A Novel Time-Domain Frequency Offset Estimation Algorithm for LTE Uplink

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***Abstract*—Frequency offset (FO) estimation and compensation is critical to the performance of orthogonal frequency division multiple access (OFDMA) systems. In uplink single carrier SC-OFDMA systems, such as long term evolution (LTE), traditional correlation-based time-domain FO estimation techniques are not valid due to the presence of multi-users. Thus, frequency-domain techniques are mostly used. In case of frequency hopping (FH) in uplink LTE, correlation-based frequency-domain techniques cannot be used and other alternative techniques give modest results. In this paper, we propose a novel time-domain FO estimation technique and show that it results in superior performance in case of FH.**

***Index Terms*—LTE; Uplink; Frequency Offset; hopping.**

I. Introduction

In recent years, orthogonal frequency division multiple access (OFDMA) has been widely adapted as a multiple access technique in wideband wireless communication systems including long term evolution (LTE) [1]. OFDMA offers several advantages over both time division multiple access (TDMA) and frequency division multiple access (FDMA) techniques, namely simpler equalization and better spectral efficiency compared to the former and the latter, respectively.

OFDMA depends on the orthogonality between subcarriers. This means that OFDMA systems are particularly sensitive to frequency offset (FO) since it ruins the subcarriers orthogonality. Thus, FO estimation and compensation in OFDMA systems is critical for acceptable system performance. The main sources of FO are the lack of frequency synchronization between the transmitter and receiver on one hand and the Doppler shift introduced by the receiver mobility on the other.

Frequency offset results in a linear phase superimposed on the time-domain signal. In downlink systems, for instance in the physical downlink shared channel (PDSCH) of LTE, the user equipment (UE) estimates the FO through the phase difference between the cyclic prefix (CP) samples and the corresponding OFDM symbo l samples. This is not feasible in the uplink, for instance in the LTE physical uplink shared channel (PUSCH). In the uplink, multiple UEs transmit at the same time but are disjoint in frequency and the enhanced node B (eNB) receiver separates UE signals in the frequency domain. Thus, typical time-domain techniques cannot be used to estimate the FO. Instead, frequency-domain FO estimation techniques have been adopted for the LTE uplink case. Most algorithms for frequency offset estimation in OFDM systems are based on the correlation based method in [2] [3]. The algorithm proposed in [4] is an example of a frequency-domain correlation technique. This algorithm estimates the average phase difference between the slot 0 and slot 1 estimated channels through the use of reference signals (RS) of PUSCH. The aforementioned algorithm results in relatively accurate FO estimation results. However, it cannot be implemented in case of frequency hopping in LTE since in that case, the slot 0 and slot 1 channels are not aligned in frequency and thus the average phase difference between pairs of corresponding subcarriers cannot be attributed to the FO alone. A *frequency bins* algorithm has been introduced in [5] for the case of FH. However, simulation results show that the FO estimation using the frequency bins algorithm is sensitive to noise and does not provide acceptable estimation accuracy in low signal to noise ratio (SNR) cases as shown in the numerical results section.

In this paper, we propose a novel time-domain FO estimation algorithm that performs well for both the hopping and non-hopping cases. Estimation accuracy is significantly improved compared to the algorithm in [5].

This paper is organized as follows: Section II presents the system model. Section III introduces the proposed time-domain FO estimation algorithm. In Section IV, the numerical results are presented. Section V concludes the paper.

II. System Model

The LTE uplink uses single carrier orthogonal frequency multiple access (SC-OFDMA). This means that at the UE transmitter, the transmit data goes through

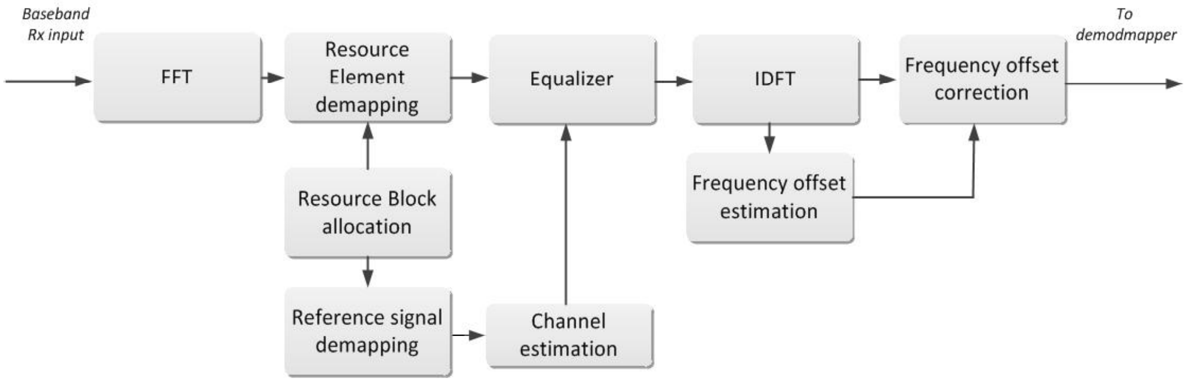

Figure 1. The block diagram of the LTE receiver.

a discrete Fourier transform (DFT) process before the OFDM symbol generation. A block diagram of an LTE receiver is shown in Figure 1. The received baseband signal is first transformed into the frequency domain where the RS is separated from the data. The RS is used to estimate the channel, which is fed to the equalizer. The equalized data is transformed into time-domain quadrature amplitude modulation (QAM) complex time samples. The proposed algorithm performs FO estimation using the inverse DFT (IDFT) output (of size N_{FFT}) time-domain QAM samples.

FO results in an excess linear phase across the time-domain QAM samples as shown in Figure 2. For OFDM symbol i, and time sample n, the excess phase due to an FO of Δf Hz can be modeled as an average phase $\bar{\theta}_i$ in addition to an additional zero-mean linear phase $\Delta\theta(n)$. The FO time sample $\tilde{s}_i(n)$ is given by

$$\tilde{s}_i(n) = s_i(n) e^{j\left(\bar{\theta}_i + \Delta\theta(n)\right)}, \tag{1}$$

where $s_i(n)$ is the time sample without FO, $\bar{\theta}_i = 2\pi\Delta f \Delta T_i$ is the mean excess phase of OFDM symbol i separated by ΔT_i seconds from a reference OFDM symbol, and $\Delta\theta(n) = 2\pi\Delta f n T_s$ is the additional zero-mean linear phase of sample n, where $-N_{FFT}/2 \leq n < N_{FFT}/2$, and T_s is the sample time. Figure 3 illustrates the time-domain constellation diagram of a 16-QAM signal offset by $\Delta f = 35$ Hz containing time samples from one subframe (12 OFDM symbols carrying data). The constellation is rotated by an average angle $\bar{\theta}_i$. Moreover, each group of samples carrying the same QAM symbol is further spread by different angles $\Delta\theta(n)$ depending on their respective sample numbers in their own OFDM symbols. In Section III, we show how the angular spread of the time-domain constellation samples is used to estimate and correct frequency offset.

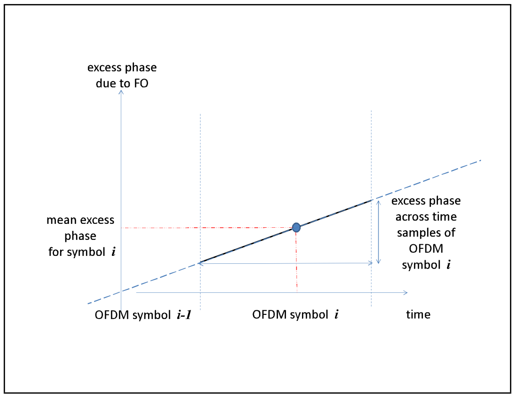

Figure 2. Excess linear phase caused by FO across OFDM symbols.

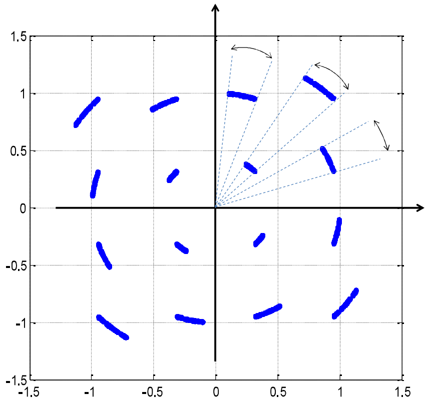

Figure 3. Rotation of constellation point with an angular spread corresponding to the linear phase spread.

III. Proposed FO Estimation Algorithm

As explained in Section II, the FO value results in a unique value of the angular rotation $\bar{\theta}_i$ and angular spread $\Delta\theta(n)$ for each OFDM symbol. Conversely, a frequency offset OFDM symbol compensated using the correct value of the FO should have minimal angular rotation and spread. In case of perfect channel equalization and absence of additive noise, the residual angular spread after compensation should ideally be zero.

In this paper, we propose an algorithm for FO estimation that processes the time-domain QAM constellation points in uplink LTE. The idea is to first specify a number of candidate values for FO spanning a reasonable range $-\Delta f_{max} \leq \Delta f \leq \Delta f_{max}$, where Δf_{max} is the maximum expected frequency offset determined by the deployment scenario. Maximum limits on the frequency error between the UE and eNB are mandated by the LTE standard [6]. Also, there are practical limits on the Doppler shift dictated by maximum expected speeds of users in the LTE system [7]. Both of these limits together determine the value of Δf_{max}. The number of candidate values spanning the specified range is a tradeoff between FO estimation accuracy and computational complexity of the algorithm. Simulation results show that a reasonable resolution (difference between two consecutive points in the range) is 100 Hz.

An exhaustive search is performed on all the candidate FO values to decide on the most accurate FO estimate. Each candidate value is used for FO compensation of the time-domain constellation. After FO compensation, the resulting signal is hard demapped to obtain different groups of constellation samples. Each group is centered around a rotated constellation point.

We propose to use the residual angular spread of each group around its center point as a metric to determine the best FO estimate, where the best estimate results in the minimum residual angular spread. A practical measure of the angular spread is the variance defined as $E[|x-\mu_x|^2]$ where x represents the constellation points in a group and the mean μ_x is the group center. Note that even if one of the candidate FO values falls exactly on the actual FO, the residual variance will not vanish since the source of the residual variance is the additive noise variance (independent of the compensation frequency value) in addition to the residual angular spread.

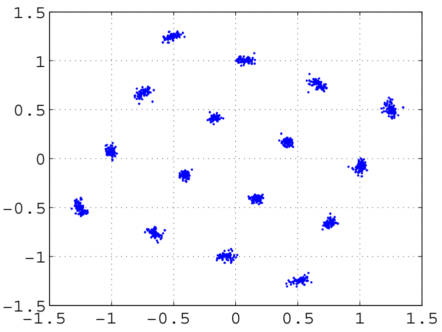

Figure 4. A noisy 16-QAM time-domain constellation diagram with an FO of 300 Hz.

Figure 4 shows the constellation diagram of a 16-QAM signal with frequency offset 300 Hz. Figure 5 shows the diagram after perfect compensation, i.e., 300 Hz is used to compensate the offset. Figure 6 is the diagram after compensation using only 100 Hz. It can be seen from both figures that when using the correct value for frequency offset compensation, the constellation rotation is eliminated and the scattering of constellation points is reduced. On the other hand, when using an incorrect value for compensation, there is a residual constellation rotation, as well as relatively large scattering of the constellation point.

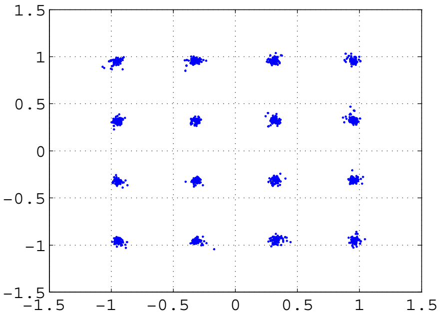

Figure 5. A noisy 16-QAM time-domain constellation diagram with an FO of 300 Hz after FO compensation of 300 Hz.

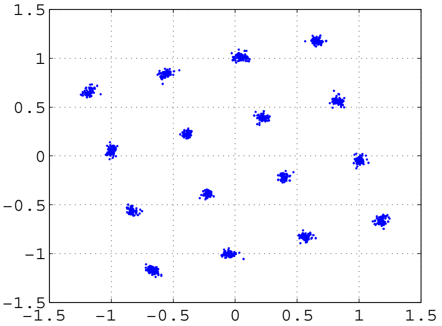

Figure 6. A noisy 16-QAM time-domain constellation diagram with an FO of 300 Hz after FO compensation of 100 Hz.

In our proposed algorithm, we measure the level of scattering through the variance of the constellaiton points around their respective centers and use that as a metric to decide on the correct FO value. The algorithm can be summarized in the following steps:

1) Set $FO = -\Delta f_{max}$ Hz.
2) Use FO to compensate the IDFT output.
3) Perform hard de-mapping of the compensated signal.
4) Group the soft values of the compensated signal based on their hard de-mapped values.
5) Calculate the variance of each group.
6) Increment FO by f_{step} Hz. If $FO > \Delta f_{max}$ Hz, go to step 8. Otherwise, proceed to step 7.
7) Go to step 2.

8) Compare all variances calculated in step 5.
9) The estimated FO corresponds to the minimum variance in step 8.

IV. Numerical Results

In this section, we present the numerical results for our proposed FO estimation algorithm.

Figure 7 is a plot of the mean estimated FO in Hz vs SNR for a 64-QAM modulation with code rate 5/6 and an FO of 300 Hz. Throughout our simulations, $\Delta f_{max} = 400$ Hz with a range resolution of 100 Hz. Note that system performance is not sensitive to small FO estimation errors within ±50 Hz.

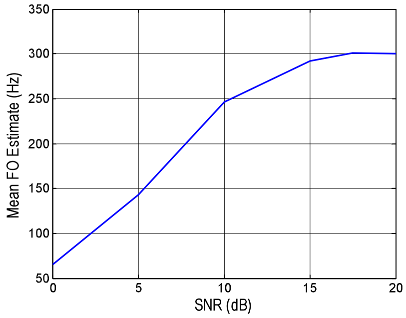

Figure 7. Mean estimated FO vs. SNR: 1 UE with 1 RBs, 64 QAM 5/6, one-tap channel with frequency offset of 300 Hz.

Figure 8 shows the block error rate (BLER) vs. SNR performance curves for both our proposed time-domain algorithm and the frequency bins algorithm proposed in [5]. These curves are for a QPSK modulation with code rate 1/3. The FO of 300 Hz in this simulation corresponds to a mobile user moving at a speed of 85 km/hr. The simulation results show that our proposed time-domain algorithm outperforms the frequency bins algorithm. The gap in performance is significant for the high SNR range.

Figure 9 shows the block error rate (BLER) vs. SNR performance curves for same aforementioned algorithms. These curves are for a 64-QAM modulation with code rate 5/6. Again, the FO of 300 Hz in this simulation corresponds to a mobile user moving at a speed of 85 km/hr. The simulation results show that our proposed time-domain algorithm outperforms the frequency bins algorithm with a significant gap for the high SNR range.

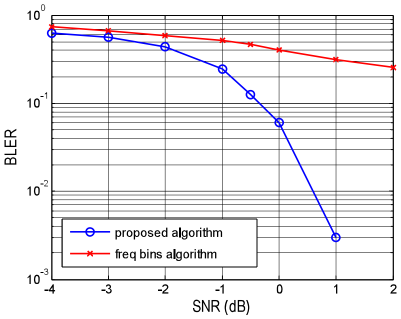

Figure 8. BLER performance of proposed and frequency-bins algorithms:1 UE with 1 RBs, QPSK 1/3, one-tap channel with frequency offset of 300 Hz.

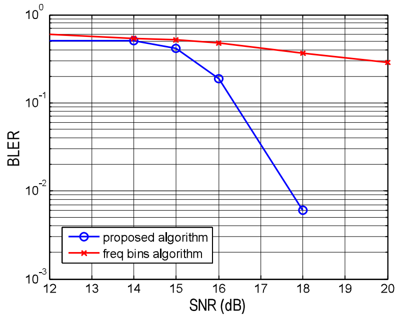

Figure 9. BLER performance of proposed and frequency-bins algorithms:1 UE with 1 RBs, 64 QAM 5/6, one-tap channel with frequency offset of 300 Hz.

V. Conclusion

In this paper, we propose a novel time-domain frequency offset estimation and compensation algorithm that can be used in case of frequency hopping uplink LTE, as well as non-hopping case. The numerical results show the superior performance of the proposed algorithm compared to the only published algorithm that can be used in the frequency hopping case to the best of the author's knowledge.

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