Bounds and Algorithms for Multiple Frequency Offset Estimation in Cooperative Networks

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***Abstract*—The distributed nature of cooperative networks may result in multiple carrier frequency offsets (CFOs), which make the channels time varying and overshadow the diversity gains promised by collaborative communications. This paper seeks to address multiple CFO estimation using training sequences in space-division multiple access (SDMA) cooperative networks. The system model and CFO estimation problem for cases of both decode-and-forward (DF) and amplify-and-forward (AF) relaying are formulated and new closed-form expressions for the Cramer-Rao lower bound (CRLB) for both protocols are derived. The CRLBs are then applied in a novel way to formulate training sequence design guidelines and determine the effect of network protocol and topology on CFO estimation. Next, two computationally efficient iterative estimators are proposed that determine the CFOs from multiple simultaneously relaying nodes. The proposed algorithms reduce multiple CFO estimation complexity without sacrificing bandwidth and training performance. Unlike existing multiple CFO estimators, the proposed estimators are also accurate for both large and small CFO values. Numerical results show that the new methods outperform existing algorithms and reach or approach the CRLB at mid-to-high signal-to-noise ratio (SNR). When applied to system compensation, simulation results show that the proposed estimators significantly reduce average-bit-error-rate (ABER).**

***Index Terms*—Cooperative communications, synchronization, carrier frequency offset estimation, Cramer-Rao Lower Bound (CRLB), MUltiple SIgnal Characterization (MUSIC).**

I. Introduction

COOPERATIVE multiplexing and diversity, which are achieved when multiple terminals collaborate through distributed transmissions, are shown to increase capacity and reliability in wireless networks [1]–[5]. However, the majority of the analysis in the area of cooperative communications is focused on improving capacity and reliability while assuming perfect frequency synchronization [1]–[5].

The presence of multiple *carrier frequency offsets (CFOs)* in distributed cooperative networks arises due to simultaneous transmissions from spatially separated nodes with different oscillators and Doppler shifts. The CFOs result in the rotation of the signal constellation causing *signal to noise ratio (SNR)* loss. The amount of SNR loss and channel estimation accuracy are highly dependent on CFO estimation precision at the receiver [6]. Thus, accurate CFO estimation is key to successful deployments of cooperative networks.

In [7]–[9] and references therein, space time coding techniques are proposed that provide full spatial diversity in the presence of CFOs. However, the schemes outlined in [7]–[9] require CFOs to be estimated and equalized at the destination and do not address CFO estimation.

Previously proposed multiple CFO estimation methods for frequency-flat *multiple-input-multiple-output (MIMO)* systems include [10]–[13]. In [10], a *maximum-likelihood estimator (MLE)* is presented that requires exhaustive search and performs poorly when the CFOs are close to one another. In [11], a *correlation-based estimator (CBE)* is proposed using orthogonal training sequences transmitted from different antennas. However, the CBE suffers from an error floor, requires the use of correlators at the receiver, and performs very poorly when normalized CFO values are larger than 0.05. In [12] and [13], iterative schemes are proposed to eliminate the CBE's error floor. However, since CBE is used as the initial estimator, the estimators in [12] and [13] also perform poorly at large CFO values. While the assumption of small CFO values in [11]–[13] might hold for point-to-point MIMO systems, it is not justifiable for cooperative systems with distributed nodes and independent oscillators. In addition, the estimators in [10]–[14] cannot be directly applied to the case of *amplify-and-forward (AF)* relaying networks due to the different training signal model.

In [15] a *maximum a posteriori (MAP)* CFO estimator for single-relay frequency-flat 3-terminal *decode-and-forward (DF)* networks is presented. However, the approach in [15] is limited to the case of DF relaying and suffers from the same shortcomings as in [10]. While a multiple CFO estimator for DF relaying cooperative networks is proposed in [16], no specific performance analysis is provided. In [17], CFO estimation in two-way AF relaying networks is investigated. However, the system model consists of a single relay only and the effect of Doppler shift is ignored. In [18], CFO estimation in multi-relay *orthogonal frequency division multiple access (OFDMA)*-based cooperative networks is addressed. However, to simplify the CFO estimation problem, it is assumed in [18] that at any given time only a single relay transmits its signal to the receiver. Finally, CFO estimation in AF relaying single-relay *orthogonal frequency division multiplexing (OFDM)*-based cooperative networks has been analyzed in [19], where similar to [18], it is assumed that the received signal is affected by only a single CFO.

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