Brief Papers

Channel Estimation and Equalization for Asynchronous Single Frequency Networks

Fábio Silva, Rui Dinis, and Paulo Montezuma

***Abstract*—Single carrier frequency-domain equalization (SC-FDE) modulations are known to be suitable for broadband wireless communications due to their robustness against severe time-dispersion effects and the relatively low envelope fluctuations of the transmitted signals. In this paper, we consider the use of SC-FDE schemes in broadcasting systems. 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. We propose an efficient method for estimating the channel frequency response and CFO associated to each transmitter and propose receiver structures able to compensate the equivalent channel variations due to different CFO for different transmitters. Our performance results show that we can have excellent performance, even when transmitters have substantially different frequency offsets.**

***Index Terms*—Single frequency network, broadcasting systems, SC-FDE, carrier synchronization.**

I. INTRODUCTION

TRADITIONAL broadcasting systems assign different frequency bands to each transmitter within a given region, to prevent interference between transmitters. 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], [15]. A promising nonlinear FDE technique is the IB-DFE (Iterative Block Decision Feedback Equalizer) [16], which can provide performances close to the MFB (Matched Filter Bound) in severely time-dispersive channels [17].

With both OFDM and SC-FDE, the data is transmitted in blocks and a suitable CP, longer than the maximum expected overall CIR length (Channel Impulse Response), is appended to each block. Since, the CP is not used for detection purposes, its length should be a small fraction of the overall block length (usually less than 25% of the length of the useful part), to avoid compromising high power and spectral efficiencies.

Since the overall channel impulse response in broadband wireless broadcasting systems is very long we need very large blocks, with hundreds or even thousands of symbols. This means that it is difficult to ensure that the channel is stationary within the block duration, something required for conventional OFDM and SC-FDE receivers. If the channel changes within the block duration we can have significant performance degradation. The channel variations can be a

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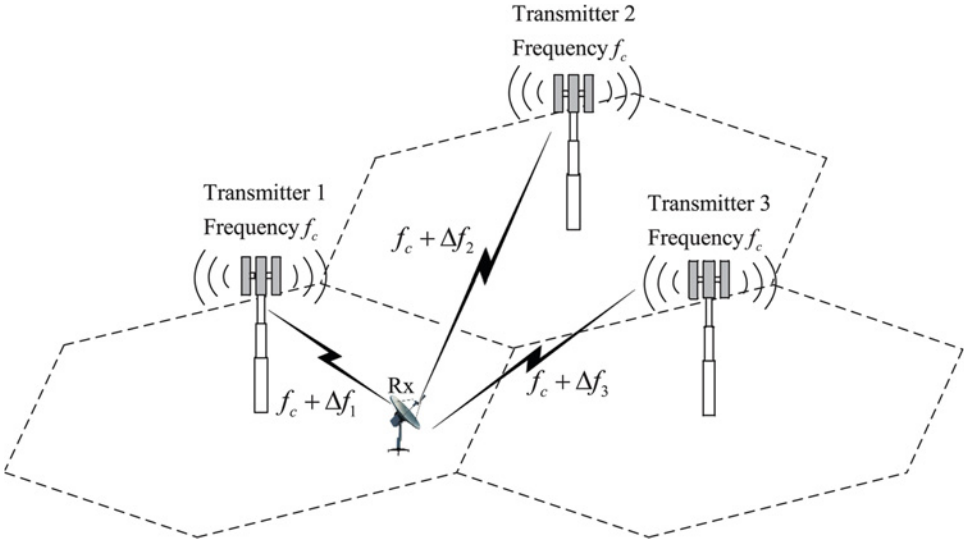

Fig. 1. SFN system.

consequence of two main factors: the Doppler effects associated to the relative motion between the transmitter and the receiver [18] and the frequency errors between the local oscillators at the transmitter and the receiver (also denoted residual CFO (Carrier Frequency Offset)). The residual CFO leads to simple phase variations that are easy to compensate at the receiver [19]–[21]. The Doppler effects are harder to compensate, but since the maximum Doppler offset is much lower than the CFO for typical systems, then also its impact on the performance is much lower. However, in SFN we have simultaneous transmitters with possible different CFOs, and this leads to a very difficult scenario where we have substantial variations on the equivalent channel that are not simple phase variations. In this paper we consider this SFN scenario, with different CFO between the local oscillators at each transmitter and the local oscillator at the receiver. In fact, even for static channels with fixed transmitters and receivers, the residual CFO (Carrier Frequency Offset) between the transmitter and the receiver local oscillators means that the equivalent channel has a phase rotation that changes within the block. This residual CFO can lead to significant performance degradation, regardless of the block transmission technique [22]. Several techniques were proposed for estimating the residual CFO in OFDM schemes [23]–[25]. In [23], a maximum likelihood frequency offset estimation technique was proposed. This method is based on the repetition of two similar symbols, with a frequency acquisition range $\pm 1/(2T)$, where T is the "useful" symbol duration. An estimator based on the BLUE (Best Linear Unbiased Estimator) principle, and requiring one training symbol with $L > 2$ similar parts, and with a frequency acquisition range $\pm L/(2T)$, was proposed in [25].

It is known that in OFDM schemes, frequency errors lead to ICI (Inter-Carrier Interference) [26], and in order to mitigate this problem, two estimation techniques were proposed in [26] and [27]. An efficient equalization technique was also proposed in [28]. However, SC-FDE schemes have higher robustness to carrier frequency errors since that, contrarily to OFDM schemes, in SC-FDE the CFO simply introduces a constellation rotation that grows linearly along the block [20]). Moreover, when an IB-DFE is employed with SC-FDE, the receiver can be specially designed for estimating and compensating the residual CFO [20], [21], allowing excellent performance even when large and/or non-uniform constellations are employed [12].

The impact of CFO errors is much more serious in SFN broadcasting systems because we can have a different CFO between the local oscillator at each transmitter and the local oscillator at the receiver, which means that even in static channels we can have variations on the equivalent channel frequency response that are not simple phase rotations (which can be easily estimated and canceled at the receiver), and for this reason conventional CFO estimation techniques such as the ones of [23]–[25] are not appropriate for estimating the different CFOs inherent to SFN scenarios.

In this paper we consider the use of SC-FDE schemes in broadcasting systems with SFN operation. The channel is assumed static, but we do not have perfect carrier synchronization between different transmitters, i.e., we have different CFO between the local oscillator at each transmitter and the local oscillator at the receiver, leading to variations on the equivalent channel that cannot be treated as simple phase rotations. We propose an efficient technique for estimating the channel associated to the transmission between each transmitter and the receiver, as well as the corresponding CFOs, which is shown to be enough for obtaining the evolution of the equivalent channel along a given frame. We also propose several iterative FDE receivers able to compensate the impact of the different CFOs between the local oscillators at each transmitter and the receiver.

This paper is organized as follows: The SFN system considered in this chapter is characterized in Section II. The CIR and CFO estimation procedure is described in Section III. Section IV describes SC-FDE receivers with joint equalization and CFO correction and a set of performance results is presented in Section V. Finally, Section VI presents the conclusions of this paper.

II. SYSTEM CHARACTERIZATION

In conventional broadcasting systems each transmitter serves a cell and the frequencies used in a cell are not used in adjacent cells. However, we can significantly improve the system's spectral efficiency if multiple transmitters employ the same frequency. In a SFN scenario [2], the transmitters send simultaneously the same signal on the same frequency band, allowing a high spectral efficiency, with a cluster size of 1 (see Fig. 1).

However, the SFN transmission causes time dispersion mainly induced by two factors: the natural multipath propagation due to the reflected or refracted waves in the neighborhood of the receiver, and the unnatural multipath propagation effect due to the reception of the same signals from multiple transmitters, which are then added being the resulting signal equivalent to consider a transmission over a single time-dispersive channel. These factors severely affect the receiver's performance since it leads to ISI (Inter-Symbol Interference) and frequency selective fading which may cause very low values of the instantaneous SNR (Signal-to-Noise Ratio) at the receiver. Thus, the modulation scheme should be able to handle with these problems.

Therefore, the adoption of SFN architectures leads to additional implementation difficulties, namely due to synchronization requirements and the need to cope with severely time-dispersive channels since the equivalent channel is the sum of the channels associated to each transmitter, with substantially different delays and each one with different multipath propagation effects [2].

Throughout this paper, we will use small letters with subscript n for time-domain samples (e.g., s_n) and capital letters with subscript k for frequency-domain samples (e.g., S_k). The letters S, Y, H and N refer to the transmitted signal, received signal, channel and noise, respectively. A superscript (i) denotes refers to the ith transmitter. Δf denotes the CFO (if appears as a superscript it means a signal with CFO) and θ_n the corresponding phase rotation. The estimates are marked with hat (e.g., $\hat{\theta}_n$).

A. Channel Characterization

The channel's impulse response corresponding to the lth transmitter is given by

$$h^{(l)}(t) = \sum_{i=1}^{N_{Ray}} \alpha_i^{(l)} \delta\left(t - \tau_i^{(l)}\right), \tag{1}$$

where $\alpha_i^{(l)}$ and $\tau_i^{(l)}$ are the complex gain and delay associated to the ith multipath component of the lth transmitter (without loss of generality we assume that all channels have the same numbers of multipath components).

The equivalent channel's impulse response at the receiver side can be seen as the sum of the impulse responses corresponding to the N_{Tx} transmitters, and can be defined as

$$h(t) = \sum_{l=1}^{N_{Tx}} h^{(l)}(t). \tag{2}$$

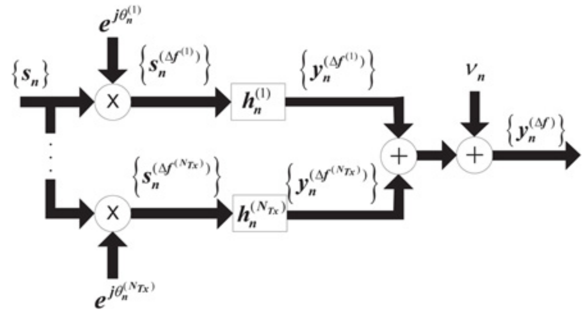

Fig. 2. Equivalent transmitter plus channel.

Let us focus on the transmission of a signal $s(t)$ through the SFN system considering the ideal case in which different transmitters emit exactly the same signal without CFO (i.e., we have perfect carrier synchronization between each transmitter). The received signal waveform $y(t)$ is the convolution of $s(t)$ with the equivalent channel's impulse response, $h(t)$, plus the noise signal $\nu(t)$, i.e.,

$$\begin{aligned} y(t) = s(t) * h(t) + \nu(t) &= \sum_{l=1}^{N_{Tx}} s(t) * h^{(l)}(t) + \nu(t) \\ &= \sum_{l=1}^{N_{Tx}} y^{(l)}(t) + \nu(t), \end{aligned} \tag{3}$$

where $*$ denotes the convolution operator, and ν_l represents AWGN samples with unilateral power spectral density N_0. The signal $y(t)$ is sampled at the receiver, and the CP is removed, leading to the time-domain block $\{y_n; n = 0, ..., N-1\}$, with

$$y_n = \sum_{l=1}^{N_{Tx}} y_n^{(l)} + \nu_n. \tag{4}$$

Since the corresponding frequency-domain block associated to the lth transmitter, obtained after an appropriate size-N DFT operation, is $\{Y_k^{(l)}; k = 0, 1, \ldots, N-1\}$=DFT$\{y_n^{(l)}; n = 0, 1, \ldots, N-1\}$, then we may write

$$Y_k = \sum_{l=1}^{N_{Tx}} Y_k^{(l)} + N_k = S_k H_k + N_k, \tag{5}$$

where

$$H_k = \sum_{l=1}^{N_{Tx}} H_k^{(l)}, \tag{6}$$

with $H_k^{(l)}$ denoting the channel frequency response for the kth subcarrier of the lth transmitter.

B. Impact of Carrier Frequency Offset Effects

Let us now consider the impact of different CFO between the local oscillator at each transmitter and the local oscillator at the receiver. For the sake of simplicity, we assume that the CFO affects the signals sent by each transmitter, i.e., the CFO induces a phase rotation that grows linearly along the block [12]. Without loss of generality, we also assume that the phase rotation is 0 for the initial sample ($n = 0$), for each transmitter[1]. In this case, the received equivalent time-domain

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[1] Clearly, the initial phase rotation can be absorbed by the channel estimate.