the complex impedance loading values necessary to achieve it.

The result of this exhaustive search process is depicted using a simple BPSK example and the 3-element ESPAR antenna of Fig. 1. If BPSK modulated symbols are used for two

TABLE I. SYMBOL COMBINATIONS FOR BPSK MODULATION

s_0	1	-1	1	-1
s_π	1	1	-1	-1
s_0/s_π	1	-1	-1	1

TABLE II. REACTANCES FOR DIFFERENT S_0/S_Π COMBINATIONS

d	s_0/s_π	x_1	x_2	error φ (deg)
λ/16	1	-500	-500	0
λ/16	-1	26	84	119.21
λ/8	1	-500	-500	0
λ/8	-1	17	69	122.32

TABLE III. REACTANCES FOR DIFFERENT S_0/S_Π COMBINATIONS WHEN QPSK MODULATION IS USED

d	s_0/s_π	x_1	x_2	error φ (deg)
λ/16	1	-500	-500	0
λ/16	-1	26	84	119.21
λ/16	i	4	17	-0.59
λ/16	-i	17	4	-90.58
λ/8	1	-500	-500	0
λ/8	-1	17	69	122.32
λ/8	i	-78	3	-62.72
λ/8	-i	3	-78	27.28

parallel symbol streams, then the possible symbol combinations within a single symbol period are described in Table I. In the same table we see that the ratio between the 2 symbols transmitted at the same time is either 1, or -1. Our exhaustive search approach has shown that these combinations are more accurately achieved by ESPAR antennas with an inter-element spacing of λ/8 or λ/16. The parasitic antenna loads that can produce these combinations are shown in Table II, and the amplitude and phase patterns of the more compact ESPAR antenna with inter-element spacing equal to λ/16 are drawn in Fig. 2 for $s_0/s_\pi=1$ and $s_0/s_\pi=-1$.

Using these two radiation patterns we can *simultaneously* transmit any two BPSK modulated symbols towards angles 0 and π, in the following way. We adjust the reactances x_1 and x_2 of the 3-element ESPAR according to the ratio s_0/s_π of the two symbols that will be transmitted in the next symbol period, from Table 2, and feed the central element with the signal

$$s=\sqrt{\frac{|s_0|^2+|s_\pi|^2}{2}}s_0e^{-j\varphi} \tag{12}$$

where φ is the phase error of the symbol "1" when transmitted towards 0 degrees using different radiation patterns, with respect to the phase of the same symbol transmitted towards the same angle when the omni-directional pattern is used. Take for example the patterns of Fig. 2 that correspond to the radiation patterns used for the s_0/s_π combinations of BPSK modulated symbols. Assume that we want to transmit the vector $\mathbf{x}_{bs}=[1\ \ 1]^T$ during the first symbol period and the vector

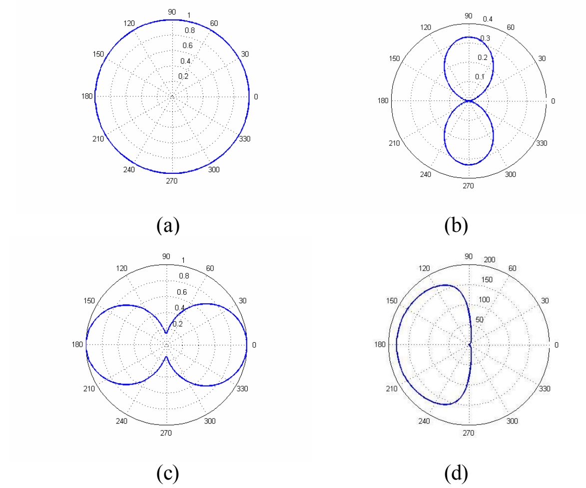

Figure 2. Amplitude (a) and phase (degrees) (b) patterns for 3-element ESPAR with d=λ/16, $s_0/s_\pi=1$. Amplitude (c) and phase (degrees) (d) patterns for 3-element ESPAR with d=λ/16, $s_0/s_\pi=-1$.

$\mathbf{x}_{bs}=[1\ \ -1]^T$ during the next symbol period. For the former combination the pattern of Fig. 2a and 2b will be used, sending symbol "1" towards 0 degrees. In the next symbol period the radiation pattern of Fig. 2c and 2d will be used. This radiation pattern ensures that the phase between symbols s_0 and s_π is equal to 180 degrees. However, the symbol sent towards 0 degrees will have a phase difference of 119,21 degrees with the symbol sent towards the same direction in the previous period. To compensate for this error, the constant φ is used to shift the phase of the transmitted symbol when the corresponding pattern is used. Phase error φ for the different radiation patterns used in this example is shown in Table II. Thus, by using these radiation patterns in Fig. 2 and by feeding the active element of the array with a signal as in (12) we can *simultaneously* transmit two diverse symbols towards angles 0 and π with respect to the x axis of the 3-element array.

We can extend the aforementioned approach to other linear modulation schemes if a set of reactive loads exists such that the radiation patterns produced by the ESPAR antenna that we are using can satisfy the relationship between the symbols transmitted towards the different virtual angles, and at the same time comply with (5). By applying the exhaustive search approach to the 3-element ESPAR antennas we have chosen, we found out that both BPSK and QPSK modulation formats can be supported, to simultaneously transmit two diverse symbols towards angles 0 and π. The corresponding pairs of reactances that satisfy (5) for the QPSK modulation formats are displayed in Table III.

The aforementioned 3-element ESPAR antennas present a compact antenna solution that can be used to send two diverse symbol streams over the air using a single RF front end, when BPSK and QPSK modulation schemes are used. The same antenna architecture can be used for all modulation schemes that produce symbol pairs s_0 and s_π having a relationship s_0/s_π that is included in Table III. Consequently, the aforementioned

ESPAR antenna can also be used for differential BPSK and QPSK modulations, as well as offset QPSK modulations.

IV. SYSTEM OVERVIEW AND SIMULATION RESULTS

In this paragraph we show how the ESPAR antennas described in Section III can be used in order to implement Beamspace-MIMO systems, for BPSK and QPSK modulation schemes.

On each symbol period the transmitting 3-element ESPAR antenna creates the radiation pattern that corresponds to the ratio s_0/s_π of the input symbol pair and is fed with a signal that satisfies (12). In order to capture the additional information at the receiver, we can use switching between the orthogonal base patterns of (11) for implementing a single RF front end receiver. In this case, the receiver should use the first cardioid radiation pattern during the first half of the symbol period, and switch to the second cardioid radiation pattern during the second half of the symbol period, as described in [4]. This way the received signals at the two consecutive half symbol periods will be

$$\left.\begin{aligned} y_0 &= s_0 h_{V11} + s_\pi h_{V12} + n_0 \\ y_\pi &= s_0 h_{V21} + s_\pi h_{V22} + n_\pi \end{aligned}\right\} \Rightarrow \mathbf{y}_{bs} = \mathbf{H}_V \mathbf{x}_{bs} + \mathbf{n}_{bs} \qquad (13)$$

where h_{Vij} describes the coupling between the orthogonal basis functions $B_{T,i}(\theta)$ and $B_{R,j}(\theta)$ of the transmitting and receiving antennas respectively.

However, this scheme suggests that since the received symbols will be sampled at half the time period of each symbol, the received energy per sample will be half the energy of a traditional MIMO receiver, resulting in a 3dB loss of the signal to noise ratio. We overcome this problem by considering a two-active antenna receiver, where each antenna is able to form independently the basis cardioid functions

$$\begin{aligned} B_{R,1}(\theta) &= (1+\cos\theta)/\sqrt{2} \\ B_{R,2}(\theta) &= (1-\cos\theta)/\sqrt{2} \end{aligned} \qquad (14)$$

The output vector $\mathbf{y}_{bs}$ is derived from the outputs of the active antenna elements and the receiver decodes the incident signals using the channel matrix information $\mathbf{H}_V$ and a maximum likelihood (ML) detector.

We evaluate the proposed architecture by extensive Monte Carlo simulations. We consider an outdoor propagation scenario, described by a 2-D geometrically based circular channel model as that described in [9], that is extended to a 2-bounce model so that the AoD are AoA of the multipath components remain uncorrelated. We assume that all signals are transmitted and received from a single location corresponding to the phase center of the transmitting and receiving arrays, respectively. We assume that the receiver can perfectly estimate the channel matrix, using training sequences, and that the channel information is static throughout the transmission of valid information. We also assume that we have a flat fading environment.

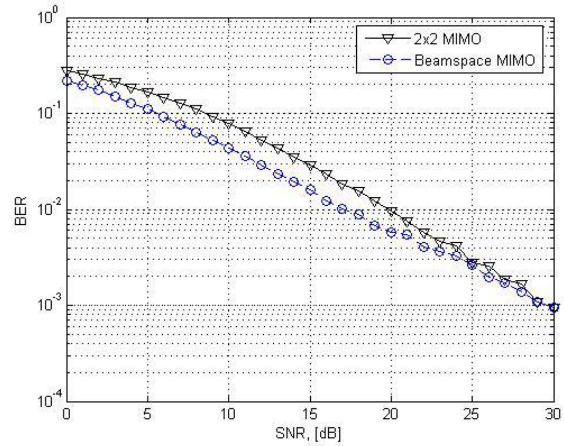

Figure 3. BER performance of a 2 by 2 beamspace MIMO system for BPSK modulation

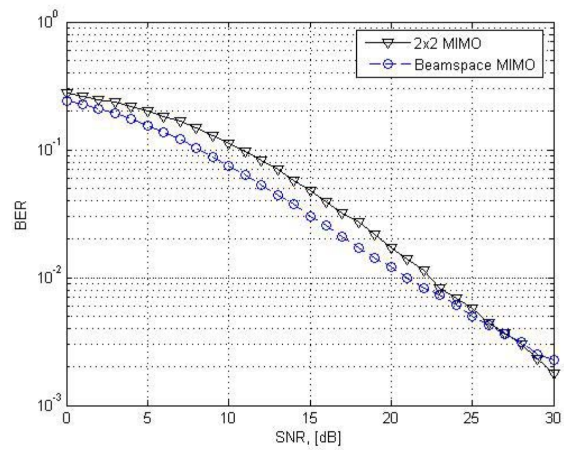

Figure 4. BER performance of a 2 by 2 beamspace MIMO system for QPSK modulation

The performance results of this communication system in terms of bit-error-probability, compared to the corresponding performance of traditional MIMO systems using BPSK and QPSK modulation schemes are presented in Fig. 3 and Fig. 4 respectively. It is evident that using the communication system described above, we can achieve performances comparable to these of traditional MIMO systems using a single transceiver and compact antennas.

V. CONCLUSION

This work has shown that using a single active antenna array architecture such as the ESPAR antenna it is possible to achieve spectral efficiency gains comparable to the case of using traditional MIMO antenna architectures for which each antenna element is weighted independently and has a dedicated IF/RF front end. This is achieved by considering the MIMO channel in the wavevector domain and computing the channel response matrix according to a set of orthogonal base radiation patterns, which also form the basis of the radiation patterns employed by the transmit and receive antennas. The orthonormal functions are modulated simultaneously at the transmitter using diverse symbol streams modulated by BPSK, QPSK or their equivalent offset and differential PSK schemes, and are switched sequentially at the receiver so as to retrieve the transmitted information. The proposed antenna architecture is therefore capable of achieving the performance gains common for MIMO systems by using a single transceiver and antenna arrays of total length as low as $\lambda/8$.

REFERENCES

[1] I. E. Telatar, "Capacity of multi-antenna Gaussian channels," *European Trans. on Telecommunications*, pp. 585-595, Nov. 1999.

[2] G. J. Foschini & M. J. Gans, "On Limits of Wireless Communication in a Fading Environment when Using Multiple Antennas", *Wireless Personal Comm.*, Vol. 6, pp. 311–335, 1998.

[3] V. Veeranalli, Y. Liang, and A. Sayeed, "Correlated MIMO Wireless Channels: Capacity, Optimal Signaling and Asymptotics", IEEE Transactions on Information Theory, June 2005.

[4] A. Kalis, A. G. Kanatas, M. Carras, A. G. Constantinides, "On the Performance of MIMO Systems in the Wavevector Domain", IST Mobile & Wireless Communications Summit, 5-8 June 2006, Mykonos, Greece.

[5] A. M. Sayeed, "Deconstructing multiantenna fading channels," IEEE Trans. Signal Processing, vol. 50, pp. 2563–2579, Oct. 2002.

[6] K. Gyoda and T. Ohira, "Design of electronically steerable passive array radiator (ESPAR) antennas," in Proc. *IEEE Antennas and Propagation Society International Symposium*, vol. 2, July 2000, pp. 922–925.

[7] T. Ohira and K. Gyoda, "Electronically Steerable Passive Array Radiator Antennas for Low-Cost Analog Adaptive Beamforming", IEEE Int. Conf. Phased Array Syst. & Tech., pp. 101-104, Dana Point, May 2000.

[8] T. Sawaya, K. Iigusa, M. Taromaru, T. Ohira, "Reactance diversity: proof-of-concept experiments in an indoor multipath-fading environment with a 5-GHz prototype planar ESPAR antenna", Consumer Communications and Networking Conference, 5-8 Jan. 2004 pp. 678 - 680

[9] J. Fuhl, A. F. Molisch and E. Bonek, "Unified channel model for mobile radio systems with smart antennas", *Proc. Ins. Elect. Eng. - Radar Sonar Navigation*, vol. 145, pp. 32-4, Feb. 1998