A Complete MIMO System Built on a Single RF Communication Ends
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Abstract — It is well known that Multiple Input-Multiple Output systems enhance significantly the spectral efficiency of wireless communication systems. However, their remarkable hardware and computational burden hinders the wide deployment of such architectures in modern systems. In this paper, we present an alternative MIMO architecture built on parasitic antenna structures with small inter-element distance. We show that exploiting appropriately the beamforming capabilities of such antennas, a cost efficient MIMO transceiver architecture emerges, with low implementation complexity. Our proposal is evaluated against the corresponding conventional MIMO systems in terms of bit error rate and capacity, and the results show a satisfactory performance.

1. INTRODUCTION

It is well known that Multiple Input-Multiple Output (MIMO) architectures improve significantly the performance of wireless communication systems. Depending on the system design, the effect of multiple antennas might be twofold: In spatial multiplexing mode, the objective is the data rate maximization, by exploiting appropriately the structure of the channel matrix to obtain independent signaling paths that can be used to support independent data streams. Alternatively, in diversity mode the multiple antennas are jointly used in order to effectively mitigate the negative effects of fading, thus improving the overall system reliability. However, the benefits of such systems are obtained at the cost of remarkable implementation complexity. Indeed, in conventional MIMO systems with Uniform Linear Arrays (ULAs) at both ends, the number of required Radio-Frequency (RF) chains equal to the number of antenna elements. Thus, increasing the number of elements the hardware complexity also increases. Obviously, the power consumption is increased accordingly. Although the deployment of such systems is quite realistic at base stations, such complex architectures are prohibitive in battery powered Mobile Terminals (MTs) due to additional implementation issues such as size and energy restrictions. Thus, although the promising performance of MIMO systems necessitates their implementation to modern wireless communications, the corresponding hardware complexity hinders the wide application of such systems.

Recently, remarkable research work is drawn in order to investigate alternative MIMO architectures with reduced hardware complexity, while maintaining the total performance close to the levels of conventional MIMO approach. Indeed, antenna selection [1, 2], and antenna subarray formation [3, 4] constitute different approaches towards this aim. Such architectures, are signal processing techniques applied at the spatial domain of a typical antenna array with fixed geometry and intend to reduce the required RF chains for a given number of antenna elements. Recently, another approach with completely different treatment has appeared, labeled as beamspace MIMO [5–7]. In this case, instead of considering antenna arrays with multiple RF chains parasitic antenna structures with a single active port are considered. Such antennas are known as Electronically Steerable Parasitic Antenna Radiators (ESPAR) and are low power consumption antenna structures [8], with fast beamforming capabilities [9]. In particular, such antennas consist of a single active element which is surrounded by several parasitic (or passive) elements in linear or planar arrangement. Beamforming abilities are achieved by tuning the varactors loaded directly to the parasitic elements. Since a single active element is present, a single driving port is required, thus reducing dramatically the implementation cost and power consumption. However, the concept of spatial sampling (as in case of ULAs) cannot be considered, implying that known MIMO signal processing techniques cannot be used directly. Instead, the beamforming capabilities of such antennas allow the angular sampling of the incident field from a single physical location. Thus, the Beamspace MIMO functionality is studied at the angular or beamspace domain. In contrast to the preceding work on this topic, we study the Beamspace approach at both communication ends. In particular, in Section 2 the beamspace system architecture is analytically presented followed by extensive performance comparisons in terms of bit error rate (BER) and ergodic capacity, in Section 3. The paper ends with the results summarized in Section 4.
2. BEAMSPACE MIMO ARCHITECTURE

In this paper, we propose the implementation of a MIMO transceiver based on a single RF front end, by mapping symbols in the beamspace domain using orthogonal radiation patterns, instead of the traditional approach of sending different symbol streams in different antenna elements. The requirement for orthogonal basis patterns is justified in Section 3.

First, let us consider a typical single user MIMO link. Following a geometrical modeling of the scattering environment, the channel matrix is given by:

$$\mathbf{H} = \sum_{i=1}^{L} b_i \mathbf{a}_R(\theta_{R,i}) \mathbf{a}_T^H(\theta_{T,i}) = \mathbf{A}_R(\hat{\theta}_R) \mathbf{H}_b \mathbf{A}_T^H(\hat{\theta}_T)$$

where \( L \) is the number of paths between the beamspace transmitter and receiver, \( \mathbf{a}_T, \mathbf{a}_R \) are the transmit and receive steering vectors and \( \hat{\theta}_T, \hat{\theta}_R \) are the direction vectors of the angles of departure (AoDs) and angles of arrival (AoAs) of all paths respectively. Moreover, \( \mathbf{H}_b \) is an \((L \times L)\) diagonal matrix which contains the complex path gains denoted as \( b_i, i = 1 \ldots L \), while \( \mathbf{A}_T(\hat{\theta}_T), \mathbf{A}_R(\hat{\theta}_R) \) are the transmit and receive steering matrices respectively.

The authors in [5], show that in case of using a Beamspace transmitter and a ULA-receiver, the channel matrix becomes \( \mathbf{H}' = \mathbf{A}_R(\hat{\theta}_R) \mathbf{H}_b \mathbf{B}_T \), where \( \mathbf{B}_T \) is a \((MT \times L)\) matrix each row of which contains \( L \) samples of an orthogonal pattern. Based on the analysis therein, the extension to the full Beamspace MIMO system is straightforward, and the channel matrix in this case is expressed as:

$$\mathbf{H}_{bs} = \mathbf{B}_T^H \mathbf{H}_b \mathbf{B}_T$$

where matrix \( \mathbf{B}_R \) is defined accordingly. Thus, the beamspace input-output relationship is:

$$\mathbf{y} = \mathbf{H}_{bs} \mathbf{x} + \mathbf{n} \iff \mathbf{y} = \mathbf{B}_T^H \mathbf{H}_b \mathbf{B}_T \mathbf{x} + \mathbf{n} \iff \mathbf{y} = \mathbf{B}_T^H \mathbf{H}_b \mathbf{P}^{(x)}_T(\hat{\theta}_T) + \mathbf{n}$$

where \( \mathbf{P}^{(x)}_T(\hat{\theta}_T) = \mathbf{B}_T \mathbf{x} \) defines a \((L \times 1)\) vector containing angular samples of the actual transmit radiation pattern at each time slot. Note that the samples of the transmit pattern emerge as a linear combination of the sampled basis patterns and the transmit symbol vector:

$$\mathbf{P}^{(x)}_T(\hat{\theta}_T) = \left[ B_{T,1}(\hat{\theta}_T) \ldots B_{T,MT}(\hat{\theta}_T) \right] \begin{bmatrix} x_1 \\ \vdots \\ x_{MT} \end{bmatrix}$$

Therefore, at each time slot, the beamspace transmitter constructs a radiation pattern given by \( \mathbf{P}^{(x)}_T(\hat{\theta}_T) = \sum_{k=1}^{MT} x_k B_{T,k}(\theta), \) where \( B_{T,k}(\theta) \), \( k = 1, \ldots MT \) are the orthogonal basis patterns used at the transmitter, and \( \mathbf{x} = [x_1 \ldots x_M]^T \) is the symbol vector emerged, e.g., directly from a PSK constellation.

Regarding the receiving mode, since just a single active port is present, instead of sampling the incident waves in the spatial domain (i.e., antenna domain) as in the typical case, samples are obtained at the beamspace from the same physical location. This is achieved by altering the receive radiation pattern during a time slot among all orthogonal basis patterns. A similar approach also has been suggested in [10], where a parasitic antenna operates in the receiving mode as a switch antenna with rotating radiation pattern. However, in our case instead of considering the rotated versions of the same narrow beam, the sampling of incident wave field is achieved by using the orthogonal basis patterns sequentially during each symbol period. Therefore, this operation can be viewed as oversampling the incident wave field at the receiver [10].

In order to evaluate the performance of the proposed scheme, a 3 element ESPAR antenna with inter-element distance \( d = \lambda/16 \) is considered. The radiation pattern of a such antenna is given by:

$$G(\theta) = i^T \mathbf{s}(\theta) = i_0 + i_1 e^{ja \cos(\theta)} + i_2 e^{-ja \cos(\theta)}$$

$$= i_0 + (i_1 + i_2) \cos(a \cos(\theta)) + j(i_1 - i_2) \sin(a \cos(\theta))$$

where \( i = [i_0 \ i_1 \ i_2]^T \) and \( \mathbf{s}(\theta) = [1 \ e^{ja \cos(\theta)} \ e^{-ja \cos(\theta)}]^T \), are the current vector and the steering vector of the ESPAR respectively, while \( a = 2\pi d/\lambda \) represents the normalized distance.
between elements. Thus, when both the transmitter and the receiver are equipped with a 3 element ESPAR, there are two orthogonal basis patterns:

\[ B_{T,k}(\theta) = B_{R,k}(\theta) = \begin{cases} i_0 + (i_1 + i_2) \cos (a \cos (\theta)) & k = 1 \\ (i_1 - i_2) \sin (a \cos (\theta)) & k = 2 \end{cases} \]  

(6)

where, \( i_0 \) is the current running on the active element and \( i_1, i_2 \) are the induced currents at the parasitic elements. Thus, different currents on the ESPAR elements produce different radiation patterns. Fig. 1(a) shows the two basis patterns normalized to unity power, while Fig. 1(b) shows an example radiation pattern \( P^T_0(\hat{\theta}_T) \) corresponding to an arbitrary chosen symbol vector \( x = [e^{j7\pi/8} e^{-j\pi/2}] \). It is noted that ESPAR antennas with different characteristics (i.e., number of elements, distance between elements and geometry) may produce larger number of basis patterns, thus leading to higher order beamspace MIMO systems while preserving low hardware complexity.

3. PERFORMANCE EVALUATION

In this Section, we evaluate the performance of beamspace MIMO systems against the corresponding conventional approach. In terms of bit error rate (BER), Fig. 2 shows that our approach performs equivalently to the typical MIMO architecture. We note that the curves in Fig. 2 correspond to a 16-PSK modulation scheme. However, although the beamspace approach leads to obvious advantages regarding complexity, the radiation pattern switching at the receiver within a symbol period has a negative impact. In particular, as mentioned in Section 2, the operation of using at the receiver different patterns sequentially can be viewed as oversampling the incident wave field. In this case, the SNR as seen at the receiver (henceforth called effective SNR) is decreased by the oversampling factor [10], which is equal to the number of pattern changes within a symbol period. Thus, when the received SNR in case of a conventional MIMO is \( \gamma_{\text{conv}} = E/N_0 \), in beamspace MIMO will be \( \gamma_{\text{bs}} = E/(M_R N_0) \). Therefore, the SNR loss due to oversampling is given as:

\[ \gamma_{\text{loss}}^{(\text{dB})} = \gamma_{\text{conv}}^{(\text{dB})} - \gamma_{\text{bs}}^{(\text{dB})} = 10\log_{10} (M_R) \]  

(7)

Thus, since in our case \( M_R = 2 \), beamspace MIMO receiver experience 3 dB SNR loss against the typical MIMO receiver.

The effect of SNR loss is clearly viewed in Fig. 3, where an indicative comparison in terms of capacity Cumulative Distribution Functions (CDFs), for two different values of \( \gamma_{\text{conv}} \) is shown. Moreover, it is known that transmit or receive signal correlation may affect significantly the spectral efficiency of conventional MIMO systems [11, 12]. For a given scattering environment increasing the
distance between the antenna elements at both ends the signals are decorrelated, thus the open loop capacity performance is maximized. Accordingly, in beamspace MIMO approach spectral efficiency maximization requires orthogonal basis radiation patterns. This is observed in Fig. 4, where ergodic capacity is plotted in two cases, one using the basis patterns in (6), and one using one pattern of (6), and the cardioid pattern $B(\theta) = 1 + \cos(\theta)$. Fig. 4 clearly depicts the performance degradation in the latter case. Note that the selection of the cardioid pattern as an example is reasonable, since it has been already considered in beamspace MIMO [5–7]. Also, in case of clustered channels the scattering distribution (as seen by the transmitter and the receiver) is not uniform any more. This fact affects the orthogonality of the basis patterns in (6), implying possible performance degradation in terms of spectral efficiency.

4. CONCLUSION

In this paper, an alternative MIMO transceiver architecture is proposed with simplified hardware complexity compared to the equivalent conventional MIMO systems. The performance results confirm that it is possible to exploit parasitic antenna structures to the design of efficient MIMO transceivers with a single RF chain at both communication ends. Although the proposed architecture induces an SNR loss compared to the conventional MIMO systems, this drawback is acceptable thinking the significant hardware savings.

REFERENCES


