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Carrier Frequency Synchronization in MIMO Systems

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***Abstract*—This paper gives a summary of the principles, key techniques and state of the art of frequency synchronization in multi-input multi-output (MIMO) systems. The system model of frequency synchronization in MIMO systems is given and some assumptions are made first, and the principles and state of the art of the estimation and compensation of carrier frequency offsets (CFOs) are discussed for co-located MIMO and distributed MIMO systems, respectively. By analyzing the disadvantages of the existing research, we present some open issues worth of studying and some promising research interest. The results of analysis show that there has been adequate intensive study on the CFO estimation for co-located MIMO systems while the CFO estimation for distributed MIMO systems and the CFO compensation for MIMO-OFDM (orthogonal frequency division multiplexing) systems appear incomplete and still need further research.**.

***Keywords*—Carrier frequency offsets; Distributed antennas; Frequency synchronization; MIMO; OFDM.**

I. INTRODUCTION

In carrier communication systems, it is the task of the local oscillator in the receiver to generate a local reference carrier, whose frequency must be exactly equal to that of the carrier generated by the transmitter, to demodulate the received signal. Unfortunately, in practical communication systems, there always exist carrier frequency offsets (CFOs) between the transmitter and the receiver, which is unavoidably present due to the possible oscillator mismatch as well as the Doppler shifts caused by the relative motion between the transmitter and the receiver. The presence of CFOs will lead to significant performance degradation in the signal detection and the estimation of other important signal parameters (e.g., channel estimation) as well [1]. Therefore, it is of primary importance to accurately estimate the CFOs and compensate for them prior to detection, which is the main goal of frequency synchronization. The technology of frequency synchronization for conventional single-antenna systems has been studied intensively and adopted widely and will not be discussed here.

As compared with single-antenna systems, multi inputmulti-output (MIMO) systems can provide significantly higher data rate without extra bandwidth [2]. On the other hand, orthogonal frequency division multiplexing (OFDM) can effectively combat the multipath fading of the wireless channel [3]. Therefore, the combination of MIMO and OFDM, resulting in a MIMO-OFDM system, can provide higher capacity and achieve better performance [4]. As another promising technique for future wireless communications, systems with distributed antennas have been attracting much research interest in recent years [5].

Like that of single-antenna systems, the performance of MIMO systems may seriously degrade in the presence of CFOs. In MIMO systems, two possible approaches may be taken to deal with the CFOs. One is based on the elaborate design of the transmitted signal at the transmitter, where some encoding scheme immune to CFOs is used to combat the CFOs and hence the signal detection can be performed as if there were not any CFOs at the receiver [6]. The alternative approach is similar to that adopted in single-antenna systems, that is, frequency synchronization at the receiver, which can be carried out in two steps, i.e., CFO estimation and CFO compensation. The CFOs is first estimated by some CFO estimation method and then compensated for using the estimated CFO values obtained in the first step. We will focus on the second approach, i.e., frequency synchronization in MIMO systems.

This paper gives a summary of the principles, key techniques and state of the art of frequency synchronization in MIMO systems. The system model of frequency synchronization in MIMO systems is given and some assumptions are made first, and the principles and state of the art of CFO estimation and CFO compensation are discussed for co-located MIMO and distributed MIMO systems, respectively. By analyzing the disadvantages of the existing research, we present some open issues worth of studying and some promising research interest.

The rest of the paper is organized as follows. In the next section, we describe the system model of frequency synchronization in MIMO systems. Section III and Section IV address the principles and state of the art of CFO estimation and CFO compensation, respectively. And Section V concludes the paper.

II. SYSTEM MODEL

Consider a MIMO system with M_T transmit antennas and M_R receive antennas. Letting the CFO between the *i*-th transmit antenna and the *j*-th receive antenna is ε_{ij}, the CFOs between the transmitter and the receiver can be expressed in matrix form by

$$\mathbf{E}=\left[\varepsilon_{ij}\right]=\begin{bmatrix} \varepsilon_{11} & \varepsilon_{12} & \cdots & \varepsilon_{1,M_R} \\ \varepsilon_{21} & \varepsilon_{22} & \cdots & \varepsilon_{2,M_R} \\ \cdots & \cdots & \cdots & \cdots \\ \varepsilon_{M_T,1} & \varepsilon_{M_T,2} & \cdots & \varepsilon_{M_T,M_R} \end{bmatrix} \tag{1}$$

which is the generalized system model of frequency synchronization in MIMO systems. In many practical cases, however, some rational assumptions can be made according to specific conditions to simplify the generalized system model presented above. Therefore, the actually applied system model is usually some special case of the generalized system model.

In conventional co-located MIMO systems, since all the transmit antennas are co-located at one geographic location and all the receive antennas are co-located at another geographic location (as shown in Fig. 1), the CFOs between different transmit antennas and receive antennas can be regarded to be identical. Under this assumption, the CFO matrix reduces to

$$\mathbf{E}=[\varepsilon] \tag{2}$$

i.e., there exists only one CFO in the system, which is similar to the case of single-antenna systems.

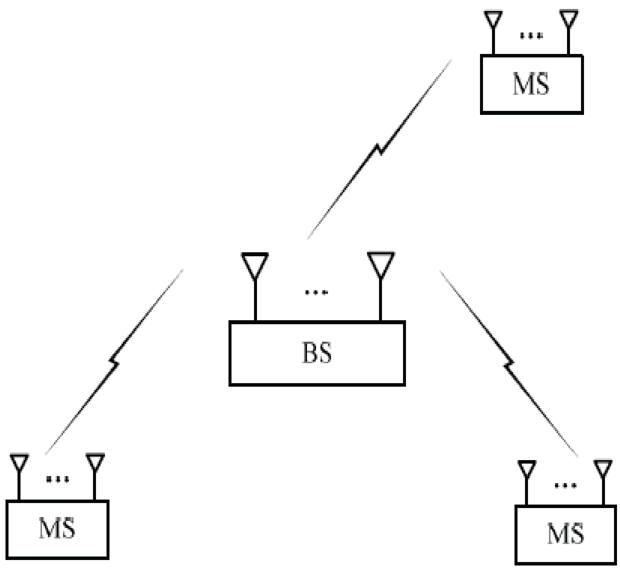

Figure 1. Co-located MIMO system

In distributed MIMO systems, since the transmit antennas or the receive antennas are distributed at separated geographic locations, either different oscillators are possibly used for each antenna [7], or the multipath components from each transmit antenna may impinge on each receive antenna from different angles of arrival [8], which leads to different CFOs between each transmit antenna and each receive antenna. Therefore, there will exist multiple CFOs in the system.

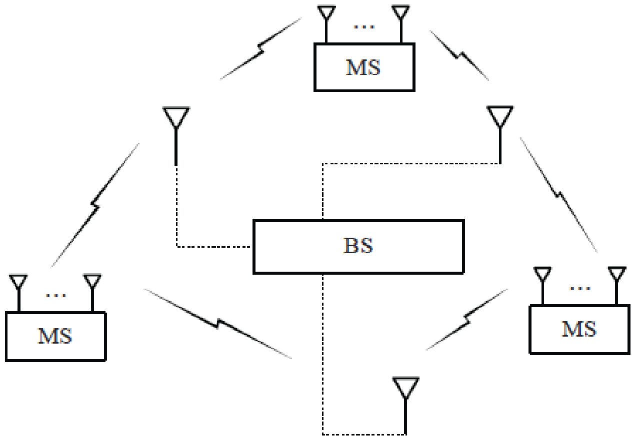

Figure 2. Distributed MIMO system

In practical systems, it is usually the truth that the antennas at the base station are distributed while those at the mobile station are still co-located due to its constrained size (as shown in Fig. 2). As a result, in the downlink, the CFOs between a certain transmit antenna and all the receive antennas are identical, while the CFOs between a certain receive antenna and each transmit antenna may be different. Under this assumption, the CFO matrix reduces to

$$\mathbf{E}=\left[\varepsilon_i\right]=\left[\varepsilon_1 \quad \varepsilon_2 \quad \cdots \quad \varepsilon_{M_T}\right]^T \tag{3}$$

which we will adopt in the following discussion on frequency synchronization in distributed MIMO systems.

III. CFO ESTIMATION IN MIMO

According to the system model given above, there is substantial difference between the CFO estimation in collocated MIMO and that in distributed MIMO. Therefore, in the following we will discuss them respectively.

A. CFO estimation in co-located MIMO

In co-located MIMO systems, since there exists only one CFO, which is the same as the case in single-antenna systems, the CFO estimation in co-located MIMO is a problem of scalar parameter estimation. It can be regarded as an extension of the CFO estimation in single-antenna systems and many existing CFO estimation methods for single-antenna systems can be extended to co-located MIMO systems.

The CFO estimation in co-located MIMO systems has been attracting much research interest and many CFO estimation methods can be found in the literature. [9] extended the CFO estimation method in [10] to systems with receive spatial diversity and studied the impact of spatial diversity on the performance of CFO estimation, while [11] and [12] aimed at systems with transmit spatial diversity. [13] and [14] focused on the data-aided and code-aided CFO estimation in flat-fading MIMO channels. [15] applied the

CFO estimation method for flat-fading MIMO channels in selective fading MIMO channels and OFDM systems. [16]~[20] addressed the CFO estimation in MIMO-OFDM systems. [21] studied the CFO estimation in MIMO-CDMA (code division multiple access) systems. [22]~[26] discussed the performance analysis and the design of training sequences for the CFO estimation in MIMO systems.

From the above analysis we can see that there has been adequate intensive study on the CFO estimation for co-located MIMO systems and it covers a variety of aspects for CFO estimation. For example, it ranges from receive diversity to transmit diversity, from flat-fading channels to selective fading channels, from CDMA systems to OFDM systems, from performance analysis to design of training sequences, and so on.

B. CFO estimation in distributed MIMO

As mentioned above, since there may exist multiple CFOs in distributed MIMO systems, the CFO estimation in distributed MIMO is a problem of vector parameter estimation. In addition, since the distances between each transmit antenna and each receive antenna may also be different, the propagation delays are possibly different as well, i.e., the signals transmitted from each transmit antenna to each receive antenna are not synchronous. These facts make the CFO estimation in distributed MIMO systems become much more complicated than that in co-located MIMO systems.

Considering the general case where the CFOs are possibly different for each transmit antenna, [8] addressed the joint maximum likelihood (ML) estimation of CFOs and channel gains for flat-fading MIMO channels, and suggested two computationally simpler methods base on a suitable choice of the training sequence. [7] proposed two computationally efficient iterative methods based on ECM (Expectation Conditional Maximization) and SAGE (Space-Alternating Generalized Expectation-Maximization) algorithms. [27] proposed a correlation based second-order estimator by utilizing the orthogonality of Walsh codes, which can eliminate the multiple antenna interference. [28] extended the work in [8] to selective fading MIMO channels, considering a more general case where the CFOs are possibly different for each path, and proposed an approximate ML estimator by exploiting the cross-correlation characteristic of the training sequences.

From the above analysis we can see that the CFO estimation for distributed MIMO systems appear incomplete. Furthermore, all the existing work only takes multiple CFOs into consideration, while still based on the assumption that the signals transmitted from each transmit antenna to each receive antenna are synchronous, which is unrealistic in practical distributed MIMO systems. Therefore, further intensive research is needed considering the generalized system model where the propagation delays between each transmit antenna and each receive antenna are possibly different.

IV. CFO COMPENSATION IN MIMO

In co-located MIMO systems, since there exists only one CFO, we can still adopt the simple CFO correction method used in conventional single-antenna systems to perform CFO compensation prior to MIMO detection. In order to correct the CFO, the received signal at each receive antenna is multiplied by a complex exponential signal (as shown in Fig. 3), where ε_0 is the CFO correction value and set equal to the estimated CFO value obtained in CFO estimation.

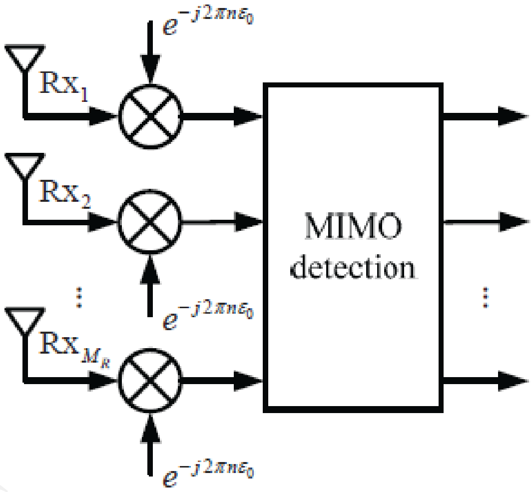

Figure 3. CFO compensation in co-located MIMO

In distributed MIMO systems, however, since there exist multiple CFOs, the simple CFO compensation method mentioned above becomes invalid. Moreover, there is substantial difference between the CFO compensation in distributed single-carrier MIMO systems and that in distributed MIMO-OFDM systems and we will discuss them respectively.

A. CFO compensation in distributed single-carrier MIMO

In distributed single-carrier MIMO systems, in spite of the presence of multiple CFOs, the spatially multiplexed substreams will be separated with their respective CFO after MIMO detection. This gives us the opportunity to use the conventional simple CFO correction method to compensate for the CFO for each sub-stream respectively after MIMO detection. This operation is illustrated in Fig. 4, where $\hat{\varepsilon}_i$, i=1,2,.....,$M\ T$ is the estimated CFO value between the i-th transmit antenna and the receiver.

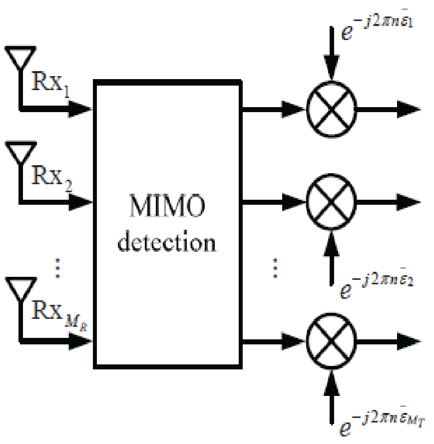

Figure 4. CFO compensation in distributed single-carrier MIMO

B. CFO compensation in distributed MIMO-OFDM

Like the single-antenna OFDM system, one of the major disadvantages of the distributed MIMO-OFDM system is its sensitivity to CFOs [29], [16]. CFOs will cause a loss in the orthogonality of the subcarriers, which results in intercarrier interference (ICI) and hence significant performance degradation [16].

In distributed MIMO-OFDM systems, the fast Fourier transform (FFT) is performed first to demodulate the received signal at each receive antenna prior to MIMO detection (as shown in Fig. 5). Thus, with the presence of CFOs, the ICI will occur after FFT processing and before MIMO detection. If conventional MIMO detection is performed after FFT, the ICI will occur among the separated sub-streams, i.e., a certain substream is affected by not only the ICI caused by itself but also the ICI introduced by other sub-streams. Therefore, the CFO compensation method proposed above for distributed singlecarrier MIMO systems, where the CFO for each sub-stream is corrected respectively after MIMO detection, is not applicable to distributed MIMO-OFDM systems.

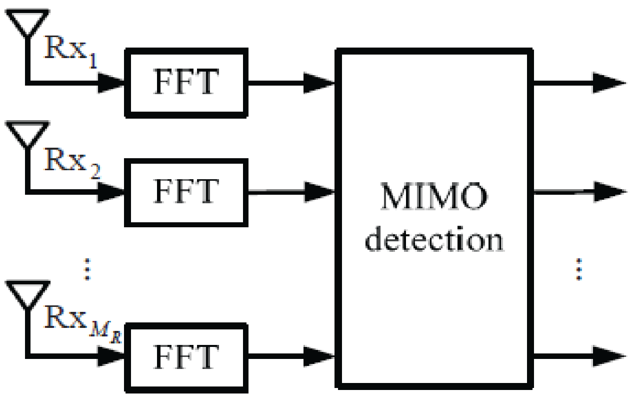

Figure 5. Receiver structure for MIMO-OFDM

In [30] and [31], some linear frequency domain equalization methods are proposed to compensate for multiple CFOs in distributed MIMO-OFDM systems. Unfortunately, they involve inversion of a large matrix that is computationally complex. Although some simpler equalization methods are also proposed, they assume small CFOs and still cannot avoid matrix inversions.

From the above analysis we can see that the problem of CFO compensation in distributed MIMO-OFDM systems has been rarely addressed in the literature. The existing methods appear hard to implement, and practical low-complexity CFO compensation methods without need for matrix inversion still need further research.

V. CONCLUSION

Aiming at co-located MIMO, distributed MIMO and MIMO-OFDM systems, we have addressed the principles, system model and state of the art of the estimation and compensation of CFOs, respectively. By analyzing the disadvantages of the existing research, we present some open issues worth of studying and some promising research interest. The results show that there has been adequate intensive study on the CFO estimation for co-located MIMO systems while the CFO estimation for distributed MIMO systems and the CFO compensation for MIMO-OFDM systems appear incomplete and still need further research.

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