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Channel Estimation and Equalization for Asynchronous Multiple Frequency Offset Networks

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Abstract: A single frequency network transmission is assumed, and we study the impact of distinct carrier frequency offset (CFO) between the local oscillator at each transmitter and the local oscillator at the receiver. Due to the nature of cooperative communications, multiple frequency offsets may occur and the traditional frequency offset compensations may not apply. For this problem, equalization for the time varying channel has been used in the literature, where the equalization matrix inverse needs to be retaken every symbol. In this paper, we propose computationally efficient minimum mean square error (MMSE) and MMSE decision feedback equalizers (MMSE-DFE) when multiple frequency offsets are present, where the equalization matrix inverses do not need to be retaken every symbol. Our proposed equalization methods apply to linear convolutively coded cooperative systems, where linear convolutive space-time coding is used to achieve the full cooperative diversity when there are timing errors from the cooperative users or relay nodes, i.e., asynchronous cooperative communication systems.

Keywords: Asynchronous cooperative networks, equalization, MMSE, MMSE-DFE, multiple carrier frequency offsets.

I. INTRODUCTION

Cooperative communications have attracted considerable attention lately due to the potential *cooperative diversity* [1] - [4]. The basic idea to achieve the cooperative diversity is similar to achieving the spatial diversity in multiple antenna systems by utilizing the multiple transmissions and possibly space-time coding. It is well-understood that a major difference between cooperative and multiple antenna systems is that the multiple transmissions in cooperative systems may not be either time or frequency synchronized since the multiple transmissions are from different user or relay node locations while they are co-located in conventional multiple antenna systems. Typically, this means a frequency reuse factor of 3 or more [1], leading to an inefficient spectrum management since the overall bandwidth required for the system is the required bandwidth for a given transmitter times the reuse factor. As an alternative, we can employ SFN (Single Frequency Network) broadcasting systems [2], where several transmitters send the same signal simultaneously and over the same bands, leading to a reuse factor of 1. Since the distance between a given receiver and each transmitter can be substantially different, the overall channel impulse response can be very long, spanning over hundreds or even thousands of symbols in the case of broadband broadcasting systems. To deal with the severe time-distortion effects inherent to SFN systems, digital broadcasting standards such as DVB (Digital Video Broadcasting) [3] and DAB (Digital Audio Broadcasting) [4] selected OFDM modulations(Orthogonal Frequency Division Multiplexing) [5], which are known to be suitable for severely time-dispersive channels. However, OFDM signals have large envelope fluctuations and high PAPR (Peak-to-Average Power Ratio) leading to amplification difficulties [6], [7].

SC modulations (Single-Carrier) combined with FDE (Frequency-Domain Equalization), also denoted as SC-FDE, are a promising alternative to OFDM schemes [8]. As with OFDM schemes, a CP-assisted (Cyclic Prefix) block transmission combined with frequency-domain channel equalization is employed in SC-FDE. Since the transmitted signals have a single carrier, SC-FDE signals have much lower envelope fluctuations than OFDM signals based on the same constellation, allowing efficient and low complexity transmitter implementations [9], [10]. For these reasons SC-FDE schemes were proposed for several broadband wireless systems [11]–[13]. The performance of SC-FDE can be improved if the conventional linear FDE is replaced by nonlinear FDE [14]. A promising nonlinear FDE technique is the IB-DFE (Iterative Block Decision Feedback Equalizer), which can provide performances close to the MFB (Matched Filter Bound) in severely time-dispersive channels.

In this paper, we consider the equalization issue for cooperative communication systems with multiple CFOs. We propose computationally efficient MMSE and MMSE-DFE equalizers when multiple frequency offsets are present, where the equalization matrix inverses do not need to be retaken every symbol in a channel coherent time duration, which may therefore significantly reduce the computational complexity for the equalization. Our proposed equalization methods apply to linear convolutively coded cooperative systems, where the DLC-STC can be used to achieve full asynchronous cooperative diversity when there are timing errors from cooperative users or relay nodes. Our proposed equalization methods also apply to frequency-selective fading channels (from relay nodes to destination node).

II. SYSTEM DESIGN MODEL

A. SYSTEM MODEL

The cooperative communication system considered in this paper is shown in Fig.1, where there are R relay nodes between the source node and the destination node. The DF protocol [2] is adopted. In the first phase, the source broadcasts the information sequence to potential relay nodes. At the relay node, the received signals are decoded and only the relay nodes that correctly decode the received signals will become active relay nodes to participate in the cooperative transmissions in the second phase. In the beginning of the second phase, the eligible relay nodes re-map the decoded information bits into symbols. Without loss of generality, we assume all R eligible relay nodes use the same signal constellation □, such as QPSK or QAM. Therefore, all the symbol sequences re-mapped at relays are the same, which can be denoted as s = [s0, s1, ・ ・ ・, sN−1]. Consider a general distributed linear convolutive coding scheme for the R relay nodes. At the r-th relay node, the information symbol sequence s is linearly transformed into cr by an N × (N + L − 1) generating matrix T(r), i.e., cr = sT(r), where T(r), r = 1, 2, ・ ・ ・ ,R, are Toeplitz matrices in the form:

$$\bar{\mathbf{T}}^{(r)} = \begin{bmatrix} \bar{t}_1^{(r)} & \bar{t}_2^{(r)} & \cdots & \bar{t}_L^{(r)} & 0 & 0 & \cdots & 0 \\ 0 & \bar{t}_1^{(r)} & \bar{t}_2^{(r)} & \cdots & \bar{t}_L^{(r)} & 0 & \cdots & 0 \\ \vdots & \vdots & \ddots & \ddots & \ddots & \ddots & \cdots & \vdots \\ 0 & 0 & \cdots & 0 & \bar{t}_1^{(r)} & \bar{t}_2^{(r)} & \cdots & \bar{t}_L^{(r)} \end{bmatrix}$$

where elements t(r) l , r = 1, 2, ・ ・ ・R, l = 1, 2, ・ ・ ・ , L, are the generating polynomial coefficients for the linear convolutive code and can be designed to satisfy, for example, the *shift-full-rank property* [8] so as to achieve the full asynchronous cooperative diversity as studied in [15]. We would like to emphasize here that our following proposed recursive equalizers are independent of the above generating polynomial coefficients.

For convenience, in what follows we assume that channels from relay nodes to destination node are flat-fading and time-invariant during the transmission of one block. In fact, as we shall see later our proposed methods apply to frequency-selective channels as well. Denote the delays of R relay nodes as _r, r = 1, 2, ・ ・ ・ ,R, respectively, and we only consider the case when the delay is a multiple of symbol duration. Without loss of generality, we assume _1 = 0 and _1 < _2 < ・ ・ ・ < _R. To deal with the timing errors, at the beginning and/or the end of each block, guard interval is inserted so that adjacent code blocks will not overlap with each other [7], [9], [10]. Therefore, we have _ > _R, where _ is the interval padding length. Here we assume _ = _R. Due to the zero padding operations at the relay nodes and the different delays between relay and destination nodes, the *equivalent code matrix* at the destination node can be written as:

$$\mathbf{C} = \begin{bmatrix} \mathbf{c}_1 \\ \mathbf{c}_2 \\ \vdots \\ \mathbf{c}_R \end{bmatrix} = \begin{bmatrix} \bar{\mathbf{c}}_1 & \overbrace{0\ 0\ 0\ 0\ 0\ 0\ \cdots\ 0}^{\tau_R} & & \\ \overbrace{0\ \cdots\ 0}^{\tau_2} & \bar{\mathbf{c}}_2 & \overbrace{0\ 0\ \cdots\ 0}^{\tau_R-\tau_2} & \\ \cdots\ \cdots & \cdots\ \cdots & \cdots\ \cdots & \\ \overbrace{0\ 0\ 0\ 0\ 0\ 0\ \cdots\ 0}^{\tau_R} & \bar{\mathbf{c}}_R & & \end{bmatrix}$$

B. RECURSIVE EQUALIZER DESIGNS

In this section, we assume that at the destination node, the channel information is known, including the delays _i, CFOs △fi, and the channel coefficients hi, i = 1, 2, ・ ・ ・ ,R, and we will derive our recursive equalization algorithms for the destination node based on (7). Different from the MMSE/MMSEDFE equalizers for time-invariant channels [23], [24], ours are for time-varying channels. However, the key observation is that the varying of the channel is only due to the CFO matrix Pk in (9), so the channels in two adjacent symbol intervals have some special relationship that we can fully take advantage of, in a way that the design result at symbol interval k can be exploited to design the equalizer at symbol interval k + 1 so that a new matrix inversion is not necessary.

I. MMSE Equalizer

At the receiver, we use an MMSE equalizer to compensate the channel and the CFOs. The finite length linear MMSE equalizer is a finite impulse response (FIR) filter with order Nf to minimize the mean square error at symbol interval k as:

$$\mathbf{f}_k^{MMSE} = arg \min_{\mathbf{f}_k \in \mathbb{C}^{N_f \times 1}} E \left| s_{k-D} - \mathbf{f}_k^{\mathcal{H}} \mathbf{y}_k \right|^2$$

where fk is the filter coefficient vector and D is the estimation delay to make the filter a causal system, which satisfies 0 6 D 6 (Nf + L′ − 2). Here, we let D = (Nf − 1)/2. Assume the symbol sequence and the additive noise are wide-sense stationary, mutually uncorrelated and white with variance _2 s and _2 n , respectively. The solution for (11) is well known

$$\mathbf{f}_k^{MMSE} = \left(\mathbf{H}_k \mathbf{H}_k^{\mathcal{H}} + c\mathbf{I}_{N_f} \right)^{-1} \mathbf{H}_k \mathbf{i}_D$$

II. MMSE-DFE Equalizer

The linear MMSE equalizer is the optimal linear equalizer in the sense of minimum mean square error. On the other hand, the decision feedback equalizer (DFE) is a well known nonlinear equalizer that can outperform the MMSE equalizer. In the following, we will derive finite-length DFE equalizer based on the minimum mean square error criteria, i.e., MMSE-DFE.

We will show that a similar recursive procedure also exists.
Let Nf and Nb be the lengths of the feedforward and feedback FIR filters, respectively. The design of DFE based on the MMSE criteria is to design fk and bk to satisfy:

$$\left\{\mathbf{f}_k^{MMSE-DFE}, \mathbf{b}_k^{MMSE-DFE}\right\} = arg \min_{\mathbf{f}_k \in \mathbb{C}^{N_f \times 1}, \mathbf{b}_k \in \mathbb{C}^{N_b \times 1}}$$

C. COMPLEXITY ANALYSIS

We derived FIR linear MMSE equalizer and MMSE-DFE equalizer for the asynchronous cooperative system with multiple CFOs. They are both *serial* equalizers, which means that at each time interval, the equalizer only estimate one symbol. However, recall that the symbols are transmitted from relay nodes block by block. Moreover, guard intervals are inserted to overcome the inter-block interference. Therefore, a *block* equalizer [25], [26] can be used to detect symbols as well, i.e., the destination node receives the whole block and then estimate all symbols in the block simultaneously and the matrix inverse is done once for a block. In this section, we first recall the block MMSE and MMSE-DFE equalizers, and then compare their computational complexities with our proposed recursive algorithms.

III. SIMULATION RESULTS

In this section, we present some simulation results to illustrate the equalization performance of our proposed linear MMSE and MMSE-DFE equalizers. Assume the carrier frequency is 2.5GHz, the symbol duration is T = 20µs, and the oscillator's stability is 10ppm. Here we present a set of performance results concerning the proposed frequency offset compensation methods for single frequency broadcast systems. We assume that identical signals emitted from

Fig 1: BER performance for the proposed methods, with a power relation of 10dBs between both transmitters, and considering values of \Deltaf(1)=\Deltaf(2)=0.05'

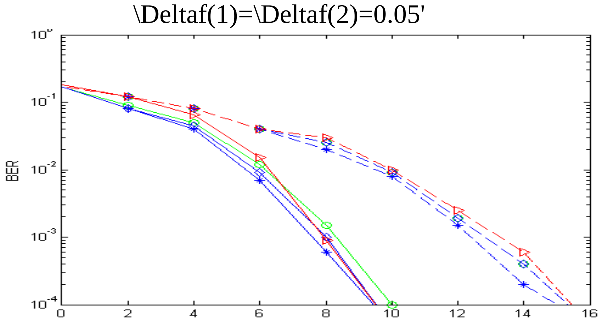


Fig 2: BER performance for the proposed methods, with a power relation of 10dBs between both transmitters, and considering values of \Deltaf(1)=\Deltaf(2)=0.1

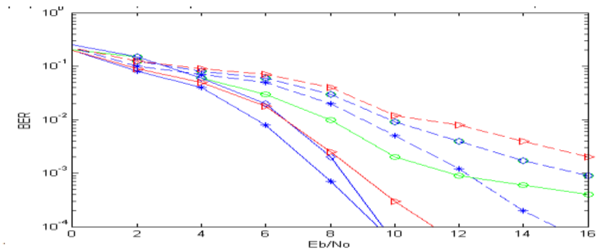


Fig 3: BER performance for the proposed methods, with a power relation of 10dBs between both transmitters, and considering values of \Deltaf(1)=\Deltaf(2)=0.15'

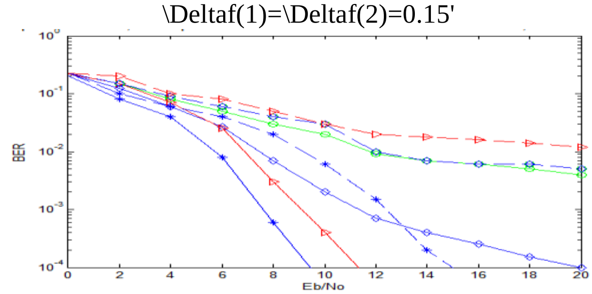


Fig 4: BER performance for the proposed methods, with a power relation of 10dBs between both transmitters, and considering values of \Deltaf(1)=\Deltaf(2)=0.175

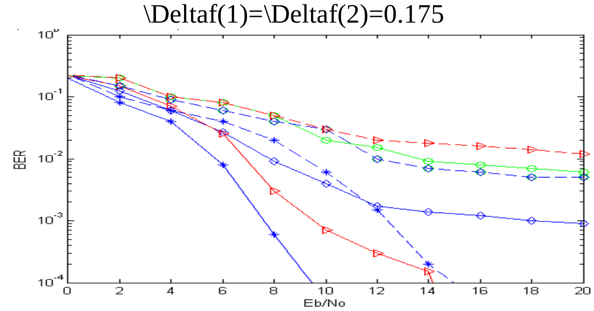


Fig 5: Method I

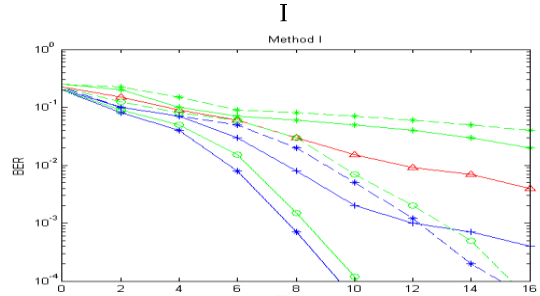


Fig 6: Method II

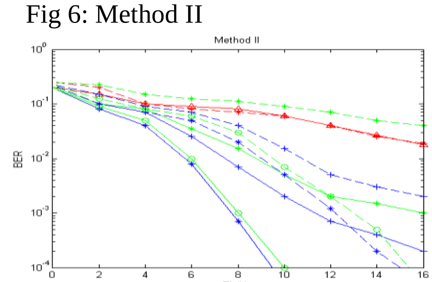


Fig 7: Method III

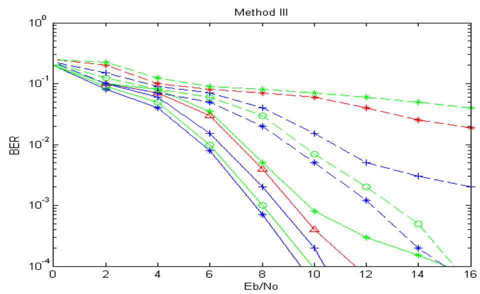


Fig 8: Impact of the received power on the BER performance, with _f(1)? _f(2) = 0.15, and employing the frequency offset compensation for Method II

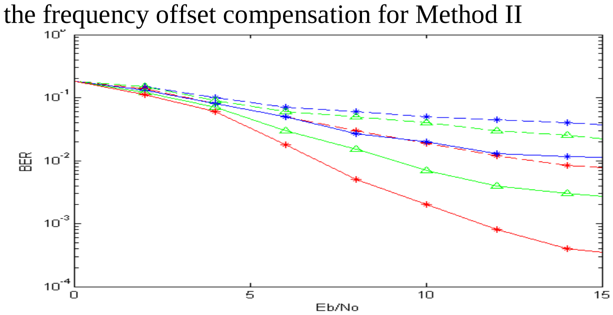


Fig 9: Impact of the received power on the BER performance, with _f(1)? _f(2) = 0.15, and employing the frequency offset compensation for Method II

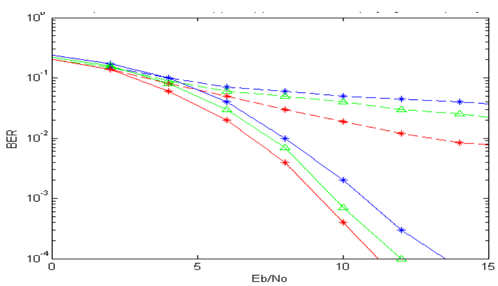
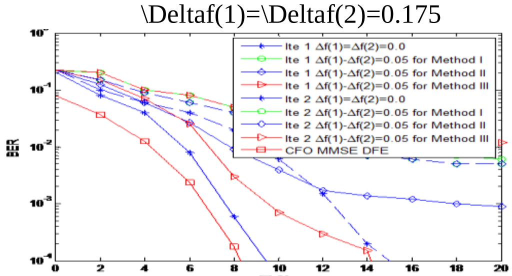


Fig 10: BER performance for the proposed methods, with a power relation of 10dBs between both transmitters, and considering values of \Deltaf(1)=\Deltaf(2)=0.175



different transmitters will arrive at the receiver with different delays, and will have different CIRs. Moreover, we assume different CFOs between the local oscillator at each transmitter and the local oscillator at the receiver. At the receiver's antenna, the signals are added being the result similar to a transmission over a single strong time-dispersive channel.

IV. CONCLUSION

In this paper, we have investigated the equalization issue for linear convolutively coded cooperative network with multiple different carrier frequency offsets and possibly different time delays. We have proposed recursive algorithms for MMSE and MMSE-DFE equalizers where equalization filter matrix inversions are not needed for every symbol in a channel coherent time duration. Our performance results show significant gains on power efficiencies, especially when the receiver is adopted. Therefore, although the slight increase on the complexity of both receivers, they ensure excellent performance allowing good BERs in severely time dispersive channels and even without perfect carrier synchronization between different transmitters.

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