Signal Processing 90 (2010) 2965–2980

Contents lists available at ScienceDirect

Signal Processing

journal homepage: www.elsevier.com/locate/sigpro

MIMO OFDM systems with digital RF impairment compensation

Deepaknath Tandur *,♣, Marc Moonen ♣

Katholieke Universiteit Leuven-ESAT/SCD-SISTA, Kasteelpark Arenberg 10, B-3001 Leuven, Belgium

ARTICLE INFO

Article history:
Received 5 August 2009
Received in revised form
18 February 2010
Accepted 27 April 2010
Available online 8 May 2010

Keywords:
IQ imbalance
CFO
Direct conversion front-end
OFDM
MIMO

ABSTRACT

Multi-input multi-output (MIMO) systems are often realized with low cost front-end architectures, e.g. the so-called direct conversion (or zero IF) architectures. However, such systems are very sensitive to imperfections in the analog front-end resulting in radio frequency (RF) impairments such as in-phase/quadrature-phase (IQ) imbalance and carrier frequency offset (CFO). These RF impairments can result in a severe performance degradation. In this paper we propose RF impairment compensation techniques for orthogonal frequency division multiplexing (OFDM) based MIMO systems. We consider a digital compensation scheme for joint transmitter/receiver frequency selective IQ imbalance, CFO and channel distortion. We also show that in the case where there is no transmitter IQ imbalance, the receiver IQ imbalance compensation can be de-coupled from the channel equalization resulting in a compensation in two stages. The two-stage scheme results in an overall lower computational requirement. The various compensation schemes are demonstrated to provide a performance close to the ideal case without RF impairments.

1. Introduction

Orthogonal frequency division multiplexing (OFDM) is a widely adopted modulation technique for broadband communication systems [1]. It has been standardized for a variety of applications, such as wireless local area networks (WLANs), digital audio broadcasting (DAB), digital video broadcasting (DVB-T) and asymmetric digital subscriber lines (ADSLs), etc.

OFDM has also become a preferred modulation format in multiple antenna based transmission systems [2]. An OFDM based so-called multi-input multi-output (MIMO) transmission system takes advantage of the spatial diversity obtained by its multiple transmit and receive antennas to improve its performance in a dense multipath fading environment. As the MIMO OFDM architecture has to support multiple parallel front-end radios, it is extremely important to keep these radio frequency (RF) front-ends simple with minimal analog electronics so as to maintain the cost, size and power consumption within an acceptable limit.

The so-called direct conversion (or zero IF) architecture provides a good implementation alternative for such systems compared to the traditional superheterodyne front-end architecture [3]. The direct conversion front-end has a small form factor and uses minimal analog electronics to convert the RF signal directly to baseband (BB) or vice-versa without using any intermediate frequencies (IF). However, a low cost direct-conversion front-end can be very sensitive to any component imperfections, mainly due to manufacturing non-uniformity, leading to RF impairments such as in-phase/quadrature-phase (IQ) imbalance, carrier frequency offset (CFO), phase noise, etc. As next generation wireless systems will require even more simplified, low cost, flexible and reconfigurable front-ends, the effect of these impairments will become even more severe. Furthermore, the demand for higher carrier frequencies and constellation sizes in these wireless systems

* Corresponding author.
E-mail addresses: deepaknath.tandur@esat.kuleuven.be (D. Tandur), marc.moonen@esat.kuleuven.be (M. Moonen).
♣ EURASIP members.

0165-1684/$ - see front matter © 2010 Elsevier B.V. All rights reserved.
doi:10.1016/j.sigpro.2010.04.023

also results in a higher sensitivity to the RF impairments. The resulting distortion may lead to a dramatic performance degradation and limit the achievable data rate and so it has to be properly compensated.

The effects of RF impairments have been studied and compensation schemes for single-input single-output (SISO) based OFDM systems have been developed in [4–13]. In [6–11] efficient digital compensation schemes have been developed for the case of receiver IQ imbalance and CFO. In [10], a specially induced phase rotated short training sequence has been proposed to estimate frequency selective receiver IQ imbalance along with CFO. However, this scheme is not directly applicable in the presence of transmitter IQ imbalance in the system. Tandur and Moonen [12] and Tandur et al. [13] extend these schemes to also consider transmitter IQ imbalance along with receiver IQ imbalance and CFO.

The influence and compensation of IQ imbalance in MIMO OFDM systems have been studied in [14–17]. In [14], the authors propose a compensation scheme for receiver IQ imbalance, while in [15] and [16] a compensation scheme for combined transmitter/receiver IQ imbalance is developed. It should be noted that most papers focusing on IQ imbalance consider only frequency independent IQ imbalance. However, for wide band systems it is also essential to consider the influence of frequency selective IQ imbalance mainly arising from the mismatch of the branch components. In [17], we have considered the combined effect of frequency selective transmitter/receiver IQ imbalance, CFO and frequency selective channel distortion in a standard MIMO OFDM system.

This paper extends the work in [17] and provides a more comprehensive treatment for the compensation of CFO and IQ imbalance distortions in MIMO OFDM receivers. We *first* propose a frequency domain per tone equalizer (PTEQ) based scheme for the joint compensation of IQ imbalance and CFO along with channel distortion. This PTEQ scheme provides a unified solution for different combinations of RF impairments. *Secondly*, in the case where there is no transmitter IQ imbalance, we propose a de-coupled two stage compensation scheme. In the first stage, receiver IQ imbalance is compensated at every receiver branch along with CFO distortions. The second stage then utilizes a standard MIMO equalizer that compensates for channel distortion. We show that this two-stage approach results in lower computational complexity than a typical frequency domain joint equalization approach. The various compensation schemes are demonstrated to provide a performance close to the ideal case without RF impairments. In our simulations, we have considered a training structure similar to the MIMO extension of the uncoded IEEE 802.11a standard [18], where a short training sequence is followed by a long training sequence for the initialization of the equalizer.

The paper is organized as follows: An input–output system model for MIMO OFDM systems is developed in Section 2. Section 3 explains the joint and the de-coupled compensation schemes. Section 4 compares the complexity of the two proposed schemes in different RF impairment scenarios. The results of the numerical performance evaluation are presented in Section 5 and finally conclusions are given in Section 6.

Notation: Vectors and matrices are indicated in bold and scalar parameters in normal font. Superscripts $\{\}^*$, $\{\}^T$, $\{\}^H$, $\{\}!$ represent the complex conjugate, transpose, Hermitian and factorial function, respectively. $\mathbf{F}$ and $\mathbf{F}^{-1}$ represent the $N\times N$ discrete Fourier transform (DFT) and its inverse. $\mathbf{I}_N$ is the $N\times N$ identity matrix and $\mathbf{0}_{M\times N}$ is the $M\times N$ all-zero matrix. Operators $\otimes$, $\star$ and $\cdot$ denote the Kronecker product, convolution and component-wise vector multiplication, respectively.

2. System model

We consider a point-to-point MIMO OFDM system. Let N_t and N_r denote the number of transmit and receive antennas. We will generally assume that $N_r \geq N_t$. Then $\mathbf{S}_{(K)}$ (for K=1 ... N_t) is the frequency domain OFDM symbol of size $(N\times 1)$, to be transmitted over the K th transmit antenna, where N is the number of tones. The frequency domain symbol is transformed to the time domain by the inverse discrete Fourier transform (IDFT). A cyclic prefix (CP) of length ν is then added, resulting in a time domain baseband symbol $\mathbf{s}_{(K)}$ given as

$$\mathbf{s}_{(K)} = \mathbf{P}\mathbf{F}^{-1}\mathbf{S}_{(K)} \tag{1}$$

where $\mathbf{P}$ is the cyclic prefix insertion matrix given by

$$\mathbf{P} = \left[\begin{array}{c|c} 0_{(\nu\times N-\nu)} & \mathbf{I}_\nu \\ \hline \multicolumn{2}{c}{\mathbf{I}_N} \end{array}\right]$$

The time domain symbol $\mathbf{s}_{(K)}$ is parallel to serial converted and then fed to the transmitter front-end. We consider a single local oscillator (LO) supporting all the transmit (receive) antennas at the transmitter (receiver) front-end. As the LO produces only a single carrier frequency, the IQ imbalance induced by the LO is generally considered to be frequency independent (FI), i.e. it is constant over the entire OFDM symbol [5]. Due to the design restrictions, the trace lengths between the LO and the individual antenna branches may not be exactly equal and this may result in a different FI IQ imbalance for each transmit antenna. We model the transmit FI IQ imbalance as an amplitude and phase mismatch of $g_{t(K)}$ and $\phi_{t(K)}$ at the K th transmit antenna.

The other analog components in the front-end such as the digital-to-analog converters (DAC), amplifiers, low pass filters (LPFs) and mixers generally result in an overall frequency selective (FS) IQ imbalance. We represent the FS transmit IQ imbalance by two mismatched filters with frequency responses given as $\mathbf{H}_{ti(K)}$=$\mathbf{F}\mathbf{h}_{ti(K)}$ and $\mathbf{H}_{tq(K)}$=$\mathbf{F}\mathbf{h}_{tq(K)}$ at the in-phase and quadrature-phase branch of the K th transmit antenna. Here $\mathbf{h}_{ti(K)}$ and $\mathbf{h}_{tq(K)}$ represent the impulse response of the mismatched filters.

Following the derivation in [5], the equivalent baseband symbol $\mathbf{p}_{(K)}$ at the K th transmit antenna can be given as

$$\mathbf{p}_{(K)} = \mathbf{g}_{ta(K)}\star\mathbf{s}_{(K)} + \mathbf{g}_{tb(K)}\star\mathbf{s}^*_{(K)} \tag{2}$$