IQ Imbalances Effects on the Performance of Combining Schemes in MIMO-OFDM Wireless Communications

B. Banitalebi
TCI, ChaharMahal va Bakhtiary, Iran
bbanitalebi@eri.ac.ir

Abstract

Orthogonal frequency division multiplexing (OFDM) is a modulation scheme widely used in high speed communications. Since multi-input multi-output (MIMO) antennas can increase the reliability of the data communications, the combination of these two techniques called MIMO-OFDM is a good suggestion for reliable high speed communications. However, these systems suffer from in-phase and quadrature-phase (IQ) imbalances. This paper focuses on the performance degradation caused by the IQ imbalances by comparison of different combination schemes in the presence of IQ imbalances. The improvement caused by increasing the number of receiver antennas in different combining schemes is also considered.

1. Introduction

Orthogonal frequency division multiplexing (OFDM) is a widely adopted modulation technique for high-speed wireless communications. IEEE 802.11a and IEEE 802.11g for Wireless Local Area Networks (WLAN), DVB-T for Digital Video Broadcasting, and IEEE 802.16 for Wireless Metropolitan Area Network are some of the standards, based on OFDM signals. Considering the large demand for such systems, a low cost, low power and fully integrated implementation of these standards is a challenge for the future high-speed wireless networks.

On the other hand, the ever increasing demands for high-speed wireless data transmission has posed great challenges for wireless system designers to achieve high-throughput wireless communications in radio channels with limited bandwidth. Multiple transmit and receive antennas are most likely to be the dominant solution in future broadband wireless communication systems. This is because the capacity of such a MIMO channel increases linearly with the minimum between the numbers of transmit and receive antennas in a rich-scattering environment without increasing the bandwidth and transmit power [1]-[4].

In case of using multiple antennas in the receiver, several replicas of the transmitted signal appear in the receiver. Combining schemes can efficiently use these replicas to detect the transmitted signal. There are several types of combiners [1, 4 and 5] established based on a compromise between complexity and efficiency. Combiners play a key role at improving the performance of MIMO and so MIMO-OFDM systems. Since, combiners use the channel state information to regenerate the transmitted signal, any uncertainty or impairment in information may degrade the receiver performance.

Low cost implementation of wireless systems is challenging in view of impairments associated with analog components. One such impairment is the mismatch between I and Q branches during down conversion of the received RF signal into baseband. These errors may severely degrade the receiver performance. MIMO, OFDM and even MIMO-OFDM systems in the presence of IQ imbalances are investigated in [3,6] and references therein. In all of these works, the same decoding scheme is considered.

In this paper, after a comparison of different combining methods, undesired effects of the IQ imbalances on the performance of data transmission are investigated. To avoid the complexity of the problem, instead of MIMO systems, Single-Input Multi-Output (SIMO) systems which use one antenna at the transmitter and several antennas at the receiver are considered [1]. Without loss of generality, results of this paper are applicable for other diversity methods or MIMO systems.

The paper is organized as follows. The signal model, receiver architecture and IQ imbalances are explained in section II. Various combining schemes and effect of the IQ imbalances on the combining schemes are described in section III and finally simulation results and performance comparison of different combining schemes are presented in section IV.

2. Receiver Structure and Signal Model

Down-conversion is a fundamental stage in radio frequency front-end architecture in which the high carrier frequency signal is multiplied by local oscillating (LO)

This paper is supported by Telecom. Co. of Chaharmahal va Bakhtiari

signals to be transferred to intermediate frequencies appropriate for further amplification and processing and eventually, to the zero frequency (baseband). There are different architectures to convert the RF signal to baseband, either through an intermediate frequency or by direct down-conversion to a baseband signal [11]. There are mainly two types of down-conversion [3]: heterodyne receiver and zero intermediate frequency (ZIF). Due to certain advantages of direct conversion (cost, area, power consumption and less off-chip components), most of the future RF designs tend to adopt this scheme. Based on the architecture of the ZIF receiver (Fig. 1), regardless of the type of the elements, one can take the following imbalances into account as the total imbalances during the down-conversion process [9, 10]:

- **Amplitude error:** difference between the amplitude of LO signals in I and Q branches
- **Phase error:** non-orthogonality of LO signals in I and Q branches
- **DC offset:** leakage of LO signal into RF port because of non perfect isolation between RF and LO inputs in I and Q branches
- **Undesired signals:** undesired RF signals transferred into the output because of non-ideal multiplication or imperfect filtering in I and Q branches.

Moreover, in each IQ branch different and independent imbalances will be accounted for.

To investigate the undesired effects of the above imbalances on the receiver output, a transmitted data sequence denoted as sn is assumed. The transmitted signal, x(t), can be described as follows

$$x(t) = As_n g(t - nT)\cos(2\pi f_c t) \quad (1)$$

where A is the amplitude, $g(t)$ is the pulse shape and fc is the carrier frequency used for up-conversion. As a result of using multiple antennas at the receiver, several replicas of x(t) impaired by independent channel effects are received. In frequency domain, after an ideal down-conversion process, r the N×1 vector of the output can be shown as

$$\mathbf{r} = \mathbf{h}s + \mathbf{n} \quad (2)$$

where

$$\mathbf{h} = [h_1 \quad h_2 \quad \dots \quad h_N]^T$$
$$\mathbf{n} = [\eta_1 \quad \eta_2 \quad \dots \quad \eta_N]^T$$

are N×1 channel and noise vectors, respectively and s is the frequency domain representation of the transmitted signal.

In order to enforce the down-conversion imbalances into the signal model, $\mathbf{r}'$ a N×1 vector is introduced as the output vector of the down-converters in discrete domain (after sampling)

$$\mathbf{r}' = \mathbf{h}'\mathbf{s} + \mathbf{n}' \quad (3)$$

where $\mathbf{h}'$ and $\mathbf{n}'$ are the channel and noise vectors, respectively, affected by the down-conversion imbalances. That is $\mathbf{h}' = \boldsymbol{\alpha} \otimes \mathbf{h}$ and $\mathbf{n}' = \boldsymbol{\alpha} \otimes \mathbf{n} + \boldsymbol{\beta}$, where $\boldsymbol{\alpha}$ and $\boldsymbol{\beta}$ are

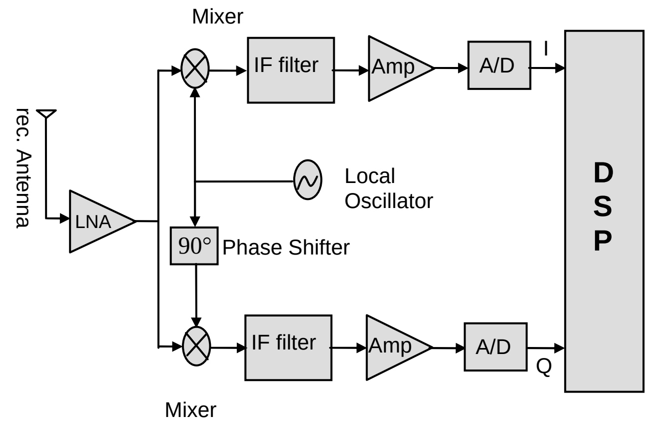

Fig. 1. A simple view of ZIF receiver

N×1 vectors. $\boldsymbol{\alpha}$ includes amplitude and phase errors and $\boldsymbol{\beta}$ represents DC offset and undesired signals. Also $\otimes$ is an element by element multiplication operator. Independent inter-element IQ imbalances are also accounted for by using different elements for $\boldsymbol{\alpha}$ and $\boldsymbol{\beta}$.

As seen in the next section, most of the combining methods are based on the knowledge of the channel state information. So, changing this information may decrease the combining performance.

3. Combining Methods

In MIMO systems, several replicas of the transmitted signal are received by the multiple receive antennas. In order to improve the regeneration of the signal by using these replicas, different combining methods are proposed [1, 5, 8], each of them established based on a trade-off between complexity and performance. In the following, some of the mostly used combining schemes are reviewed. Generally, an inverse relationship exists between the complexity and performance. As seen in the following, all combining methods discussed in this paper act based on the knowledge of the channel state information.

2.1 Maximum Ratio Combining (MRC)

MRC is one of the most popular combining methods applied to estimate the transmitted signal from different replicas. MRC is based on using all replicas to achieve the highest output SNR. The output of this combiner is a weighted combination of the received replicas.

$$\hat{s} = \sum_{i=1}^{N} w_i u_i \ . \quad (4)$$

Weighted coefficients should be calculated so that the output SNR is maximized. Based on Maximum Likelihood method, in an ideal case (which no IQ imbalances), the optimum weights are $w_i = h_i^*$ for i = 1, 2, …, N [1]. By using these weighting coefficients, $\hat{s}_n$, the n-th detected symbol is

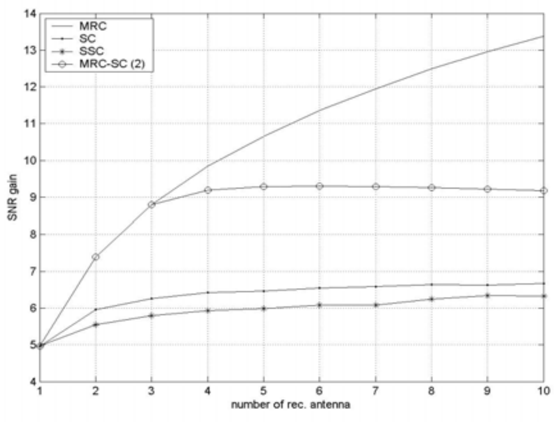

Fig. 2: SNR gain vs. number of receive antenna for different combining methods

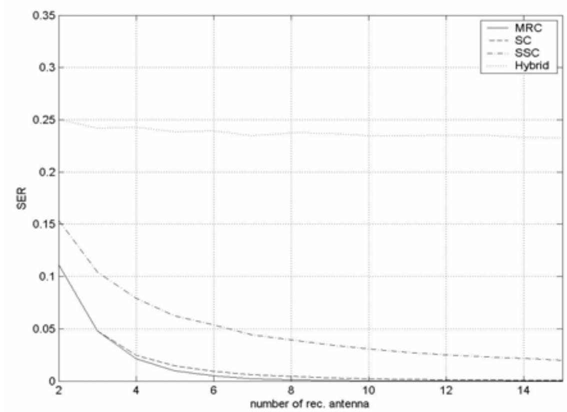

Fig. 3: SER vs. number of receive antenna for different combining methods

$$\hat{s}_n = \sum_{m=1}^{N} r_m h_m^* = \sum_{m=1}^{N} (h_m s + \eta_m) h_m^* = \sum_{m=1}^{N} |h_m|^2 s + \sum_{m=1}^{N} \eta_m h_m^* \cdot \quad (5)$$

Finally, the output SNR is

$$\gamma = \frac{\left(\sum_{m=1}^{N} |h_m|^2\right)^2 E_s}{\sum_{m=1}^{N} |h_m|^2 N_0} = \sum_{m=1}^{N} |h_m|^2 \frac{E_s}{N_0} = \sum_{m=1}^{N} \gamma_m \cdot \quad (6)$$

It shows that in MRC scheme, the output SNR is equal to the combination of the SNR's at multiple received antennas. In the presence of down-conversion imbalances, the previous equality is changed as follows

$$\gamma = \frac{\left(\sum_{m=1}^{N} |h_m|^2 \alpha_m\right)^2 E_s}{\sum_{m=1}^{N} |h_m|^2 \alpha_m^2 N_0 + N_0'} . \quad (7)$$

Although (7) indicates small changes in the output SNR of the combiner, simulation results show severe degradation in the quality of the received signal. This will be further discussed in section IV.

2.2 Selection Combining

As seen before, IQ imbalances have significant undesired effects on the signal parameters. On the other hand, in some situations because of physical or commercial limitations, it is impossible to use large number of RF-IF chains. In such cases, selection combining (SC) can be a good suggestion. In this scheme, after a comparison between the SNR's of different received replicas, the received signal with the highest SNR is chosen as the output. Based on the rate of the channel parameter variations, combiner repeats the comparison again. The output of the combiner enters to the RF-IF chain for down conversion. After sampling, the output of the down-converter is used to estimate the transmitted sequence.

For more simplification, it is possible to modify the selection combining scheme. In the modified scheme, called Scanning Selection Combining (SSC), instead of choosing the most powerful replica, a threshold level is decided based on the power of different replicas. The first replica whose SNR is higher than the threshold is selected as the output. This signal is then used until it goes down the threshold. Here the combiner searches to find another signal above the threshold.

2.3 Hybrid or MRC-SC Combining

To increase the flexibility of combiners, hybrid MRC-SC combining method can be established. This scheme is something between MRC and SC. Here, all replicas are sorted in SNR and the first L signals with highest SNRs are selected to be combined in a MRC combiner. The complexity and performance of this method can be controlled by varying L. As L decreases, the hybrid combiner resembles SC whereas an increase in L yields a scheme similar to MRC.

4. Simulation Results

In the simulations of this paper, it is assumed that a data stream with 4000 bit length is modulated with 4QAM. The resulting signal is up-converted to RF and transmitted by a transmit antenna into a single-input multi-output channel. This signal goes through different and independent paths to the multiple antennas at the receiver. Number of the paths in simulations equals to the number of multiple receives antennas.

The channel is Rayleigh fading with additive white Gaussian noise. Each replica of the received signal is affected by an independent fading. Undesired effects of the IQ mismatches are considered before combination. IQ errors are assumed to have uniform distribution in different intervals.

Because of the complexity of the theoretical analysis, a large part of our investigations is based on simulation. So we attempt to reach the simulations confirmative with the real world. In what follows, after a comparison of the performance of different combining methods in ideal case, the performance degradations caused by IQ mismatches are investigated. To evaluate the performance of combining

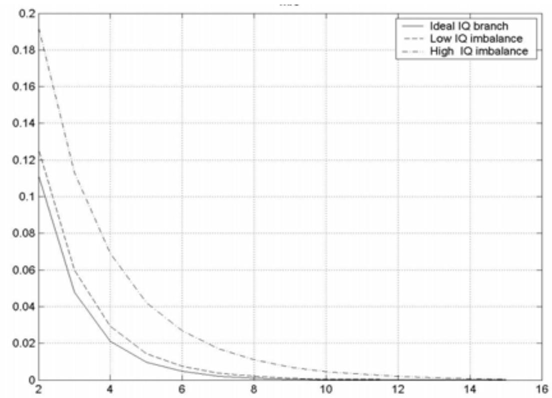

Fig. 4: SER of MRC method *vs.* number of receive antenna for different IQ error levels

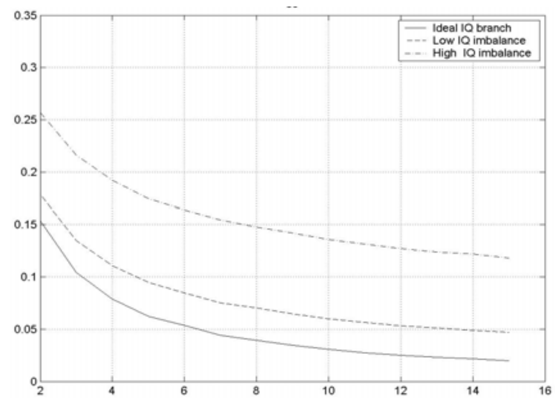

Fig. 5: SER of SC method vs. number of receive antenna for different IQ error levels

methods, SNR gain (improvement caused by using combining method) and Sample Error Rate (SER) are studied.

Fig. 2 shows the SNR gain of different combiners for various number of receive antennas (N = 1, 2, …, 10) at the same input SNR level. As observed, by increasing the number of receive antennas, the SNR gain of the MRC combiner increases significantly. It is mainly because of the perfect use of all received replicas to regenerate the output. After MRC, the hybrid method has the best performance. It is clear that for small values of N, MRC-SC yields the same results as MRC. For large values of N, SNR gain is approximately constant which is because of choosing only L receive antennas.

So increasing N has no effect on the MRC-SC performance. Fig. 2 also shows that since in SC and SSC methods only one signal is chosen, increasing the number of receive antennas has no significant effect on the SNR gain, especially for large values of N. Little increment in these curves is mainly due to the higher probability of the existence of any strong replica by increasing N.

Compared to SNR gain, SER is a better measure of signal quality. Fig. 3 shows the output SER of different combiners for various numbers of receive antennas. In this figure, results demonstrated by the SER curves confirm with the explanations of Fig. 2. But this figure presents a better understanding of the performance of different combiners. It shows that the performance of MRC and hybrid combiner is approximately the same. Although SC is less efficient than MRC and MRC-SC, its performance is still acceptable. In contrast to Fig. 2, Fig. 3 demonstrates a sever degradation in SSC method compared to SC.

In Fig’s 4-7 the effect of IQ imbalances on different combining methods are depicted. Each curve demonstrates the output SER versus number of receive antennas (N = 2 to 15) for a known level of IQ imbalances.

As seen in these figures, MRC can overcome IQ imbalances significantly especially for large number of receive antennas.

SER curves also demonstrate that the performance of hybrid method is much better than SC and SSC. This method can overcome IQ imbalances to some extent and by increasing the number of receive antennas its performance is further improved.

Increasing the number of receive antennas yields a more significant improvement in MRC than the hybrid method. But this improvement is at the expense of a more increase in the complexity. Since the complexity of hybrid method doesn’t increase with increasing the number of receive antennas, especially in wireless communications, this method is more advantageous than the others.

5. Conclusion

Analyzing the performance of different combining schemes in the presence of IQ imbalances shows that MRC is the best scheme. The SER curve of hybrid method demonstrates that this scheme is less efficient but very close to MRC. The simple algorithms of SC and SSC methods make them not a proper choice compared to other combiners. Considering the constraints of dimension, weight and cost of mobile handsets, we conclude that the hybrid method is the most efficient to be used in mobile communications.

REFERENCES

[1] H. Jafarkhani, *Space-Time Coding*: *Theory and practice* (Cambridge University Press, 2005).

[2] P. A. Dighe, *et al*., Analysis of Transmit-Receive Diversity in Rayleigh Fading, *IEEE Trans. Communications*, *51*(4), 2003, 694-703.

[3] A. Tarighat, R. Bagheri, A. H. Sayed, Compensation Schemes and Performance Analysis of IQ Imbalances in OFDM Receivers, *IEEE Trans. Signal Processing*, *53*(8), 2005.

[4] C. N. Chuah, D. N. C. Tse, J. M. Kahn, and R. A. Valenzuela, Capacity scaling in MIMO wireless systems under correlated fading, *IEEE Trans. Inform. Theory*, *48*, 637–650, 2002.

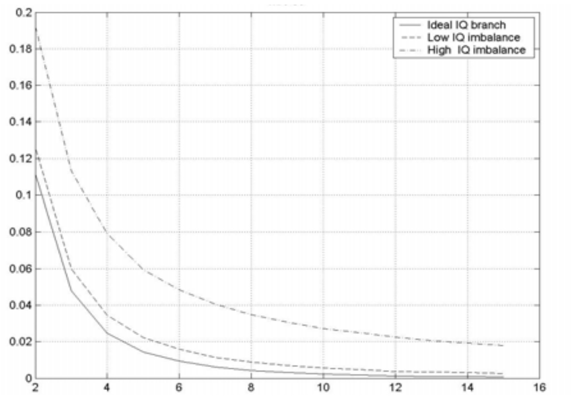

Fig.6. SER of MRC-SC method *vs.* number of receive antenna for different IQ error levels

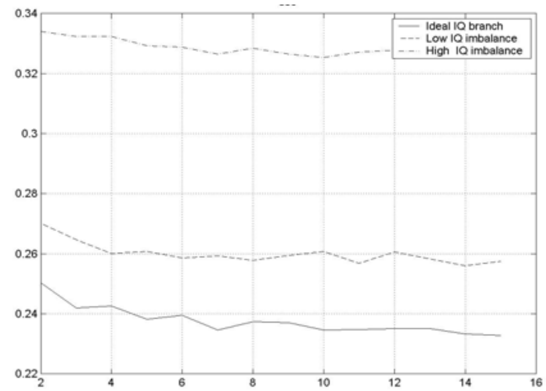

Fig.7. SER of SSC method vs. number of receive antenna for different IQ error levels

[5] T. E. N. Kong, L. B. Milstein, Comparison of diversity combining techniques for Rayleigh Fading channels, *IEEE Trans. Communications*, *44*, 1996, 1117-1129.

[6] A. Tarighat and A. H. Sayed, MIMO OFDM receivers for systems with IQ imbalances, *IEEE Trans. Signal Processing*, *53*(9), 2006.

[7] T. K. Y. Lo, Maximum Ratio Transmission, *IEEE Trans. Communications*, *47*, 1985, 1458-1461.

[8] S. Z. Asif, Mobile receive diversity technology improves 3G systems capacity, *IEEE Radio and Wireless Conf.*, 2004, 371-374.

[9] S. J. Roome, Analysis of Quadrature Detectors Using Complex Envelope Notation, *IEE Proceeding*, *136*(2), 1989, 95 – 100.

[10] K. Garlach, The effect of IQ mismatch errors on adaptive cancellation, *IEEE Trans. Aerosp. Electron. Sys.*, *28*(3), 1992, 729 – 740.

[11] R. A. Green, R. Aanerson-Sprecher, and J. W. Pierre, Quadrature Receiver Mismatch Calibration, *IEEE Trans. Signal Processing*, 47(11), 1999, 3130 – 3133.