Constellation-Switching Precoding for Blind Detection of Co-Channel Signals: Application to 8-ary Signaling

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Abstract—Blind detection of co-channel signals in wireless scenarios may be achieved with the help of data precoding techniques [6]-[9]. In this letter we propose a new data precoding / blind detection approach that is based on a unique modification to the signal constellation of each of the co-channel signals. Detection is based on exploiting the embedded constellation property. The new approach can be seen as a generalization to some earlier precoding techniques [8][9] that were based on phase modifications. Demonstration of the proposed method involves application to 8-ary amplitude-phase modulations, with performance shown to be reasonably close to an MMSE receiver. Performance results for a semi-blind receiver for 4-ary signaling are also given to demonstrate further possible applications of the new scheme.

Index Terms—Co-channel signals, blind detection, data precoding, amplitude-phase constellations, 8-ary QAM, MIMO channels.

I. INTRODUCTION

The future demands for very high speed wireless links has motivated significant research efforts in the area of blind detection of co-channel signals and interference cancellation in wireless channels [1]-[5]. Examples of wireless systems with co-channel signals are Code-Division Multiple-Access (CDMA), Space-Division Multiple-Access (SDMA), and Multiple-Input Multiple-Output (MIMO) systems with multiple TX and RX antennas. Out of the numerous techniques for blind detection of co-channel signals, a number of methods were based on data precoding, where data is modified at the transmitter in a certain manner that will assist in its blind detection at the receiver [6]-[9]. These techniques derive the detector blindly by exploiting the embedded properties in each signal.

In this letter we propose a new data precoding approach that is based on modifications in the signal constellation that will enable a receiver to carry out blind signal recovery. This approach, termed 'Constellation-Switching Precoding' (CSP), can be seen as a generalization to the precoding techniques in [8][9] for BPSK and QPSK signals. The new approach is demonstrated by application to 8-ary amplitude-phase (QAM) modulations, since many applications may require higher bandwidth efficiency than that provided by binary or 4-ary signaling studied earlier [8][9]. Computer simulation results of the proposed approach in a MIMO/Vertical Bell Labs Layered Space-Time (VBLAST) system [10][11] demonstrate that it has a good performance that is reasonably close to an MMSE receiver with perfect channel knowledge. We also describe a CSP based semi-blind receiver for 4-ary signaling to further demonstrate the possible applications and advantages of the CSP technique. The letter is organized as follows: In section II we describe the CSP concept. In section III we describe the signal model and the precoding operation. Section IV describes the blind detection algorithm. Finally, simulation examples are given in section V to illustrate performance.

II. CONSTELLATION-SWITCHING PRECODING (CSP)

In data precoding, the data sequence of each signal is modified in a certain manner to characterize the signal by a unique property. The CSP scheme proposed here is based on modifications to the signal constellation used over a block of symbols. Instead of using the same set of constellation points over an entire block of data, the CSP scheme uses two constellation sets and switches between them pseudorandomly. The switching sequence is unique for each signal in the channel and hence the block-constellation structure becomes a property that characterizes each of the signals sharing the channel. The two constellations $C_1$ and $C_2$ used here, however, must have approximately the same error performance (i.e., the same average constellation power - to - minimum distance between constellation points) and must have the same data rate (i.e., number of bits per symbol). This choice ensures that the precoding operation does not degrade the error performance or bandwidth efficiency. Blind recovery of each signal will then depend on whether it is possible to exploit the embedded block constellation property for detection, and whether this property provides good separation between signals.

Our choice for the constellations $C_1$ and $C_2$ for 8-ary QAM is shown in Fig.1. The constellation $C_1$ is known to be the best 8-ary QAM constellation [12], i.e. it requires the least power among all 8-ary QAM constellations for a given minimum distance between signal points. The constellation $C_2$ has a 1 dB higher power than $C_1$ for the same minimum distance. Hence using $C_1$ and $C_2$ with nearly equal probability would result in a signal that has an average power of 0.5 dB larger than if $C_1$ alone is used, while keeping nearly the same performance since the minimum distance is fixed. Alternatively we can describe the $C_1$-$C_2$ constellation as having a 0.5 dB loss in performance compared to $C_1$ alone. The advantage, however, of using the $C_1$-$C_2$ constellation in the CSP scheme is to enable blind signal recovery for each of the signals in the channel. The distinguishing property that these two constellations provide through the CSP scheme is that at the $C_2$ locations corresponding to a desired signal, this signal will be the only one that has a Constant Magnitude Imaginary Part (CMIP) property (see Fig.1). This property,
as shown next, is sufficient for blind recovery of the desired signal.

It may be important to note here that while the CSP scheme manages to add a new feature to characterize each signal, it does this almost without paying a price in terms of SNR or data rate. Hence, even if the resulting performance of the blind detector is not satisfactory, it may still be advantageous to use the CSP technique with a semi-blind receiver. The role of the CSP scheme in such a case would be to reduce training size requirement by exploiting the additional CSP embedded training. As an example for this case we describe a semi-blind CSP receiver scheme for 4-ary signaling consisting of two constellations $C_1$ and $C_2$ in fig.2, both having the same average power-to-minimum distance between constellation points. Semi-blind signal recovery is achieved by exploiting the constant modulus property restricted to the symbols having $C_1$-constellation within the data stream of the desired signal, in addition to the knowledge of few training symbols.

III. THE SIGNAL MODEL AND THE PRECODING OPERATION

To demonstrate the new approach we assume that the CSP scheme is implemented in a MIMO/VBLAST wireless system. Hence we consider a MIMO system composed of $N$ transmit antennas and $M$ receive antennas ($M \geq N$). The 8-ary QAM data stream is divided into $N$ sub-streams transmitted from $N$ antennas and received by $M$ antennas. A flat fading channel is assumed between each transmit and receive antennas. Define a channel matrix $H$ of size $(N \times M)$ where $h_{ij}$ is the complex transfer function from transmit antenna $i$ to receive antenna $j$. These $h_{ij}$ elements are assumed to be uncorrelated zero-mean complex Gaussian random variables with unit variance. Assuming symbol-synchronous receiver with perfect sampling time, the discrete-time complex base-band model of the received signal vector at sampling instant ($k$) is given by

$$r(k) = H^T(k)s(k) + v(k),$$

(1)

where $r(k) = [r_1(k) \ldots r_M(k)]^T$ and $s(k) = [s_1(k) \ldots s_N(k)]^T$ and where $r_m(k)$ is the signal received at the $m^{th}$ antenna at the $k^{th}$ sample instant. $s_n(k)$ is the $k^{th}$ (precoded) symbol of the $n^{th}$ signal (i.e. of the $n^{th}$ transmit antenna) and is expressed in terms of the $k^{th}$ information 8-ary symbol $d_n(k)$ of the $n^{th}$ transmit antenna, and the pseudorandom constellation-switching (precoding) sequence expressed in terms of a 0/1 element vector $w_n$ of the $n^{th}$ transmit antenna also, by the relation

$$s_n(k) = \begin{cases} 
C_1[d_n(k)] & \text{if } w_n(k) = 0 \\
C_2[d_n(k)] & \text{if } w_n(k) = 1
\end{cases}$$

(2)

$C_1$ and $C_2$ here are the two mapping functions of the CSP scheme that map each 8-ary information symbol into a suitable constellation point. The precise rule for assignment of an information symbol to one of the constellation points is of no significance here since all 8-ary information symbols are assumed to be equally probable. $w_n(k)$ represents the $k^{th}$ element in the vector $w_n$. The precoding sequence is a periodic $K$-length sequence with $K_n$ 'ones' and $K - K_n$ 'zeros' for the $n^{th}$ signal, where $K_n \approx K/2$. $v(k) = [v_1(k) \ldots v_M(k)]^T$ is the noise vector observed at $M$ receive antennas, at the $k^{th}$ sample instant, and it represents white Gaussian noise with zero-mean and variance $\sigma_n^2$. Assuming the channel is constant over the time period of $K$-symbols (thus dropping the index $k$ from $H$), we collect $K$ receive signal vectors in a signal matrix $X$ (of size $K \times M$) given by $X = [r(1) \ r(2) \ldots \ r(K)]^T$. It is easy to see that the matrix $X$ can be expressed as $X = SH + N$ where $S = [s_1 \ s_2 \ldots \ s_N]$ and $s_n = [s_n(1) \ s_n(2) \ldots \ s_n(K)]^T$, and obviously $N$ is the noise matrix.

IV. DETECTION

The derivation of the blind detector is based on utilizing the CMIP property of the $C_2$ constellation. To simplify the derivation we will define a selection operator $T_{s}$ for the $n^{th}$ signal that operates on a matrix (or a vector) of $K$ rows and selects and stacks only those rows corresponding to ones in the precoding vector $w_n$ of the $n^{th}$ signal. For example if we assume that $w_1 = [1 \ 0 \ 0 \ 1 \ 1 \ 0 \ 1 \ldots]$, then applying
Construct the matrix $T_1$ on $s_n$ yields $T_1(s_n) = [s_n(1) s_n(4) s_n(5) s_n(7) \ldots]^T$. This operator will be used to select the data portion that has the CMIP property from the rest of the data block. Before we proceed to derive the detector we will replace the signal matrix $X$, of size $(K \times M)$, by a minimum vector set that has the same column span as the signal subspace, a step that is seen necessary for proper derivation of the detector. Hence we define the matrix $V$ of size $(K \times N)$, whose columns are the $N$ dominant left singular vectors of $X$. The following derivation will therefore be based on this new, reduced size, signal matrix $V$. Without loss of generality we assume that it is desired to obtain the detector of the first signal (i.e. transmitted from the first antenna). The derivation starts by using the CMIP property of $C_2$ and the $T_n$ operator to write the following equation

$$|\text{Imag} [T_1(s_1)]| = 1$$

where the $1$ on the right hand side of the equation is a vector of all ones of size $(K_1 \times 1)$. In the absence of noise, equation (3) may be written in terms of a zero-forcing detector $t_1$ (of size $N \times 1$) of the $1^{st}$ signal which operates on the matrix $V$ as follows

$$|\text{Imag} [T_1(Vt_1)]| = 1 = |\text{Imag} [T_1(V)t_1]| = \begin{bmatrix} [T_1(V)]_{(i)} & [T_1(V)]_{(r)} \end{bmatrix} \begin{bmatrix} t_1(i) \\ t_1(r) \end{bmatrix}$$

where the subscripts $(i)$ and $(r)$ denote imaginary and real parts of the mentioned quantity. In this step we have assumed that the preceding sequence of the receiver is synchronized to that embedded in the received signal, which can be achieved using pilot signals or a blind search. To simplify the formulation we define a matrix $B$ of size $(K_1 \times 2N)$ as $B = \begin{bmatrix} [T_1(V)]_{(i)} & [T_1(V)]_{(r)} \end{bmatrix}$, and let $b_i$ be the $i^{th}$ row of $B$. We can now rewrite (4) using $B$, after replacing the absolute value by squaring, as $|b_k g|^2 = 1$ (for $k = 1, 2, \ldots, K_1$), where $g = \begin{bmatrix} t_{1(i)}^T \\ t_{1(r)}^T \end{bmatrix}$. This, in turn, may be written as $g^T b_k^T b_k g = 1$ (for $k = 1, 2, \ldots, K_1$). This set of $K_1$ equations may be written in one matrix equation given by $P y_1 = 1$ where $y_1 = bvec(gg^T)$ and has a size of $N(2N + 1)$, where the $bvec$ operator is given by

$$bvec(A_{K \times K}) = [A_{1,1}, A_{1,2}, \ldots, A_{1,K}, A_{2,1}, A_{2,2}, A_{2,3}, \ldots, A_{2,K}, A_{3,1}, \ldots, A_{K-1,K-1}, A_{K-1,K}, A_{K,K}]^T$$

The matrix $P$ (assumed to be tall) has a size of $K_1 \times N(2N + 1)$ and is defined by $P(i,:) = \{a vec(b_i^T b_i)\}^T$ where the $a vec$ operator is defined by

$$a vec(A_{K \times K}) = [A_{1,1}, (A_{1,2} + A_{2,1}), (A_{1,3} + A_{3,1}) \ldots (A_{1,K} + A_{K,1}), A_{2,2}, (A_{2,3} + A_{3,2}), (A_{2,4} + A_{4,2}), \ldots (A_{2,K} + A_{K,2}), A_{3,3}, \ldots, A_{K-1,K-1}, (A_{K-1,K} + A_{K,K})]$$

It is not difficult to show that the matrix $P$ here is of full column rank and hence $P y = 1$ can only have one solution. Since $y_1$ (corresponding to the first signal) satisfies $P y = 1$, it is therefore the desired unique solution to this equation. In the presence of noise, the least-squares estimate for the vector $y_1$ that corresponds to the signal of the $1^{st}$ transmit antenna is therefore given as

$$y_1 = P^+ 1$$

Having obtained $y_1$, it is easy to see that $g$ can be estimated as the dominant eigenvector of the matrix $\{bvec^{-1}(y_1)\}$, where the $bvec^{-1}$ operator simply inverts the $bvec$ operation. After finding $g$ we can find $t_1$ as $t_1 = g_1 + jg_2$, where $g_1 = g(1) \cdots (N)^T$, $g_2 = g(N+1) \cdots (2N)^T$. The detector $t_1$ has now been estimated up to a real scaling ambiguity, and up to a $\pm 180^\circ$ phase ambiguity. This can be explained as follows: Solving (5) yields $y_1$, which is obviously a real vector. Hence the vector $g$ obtained by inversion of $y_1 = bvec(gg^T)$ is also real, and is obtained up to a real scaling ambiguity. It follows that dividing $g$ into two parts (i.e. $g_1$ and $g_2$), would yield $t_1$ up to a real scaling ambiguity and with a $\pm$ ambiguity factor since both $-t_1$ or $t_1$ would satisfy the CMIP property. Finally, the $\pm$ scaling ambiguity in the detector $t_1$ can be resolved with the help of few known symbols in each data block, based on the squared error between the known and the corresponding recovered symbols.

### V. COMPUTER SIMULATIONS

The performance of the proposed precoding / blind detection algorithm is compared with that of the MMSE receiver without precoding (with a $C_1$ constellation) with perfect channel knowledge in a flat Rayleigh fading MIMO channel. Symbol error rate (SER) for the $1^{st}$ signal is plotted against the SNR of this signal where the SNR is the ratio of the average power received by each antenna from the $1^{st}$ transmit antenna-to-the noise power. We assume that detection is carried out over a block of $K$ symbols over which the channel is assumed to be constant. Figure 3 shows the SER (averaged over 10000 runs) of the proposed and of the MMSE receivers for the case of $N = 3$ and $M = 6$ for a block size of $K = 400$ symbols. We assume that 10 known symbols in each block are used to resolve the $\pm$ ambiguity. The important point that this figure demonstrates is that the performance of the proposed decoding-detection algorithm (with $K = 400$ symbols) is reasonably close (1-2 dB worse) to that of the MMSE receiver with perfect channel knowledge. This result demonstrates that the CSP scheme is a useful new dimension for signal characterization.
not satisfactory, the semi-blind CSP based receiver has an excellent performance. Using 16 training symbols in a block of 400 symbols, the semi-blind receiver is equivalent to a supervised receiver which uses 50 training symbols. Hence, the CSP semi-blind receiver can provide significant savings in data throughput compared to a conventional trained receiver, thanks to the embedded CSP training.

VI. CONCLUSIONS

A new data precoding / blind detection approach is proposed for wireless channels with co-channel signals. This new scheme is based on modifying the set of constellation points used for each signal. Detection is based on exploiting the unique block constellation structure of each signal. The new technique is demonstrated by application to an 8-ary QAM signal and tested in a MIMO/VBLAST channel scenario with performance seen to be reasonably close to an MMSE receiver with perfect channel knowledge. A semi-blind CSP based receiver is also demonstrated for 4-ary signaling providing significant reduction of the required size of training sequences. Hence the CSP scheme makes a good candidate for employment in various wireless scenarios.

REFERENCES


