

Simplified Architectures for Analogue Antenna Combining

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Abstract: An architecture for implementing the maximum ratio combining (MRC) in the radio-frequency (RF) domain has recently been proposed based on applying vector modulators at each branch. In this paper we study a simplified architecture, which eliminates the need for IQ mixing and reduces the number of adders. Interestingly, the optimal beamforming solution, derived according to a minimum mean-square error (MMSE) criterion, reduces to the application of beamformers with real coefficients. Moreover, the real beamformer is given by the largest eigenvector of a $n_R \times n_R$ real matrix formed by adding the outer products of the real and imaginary parts of the single-input multiple-output (SIMO) channel, which must be known at the receiver. From our point of view, the reduction in system size and power consumption of the simplified architecture justifies its performance degradation, which is always lower than 3 dB. Finally, the performance of the proposed scheme is illustrated by means of some numerical results.

Keywords: Analog beamforming, diversity combining, maximum ratio combining (MRC), minimum mean-square error (MMSE).

1. Introduction

An alternative to achieve most of the benefits of multiple-input multiple-output (MIMO) systems (e.g., spatial diversity and array gain), without excessively increasing the hardware cost and system size, consists of performing the spatial processing in the radio-frequency (RF) domain. Several alternatives for analog combining of multiple receive antennas have been proposed in the last decade, mainly based on variable-gain amplifiers (VGA) and phase shifters applied on each branch [1, 2]. Until very recently, these RF combining schemes provided limited performance, especially because phase shifters tend to exhibit significant amplitude variations. However, some recent advances on SiGe-BiCMOS-technology, jointly with some innovative concepts introduced for phase and amplitude control circuits [3] have made possible to develop a full 360° control range of the phase shifter together with an amplitude control of more than 20 dB. Consequently, the use of RF architectures for analog combining has recently received renewed interest as an enabling technology for compact mobile handhelds equipped with multiple antennas [4–7].

A general RF beamformer architecture that uses a vector modulator approach is shown in Fig. 1. If the SIMO channel is known at the receiver, this scheme can implement the optimal maximum ratio combining (MRC) solution by choosing properly the gains of the inphase and quadrature signals at each branch. Despite its advantages in

comparison to a full baseband implementation (which would require a complete down-conversion chain followed by an analog-to-digital converter per receive antenna), this MRC analog combining scheme still requires a considerable amount of components. Taking this into account, the goal of this paper is threefold: i) to propose a simplified architecture for analog combining; ii) to derive the minimum mean-square error (MMSE) beamformer for the new architecture, and iii) to perform a comparative analysis of the proposed RF architecture with respect to the optimal MRC analog combining scheme in terms of system size, power consumption and performance (bit error rate).

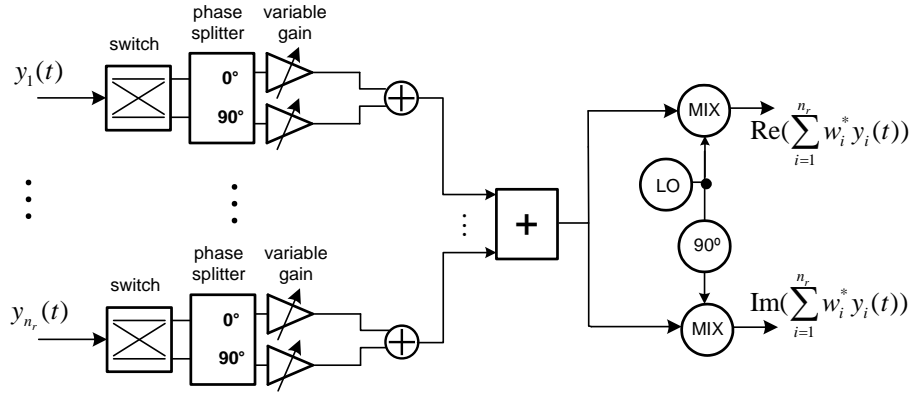


Figure 1: MRC analog combining architecture.

The proposed system architecture, which we refer to as real beamforming (RB), allows a significant complexity reduction while maintaining a small performance degradation with respect to the MRC solution. Finally, we must point out that, in order to simplify the presentation of the main ideas, the system analysis and design is carried out from a baseband point of view. Furthermore, in this paper we do not consider potential implementational issues such as IQ imbalance, which are left as a topic for future research.

2. A new RF architecture for analog receive beamforming

In this paper we assume a flat fading single-input multiple-output (SIMO) channel, and a receiver equipped with n_R antennas. An RF analog combining (i.e., receive beamforming) architecture that uses a vector modulator at each branch [4] is shown in Fig. 1.

By properly choosing the analog weights, this scheme can implement in the RF domain the conventional baseband operation given by

$$z = \mathbf{w}^H \mathbf{y} = (\mathbf{w}^H \mathbf{h}) s + \mathbf{w}^H \mathbf{n}, \quad (1)$$

where $\mathbf{h} = (\mathbf{h}_1, \dots, \mathbf{h}_{n_R})^T$ is the SIMO channel, \mathbf{y} is the received signal, s is the transmitted symbol, \mathbf{n} is the noise and $\mathbf{w} = (\mathbf{w}_1, \dots, \mathbf{w}_{n_R})^T$ is the complex beamvector. Under the common assumption of i.i.d Gaussian noise with variance σ^2 , the optimal diversity combining solution for this architecture is the well-known maximum ratio combining (MRC) beamformer $\mathbf{w} = \mathbf{h} / \|\mathbf{h}\|$.

Fig. 2 shows an alternative simplified RF architecture which eliminates the adder stage after the vector modulators and the IQ mixing. The baseband model corresponding to the operations carried out by this scheme is equivalent to an independent processing of the real and imaginary parts of the received signal, i.e.,

$$\underbrace{\begin{pmatrix} z_R \\ z_I \end{pmatrix}}_{\mathbf{z} \in \mathbb{R}^{2 \times 1}} = \underbrace{\begin{pmatrix} \mathbf{w}_R^T & \mathbf{0} \\ \mathbf{0} & \mathbf{w}_I^T \end{pmatrix}}_{\mathbf{W} \in \mathbb{R}^{2 \times 2n_R}} \underbrace{\begin{pmatrix} \mathbf{y}_R \\ \mathbf{y}_I \end{pmatrix}}_{\mathbf{y} \in \mathbb{R}^{2n_R \times 1}}. \quad (2)$$

where \mathbf{w}_R and \mathbf{w}_I define the real and imaginary parts of the complex beamformer: $\mathbf{w} = \mathbf{w}_R + j\mathbf{w}_I$. This RF architecture is denoted in this paper as real beamforming (RB) for reasons that will be evident later.

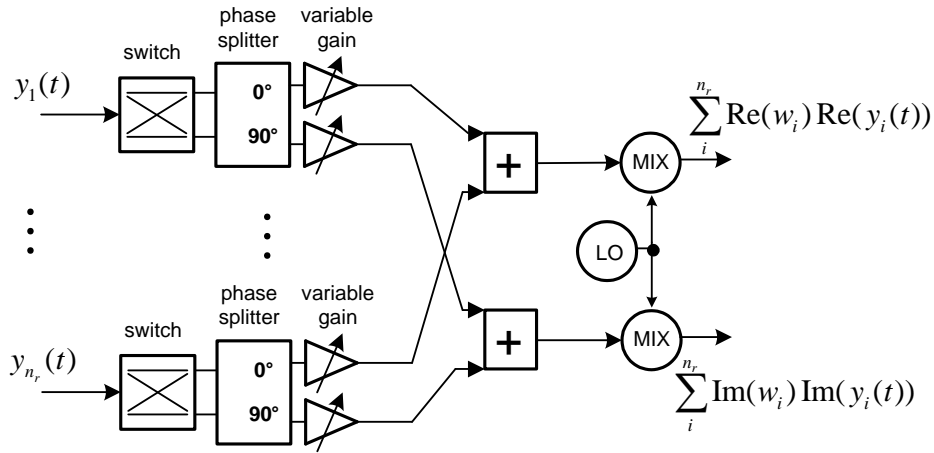


Figure 2: New analog combining architecture (*real beamforming*).

3. Optimum weights for the new architecture

Using vectors and matrices with real elements, the equivalent base band signal model can be expressed more compactly as

$$\mathbf{z} = \mathbf{W}(\mathbf{H}\mathbf{s} + \mathbf{n}), \quad (3)$$

where, for instance, the $2n_R \times 2$ real equivalent channel is obtained from the SIMO channel $\mathbf{h} = \mathbf{h}_R + j\mathbf{h}_I$ as

$$\mathbf{H} = \begin{pmatrix} \mathbf{h}_R & -\mathbf{h}_I \\ \mathbf{h}_I & \mathbf{h}_R \end{pmatrix}.$$

As an optimality criterion we consider the minimum mean-square error (MMSE) between the transmitted signal and its estimate at the output of the beamformer. Thus, the question of what is the optimal (MMSE) beamformer for this new scheme is not as trivial as it might appear at first glance.

3.1 MMSE beamformer design

According to model (3) and under the assumption of unit power transmissions ($E[|s|^2] = 1$), the linear minimum mean square error (LMMSE) estimator of \mathbf{s} given \mathbf{H} and \mathbf{W} is

$$\hat{\mathbf{s}} = \left(\sigma^2 \mathbf{I} + (\tilde{\mathbf{W}}\mathbf{H})^T (\tilde{\mathbf{W}}\mathbf{H}) \right)^{-1} (\tilde{\mathbf{W}}\mathbf{H})^T \mathbf{y}, \quad (4)$$

where

$$\tilde{\mathbf{W}} = (\mathbf{W}\mathbf{W}^T)^{-1/2} \mathbf{W} = \begin{pmatrix} \tilde{\mathbf{w}}_R & \mathbf{0} \\ \mathbf{0} & \tilde{\mathbf{w}}_I \end{pmatrix},$$

and $\tilde{\mathbf{w}}_R = \mathbf{w}_R / \|\mathbf{w}_R\|$, $\tilde{\mathbf{w}}_I = \mathbf{w}_I / \|\mathbf{w}_I\|$. Thus, the MSE matrix is given by

$$\varepsilon(\tilde{\mathbf{W}}) = E[(\mathbf{s} - \hat{\mathbf{s}})(\mathbf{s} - \hat{\mathbf{s}})^T] = \left(\mathbf{I} + \frac{1}{\sigma^2} (\tilde{\mathbf{W}}\mathbf{H})^T (\tilde{\mathbf{W}}\mathbf{H}) \right)^{-1}. \quad (5)$$

For any Schur-concave objective function of the vector containing the individual MSEs, the optimal beamformer coefficients are those that diagonalize the MSE matrix while minimizing its trace [8]. On the other hand, for Schur-convex objective functions the optimal beamformers must give an MSE matrix with equal diagonal elements (i.e., equal MSEs for s_R and s_I) and minimum trace. For our problem, the matrix $(\tilde{\mathbf{W}}\mathbf{H})^T (\tilde{\mathbf{W}}\mathbf{H})$ in (5) is given by

$$(\tilde{\mathbf{W}}\mathbf{H})^T (\tilde{\mathbf{W}}\mathbf{H}) = \begin{pmatrix} \tilde{\mathbf{w}}_R^T \mathbf{h}_R \mathbf{h}_R^T \tilde{\mathbf{w}}_R + \tilde{\mathbf{w}}_I^T \mathbf{h}_I \mathbf{h}_I^T \tilde{\mathbf{w}}_I & -\tilde{\mathbf{w}}_R^T \mathbf{h}_I \mathbf{h}_R^T \tilde{\mathbf{w}}_R + \tilde{\mathbf{w}}_I^T \mathbf{h}_R \mathbf{h}_I^T \tilde{\mathbf{w}}_I \\ -\tilde{\mathbf{w}}_R^T \mathbf{h}_R \mathbf{h}_I^T \tilde{\mathbf{w}}_R + \tilde{\mathbf{w}}_I^T \mathbf{h}_I \mathbf{h}_R^T \tilde{\mathbf{w}}_I & \tilde{\mathbf{w}}_R^T \mathbf{h}_I \mathbf{h}_I^T \tilde{\mathbf{w}}_R + \tilde{\mathbf{w}}_I^T \mathbf{h}_R \mathbf{h}_R^T \tilde{\mathbf{w}}_I \end{pmatrix}. \quad (6)$$

Therefore, the MSE matrix is diagonalized as long as the real and imaginary parts of the beamformer are equal, i.e., $\tilde{\mathbf{w}}_R = \tilde{\mathbf{w}}_I$. Interestingly, with this choice of the beamformer, the MSE matrix not only becomes diagonal, but it also has equal diagonal elements

$$(\tilde{\mathbf{W}}\mathbf{H})^T (\tilde{\mathbf{W}}\mathbf{H}) = \begin{pmatrix} \tilde{\mathbf{w}}_R^T (\mathbf{h}_R \mathbf{h}_R^T + \mathbf{h}_I \mathbf{h}_I^T) \tilde{\mathbf{w}}_R & 0 \\ 0 & \tilde{\mathbf{w}}_I^T (\mathbf{h}_R \mathbf{h}_R^T + \mathbf{h}_I \mathbf{h}_I^T) \tilde{\mathbf{w}}_I \end{pmatrix}. \quad (7)$$

Finally, to minimize the trace of the MSE matrix, $\tilde{\mathbf{w}}_R$ (and $\tilde{\mathbf{w}}_I$) must be the eigenvector corresponding to the largest eigenvalue of the following $n_R \times n_R$ real matrix

$$\mathbf{R} = \mathbf{h}_R \mathbf{h}_R^T + \mathbf{h}_I \mathbf{h}_I^T. \quad (8)$$

3.2 Analysis of the performance loss

It is well known that, in the case of the MRC receiver (see Fig. 1), the equivalent system after beamforming is

$$z = \|\mathbf{h}\|s + n,$$

where n is the complex i.i.d noise with zero mean and variance σ^2 . Therefore, the signal to noise ratio is

$$\text{SNR}_{\text{MRC}} = \frac{\|\mathbf{h}\|^2}{\sigma^2}.$$

In the case of the new architecture, the equivalent system after receive beamforming and MMSE receiver is

$$z = \sqrt{\lambda_1(\mathbf{R})}s + n,$$

where n is the complex i.i.d. noise with variance σ^2 and $\lambda_1(\mathbf{R})$ denotes the largest eigenvalue of \mathbf{R} . Thus, the signal to noise ratio is

$$\text{SNR}_{RB} = \frac{\lambda_1(\mathbf{R})}{\sigma^2}.$$

Now, taking into account that \mathbf{R} is a rank-two matrix with trace $\text{Tr}(\mathbf{R}) = \|\mathbf{h}\|^2$, it can be easily seen that

$$\frac{\|\mathbf{h}\|^2}{2} \leq \lambda_1(\mathbf{R}) \leq \|\mathbf{h}\|^2,$$

where the lower (resp. upper) bound is attained when \mathbf{h}_R and \mathbf{h}_I are orthogonal (resp. colinear). Thus, we can conclude that the performance loss of the RB architecture with respect to a MRC system is never higher than 3 dB.

4. Simplifying the real beamformer

Interestingly, the equality between the real and imaginary parts of the optimal beamformer allows a further simplification of the proposed combining architecture, which is shown in Fig. 3. We denote this RF architecture as simplified real beamforming (SRB).

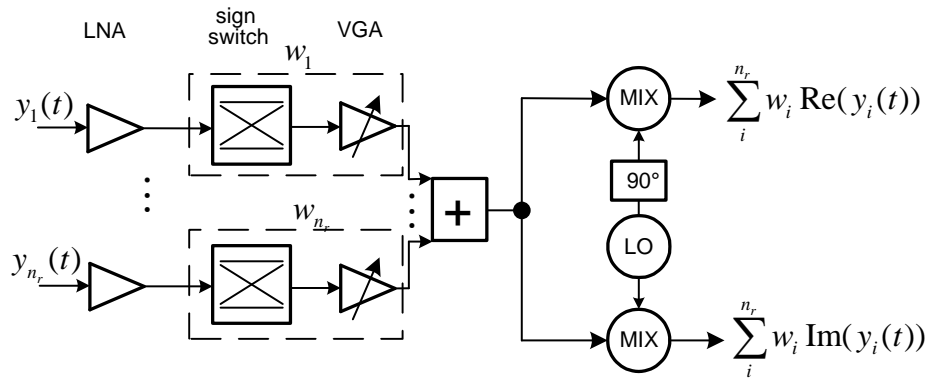


Figure 3: Simplified architecture for analog *real beamforming*.

Notice that, when the optimal beamformer obtained in the last section is used, the RB and SRB schemes, which are shown in Figs. 2 and 3 respectively, are equivalent in terms of performance. However, the presented architectures of the receiver front-ends result in different properties with respect to the consumed power and their system sizes. As can be concluded from Figs. 1, 2 and 3, the amount of components change with the architectural concept and, moreover, also the requirements for some specific subsystems. E.g. the oscillator needed for the RB architecture would consume less power because it can operate at half the frequency compared to the MRC concept.

All subsystems for the three different architectures were designed in a $0.25 \mu\text{m}$ SiGe-BiCMOS technology to elaborate their difference in power consumption and system size. Table 1 shows the results for the synthesized circuits. Albeit the MRC architecture achieves similar system area, it suffers from the largest power consumption of the three concepts because it is the most complex in terms of required components. Consequently, the SRB approaches consumes the least power and area because of its simple architecture. Therefore, this architecture is highly suited for mobile handhelds that demand for energy efficient system concepts due to their limited battery lifetimes.

Table 1: Properties of concepts regarding RF circuit performance.

Parameter	MRC	RB	SRB
Power consumption [mW]	(330)	(320)	(250)
System area [mm^2]	(2.6)	(3.0)	(2.0)

5. System performance

In this section we compare the performance of the analog MRC beamformer (shown in Fig. 1), the proposed simplified architecture using a beamformer with equal real and imaginary parts (shown in Figs. 2, and 3), which we refer to as RB, and the equal gain combining (EGC) beamformer, which only changes the phase of each receiving branch [9, 10].

We have considered QPSK signals and Rayleigh SIMO channels with $n_R = 4$ and $n_R = 10$ receiving antennas. The obtained results are shown in Figures 4 and 5.

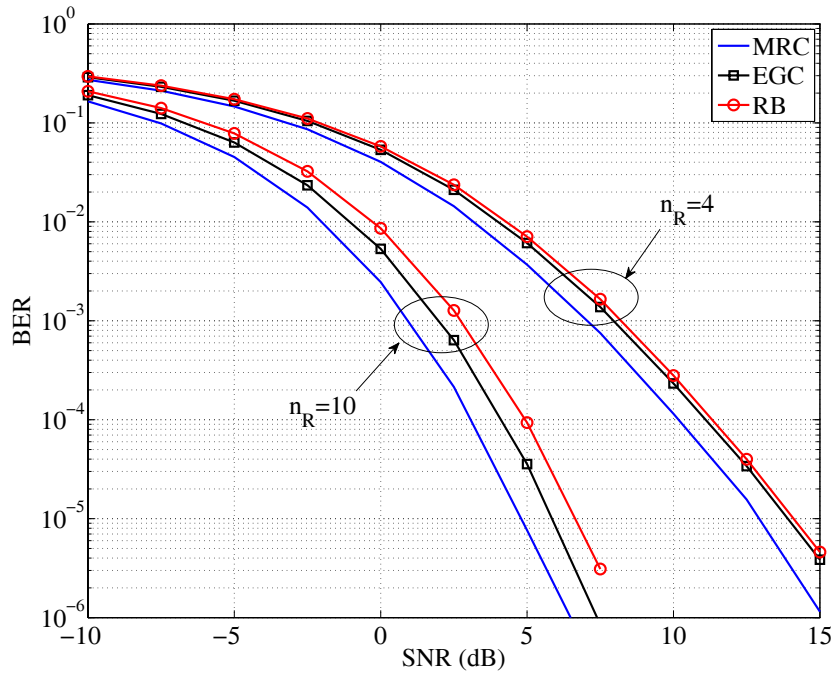


Figure 4: BER vs SNR for MRC, EGC and the proposed real beamforming (RB). i.i.d. Rayleigh channels.

On the one hand, Fig. 4 shows the bit error rate (BER) for the three considered schemes in the case of i.i.d. channels. On the other hand, Fig. 5 shows the results in the case of correlated channels. In particular, we have employed the Jake's model with antenna spacing $d = \lambda/4$. In both cases, we can see that, in comparison to the optimal MRC, the SNR reduction provoked by the simplified analog combining architecture increases with the number of receiving antennas¹, but it is always smaller than 3 dB

¹Note that as n_R increases, \mathbf{h}_R and \mathbf{h}_I tend to become orthogonal.

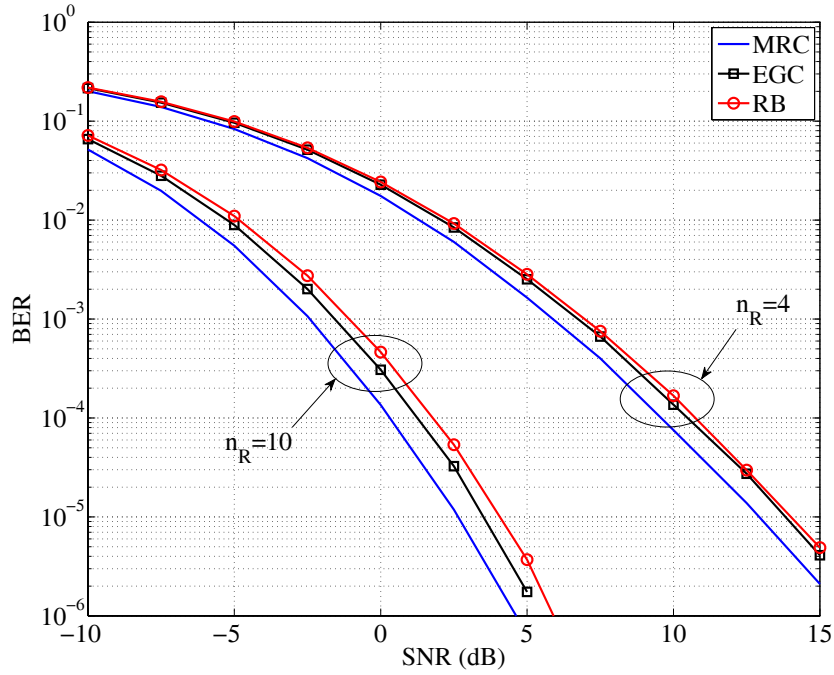


Figure 5: BER vs SNR for MRC, EGC and the proposed real beamforming (RB). Correlated Rayleigh channel with antenna spacing $d = \lambda/4$.

as analytically proved in subsection 3.2. In comparison to an EGC beamformer, the performance is similar for a moderate number of antennas ($n_R = 4$) and it is slightly worse for a large number of antennas ($n_R = 10$).

Finally, it is worth mentioning that in terms of the associated RF circuitry it is easier to achieve a constant gain over a certain bandwidth using the proposed SRB architecture than it is to obtain a constant phase shift for the same band using an EGC approach. This is particularly important for wideband standards such as 802.11a, 802.16e (WiMAX) or 3GPP LTE, which use orthogonal frequency division multiplexing (OFDM) modulations.

6. Conclusions

In this paper we have obtained the optimal MMSE beamformer for a new RF analog combining architecture. The optimal solution turns out to be a real processing of the complex RF signals received at each branch, for this reason the scheme is denoted as real beamforming. Furthermore, the real beamformer is obtained as the largest eigenvector of a matrix formed by adding the outer products of the real and imaginary parts of the SIMO channel, which must be known at the receiver.

It has also been shown that the real beamforming architecture can be further simplified, since the use of real weights avoids the need of a phase splitter at each branch. In comparison to the MRC analog architecture, the proposed simplified real beamforming (SRB) notably reduces the required system area and power consumption with a loss in performance that is upper bounded by 3 dB. These interesting results make the proposed SRB a suitable candidate for low cost and compact handheld mobile terminals

equipped with multiple antennas.

In our future work, the proposed RB and SRB architectures will be extended to multicarrier systems, where we expect significant gains with respect to the EGC paradigm. Additionally, we will study and evaluate the effects of channel estimation errors, IQ imbalance, or other implementational issues.

References

- [1] S. Sandhu and M. Ho, "Analog combining of multiple receive antennas with OFDM," in *IEEE International Conference on Communications (ICC '03)*, vol. 5, pp. 3428–3432, May 2003.
- [2] S. Jeon, Y. Wang, Y. Qian, and T. Itoh, "A novel smart antenna system implementation for broad-band wireless communications," *IEEE Transactions on Antennas and Propagation*, vol. 50, pp. 600–606, May 2002.
- [3] F. Ellinger, *Radio Frequency Integrated Circuits and Technologies*. Berlin: Springer-Verlag, 2007.
- [4] R. Eickhoff, F. Ellinger, U. Mayer, M. Wickert, I. Santamaría, R. Kraemer, L. González, P. Sperandio, and T. Theodosiou, "MIMAX: Exploiting the maximum performance and minimum system costs of wireless MIMO systems," in *17th ICT Mobile and Wireless Summit, Stockholm, Sweden*, June 2008.
- [5] I. Santamaría, V. Elvira, J. Vía, D. Ramírez, J. Pérez, J. Ibáñez, R. Eickhoff, and F. Ellinger, "Optimal MIMO transmission schemes with adaptive antenna combining in the RF path," in *16th European Signal Processing Conference (EUSIPCO 2008)*, (Lausanne, Switzerland), August 2008.
- [6] J. Vía, V. Elvira, I. Santamaría, and R. Eickhoff, "Minimum BER beamforming in the RF domain for OFDM transmissions and linear receivers," in *IEEE International Conference on Acoustics, Speech and Signal Processing (ICASSP 2009)*, (Taipei, Taiwan), Apr. 2009.
- [7] J. Vía, V. Elvira, I. Santamaría, and R. Eickhoff, "Analog antenna combining for maximum capacity under ofdm transmissions," in *IEEE International Conference on Communications (ICC 2009)*, (Dresden, Germany), June 2009.
- [8] D. P. Palomar, J. M. Cioffi, and M. A. Lagunas, "Joint Tx-Rx beamforming design for multicarrier MIMO channels: A unified framework for convex optimization," *IEEE Transactions on Signal Processing*, vol. 51, pp. 2381–2401, September 2003.
- [9] D. J. Love and R. W. Heath, "Equal gain transmission in multiple-input multiple-output wireless systems," *IEEE Transactions on Communications*, vol. 51, pp. 1102–1109, July 2003.
- [10] A. Annamalai, C. Tellambura, and V. K. Bhargava, "Equal-gain diversity receiver performance in wireless channels," *IEEE Transactions on Communications*, vol. 48, pp. 1732–1745, October 2000.