Equal Gain MIMO Beamforming in the RF Domain for OFDM-WLAN Systems

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Abstract. Equal gain beamforming (EGB) schemes are typically applied in the baseband domain and hence require complex RF transceivers. In order to simplify the circuitry and energy consumption of the MIMO transceiver, in this paper we consider an EGB scheme that operates in the RF domain by means of analog phase shifters. Under OFDM transmissions, the design of the optimal phases is a complicated nonconvex problem with no closed-form solution. Building upon a previously proposed solution for flat-fading MIMO channels, this paper describes an alternating minimization algorithm to find an approximate (suboptimal) solution for the OFDM case. Monte-Carlo simulations are performed in order to demonstrate the effectiveness of this new analog beamforming scheme under coded and uncoded WLAN 802.11a transmissions.

Keywords: Analog Combining, Multiple-Input Multiple-Output (MIMO), Equal-Gain MIMO Beamforming, Orthogonal Frequency Division Multiplexing (OFDM), Wireless Local Area Networks (WLAN).

1 Introduction

Conventional multiple-input multiple-output (MIMO) systems require all antenna paths to be independently acquired and jointly processed at baseband. The hardware cost, complexity and power consumption are therefore increased accordingly. These drawbacks might explain, at least partially, why MIMO technologies have not found yet widespread use in low-cost wireless terminals. One way to increase the energy-efficiency of MIMO terminals and reduce their costs is to simplify the associated hardware and radio-frequency (RF) circuitry as much as possible, while still retaining some of the benefits provided by the MIMO channel (e.g., spatial diversity) by means of specifically designed signal processing algorithms. With this goal in mind, a RF-MIMO architecture that performs spatial processing directly in the analog domain is currently being developed within the EU-funded project MIMAX [1,2].

The combining scheme considered in [1,2], which is depicted for convenience in Fig. 1, permits to change the amplitudes and phases of the transmitted/received RF signals by means of vector modulators (VM). Therefore, for flat-fading MIMO channels and assuming perfect channel state information at both sides

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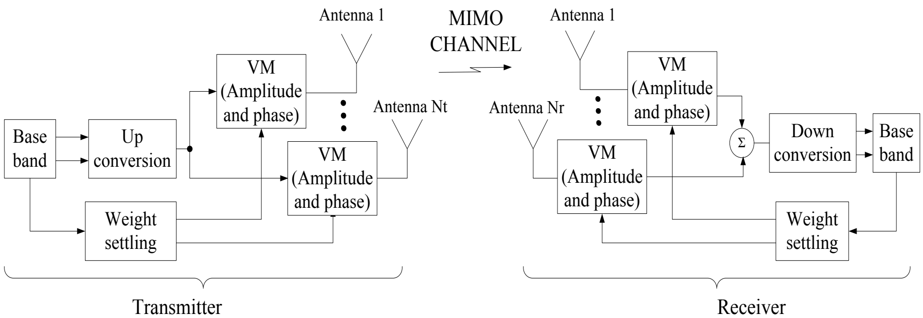

Fig. 1. Maximum ratio beamforming in the radio-frequency domain (RF-MRB)

of the link, it can implement the optimal maximum ratio beamforming (MRB) solution. For this reason, in this paper we will refer to this architecture as RF-MRB (i.e., radio-frequency maximum ratio beamforming). A drawback of the RF-MRB topology is that the average power can vary widely across antennas, which is undesirable for the amplifiers since it can decrease their efficiency [3]. In order to mitigate this problem, in this paper we investigate an alternative radio-frequency equal gain beamforming (RF-EGB) scheme, which substitutes the vector modulators along each branch by analog phase shifters. Specifically, we focus on the optimization problem that results from this beamforming architecture.

For flat-fading single-input multiple-output (SIMO) or multiple-input single-output (MISO) channels, the equal gain beamformers that maximize the signal-to-noise (SNR) ratio are given by the phases of the SIMO or MISO channel, respectively [4]. For flat-fading MIMO channels, however, the optimization problem is nonconvex and no closed-form solution is known. Recently, Zheng et. al. have proposed in [5] an alternating minimization algorithm for the flat-fading MIMO case that uses the SIMO and MISO closed-form solutions iteratively by fixing one side of the link and solving for the other. Under OFDM transmissions the optimization problem becomes more challenging, since now we have to optimize a global measure of performance (typically the SNR) using a common set of Tx-Rx phases for all subcarriers. Building upon [5] and our own previous work in [6,7,8], the main contribution of this paper is to provide a suboptimal solution for this optimization problem and study its performance by means of simulations.

This paper is organized as follows. In Section 2 we present the analog MIMO beamforming architecture based on phase shifters. In Section 3 we summarize the EGB algorithm for flat-fading MIMO channels proposed in [5]. Section 4 contains the main contribution of this paper, which is the approximate maximum SNR solution for the RF-EGB architecture under OFDM transmissions. In Section 5 we compare the performance in 802.11a WLAN systems of the proposed RF-EGB beamforming architecture with the RF-MRB, the full-baseband MIMO and the SISO schemes. Finally, the main conclusions are summarized in Section 6.

1.1 Notation

Bold upper and lower case letters denote matrices and vectors respectively; light-faced lower case letters denote scalar quantities. We use $(\cdot)^H$, $(\cdot)^T$ and $\|\cdot\|$ to denote Hermitian, transpose and the Frobenius norm, respectively. $\mathbf{v}_{max}(\mathbf{A})$ is the principal eigenvector of the Hermitian semidefinite positive matrix $\mathbf{A}$. We use $\mathrm{dist}(\mathbf{x}, \mathbf{y})$ to denote the Euclidean distance between vectors $\mathbf{x}$ and $\mathbf{y}$. The vector formed by the phase angles of $\mathbf{x}$ is denoted as $\angle\mathbf{x}$. Finally, the expectation operator is denoted as $E[\cdot]$.

2 Proposed RF-EGB Architecture

The RF-EGB MIMO architecture studied in this paper is schematically shown in Fig. 2. Essentially, the vector modulators in Fig. 1 are now substituted by wide-band analog phase shifters. In this way, we avoid the power imbalance among the various antenna branches and the wide power variations that can happen in maximum ratio beamforming schemes. As long as the gains of the amplifiers of the various branches match, the rest of the parameters can be relaxed and inexpensive amplifiers can then be utilized. We consider WLAN 802.11a transmissions [9] that use orthogonal frequency division multiplexing (OFDM) and achieve a data transmission of up to 54 Mbps. It is important to mention here that the RF-EGB architecture does not try to solve the PAPR (peak-to-average power ratio) problem of OFDM modulations, it just avoids power variations among the analog signal paths. To mitigate this important problem of OFDM systems, we could apply one of the many proposed PAPR reduction techniques [10] or operate the amplifiers with some back-off.

It is also assumed that both the transmitter and the receiver have perfect channel state information, which has been obtained using specifically designed training sequences. The system is intended for low-mobility indoor scenarios as those encountered in WLAN transmissions, therefore we consider that the channel remains static during the transmission of several frames. More details about the training procedure and other implementation aspects of RF-MIMO transceivers can be found in [1,2] and the references therein.

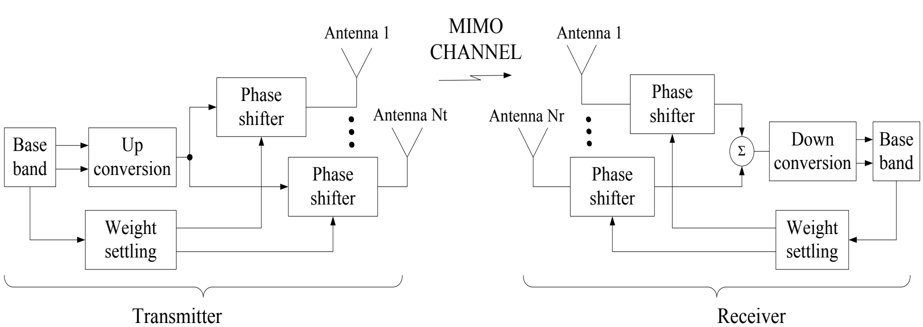

Fig. 2. Equal gain beamforming in the radio-frequency domain (RF-EGB)

The RF-EGB architecture poses several implementation challenges. For instance, it can be difficult to design wideband phase shifters achieving a constant phase change without any amplitude variation over the 20 MHz bandwidth required in WLAN 802.11a transmissions. Also, the automatic gain control system at the receiver side can affect the equal gain beamforming. To simplify the analysis, however, in this paper we will consider an idealized system in which all these circuitry impairments are neglected, and we will focus just on the optimization problem.

3 RF-EGB Solution for Flat-Fading MIMO Channels

In this section we describe the baseband model for MIMO beamforming schemes, and summarize the iterative EGB solution proposed in [5] for flat fading MIMO channels. Let us consider an $N_r \times N_t$ MIMO system with N_t transmit and N_r receive antennas. The unit-norm transmit and receive beamformers are $\mathbf{w}_t = (w_{t,1} w_{t,2} ... w_{t,N_t})^T$ and $\mathbf{w}_r = (w_{r,1} w_{r,2} ... w_{r,N_r})^T$, respectively. Although these beamformers are implemented in the RF domain, we can use the conventional baseband model for the received signal

$$y = \mathbf{w}_r^H \mathbf{H} \mathbf{w}_t s + \mathbf{w}_r^H \mathbf{n},$$

where $s \in \mathbb{C}$ is the transmitted symbol, $\mathbf{H} \in \mathbb{C}^{N_r \times N_t}$ is the flat-fading MIMO channel matrix, and $\mathbf{n} \in \mathbb{C}^{N_r \times 1}$ is the noise vector, whose entries are independent identical distributed (i.i.d.) complex Gaussian random variables with zero-mean and variance σ_n^2.

Notice that using MIMO beamforming the symbols are transmitted through an equivalent SISO channel: $h = \mathbf{w}_r^H \mathbf{H} \mathbf{w}_t$. Assuming now that the transmitted sequence has unit power, the receive SNR is given by

$$\mathrm{SNR} = \frac{E\left[\left|\mathbf{w}_r^H \mathbf{H} \mathbf{w}_t s\right|^2\right]}{E\left[\left|\mathbf{w}_r^H \mathbf{n}\right|^2\right]} = \frac{\left|\mathbf{w}_r^H \mathbf{H} \mathbf{w}_t\right|^2}{\sigma_n^2} . \tag{1}$$

With maximum ratio beamforming we obtain the beamformer weights (amplitudes and phases) that maximize the receive SNR given by (1). As it is well-known, this maximization problem has a closed-form solution which is given by the left and right singular vectors corresponding to the largest singular value of $\mathbf{H}$ [11]. However, for equal gain beamforming an additional constraint must be added to the problem: the elements of the transmit and receive beamformers have a constant modulus, $1/\sqrt{N_t}$ for $\mathbf{w}_t$, and $1/\sqrt{N_r}$ for $\mathbf{w}_r$. Therefore, the SNR maximization problem with EGB can be formulated as

$$\max_{\{\mathbf{w}_r, \mathbf{w}_t\}} \left|\mathbf{w}_r^H \mathbf{H} \mathbf{w}_t\right|^2 \tag{2}$$

$$\text{subject to}: \left|\mathbf{w}_{r,i}\right|^2 = \frac{1}{N_r}, \qquad i = 1, 2, \ldots, N_r,$$

$$\left|\mathbf{w}_{t,j}\right|^2 = \frac{1}{N_t}, \qquad j = 1, 2, \ldots, N_t.$$

This is a nonconvex optimization problem which has no known closed-form solution. In [5] this problem is solved by means of a cyclic algorithm. First, it is shown that, unlike the MIMO case, for MISO and SIMO channels the equal gain beamforming problems have the following well-known closed-form solutions [4]

$$\mathbf{w}_t = \frac{e^{j\angle \mathbf{h}_{\mathrm{MISO}}{}^H}}{\sqrt{N_t}}, \qquad \mathbf{w}_r = \frac{e^{j\angle \mathbf{h}_{\mathrm{SIMO}}}}{\sqrt{N_r}} . \tag{3}$$

where $\mathbf{h}_{\mathrm{MISO}} \in \mathbb{C}^{1\times N_t}$ and $\mathbf{h}_{\mathrm{SIMO}} \in \mathbb{C}^{N_r\times 1}$ are the MISO and SIMO channel vectors, respectively. By exploiting this result, the equal gain beamformers for the MIMO case are obtained in [5] applying an alternating minimization approach as follows:

1. **Step 0:** Initialize $\mathbf{w}_r$ as the left singular vector of $\mathbf{H}$ corresponding to its largest singular value.
2. **Step 1:** Fix $\mathbf{w}_r$ and obtain $\mathbf{w}_t$ as the solution of the MISO case by taking $\mathbf{h}_{\mathrm{MISO}} = \mathbf{w}_r\mathbf{H}$ as the effective (equivalent) MISO channel

$$\mathbf{w}_t = \frac{e^{j\angle \mathbf{H}^H \mathbf{w}_r}}{\sqrt{N_t}} . \tag{4}$$

3. **Step 2:** Fix $\mathbf{w}_t$ and obtain $\mathbf{w}_r$ as the solution of the SIMO case by taking $\mathbf{h}_{\mathrm{SIMO}} = \mathbf{H}\mathbf{w}_t$ as the effective SIMO channel

$$\mathbf{w}_r = \frac{e^{j\angle \mathbf{H}\mathbf{w}_t}}{\sqrt{N_r}} . \tag{5}$$

Iterate steps 1 and 2 until a given stop criterion is satisfied, in our case we proposed to use the Euclidean distance between two consecutive beamformers

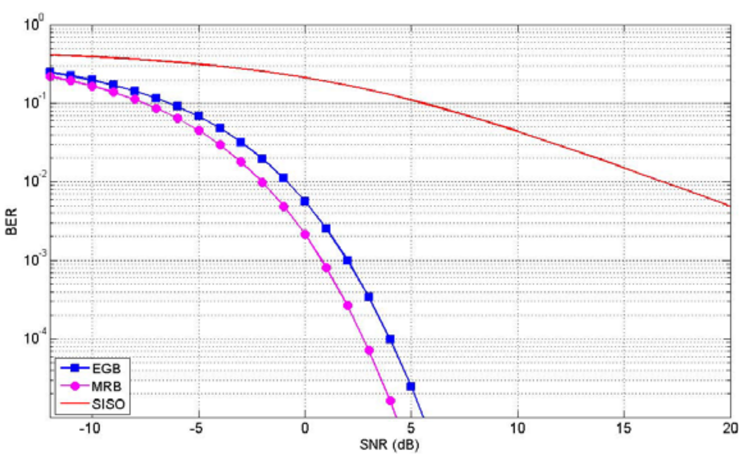

Fig. 3. Bit error rate comparison for EGB and MRB. QPSK symbols.

as the stop criterion. Specifically, the algorithm is stopped when the following two conditions are simultaneously satisfied:

$$|\mathrm{dist}(\mathbf{w}_{t,k}, \mathbf{w}_{t,k-1})| < \mathrm{dist}_{\max} \quad \text{and} \quad |\mathrm{dist}(\mathbf{w}_{r,k}, \mathbf{w}_{r,k-1})| < \mathrm{dist}_{\max}, \tag{6}$$

where k denotes iteration and $\mathrm{dist}_{\max}$ is the maximum error allowed. As an example of its performance, we show in Fig. 3 a comparison between MRB and EGB for a 4x4 Rayleigh flat-fading MIMO channel. It is clear that EGB attains the same spatial diversity than MRB, although we are losing part of the array gain, about 1.2 dB in this particular example.

4 RF-EGB Solution for OFDM-MIMO Channels

Under OFDM transmissions, the RF-EGB optimization problem becomes even harder due to the coupling among subcarriers. In fact, this problem is closely related to the design of pre-FFT schemes, which have been proposed to reduce the computational cost of conventional OFDM-MIMO transceivers [12,**?**]. However, these pre-FFT techniques are applied in the baseband and typically optimize the amplitudes and phases, therefore they are not directly applicable to our system.

Assume an OFDM transmission scheme with N_c data carriers and with a cyclic prefix longer than the channel impulse response and let $\mathbf{H}_k \in \mathbb{C}^{N_r \times N_t}$ be the MIMO channel for the k-th data-carrier. After analog Tx-Rx beamforming, at each carrier we have an equivalent SISO channel given by

$$h_k = \mathbf{w}_r^H \mathbf{H}_k \mathbf{w}_t, \qquad k = 1, \ldots, N_c \; .$$

Our goal is to find the equal gain Tx-Rx beamformers maximizing the overall receive SNR, i.e.,

$$\mathrm{SNR} = \frac{\displaystyle\sum_{k=1}^{N_c} \left|\mathbf{w}_r^H \mathbf{H}_k \mathbf{w}_t\right|^2}{\sigma_n^2} \; . \tag{7}$$

Therefore we can pose the RF-EGB SNR maximization problem as follows

$$\begin{aligned} &\max_{\{\mathbf{w}_r, \mathbf{w}_t\}} \sum_{k=1}^{N_c} \left|\mathbf{w}_r^H \mathbf{H}_k \mathbf{w}_t\right|^2 \\ &\text{subject to} : |\mathbf{w}_{r,i}|^2 = \frac{1}{N_r}, \qquad i = 1, 2, \ldots, N_r \\ &\qquad\qquad\quad |\mathbf{w}_{t,j}|^2 = \frac{1}{N_t}, \qquad j = 1, 2, \ldots, N_t. \end{aligned} \tag{8}$$

To obtain a suitable solution to this problem, we suggest a cyclic algorithm inspired by the one previously described for the flat-fading case in Section 3. In the next subsection we first propose a closed-form (but suboptimal) solution for the frequency-selective MISO/SIMO cases.

4.1 EGB for Frequency-Selective MISO/SIMO Channels

For a MISO channel, the problem (8) is reduced to

$$\max_{\{\mathbf{w}_t\}} \sum_{k=1}^{N_c} | \mathbf{h}_{\text{MISO}k} \mathbf{w}_t|^2 \tag{9}$$
$$\text{subject to} : |\mathbf{w}_{t,i}|^2 = \frac{1}{N_t}, \qquad i = 1, 2, \ldots, N_t$$

where $\mathbf{h}_{\text{MISO}k} \in \mathbb{C}^{1\times N_t}$ is the MISO channel vector for the k-th carrier. In order to derive a suboptimal solution for this problem let us rewrite (9) as

$$\max_{\{\mathbf{w}_t\}} \mathbf{w}_t^H \mathbf{R}_{\text{MISO}} \mathbf{w}_t \tag{10}$$
$$\text{subject to} : |\mathbf{w}_{t,i}|^2 = \frac{1}{N_t}, \qquad i = 1, 2, \ldots, N_t$$

where

$$\mathbf{R}_{\text{MISO}} = \sum_{k=1}^{N_c} \mathbf{h}_{\text{MISO}k}^H \mathbf{h}_{\text{MISO}k} \ .$$

Again, the max-SNR problem for the MISO case in Eq. (10) is a complicated nonconvex problem with no closed-form solution. In this paper we propose to use the following simple, yet accurate, approximate solution given by the phases of the principal eigenvector of $\mathbf{R}_{\text{MISO}}$

$$\mathbf{w}_t = \frac{1}{\sqrt{N_t}} e^{j\angle \mathbf{v}_{max}(\mathbf{R}_{\text{MISO}})} \ . \tag{11}$$

This solution is motivated by the fact that the main eigenvector of $\mathbf{R}_{\text{MISO}}$ contains most of the channel energy averaged across carriers and, in consequence, its phases should be close to the optimal solution of (10). In the simulation section we will show some results supporting this claim.

Analogously, the solution for the SIMO case is given by

$$\mathbf{w}_r = \frac{1}{\sqrt{N_r}} e^{j\angle \mathbf{v}_{max}(\mathbf{R}_{\text{SIMO}})} \ , \tag{12}$$

where $\mathbf{R}_{\text{SIMO}} = \sum_{k=1}^{N_c} \mathbf{h}_{\text{SIMO}n} \mathbf{h}_{\text{SIMO}n}^H$.

4.2 Alternating minimization Algorithm

Inspired by the cyclic algorithm in [5], which was summarized in Section 3, we solve the SNR maximization problem in (8) as follows

1. **Step 0:** Initialize $\mathbf{w}_r$ (e.g., to a random value).
2. **Step 1:** Consider $\mathbf{w}_r$ fixed and take $\mathbf{h}_{\text{MISO}k} = \mathbf{w}_r^H \mathbf{H}_k$ as the equivalent MISO channel for each subcarrier. The solution for $\mathbf{w}_t$ is then given by (11).
3. **Step 2:** With $\mathbf{w}_t$ fixed to the value obtained in the previous step, construct the equivalent SIMO channels as $\mathbf{h}_{\text{SIMO}k} = \mathbf{H}_k \mathbf{w}_t$ and obtain the solution for the receive equal gain beamformer as (12).

Steps 1 and 2 are iterated until the criterion defined in (6) is satisfied.

5 Simulation Results

In this section, we evaluate the performance of the proposed algorithm by means of numerical simulations in MATLAB. For all simulations we consider a Rayleigh 4x4 MIMO channel model with an exponential power delay profile parameterized by ρ, i.e.,

$$E\left[\|\mathbf{H}[l]\|^2\right] = \rho^l \frac{1-\rho}{1-\rho^L} N_r N_t \qquad l = 0, \ldots, L-1,$$

where $L = 16$ is the length of the channel impulse response which is assumed to be equal to the cyclic prefix length. To check the convergence of the algorithm we use a maximum error of $\text{dist}_{\max} = 10^{-3}$ (see Eq. (6)).

To verify the goodness of our method we first study how far is the proposed suboptimal solution from the optimal one obtained by means of a brute-force search. To this end we consider simple 1×2 and 1×3 MISO systems and evaluate the energy of the equivalent SISO channel, $\sum_{k=1}^{N_c} | \mathbf{h}_{\text{MISO}k} \mathbf{w}_t|^2$, for both the suboptimal and optimal solutions. For high frequency-selective channels (i.e., $\rho = 1$), we found that the optimal equal-gain beamformer outperforms our suboptimal solution by less than 10^{-3} dB and 10^{-2} dB for the 1×2 and 1×3 MISO channels, respectively. In addition, we found that as the channel becomes less frequency selective our suboptimal solution gets even closer to the optimal one. This support our claim that the proposed method provides a good approximation of the optimal equal-gain beamforming phases.

Now, we compare the performance of the following methods:

1. RF-MIMO architecture with the proposed equal gain beamforming algorithm (RF-EGB).
2. RF-MIMO architecture with maximum ratio beamforming (RF-MRB)
3. Conventional baseband MIMO-OFDM system with optimal (per-carrier) maximum ratio beamforming (Full-MIMO)
4. SISO system.

For the RF-MRB architecture we apply the maximum SNR solution obtained with the algorithm described in [8]. The Full-MIMO and the SISO schemes can be seen as the upper and lower bounds, respectively, for the performance of any system. For these simulations ρ has been fixed as $\rho = 0.7$, which represents a high frequency-selective MIMO channel.

We consider coded and uncoded transmissions with frames generated according to the 802.11a WLAN standard [9] (OFDM symbols with 64 carriers, out of them 48 are data carriers, 4 are pilots and the rest are unused). Nevertheless, let us remark that throughout this paper we have assumed perfect channel knowledge and therefore the pilots were not used for channel estimation. The impact of the channel estimation errors and other RF impairments is left for future work.

In the first simulation example we consider uncoded QPSK modulated data to be transmitted over the 48 data carriers. The bit error rate (BER) curves

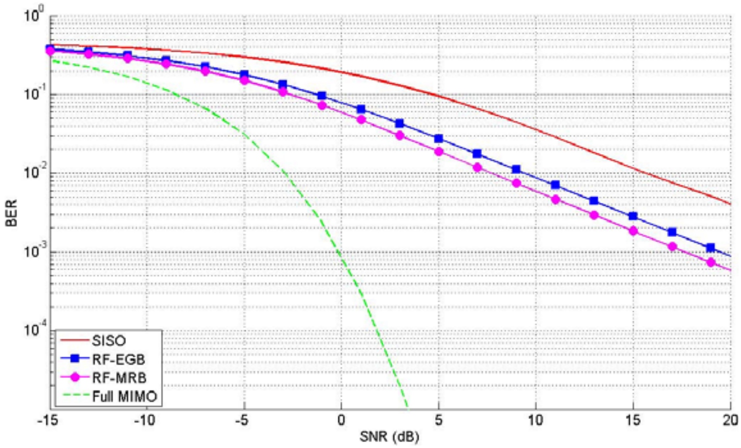

Fig. 4. Bit error rate vs. SNR for the compared algorithms. Uncoded QPSK symbols.

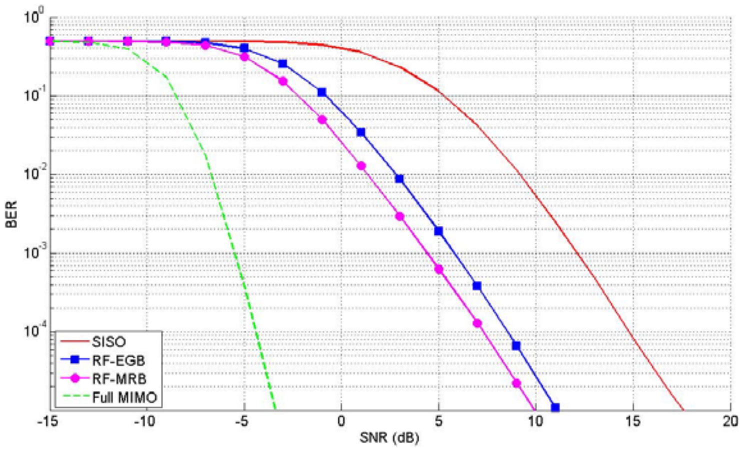

Fig. 5. Bit error rate for the compared algorithms. Coded QPSK symbols, R=1/2, 12 Mbps.

for the different methods are shown in Fig. 4. As we can observe, for uncoded transmissions and high frequency-selective MIMO channels, both RF-MIMO architectures fail to extract any or almost no frequency/spatial diversity, since the performance is limited by the worst subcarriers. Both schemes, however, achieve an important array gain in comparison to a SISO system. The RF-EGB performance is always inferior to the RF-MRB performance and the gap depends on the number of antennas and the frequency selectivity of the channel (i.e., ρ). For a BER=10^{-3} this loss is approximately 1.8 dB.

For the second example we have chosen a more realistic scenario using coded transmissions under the 802.11a standard for a 12 Mbps rate (QPSK modulation

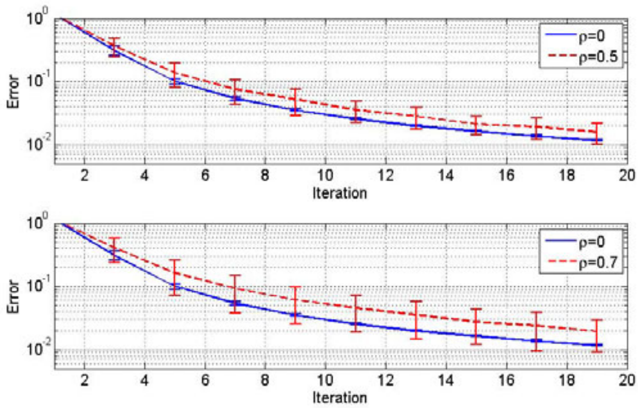

Fig. 6. Convergence of the algorithm for different values of ρ. 4x4 antenna configuration.

and a code rate of 1/2). The data bits are encoded with a convolutional code and block interleaved as specified in the 802.11a standard. The receiver is based on a hard decision Viterbi decoder. The results are shown in Fig. 5: with coded transmissions, both analog combining schemes are able to extract, at least partly, the frequency and spatial diversity of the channel, although there is still an important gap with respect to the Full-MIMO architecture. Nevertheless, as it has been shown in [6,7,8] this gap can be diminished by optimizing other cost functions (the mean square error, for instance) instead of the SNR. Obviously, MRB achieves better results than EGB; however, the difference for a BER=10^{-3} is about 1.4 dB. Again, this supports our claim that the approximate EGB solution proposed in this paper is close to the optimal one.

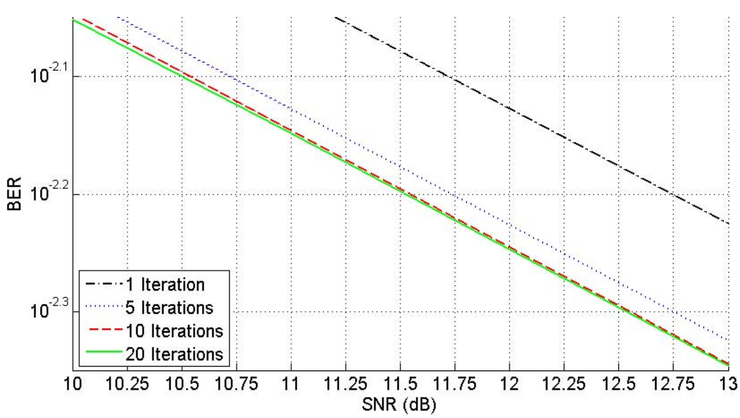

Fig. 7. BER curves for different number of iterations. 4x4 RF-EGB system, QPSK uncoded symbols and channel with $\rho = 0.7$.

In Fig. 6 we illustrate the convergence of the proposed alternating minimization algorithm for different values of ρ. These plots represent the Euclidean distance between beamformers obtained in two consecutive iterations. The convergence curves have been obtained by averaging 500 independent trials, and the vertical bars indicate the variance. Finally, Fig. 7 presents the evolution of the BER curves with the number of iterations in the SNR range of 10-13 dB. We can conclude that the algorithm converges very fast within the first 10 iterations, although the convergence speed decreases and the variance increases for larger values of ρ (i.e., for high frequency-selective channels).

6 Conclusions

MIMO transceivers performing spatial processing in the RF domain (RF-MIMO) are a good alternative in order to reduce the hardware cost and system size, as well as to increase the energy-efficiency of the system. In this paper we have studied a particular scheme (RF-EGB), which applies the equal gain combining concept and only uses phase shifters before the analog combiner, instead of full vector modulators as previously proposed (RF-MRB scheme). Under OFDM-WLAN transmissions, the proposed scheme results in a complicated optimization problem since the Tx-Rx analog equal gain beamformers simultaneously affects all subcarriers. We have proposed simple (but suboptimal) solutions for the MISO and SIMO cases, and based on these, a cyclic minimization algorithm to get the maximum SNR solution for the MIMO case. The proposed algorithm has been shown to provide good results with a low computational complexity, since it converges in very few iterations. Coded and uncoded data 802.11a transmissions have been simulated, and in both cases, RF-EGB has shown to behave only slightly inferior to the RF-MRB scheme.

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