OPTIMAL MIMO TRANSMISSION SCHEMES WITH ADAPTIVE ANTENNA COMBINING IN THE RF PATH

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ABSTRACT

In this paper we study space-time coding schemes for a novel MIMO transceiver which performs adaptive signal combining in radio-frequency (RF). The limitations of the RF circuitry make necessary to develop specific designs for this architecture. For instance, the space and time encoders must operate separately (the former works in the RF domain and the latter works in baseband), and at different time scales: the spatial encoder or RF beamformer must remain fixed during the transmission of a probably large number of symbols, whereas the time-encoder can work at the symbol rate. We show in the paper that although the multiplexing gain of the system is limited to one, we are still able to achieve the full spatial diversity of the MIMO channel as well as to increase the received signal-to-noise ratio through array gain.

Specifically, when perfect channel state information (CSI) is available only at the receiver we propose to use a scheme referred to as orthogonal beam division multiplexing (OBDM). With this scheme the symbols are time-precoded with a unitary discrete Fourier transform (DFT) matrix, then they are successively transmitted through orthogonal directions and, finally, we use a receiver comprising maximal ratio combining (MRC) followed by a minimum mean-square error (MMSE) decoder. The performance of the proposed techniques in terms of outage capacity and bit error rate is illustrated by means of several simulations examples.

1. INTRODUCTION

The last years have witnessed a steady trend to move the baseband of digital communications systems as close as possible to the antenna. High speed ADCs (analog-to-digital converters) together with more powerful digital signal processors have enabled this change of paradigm, which has brought the development of the software defined radio (SDR) concept [1]. However, for multiple-input multiple-output (MIMO) systems, which must simultaneously process several independent channels, the hardware cost and power consumption associated to a full baseband processing can still be very high.

In order to mitigate these drawbacks it is interesting to re-think about the pros and cons of moving some processing from the baseband to the radio frequency (RF) front-end. This interest is also propelled by recent advances in RF integrated circuits designed in SiGe-BiCMOS technology [2], which make feasible to combine the RF signals using pre-

cise phase shifters with 360º control range and an amplitude dynamic range of more than 20 dB.

Obviously, by performing adaptive combining in the radio frequency domain at both the transmitter and the receiver sides, the multiplexing gain of the MIMO system is always limited to one (like a single-input single-output system or a MIMO system using orthogonal space-time block coding [3]); and correspondingly the capacity is also limited. However, as we will show in the paper, other important benefits of the MIMO channel such as diversity or array gain can be retained by the new architecture.

From a signal processing point of view, one of the distinguishing features of the novel topology is that the space and time encoders operate separately and at different time scales. Specifically, beamforming (here also referred to as spatial encoder) is performed in the radio frequency domain by the adaptive combiner, whereas time encoding is carried out in the baseband. On the other hand, the complex weights in the RF path change at a much slower rate than the time encoder, which typically works at the symbol rate.

In this paper we study the optimal design of the beamformer and the time encoder for this RF adaptive combining architecture under various assumptions regarding channel state information (CSI). For the case of perfect CSI at the receiver (CSIR) and at the transmitter (CSIT), the optimal transmission scheme reduces to the well-known dominant eigenmode transmission (DET) [4]. On the other hand, we show that when only CSIR is available the time and the space encoding matrices must be both unitary to achieve optimal performance. A particularly interesting case arises when the time and space encoding matrices are chosen as probably shifted versions of the discrete Fourier transform (DFT) matrix. We refer to this transmission scheme as orthogonal beam division multiplexing (OBDM), since it is reminiscent of conventional orthogonal frequency division multiplexing (OFDM) systems, but replacing frequency by space-time. The performance of DET and OBDM in terms of outage capacity and BER is illustrated by means of several simulations examples.

2. MIMO TRANSCEIVER USING RF ADAPTIVE ANTENNA COMBINING

The novel architecture for adaptive antenna combining in the RF domain is shown in Fig. 1. After the RF signal combining, only one signal path is required for the second mixer/intermediate-frequency chain, the ADCs and the baseband. Consequently, with this topology the system costs and size can be significantly reduced compared to a full base-

Figure 2: Frame structure: the grey columns form an $M \times M$ codeword that conveys M time-precoded symbols transmitted through M different beamformers.
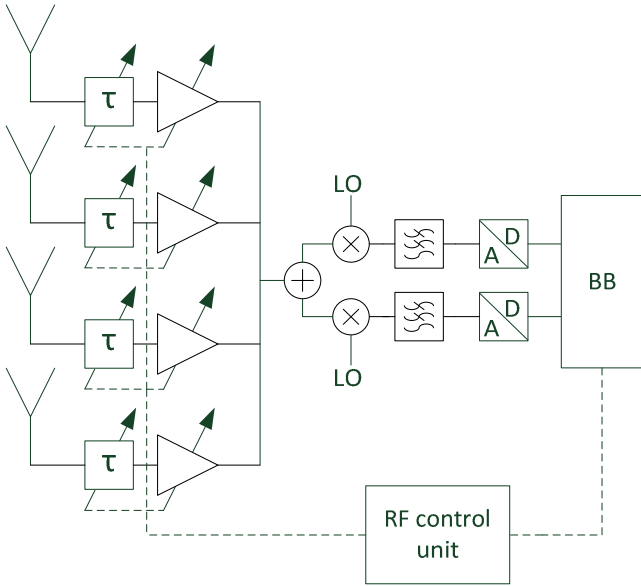
Figure 1: Adaptive antenna combining in the RF path for MIMO communications systems.

band MIMO architecture, for which the power consumption and cost are multiplied by the number of transmitting or receiving antennas.

The major scientific challenge of adaptive antenna combining in the radio front-end is to achieve precise phase shifters with 360° control range and an amplitude control with a dynamic margin of at least 20 dB. To relax the specifications of the phase shifters, the phase shift can be performed by adjusting the phase in the local oscillator path and by quadrupling the frequency of the voltage controlled oscillator. Thus, the phase is multiplied by a factor of 4 [2,5] and hence only a 90° phase shift is required. The development of this type of analogue weighting RF circuits in BiCMOS technology suitable for mass fabrication is currently being pursued within the EU funded project MIMAX (*MIMO Systems for Maximum Reliability and Performance*).

In this paper we consider an idealized system that neglects potential RF impairments such as cross-coupling between amplitude and phase, limited dynamic margin for the amplitude or phase errors. Our focus will be to study from a signal processing point of view the best space-time coding schemes for this RF adaptive antenna combining transceiver.

3. MIMO TRANSMISSION SCHEMES

3.1 Tx-Rx signal model

To study the limitations and advantages of the proposed architecture is enough to consider a flat-fading single-carrier $M \times M$ MIMO system. The MIMO channel is assumed to be static during the transmission of a frame composed of L symbols. As we already pointed out, due to technological limitations of the RF circuitry, the beamformer weights must remain fixed during the transmission of a probably large number of symbols. Without losing generality, we assume that the beamformer can change M times per frame, and that the changes occur synchronously at both the transmitter and the receiver. The frame structure is depicted in Fig. 2, where we
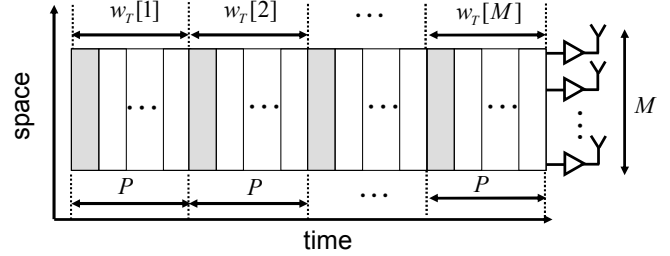
have assumed that P time precoded symbols are transmitted with each beamformer (i.e., $L = PM$). The set of P symbols transmitted with a common beamformer is denoted here as a block.

Let $\mathbf{w}_T[n] = (w_{T,1}[n], \cdots, w_{T,M}[n])^T$ and $\mathbf{w}_R[n] = (w_{R,1}[n], \cdots, w_{R,M}[n])^T$ be the beamformer weights at the transmitter and receiver sides, respectively, for $n = 1, \ldots, M$. Let us now define the $M \times M$ matrices

$$\mathbf{W}_T = (\mathbf{w}_T[1], \ldots, \mathbf{w}_T[M])$$

and

$$\mathbf{W}_R = (\mathbf{w}_R[1], \ldots, \mathbf{w}_R[M]),$$

which contain all the beamformers used during the frame.

By grouping now the first columns of each block within a frame (the grey columns in Fig. 2), we form the following $M \times M$ codeword

$$\mathbf{X} = \mathbf{W}_T \text{diag}(\mathbf{Gs}), \quad (1)$$

where $\mathbf{G}$ is an $M \times M$ time-encoding matrix, $\mathbf{s} = (s[1], \cdots, s[M])^T$ contains the information symbols to be transmitted, and $\text{diag}(\mathbf{d})$ denotes the operator which builds a diagonal matrix from a vector $\mathbf{d}$. Note that with this scheme each codeword can be coded and decoded independently from others.

Since the receiver beamformer is changed synchronously with the transmitter beamformer, the received signal when transmitting $\mathbf{X}$ can be written as

$$\mathbf{y} = \text{diag}\left(\mathbf{W}_R^H \mathbf{H} \mathbf{W}_T\right) \mathbf{Gs} \quad (2)$$

where, with some abuse of notation, $\text{diag}(\mathbf{A})$ is used now to denote a diagonal matrix constructed from the main diagonal of matrix $\mathbf{A}$, i.e., $\text{diag}\left(\mathbf{W}_R^H \mathbf{H} \mathbf{W}_T\right)$ is the following matrix

$$\begin{pmatrix} \mathbf{w}_R^H[1]\mathbf{H}\mathbf{w}_T[1] & 0 & \cdots & 0 \\ 0 & \mathbf{w}_R^H[2]\mathbf{H}\mathbf{w}_T[2] & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & \mathbf{w}_R^H[M]\mathbf{H}\mathbf{w}_T[M] \end{pmatrix}.$$
$$(3)$$

From (2) and (3) it is clear that the overall MIMO system has been transformed in this way into a set of M orthogonal SISO channels through which M precoded symbols are transmitted.

In the next subsections we discuss how to select the optimal matrices for the beamformers ($\mathbf{W}_T$, $\mathbf{W}_R$) and the pre-

coder ($\mathbf{G}$), under various assumptions regarding CSI.

3.2 Optimal solution with CSIT and CSIR

When perfect CSI is available at both the transmitter and the receiver sides, the optimal transmission scheme for our RF combining architecture is the well-known dominant eigenmode transmission (DET) technique [4, 6]. Specifically, the optimal Tx and Rx beamformers are given by

$$\mathbf{w}_T[n] = \mathbf{v_H}, \quad n = 1\ldots,M$$
$$\mathbf{w}_R[n] = \mathbf{u_H}, \quad n = 1\ldots,M;$$

where $\mathbf{v_H}$ and $\mathbf{u_H}$ are the main right and left singular vectors of the MIMO channel matrix $\mathbf{H} = \mathbf{U}\mathbf{\Lambda}\mathbf{V}^H$ (those associated with the largest singular value).

With DET we are transmitting over the strongest spatial mode of the matrix channel. Therefore, the signal-to-noise ratio (SNR) for every realization of the channel is maximized. Moreover, using DET we do not need to precode the symbols to achieve the full diversity gain of the MIMO channel, i.e., we can take $\mathbf{G} = \mathbf{I}$.

The advantages of DET are manifold: it provides full spatial diversity gain (M^2) and an array gain that asymptotically increases as $4M$ [4][1]; the weights of the RF combiner can be kept fixed at Tx and Rx during the transmission of the whole frame, thus relaxing the requirements of the RF circuitry; and, since no time precoder is needed, the optimal detector can work on a symbol-by-symbol basis. Finally, as it was pointed out in [6], for time division duplex (TDD) systems exhibiting reciprocity DET can be implemented in a blind fashion (without resorting to pilot sequences).

3.3 Optimal solution with CSIR only

Now we assume that only channel distribution information is available at the transmitter side. Specifically, the channel matrix $\mathbf{H}$ is assumed to have i.i.d. complex Gaussian entries. On the other hand, perfect CSIR is still available. In this situation the design of the optimal Tx-Rx scheme is more challenging.

Let us start by considering the design of the best Tx beamforming matrix $\mathbf{W}_T$ and the time-encoding matrix $\mathbf{G}$. It is known that at high SNRs the pairwise error probability of transmitting codeword $\mathbf{X}^i$ and deciding for the codeword $\mathbf{X}^j$, assuming maximum likelihood detection and averaging over all channel realizations, depends on the rank and the determinant of the following matrix [7]

$$\mathbf{G}_{ij} = (\mathbf{X}^i - \mathbf{X}^j)(\mathbf{X}^i - \mathbf{X}^j)^H,$$

which, taking into account the codeword structure (1), becomes

$$\mathbf{G}_{ij} = \left(\mathbf{W}_T \mathrm{diag}(\mathbf{G}(\mathbf{s}^i - \mathbf{s}^j))\right) \left(\mathbf{W}_T \mathrm{diag}(\mathbf{G}(\mathbf{s}^i - \mathbf{s}^j))\right)^H.$$

A necessary and sufficient condition on $\mathbf{W}_T$ to optimize the rank and determinant criteria [7, 8], is that

$$\mathbf{W}_T^H \mathbf{W}_T = \mathbf{I}. \tag{4}$$

On the other hand, for any $\mathbf{W}_T$ fulfilling (4) we find that a necessary condition on $\mathbf{G}$ to optimize the rank criterion is given by

$$\mathbf{G}^H \mathbf{G} = \mathbf{I}. \tag{5}$$

Condition (5) is necessary but not sufficient: intuitively, to achieve full diversity it is necessary to spread the symbols over the M time instants and the M antennas. With our RF adaptive antenna combining architecture, this spreading must be performed by the time-encoding matrix $\mathbf{G}$. Therefore, we can take any unitary matrix $\mathbf{W}_T$ for the Tx beamformer (an identity matrix or the $M \times M$ discrete Fourier transform matrix are good candidates to simplify the RF circuitry), and then design $\mathbf{G}$ to achieve full diversity following the ideas discussed in [8–10]. Specifically, assuming maximum likelihood decoding, the optimal $\mathbf{G}$ is given by a shifted version of the Fourier matrix

$$\mathbf{G}(\alpha) = \mathbf{F}^H \mathbf{D}_\alpha,$$

where $\mathbf{F}$ is the $M \times M$ Fourier matrix whose k-th column is

$$\mathbf{f}(\omega_k) = \left(1, e^{-j\omega_k}, \cdots, e^{-j\omega_k(M-1)}\right)^T,$$

where $\omega_k = 2\pi(k-1)/M$; and $\mathbf{D}$ is a diagonal matrix that shifts the frequencies of the Fourier grid an amount α, i.e.,

$$\mathbf{D} = \mathrm{diag}\left(1, e^{-j\alpha}, \ldots, e^{-j(M-1)\alpha}\right).$$

The optimal α depends on the codeword size; for instance, for M power of two we should use $\alpha = \frac{3\pi}{2M}$ [9].

Typically, the implementation of the ML decoder needed to get full diversity has a prohibitively high complexity. Therefore, in practice we are willing to give up some diversity (which only shows up at very high SNRs), and work with a minimum mean-square error (MMSE) detector. In this case, the value of α is irrelevant and we can work with a time encoder given by $\mathbf{G} = \mathbf{F}^H$ [8].

Finally, once a particular unitary matrix has been chosen at the transmitter RF beamformer, the best receiving RF beamformer is given by the maximal ratio combining (MRC) receiver

$$\mathbf{w}_R[n] = \frac{\mathbf{H}\mathbf{w}_T[n]}{||\mathbf{H}\mathbf{w}_T[n]||} \quad n = 1, \cdots, M, \tag{6}$$

which maximizes the SNR [11].

To summarize, the proposed Tx-Rx scheme for the considered scenario is to use $\mathbf{W}_T = \mathbf{F}$, $\mathbf{G} = \mathbf{F}^H$ and $\mathbf{W}_R$ given by (6). That is, the original M symbols are time-precoded with a unitary DFT matrix, then they are successively transmitted through M orthogonal directions and finally the receiver uses MRC followed by an MMSE decoder. We refer to this transmission scheme as orthogonal beam division multiplexing (OBDM), since it mimics orthogonal frequency division multiplexing (OFDM) systems. More precisely, in OFDM systems precoding and multiplexing are performed in the frequency domain, whereas in OBDM precoding is carried out in the time domain and multiplexing is performed in space-time.
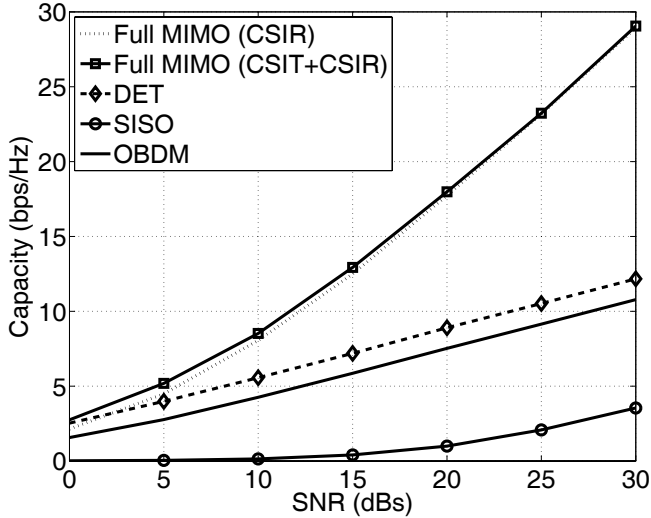
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[1]In the i.i.d. Rayleigh case, the asymptotic array gain of DET is $G_a = \left(\sqrt{n_t} + \sqrt{n_r}\right)^2$, where n_t and n_t are the number of transmitting and receiving antennas, respectively. When $n_t = n_r = M$ the array gain is $G_a = 4M$.

Figure 3: Outage capacity (0.01%) for DET, OBDM, Full MIMO and SISO for a 4x4 i.i.d. Rayleigh MIMO channel.

Figure 4: Outage capacity (0.01%) for DET, OBDM, Full MIMO and SISO for a 4x4 correlated (0.1λ) Rayleigh MIMO channel.

4. SIMULATION RESULTS

In this section we evaluate the performance of the proposed adaptive RF combining architecture using DET and OBDM for a 4×4 MIMO system. We consider a block-fading model in which the propagation coefficients remain constant for a coherence interval of *PM* symbols (i.e., the frame duration in Fig. 2), after which they change to new independent values which are kept constant during the next frame. If channel coding is performed over a single frame, a sensible figure of merit is the $p\%$ outage capacity, defined as the transmission rate that can be supported $1 - p\%$ of the time.

Fig. 3 shows the 0.01% outage capacity of DET and OBDM assuming an i.i.d. Rayleigh MIMO channel. For comparison we also include in the plot the outage capacity of a full MIMO system with either full CSIT+CSIR or CSIR only, and that of a SISO (single-input single-output) channel. As expected, the multiplexing gain (i.e., the slope of the outage capacity curve at a high SNR) for DET and OBDM is just one, the same as a SISO channel. However, the SNR improvement obtained by coherently combining the RF branches in both DET and OBDM, results in a noticeable increase of capacity in comparison to the single antenna system. On the other hand the full MIMO system achieve a multiplexing gain of four, since the four channel modes are being used for transmission.

A final remark from Fig. 3 is that for an i.i.d. MIMO channel the benefit of having perfect CSIT is approximately 1bps/Hz for the proposed architecture (DET versus OBDM), while for a full MIMO system the difference is even smaller. Actually, for a full MIMO system the improvement is only relevant at low SNR: a fact that has been reported before by both theoretical and measurement studies [12].

The impact of spatial channel correlations on the outage behavior of DET and OBDM is of interest because the new transceiver based of RF combining techniques must be very compact in size, which imposes some limitations on the antenna size, especially for mobile terminals. To illustrate the effect of spatial correlation, Fig. 4 shows again the 0.01% outage capacity of the systems under comparison but now
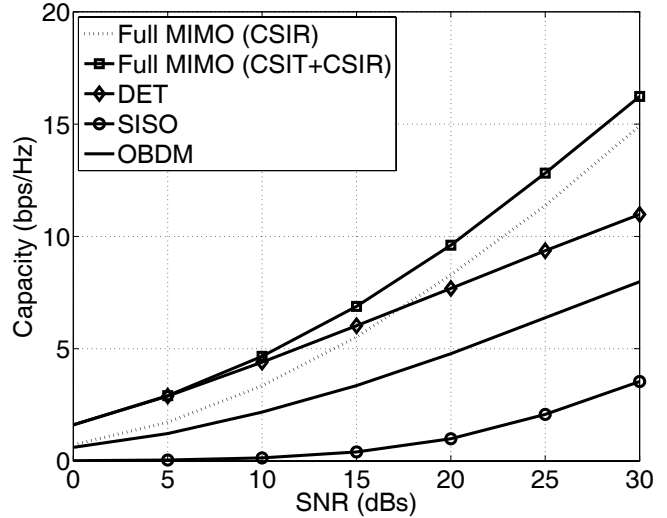
the spacing between antennas is reduced to 0.1λ at Rx and Tx. For this scenario we see that the impact of having CSIT is much more important. Also, there is a clear reduction in the multiplexing gain of the full MIMO systems, because correlation provokes poorly conditioned channels so there is no point in transmitting through different channel modes. In fact, DET has a larger capacity than a full MIMO system with CSIR at low and moderate SNRs. Notice also that for correlated channels DET is still the best strategy, however OBDM is no longer optimal, since in this case the best transmitting directions ($\mathbf{W}_T$) should take into account the transmit and receive correlation matrices. Therefore for correlated channels there is still room for improvement in the perfect CSIR case.

Finally, we compare the performance of DET, OBDM and a full MIMO system in terms of bit error rate (BER). For DET and OBDM a 16-QAM modulation is transmitted, whereas the full MIMO system transmits BPSK signals encoded with a linear trace-orthogonal space-time block code (TOSTBC); therefore the spectral efficiency of all three schemes is 4bps/Hz. It is interesting to remind that TOST-BCs are full-rate, full-diversity and information lossless linear ST codes [13, 14]. Furthermore, they are also optimal in the sense that minimize the BER when a linear MMSE receiver is used and the transmitted signal belongs to a QPSK constellation [15].

Fig. 5 shows the BER for the three schemes assuming an i.i.d. Rayleigh MIMO channel. We see that dominant eigenmode scheme achieves the slope corresponding to full-diversity whereas the TOSTBC and the OBDM do not achieve full-diversity due to the MMSE detector. We also see that TOSTBC saves up to 2 dB of SNR compared to OBDM.

5. CONCLUSIONS

In this paper we have discussed the design of specific signal Tx-Rx schemes for a novel MIMO transceiver that performs signal combining in the radio-frequency domain. The main advantage of this topology is that, after combining in the RF
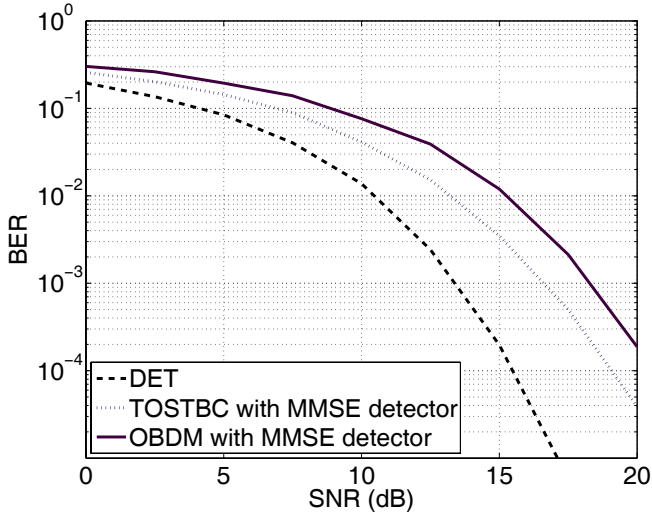
Figure 5: BER for DET, OBDM with MMSE decoding, and a full-rate full-diversity 4×4 TOSTBC with MMSE decoding.

path, there is only one signal stream for baseband processing. Consequently, the power consumption, the size and the system cost can be significantly reduced compared to a conventional (full baseband) MIMO system, for which the hardware must be replicated for each Tx/Rx signal stream. Obviously, since a single stream of data can be transmitted or received at a time, the multiplexing gain of the system is also limited to one. Furthermore, the RF circuitry of the system imposes some limitations on the speed of change of the RF beamformers and, consequently, on the construction of the codewords. Taking into account all these aspects, we have proposed in the paper specific Tx-Rx schemes, which transform the MIMO channel into a set of reliable SISO channels. In this way other benefits of the MIMO channel such as spatial diversity or array gain can be retained by the new architecture.

In particular, when perfect CSI is available at both the transmitter and the receiver sides, the optimal scheme is the well-known dominant eigenmode transmission (DET) technique, which transmits over the strongest spatial mode. When only CSIR is available we have proposed a new technique referred to as orthogonal beam division multiplexing (OBDM), which uses the DFT matrix for both the time and the spatial encoders. This scheme can achieve the full diversity gain under maximum likelihood decoding. If MMSE decoding is used we loose some diversity but the receiver is greatly simplified.

In summary, equipped with the proposed algorithms the RF adaptive antenna combining architecture is an interesting, low cost, and compact solution for MIMO processing; which provides much better performance than a single antenna system and can even be competitive with full MIMO designs in some realistic scenarios. In future work we will consider multicarrier schemes and how to cope with RF impairments such as cross-coupling or phase errors.

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