TELKOMNIKA, Vol.17, No.6, December 2019, pp.2722~2728
ISSN: 1693-6930, accredited First Grade by Kemenristekdikti, Decree No: 21/E/KPT/2018
DOI: 10.12928/TELKOMNIKA.v17i6.11957

Blind frequency offset estimator for OFDM systems

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Abstract

Orthogonal Frequency Division Multiplexing (OFDM) is of great interest for the development of the fifth-generation technology. It is the cornerstone of Multiple-input multiple-output (MIMO) systems. Even though inter carrier interference (ICI) and inter symbol interference (ISI) have been processed for the fourth-generation standards, they still present a huge problem for the fifth-generation standards. This paper explores the tradeoff between the length of the cyclic prefix and the performances of the OFDM system. It also studies the effect of carrier frequency offset (CFO) on OFDM systems. A blind frequency offset estimator that uses the correlations between the remodulated sequence in the receiver side and the conventional received symbol is presented and a closed form solution is derived. The proposed estimator is derived under short interval when the correlation is high, so it has low computational complexity. Lin and Beek's estimators are used for comparison. Simulations demonstrate the effectiveness of the proposed estimator under Rayleigh fading channel.

***Keywords**: AWGN channel, carrier frequency offset (CFO), inter-carriers' interference (ICI), orthogonal frequency division multiplexing (OFDM), Rayleigh fading channel*

1. Introduction

OFDM system has the possibility to be used in the development of the fifth-generation standards because of its high robustness against channel dispersion and multipath channels [1]. This muti-carrier modulation technique was used by several standards likewise Enhanced mobile broadband (eMBB) and ultra-reliable low latency communication (URLLC) services at below 40 GHz carriers [2]. However, further research is needed to define the key performance requirements on spectral efficiency, unwanted emission limits and the carrier synchronization [3, 4]. Hence, several techniques that used OFDM are developed to overcome the needs of the fifth-generation about technological challenges. One of the major disadvantages in OFDM system is the inter carrier interference (ICI) caused by the carrier frequency offset (CFO) between the transmitter and the receiver or by Doppler spread [5, 6]. This CFO destroys the orthogonality between sub-carriers. While, due to the requirements of the speed data, orthogonality [7] needs to be maintained. Hence, the estimation of carrier frequency offsets (CFOs) is an interesting problem [8] to be addressed for OFDM system.

Many data aided techniques have been proposed to correct frequency offset and avoid ICI [9-13]. Although these algorithms can effectively estimate frequency offset, they reduce the bandwidth efficiency. To eliminate this reduction, non-data-aided algorithms that exploit the redundancy of the cyclic prefix (CP) have been developed [14-20]. The joint maximum-likelihood (ML) estimation of the symbol-time and carrier frequency offset [14], referred to as VDB-MLA, is assumed in additive white Gaussian noise (AWGN) channels. However, its performance might be degraded over multipath channels. To overcome this shortage, authors in [18-20] propose a joint ML synchronization algorithm for symbol timing and CFO in OFDM systems over dispersive fading channels, based on the redundancy of the CP. In order to avoid the high complexity and the impractical implementation of joint ML estimation of the timing error, the FFO, the IFO and the preamble index, a realistic approach based on two-stage procedure is proposed in [21]. In the first stage, timing offset and FFO is estimated using Blind estimation based on redundant information from the cyclic prefix. In the second stage, the IFO and the preamble index recovery are accomplished in a joint ML estimation and also suboptimal algorithms are developed. B. Xie and all [22] studied the effects of

Received December 4, 2018; Revised February 24, 2019; Accepted March 12, 2019

CFO-induced spectral misalignment for OFDM systems in frequency-selective channels and generated an exact signal model. However, this exact signal model didn't include timing and sampling offsets. A generalization of ref [22] is presented in [23]. It incorporates timing and sampling offsets and studies what effects the accurate signal model brings to the CFO estimation and how to address them. P. S. Wang and all [24] used a more complete signal correlation function over wide-sense stationary uncorrelated scattering (WSSUS) channels involving triplet structure. Based on this model an exact likelihood function is derived. It is found that the ML CFO estimate is the solution of a quartic equation, rather than the phase angle of a complex number as obtained in many previously derived methods. T. C. Lin and all [25] developed a solution to exploit the repetitive structure of CP samples in multipath channels by using the so-called remodulated received vectors [26]. The authors developed a blind estimator for fractional CFO. They proposed a new CP-based algorithm for blind CFO estimation in OFDM systems. Both the Cramer-Rao bound (CRB) on MSE and a closed form formula for the theoretical MSE is derived for multipath channels. Using the remodulation of the received signal in presence of CFO for blind estimation, coarse and fine CFO estimators are derived. The distributed multiple-input multiple-output (DMIMO) system, combined with orthogonal frequency division multiplexing (OFDM), is an arising model with high data rate for the fifth-generation [27]. DMIMO-OFDM system demands rigorous synchronization and tracking because the received signal has multiple timing offsets MTOs, multiple frequency offsets MCFOs and frequency-selective channel gains. Thus, the reference [27] proposed two iterative estimators: expectation conditional maximization (ECM) and space-alternating generalized expectation maximization (SAGE) to mitigate these impairments. The residual time-frequency estimation errors at the relays are improved.

OFDM leads to high spectral efficiency over multipath channel, which makes its use in the fifth-generation more suitable and relevant [28]. However, its sensibility to inter carrier interference ICI is a real obstacle that prevents its use. Although the very large number of works dealing with the problem of synchronization [29-31], the OFDM still requires additional research to overcome this disadvantage which penalizes the use of its capabilities in the fifth generation. Due to foregoing problem, our contribution in this paper focalizes on the problem of ICI. We develop a blind frequency offset estimator CFO based on the correlation between samples in the cyclic prefix over Rayleigh fading channel. We use the remodulated sequence proposed in [25, 26]. A closed form solution is derived using the correlation characteristic and the log likelihood function. This paper shows that the new frequency offset estimator can ameliorate the results of OFDM system for different length of cyclic prefix. The rest of this paper is organized as follows. Section 2 introduces the effect of CFO in OFDM systems. The proposed CFO estimator is explained in detail in section 3. Results and discussions are provided in section 4. Finally, some conclusions are presented in section 5.

2. The Effect of CFO in OFDM Systems

An OFDM symbol consists of N subcarriers is given by the (1):

$$z(n) = \sum_{k=0}^{N-1} Z(k) e^{\frac{j2\pi kn}{N}} \tag{1}$$

where $z(n)$ is the IDFT (Inverse Discrete Fourier Transform) of the transmitted symbol $Z(k)$ for k=0,.., N-1. We assume that a_0 is the normalized frequency offset and τ_0 is the time offset. Carrier frequency offset is modulated by a phase shift of $2\pi a_0 n/N$. Assuming that N_{cp} is the length of the cyclic prefix which is used to avoid ISI and $h(l)$ is the multipath fading channel of length L where $L \leq N_{cp}$. The observed window is assumed of length *($2N+N_{cp}$)*.

After going across multipath channel and AWGN channel the received signal is given by:

$$u(n) = \sum_{l=0}^{L-1} h(l) z(n - l - \tau_0) e^{\frac{j2\pi n_a}{N}} + w_n \tag{2}$$

where w_n is an additive white Gaussian noise. Then, the DFT of received signal can be written as [10]:

$$U(k) = DFT\big(u(n)\big) \tag{3}$$

$$U(k) = Z(k)H(k)\{(\sin \pi a_0)/(N \sin(\pi a_0/N))\}e^{j\pi a_0(N-1)/N} + I_k + W_k \tag{4}$$

where H is the DFT of the multipath channel h and W_k is the DFT of the additive white Gaussian noise w_n. The data is attenuated by the term $\{(\sin \pi a_0)/(N \sin(\pi a_0/N))\}$ and shifted by the term $e^{j\pi a_0(N-1)/N}$. I_k represents the inter carrier interference and is expressed as [10]:

$$I_k = \sum_{\substack{i=0 \\ i\neq k}}^{N-1} Z_i H_i \big\{\sin \pi(i-k+a_0)\,/\big(N \sin\big(\pi(i-k+a_0)\big)\big)/N\big\} \cdot e^{j\pi a_0(N-1)/N} e^{j\pi(i-k)/N} \tag{5}$$

3. Proposed CFO Estimator

Utilizing the remodulated sequence [25, 26]; a proposed CFO estimator is derived. Before removing the cyclic prefix, on the receiver side, the received data is given by:

$$U_k = \big[u_k(\tau_0) \dots u_k\big(N_{cp}+\tau_0-1\big) \dots u_k\big(N+N_{cp}+\tau_0-1\big)\big]^T \tag{6}$$

the remodulated vector is formed by bringing together the last *N* carriers of u_{k-1} and the first N_{cp} carriers of u_k as presented in (7):

$$U_r = \big[u_{k-1}\big(N_{cp}+\tau_0\big) \dots u_{k-1}\big(N+N_{cp}+\tau_0-1\big)u_k(\tau_0) \dots u_k\big(N_{cp}+\tau_0-1\big)\big]^T \tag{7}$$

the calculation interval I_c is given by:

$$I_c = \big[\tau_0, \dots, \tau_0+N_{cp}-1, \tau_0+N, \dots, \tau_0+N+N_{cp}-1\big] \tag{8}$$

the correlation between remodulated samples and received samples is given by:

$$\forall k \in I_c, \mathrm{E}\big\{u(k)u^{r^*}(k)\big\} = \sigma_u{}^2 e^{-j2\pi a_0} \sum_{m=1}^{M} |h(m)|^2 \tag{9}$$

Assuming that the length L of the channel $h(l)$ is inferior to the length of cyclic prefix N_{cp} and the channel taps slide into the calculation interval I_c. Thus, the channel effect is neglected in the manipulations. Using the log likelihood function of the received samples and remodulated samples as:

$$\Im(\tau_0, \alpha_0) = \log \prod_{k\in I_c} \frac{f\big(u(k), u^r(k)\big)}{f\big(u(k)\big)f\big(u^r(k)\big)} \tag{10}$$

by inserting the probability density function (pdf) $f\big(u(k)\big)$, $f\big(u^r(k)\big)$ and the joint Gaussian pdf $f\big(u(k), u^r(k)\big)$ and after some algebraic manipulations, we get:

$$\Im(\tau_0, \alpha_0) = \sum_{k\in I_c} \left\{ \frac{2\left(\rho_k\big(\chi(k) - p_k^2 \beta(k)\big)\right)}{(\sigma_u^2+\sigma_w^2)(1-p_k^2)} - \log(1-p_k^2) \right\} \tag{11}$$

where

$$\chi(k) = \sum_{k\in I_c} \mathrm{Re}\left\{E\left(u(k)u^{r^*}(k)\right)\right\} \tag{12}$$

$$\beta(k) = \sum_{k \in I_o} \frac{1}{2} (|u(k)|^2 + |u^r(k)|^2) \tag{13}$$

$\chi(k)$ is the sum of the real consecutive correlation, $\beta(k)$ is the energy term.

The LL function $\Im$ is a function of α_0, the correlation coefficient and τ_0. It's clear that if the correlation coefficient is high ($\rho_k \cong 1$) the LL function is high ($\Im \to +\infty$) and if the correlation coefficient is null. The LL function is also null. Thus, we derive the log likelihood function in the interval $\Im$ where the correlation coefficient is high. So, to obtain the maximum of the LL function $\Im(\tau_0, \alpha_0)$, we only maximize the (14):

$$\max \Im(\tau_0, \alpha_0) = \max[\chi(\tau_0, \alpha_0) - \rho_k \beta(\tau_0, \alpha_0)] \tag{14}$$

This equation depends on the frequency offset $\alpha_0$and the time offset τ_0. Then the new estimator is derived as

$$\tilde{\tau}_0 = \arg\max[\chi(\tau_0) - \rho_k \beta(\tau_0)] \tag{15}$$

$$\tilde{\alpha}_0 = -\frac{1}{2\pi} \angle \chi(\tilde{\tau}_0) \tag{16}$$

a similar frequency offset estimator has been proposed in [14, 18]. The developed carrier frequency offset estimator is derived when the correlation coefficient is high to deal with the carrier frequency offset.

4. Results and Discussion

The performances of our estimator are evaluated and Monte-carlo methods are employed. Different OFDM systems are used to assess the proposed estimator. The first OFDM system consists of ten symbols, the used parameters are N = 128 and N = 64 subcarriers for different lengths of Ncp, frequency offset α_0 = 0.295 and 0.25. The time offset is assumed null. The signal passes through the Rayleigh fading channel with five paths with delays of [0 1 2 6 11] and variances [0.34 0.28 0.23 0.11 0.04] respectively, as given in [25]. A Quadrature Amplitude Modulation 16-QAM is utilized. The performances of proposed estimator are evaluated by calculating the Mean Squared Error (MSE) compared with signal to noise ratio (SNR).

The MSEs of the proposed estimator (MSE-Proposed-2), Lin's estimator (Lin-coarse and Lin-fine) [25] and Beek's estimator (VDB-MLA) [14] are presented in the figure below versus SNR for N = 64 and $N_{cp} = 16$. The obtained results in Figure 1 show clearly the effectiveness of the proposed estimator compared with Lin's and Beek's estimators. Lin-coarse and VDB-MLA have closer results. The proposed estimator gives lower MSE than the others for all SNR values. These results can be explained by the good choice of the correlation interval where it is taken when the correlation coefficient is elevated (close to 1). In addition, the proposed estimator has low computational complexity compared to the Lin estimator which divides the estimation into two steps and thus increases the computation.

Our goal is to adapt the OFDM symbol so that it can be used for the fifth generation. In other way how to deal with frequency offset without decreasing the bandwidth efficiency. We employ different lengths of cyclic prefix to show the robustness of the proposed estimator with lower lengths of the guard interval. Figures 2 and 3 give the MSE of the frequency offset versus SNR under Rayleigh channel for $N_{cp} = 8$ and $N_{cp} = 6$ respectively. It can be seen clearly that the proposed estimator outperforms Lin estimator [25] and Beek estimator [14] for all SNR values and for all CP lengths. We can notice that as N_{cp} increases the efficiency increases.

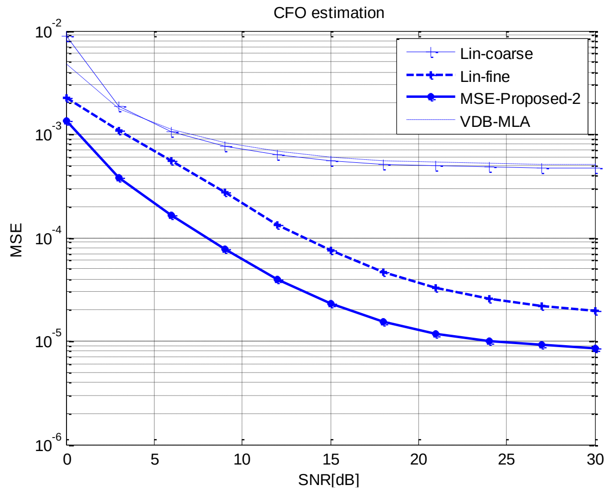

Figure 1. MSE of the proposed estimator, Lin’s estimator and Beek estimator under Rayleigh fading channel for $N_{cp} = 16$ and $\alpha_0 = 0.295$

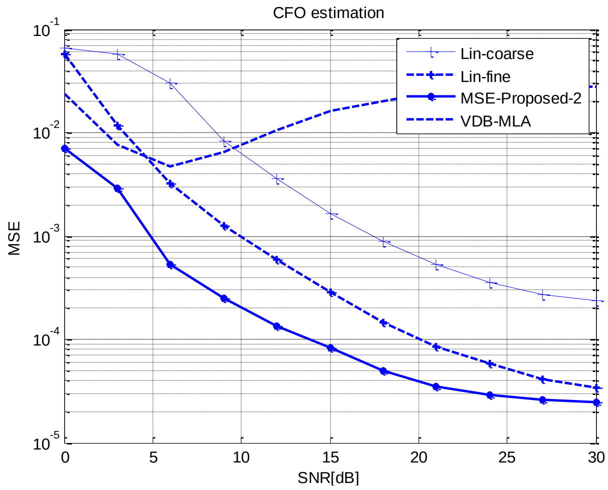

Figure 2. MSE of the proposed estimator, Lin’s estimator and Beek estimator under Rayleigh fading channel for $N_{cp} = 8$ and $\alpha_0 = 0.25$

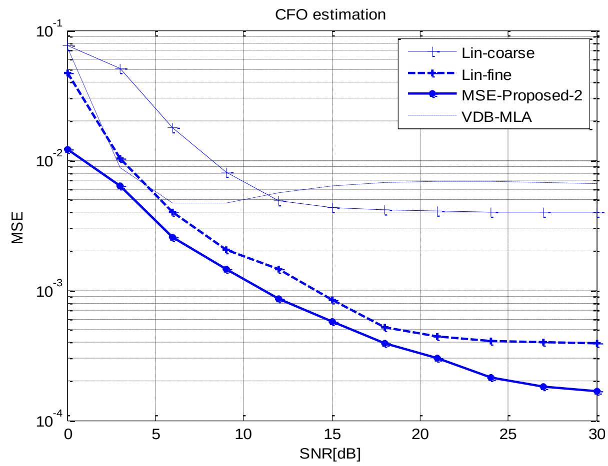

Figure 3. MSE of the proposed estimator, Lin’s estimator and Beek estimator sunder Rayleigh fading channel for $N_{cp} = 6$

Figure 4 displays the MSE of the proposed estimator and Lin's fine estimator over Rayleigh fading channel for different length of cyclic prefix. For $N_{cp} = 32$, the proposed estimator gives better results than Lin's fine estimator for SNR inferior to 22dB and gives closely results for SNR between 22.5 dB and 24 dB. However, its performances decrease for SNR superior to 24 dB compared to Lin's fine estimator. For $N_{cp} = 8, N_{cp} = 16$, the proposed estimator outperforms Lin's fine estimator [25] for all SNR values. Thus, this estimator can effectively decrease the effect of intercarrier interference ICI and can enhance the performances of OFDM system. According to the obtained results, while the cyclic prefix decreases, the undesirable MSE increases. However, the unwanted MSE is decreased compared to the previous work [25].

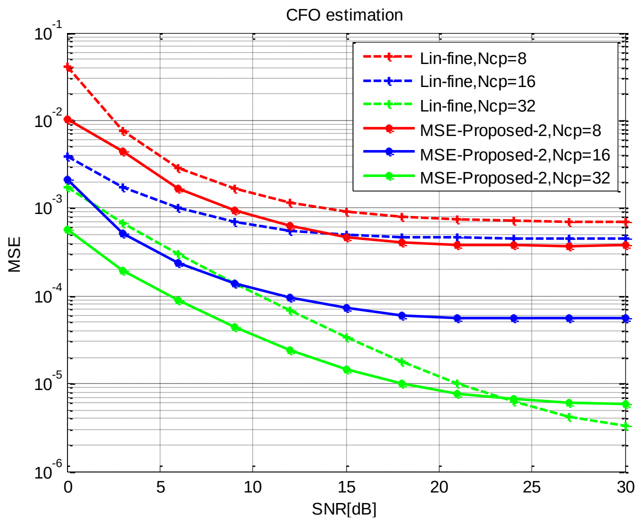

Figure 4. MSE of the proposed estimator Lin-fine estimator for N=128, $N_{cp} = 8, 16, 32$ and $\alpha_0 = 0.25$

5. Conclusion

A proposed ML estimator of carrier frequency offset for OFDM systems over Rayleigh channel is presented. This estimator based on the correlation between the remodulated and received samples in the receiver side. The results prove the effectiveness of the proposed estimator compared with Lin's coarse and fine estimators and also Beek's estimator. In addition, the proposed estimator can achieve a much lower MSE using a short guard interval with lower computational complexity. Although the results indicate an improvement in terms of reducing the length of the cyclic prefix and increasing the OFDM performance; further research is needed to further reduce the length of the cyclic prefix, completely eliminate ICI and thus be able to increase better the performance of the OFDM systems.

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