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ECM and SAGE based joint estimation of timing and frequency offset for DMIMO–OFDM system

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ABSTRACT

Distributed multiple-input multiple-output (DMIMO) technology is a key enabler of coverage extension and enhancement of link reliability in wireless networks through distributed spatial diversity. DMIMO employs classic relay channels in between the source and the destination to opportunistically form a virtual antenna array (VAA) for emulating cooperative diversity. Use of multiple antennas at the relays further increases capacity and reliability of the relay–destination channel through multiplexing and diversity of MIMO antennas respectively. In such network, the signal received at the destination is characterized by multiple timing offsets (MTO) due to different propagation delay and multiple carrier frequency offsets (MCFO) due to independent oscillators of the relays. Hence, synchronization becomes a crucial issue in DMIMO in order to realize the distributed coherence. In this paper, we address joint estimation of MCFO and MTO in DMIMO orthogonal frequency division multiplexing (OFDM) with MIMO configuration at the relays for estimate-and-forward (EF) relaying protocol. Two iterative algorithms, based on expectation conditional maximization (ECM) and space alternating generalized expectation–maximization (SAGE) are proposed for joint estimation in presence of inter carrier interference (ICI). The robustness of both the estimators to ICI is evaluated by mathematical analysis and supported by extensive simulations. The performance of the proposed estimators is assessed in terms of mean square error (MSE) and bit error rate (BER). The theoretical Cramer–Rao lower bound (CRLB) of estimator error variance is also derived.

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1. Introduction

In recent times, cooperative communications also known as distributed multiple-input multiple-output (DMIMO) communications have emerged as a potential technology to improve spectral efficiency, facilitate small cell deployment, and provide coverage extension in 4G and beyond wireless communication systems. It enables wireless nodes to collaborate with each other during information exchange resulting in increased reliability. On the other hand, to combat multipath fading and achieve high data rate, orthogonal frequency division multiplexing (OFDM) has emerged as a popular multi carrier technique. The combination of DMIMO and OFDM is therefore envisaged to be an effective method of improving capacity and coverage in wireless communications. For example, DMIMO finds application in vehicular networks in order to accelerate information exchange and provide coverage extension [1,2], where vehicles cooperate to opportunistically form a virtual antenna array (VAA) with 4G cellular infrastructure. In order to ensure high reliability of information exchange in such networks, coherent reception of data assumes prime importance. A typical DMIMO system

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employs several co-ordinating nodes, each of which may also function as a relay equipped with multiple antennas. Since, the distributed relays employ different oscillators, the signal received at the destination via such relays is distorted by multiple timing offsets (MTO) and multiple carrier frequency offsets (MCFO). The high sensitivity of OFDM modulation to MTO and MCFO further compounds this problem. As such, the DMIMO–OFDM system faces a fundamental difficulty of coherent deployment [3]. Hence, joint estimation of MCFO and MTO is a crucial issue to be addressed in a DMIMO–OFDM system.

Most of the existing literature either addresses MTO [4,5] or MCFO estimation [6–8] considering the other parameter to be constant. However, estimating one set of parameters does not result in successful signal detection in the presence of both offsets. Again, joint estimation poses distinct challenges in single and multi carrier systems. For single carrier (SC) systems in cooperative networks the problem is well addressed in [9–13]. An optimal and sub-optimal minimum mean-square error (MMSE) receiver design at the destination with maximum likelihood (ML) estimates is proposed in [9] in contrast to the blind estimation of MTO and MCFO reported in [10]. A joint estimation of channel coefficients and frequency offsets using expectation conditional maximization (ECM) and space alternating generalized expectation–maximization (SAGE) over a frequency-flat channel for decode-and-forward (DF) relaying protocol is presented in [12]. These two are well known algorithms which iteratively achieve maximum likelihood estimate (MLE). The authors of [13] introduce a differential evolution (DE) based estimation algorithm for MTO and MCFO estimation in amplify-and-forward (AF) cooperative networks.

As compared to the SC system, the popularity of multi carrier system comes from its high immunity to channel dispersion over frequency-selective channels. Here, the introduction of multiple timing and frequency offsets reduces data throughput and diversity potential. If the timing offset (TO) falls beyond the cyclic prefix length, inter symbol interference (ISI) adversely affects the orthogonal relation between the subcarriers. On the other hand, the presence of CFO in OFDM systems attenuates the desired signal and introduces inter carrier interference (ICI) since the carrier is demodulated at an offset frequency in the receiver. The objective of time and frequency synchronization in OFDM is to accurately identify the start of the OFDM window and to demodulate the signal at perfect carrier frequency respectively. When cooperative communication is used in conjunction with OFDM, MTO and MCFO are required to be estimated and compensated in order to mitigate ICI. Hence, for DMIMO–OFDM, synchronization is more challenging. Estimation of MTO and MCFO for DF cooperative network with OFDM modulation is proposed in [14–17] for single relay antenna. Fine timing estimation and fractional frequency offset estimation schemes are separately addressed in [15,17]. Authors of [16,17] propose a preamble design based on constant amplitude zero auto-correlation (CAZAC) sequence for synchronization.

Based on the aforementioned survey of reported work, it is clear that the joint estimation of timing and frequency offsets for a DMIMO–OFDM system with multiple antennas relay configuration has not been addressed in existing literature. The emerging scenario, particularly in the context of 5G system development indicates a paradigm shift in MIMO technology with large scale antenna system (LSAS) being the subject of rigorous investigations. As such, the evolution of existing uncoordinated single relay antenna based wireless communication system to a DMIMO system employing a distributed antenna system (DAS) with scalable number of antennas at the relay is inevitable.

Although the potent combination of a truly large and intelligent DMIMO system with OFDM seems an attractive solution to ensure reliability, coverage and high data rate support, the technology presents a set of formidable challenges. To begin with, due to resource constraints mandating a cost reduction at the multiple-antenna relay nodes, the estimate-and-forward (EF) protocol finds suitability due to its low complexity feature. However, the EF relaying protocol provides a coarse estimation of synchronization parameter offsets leading to pronounced ICI.

Secondly, since the relay node is equipped with multiple antennas, there exist a corresponding number of multiple channel paths between the relay nodes and destination. The resulting implication is a linear increase in the dimension of the parameter vector to be estimated with the order of the DAS structure. This will further worsen ICI effects due to addition of multipath signals at the destination. Finally, the use of OFDM escalates the estimation problem due to the inherent sensitivity of OFDM to ICI.

Considering the three-fold problem in the foregoing description, it is evident that conventional synchronizers are not optimal for a DAS based DMIMO–OFDM system, which is also established through mathematical analysis in this paper. Also, the well-known ML estimator is impractical for such systems due to latency issues involved in estimation. In contrast, ECM and SAGE algorithms iteratively achieve ML estimates consuming reasonably less time with stable convergence properties. In this paper, we propose two ECM and SAGE based estimation procedures for DMIMO systems with multiple relay antennas employing EF relaying protocol in order to tackle the challenge of MTO and MCFO estimation in the presence of severe ICI effects which is peculiar in such systems. To the best of our knowledge, a holistic approach to the solution of this rather complex estimation problem has not been proposed in the existing body of work in reported literature. The key contributions of this paper can be summarized as follows:

- A system model for DMIMO with multiple antennas at the relay nodes is proposed along with the mathematical framework to analyse performance of OFDM based DAS in presence of multiple time–frequency offsets and ICI for the EF relaying protocol in order to provide guidelines and overcome the criticality in the baseband algorithms (synchronizer, equalizer) design for such system.
- Thereafter, we propose two synchronizers by modifying the conventional framework (ECM and SAGE) to incorporate the effect of ICI following the guidelines obtained from analysis.
- We further derive the mathematical expressions for complexity, convergence and Cramer–Rao lower bound (CRLB) of the proposed algorithms to enable performance evaluation and comparison.

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