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Effect of OFDM Transmission Mode on Frequency Synchronization Performance

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ABSTRACT

This paper investigates the effect of orthogonal frequency division multiplexing (OFDM) transmission mode on the performance of the cyclic prefix- (CP) based frequency synchronization technique. An OFDM block consists of the inverse fast Fourier transform (IFFT) window and the CP. A transmission mode refers to the IFFT size used for the OFDM symbol. The frequency synchronization technique involves the use of the CP for estimating and correcting the carrier frequency offset (CFO) in an OFDM signal. Five different OFDM transmission modes are developed and frequency synchronization is performed on each of them in turn. The OFDM-16QAM scheme is utilized and the synchronization performance is evaluated for each of the transmission modes in terms of the mean squared error (MSE), bit error rate (BER) and CFO estimation time. The results show that synchronization performance improves with increase in the order of transmission mode (IFFT size) but with increase in CFO estimation time.

Keywords- Carrier frequency offset, Cyclic prefix, IFFT size, OFDM, Synchronization,

1. Introduction

The robustness of the orthogonal frequency division multiplexing (OFDM) scheme for mitigating wideband (or frequency-selective) fading has given it attention in recent times for wideband digital communications [1], [2]. OFDM is a multicarrier transmission technique that converts a serial high rate (or rapidly-modulated wideband) data stream into a number of parallel low rate (or slowly-modulated narrowband) streams [3]. OFDM has found applications in many digital wireless communication systems such as digital audio and video broadcasting (DAB and DVB) systems, wireless local area networks (WLANs), worldwide interoperability for microwave access (WiMAX), 3GPP long term evolution (LTE) [4], [5], [6], [7] and now in a multi-antenna communication system (MIMO-OFDM) [8]. The main drawback of the OFDM system is the occurrence of carrier frequency offset (CFO) caused by Doppler shift and/or instabilities in local oscillator [9], [4], [10]. Hence, accurate carrier frequency synchronization is required in order for the OFDM system to operate correctly. Many frequency synchronization techniques and their performances have been presented in the literature using different transmission modes [11] [12], [13], [14]. A transmission mode refers to the IFFT size of the OFDM symbol, and 1K mode implies IFFT size of 1024 [15]. The commonest method for estimating and compensating CFO involves the use of cyclic prefix (CP) inherent in the OFDM symbol [7]. The CP is a portion of the OFDM symbol appended in guard interval to eliminate intercarrier interference (ICI).

[11] utilized the 0.25K mode (256 IFFT size) to evaluate the performance of a CP-based CFO estimator in an OFDM system. The use of one training symbol of more than two identical parts for frequency synchronization was evaluated using the 1K mode by [12]. A blind feedforward CFO recovery algorithm was investigated using the 2K mode by [13]. The 1K mode was employed in the evaluation of a data-aided synchronization technique that involves a constant envelope preamble by [10]. [6] proposed a novel carrier frequency synchronization method for WiMAX OFDM systems and the 0.25K mode was used to evaluate the performance of the method. [4] proposed a fast and low-complex time-domain timing and frequency synchronization technique for the OFDM system, and a comparison was made between the technique and some existing ones using the 1K mode. The 0.5K (512 IFFT size) mode was employed to investigate the performance of a proposed hybrid integer CFO estimator for OFDM systems by [9]. [15] utilized the 4K mode to investigate the performance of the CP-based frequency synchronization technique for a DVB-H system. A joint timing and frequency synchronization technique was proposed by [5], and the 0.25K mode was considered for the evaluation of the performance of the technique. A hybrid fractional CFO estimator for OFDM systems was investigated by [14] and a 1K mode was used for performance evaluation of the estimator.

The effect of OFDM transmission modes; 0.25K, 0.5K, 1K, 2K and 4K, on the performance of the CP-based carrier frequency synchronization technique was investigated in terms of the mean squared error (MSE), bit error rate (BER) and CFO estimation time by computer simulation.

2. OFDM Signal Model

The samples of the OFDM symbol, $s(n)$, after taking the IFFT is expressed as:

$$s(n) = \frac{1}{\sqrt{N}} \sum_{k \in \Gamma_n} S_k e^{j2\pi nk/N} \quad , n = 0,1,\ldots,N-1 \qquad (1)$$

where Γ_n is the set of indices of all the subcarriers; S_k denotes the data symbol on the k-th carrier and N is the IFFT size. After appending the CP, the transmitted OFDM symbol can be represented as $s(N-T_g),\ldots,s(0),\ldots,s(N-1)$ where T_g denotes the length of the CP.

At the receiver, after removing the CP, the received OFDM symbol $y(n)$ in time-domain is expressed as:

$$y(n) = \frac{1}{\sqrt{N}} \sum_{k \in \Gamma_n} H_k S_k e^{j2\pi n(k+\varepsilon)/N} + w(n) \qquad (2)$$

where H_k is the frequency response of the channel at the k-th subcarrier frequency; S_k is the received symbol at the k-th subcarrier, $w(n)$ is the AWGN and ε is the CFO to be estimated which results in phase rotation of $2\pi n\varepsilon/N$ in the received signal.

3. CP-based Carrier Frequency Synchronization

This involves using the CP for estimating the CFO in (2) and correcting it using the estimate $\hat{\varepsilon}$ in the time domain The corrected received signal is given by:

$$y_c(n) = y(n) e^{-j\frac{2\pi n\hat{\varepsilon}}{N}},$$

$$n = 0,1,\ldots,N-1 \qquad (3)$$

The CFO estimate is obtained using the log-likelihood function (LLF) as:

$$\hat{\varepsilon} = \frac{1}{2\pi}\arg[R_c] \qquad (4)$$

with

$$R_c = \sum_{n=d}^{d+L-1} y^*(n) y(n+N) \qquad (5)$$

where $\arg$ denotes the argument of a complex number, $(\cdot)^*$ denotes complex conjugate, d is the timing metric which is assumed to be zero because perfect timing is assumed, L is the length of the CP and R_c is the cross-correlation of the cyclic prefix samples with the corresponding samples in the OFDM symbol. The mean squared error (MSE) of the CFO estimator is obtained as:

O estimator is obtained by:

$$MSE = \frac{1}{I_t}\sum_{i=1}^{I_t}\left(\varepsilon - \bar{\varepsilon}(i)\right)^2 \qquad (6)$$

where I_t is the number of Monte-Carlo simulations, ε is the true CFO and $\bar{\varepsilon}(i)$ is the estimated CFO at the i-th iteration.

3.1 Design of the OFDM Symbol

In the design of the OFDM symbol, the 0.25K mode (N = 256) is assumed with 5% of N as virtual carriers, that is subcarriers with zeros. The 12 virtual carriers K_z are consecutively placed at both ends of the OFDM symbol as guard channels. The number of non-silent carriers K_u is obtained as:

$$K_u = N - K_z \qquad (7)$$

Table 1 presents the data for all the transmission modes considered. For channel estimation, pilot tones are inserted within the OFDM symbol. With 4% of K_u used as pilot carriers, K_p, for channel estimation, the number of subcarriers available for information data is obtained as:

$$K_d = K_u - K_p \qquad (8)$$

Table 1: OFDM samples for different transmission modes

Mode	K_u	K_z	K_p	K_d
0.25K	244	12	10	234
0.5K	486	26	20	466
1024K	974	50	38	936
2048K	1946	102	78	1868
4096K	3892	204	156	3736

3.2 Derivation of the Cyclic Prefix Length

The CP length (T_g) used is obtained from the OFDM symbol period (T_u). With the 0.25K mode and the total available system bandwidth, B_c, of 6 MHz, the T_g can be computed as follows:

$$\Delta f = \frac{B_c}{N} = \frac{6\times 10^6}{256} = 23.44 \text{ kHz} \qquad (9)$$

and

$$T_u = \frac{1}{\Delta f} = 42.7 \,\mu\text{s} \qquad (10)$$

where Δf is the subcarrier spacing. Also, 12.5% of the OFDM symbol length is used for the CP; therefore,

$$T_g = \frac{1}{8}\times 42.7 = 5.33 \,\mu\text{s}$$

The T_g of 5.33 μs is equivalent to 32 samples. Also, if the maximum excess delay $\tau_{\max}$ caused by the frequency-selective fading channel is 75% of T_g, that is $\tau_{\max} \approx 4$ μs, therefore $\tau_{\max} < T_g$ and ICI will be eliminated. Table 2 presents the CP length for all the transmission modes considered.

After appending the CP, the OFDM block length (T_f) is the addition of the OFDM symbol length and CP length, that is

$$T_f = T_g + T_u \qquad (11)$$

Table 2: Symbol period for different transmission modes

Mode	T_u (μs)	T_g (μs)	T_f (μs)	Δf (kHz)
0.25K	42.7	5.33	48	23.44
0.5K	85.3	10.67	96	11.72
1024K	170.7	21.33	192	5.86
2048K	341.3	42.67	384	2.93
4096K	682.7	85.33	768	1.47

4. Results and Discussion

The developed OFDM system was investigated by computer simulation using MATLAB software package and the results plotted. The information bits are gray mapped onto 16-QAM constellation and two OFDM symbols are transmitted for each of 0.25K (N=256), 0.5K (N=512), 1K (N=1024), 2K (N=2048) and 4K (N=4096) transmission modes in turn. The useful part of each OFDM symbol is preceded by a CP that is longer than the channel impulse response. A system bandwidth of 6 MHz and carrier frequency of 2.2 GHz are assumed. Multipath Rician fading channel with a Rice factor of three; maximum Doppler frequency shift of 244.44 Hz (equivalent to mobile speed of 120 km/h) is used and delay length is 75% of the CP length. The CFOs considered are 0.125 and 0.25 and 100 simulation runs were used for each SNR between 0 dB and 15 dB.

Fig.1 illustrates the MSEs versus SNR for the estimation of CFO of 0.125. The average MSE with SNR of 0 to 15 dB for the 0.25K, 0.5K, 1K, 2K and 4K transmission modes are 3.3049×10^{-5}, 2.9083×10^{-6}, 9.3492×10^{-7}, 6.3163×10^{-7} and 2.6435×10^{-7} respectively. Also, the average MSEs obtained from the estimation of CFO of 0.25 are shown in Fig. 2. The 0.25K, 0.5K, 1K, 2K and 4K modes give 4.5310×10^{-5}, 4.0473×10^{-6}, 9.4144×10^{-7}, 3.3524×10^{-7}, 6.9977×10^{-8} respectively. Fig. 3 presents the MSE comparison between estimated CFO of 0.125 and 0.25 for both the 0.25K and 0.5K modes. For the 0.25K mode, average MSE of 3.3049×10^{-5} and 4.5310×10^{-5} are obtained for CFO of 0.125 and 0.25 respectively; showing that 0.125 gives a lower average MSE of 1.2261×10^{-5}. For the 0.5K mode, average MSE of 2.9083×10^{-6} and 4.0473×10^{-6} are obtained for CFO of 0.125 and 0.25 respectively; showing that 0.125 gives a lower average MSE of 1.139×10^{-6}. In Fig. 4, the MSE comparison between estimated CFO of 0.125 and 0.25 for the 1K, 2K and 4K modes are shown. The 1K mode gives average MSE of 9.3492×10^{-7} and 9.4144×10^{-7} for CFO of 0.125 and 0.25 respectively; showing that 0.125 gives a higher average MSE of 0.0652×10^{-7}. For the 2K mode, average MSE of 6.3163×10^{-7} and 3.3524×10^{-7} are obtained for CFO of 0.125 and 0.25 respectively; showing that 0.125 gives a higher

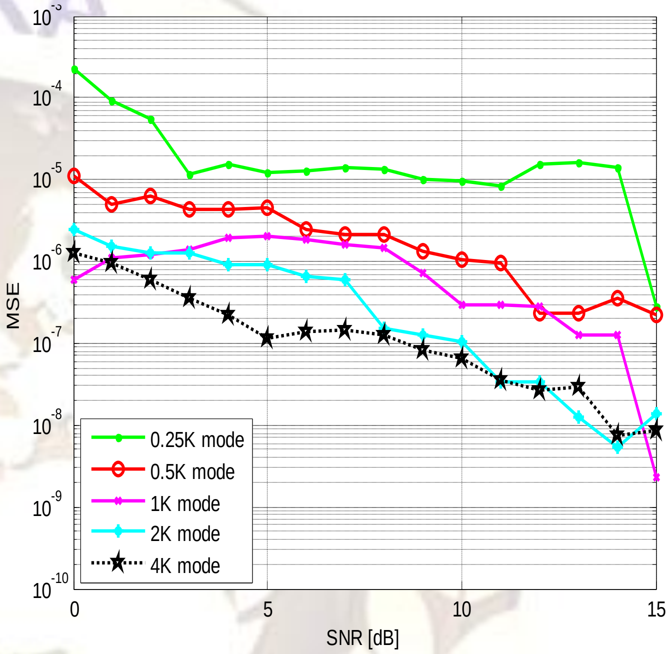

Fig. 1: Mean-squared error for the estimation of CFO of 0.125

average MSE of 2.9639x10^{-7}. The 4K mode gives average MSE of 2.6435 x10^{-7} and 6.9977x10^{-8} for CFO of 0.125 and 0.25 respectively; showing that 0.125 gives a higher average MSE of 1.9437 x10^{-7}.

Fig. 5 illustrates the BER versus SNR for CFO of 0.125. For SNR of 0 to 15 dB, the 0.25K, 0.5K, 1K, 2K and 4K modes give mean BER of 0.1129, 0.1076, 0.1079, 0.0671 and 0.0387 respectively. The BER performances for CFO of 0.25 are shown in Fig. 6. Mean BER of 0.1169, 0.1088, 0.1109, 0.0659 and 0.0385 are obtained for the 0.25K, 0.5K, 1K, 2K and 4K modes respectively. This reveals that the 4K mode has approximately 3% BER advantage over the 2K mode; the 2K mode has approximately 5% BER advantage over the 1K mode; and the 0.5K mode has approximately 0.8% BER advantage over the 0.25K mode. Lower BER implies better performance.

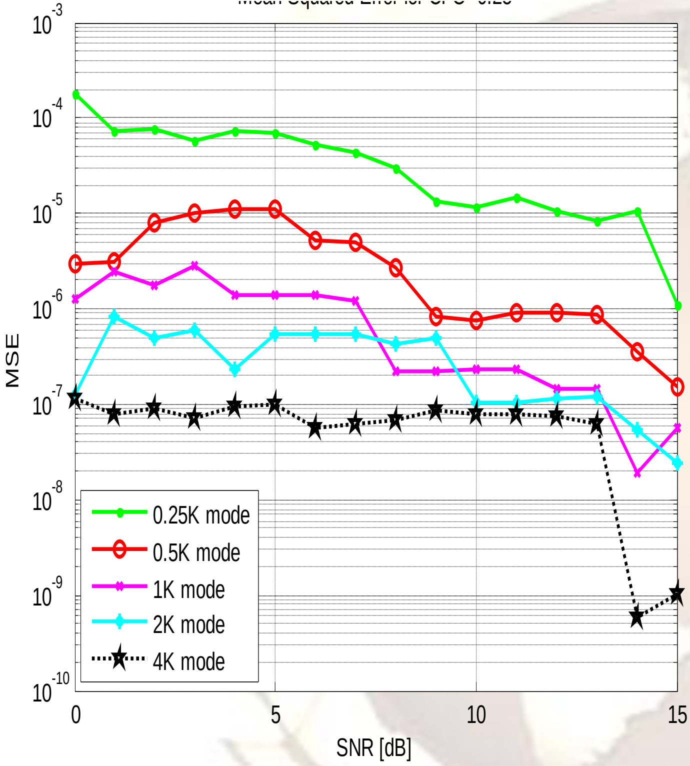

Fig. 2: Mean-squared error for the estimation of CFO of 0.25

Fig. 7 presents the BER comparison between CFO of 0.125 and 0.25 for both the 0.25K and 0.5K modes. For the 0.25K mode, mean BER of 0.1129 and 0.1169 are obtained for CFO of 0.125 and 0.25 respectively; showing that 0.125 gives a lower mean BER of 0.004. For the 0.5K mode, mean BER of 0.1076 and 0.1088 are obtained for CFO of 0.125 and 0.25 respectively; showing that 0.125 gives a lower mean BER of 0.0012. In Fig. 8, the BER comparison between CFO of 0.125 and 0.25 for the 1K, 2K and 4K modes are presented. The 1K mode gives a mean BER of 0.1079 and 0.1109 for CFO of 0.125 and 0.25 respectively; showing a BER difference of 0.003. For the 2K mode, mean BER of 0.0671 and 0.0659 are obtained for CFO of 0.125 and 0.25 respectively; showing a BER difference of 0.0012. The 4K mode gives mean BER of 0.0387 and 0.0385 for CFO of 0.125 and 0.25 respectively; showing a BER difference of 0.0002.

Fig. 9 represents the effect of transmission mode on the CFO estimation time (in milliseconds) for CFO of 0.125. Estimation time of 0.0221 ms, 0.0372 ms, 0.0724 ms, 0.1467 ms and 0.3125 ms are obtained for the 0.25K, 0.5K, 1K, 2K and 4K modes respectively. The effect of CFO value on the estimation time is shown in Fig. 10. For CFO of 0.25, the estimation time for the 0.25K, 0.5K, 1K, 2K and 4K modes are 0.0106 ms, 0.0183 ms, 0.0363 ms, 0.0735 ms, 0.1563 ms. This reveals that for the 0.25K, 0.5K, 1K, 2K and 4K modes, CFO of 0.125 gives higher estimation time of 0.0115 ms, 0.0189 ms, 0.0361 ms, 0.0732 ms, 0.1562 ms respectively, compared to CFO of 0.25.

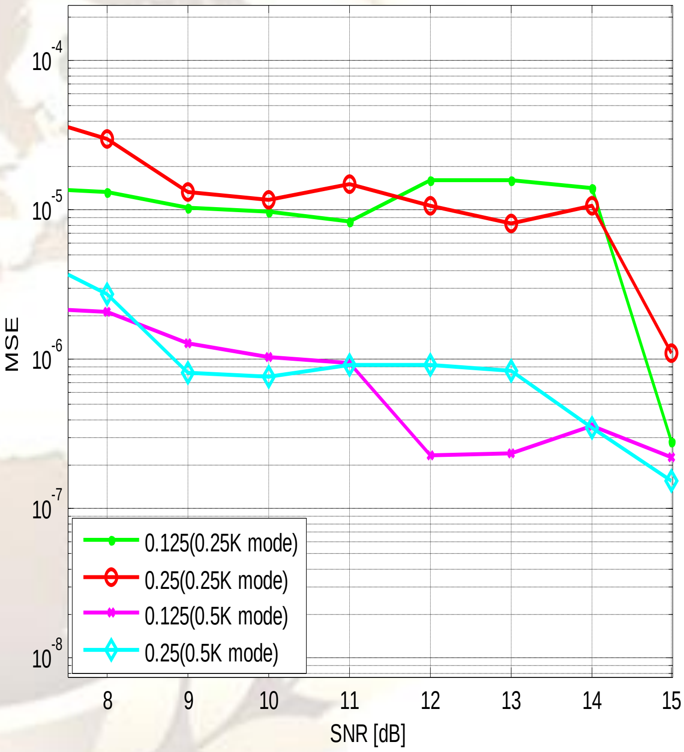

Fig. 3: Mean-squared error comparison between estimated CFO of 0.125 and 0.25 for the 0.25K and 0.5K modes.

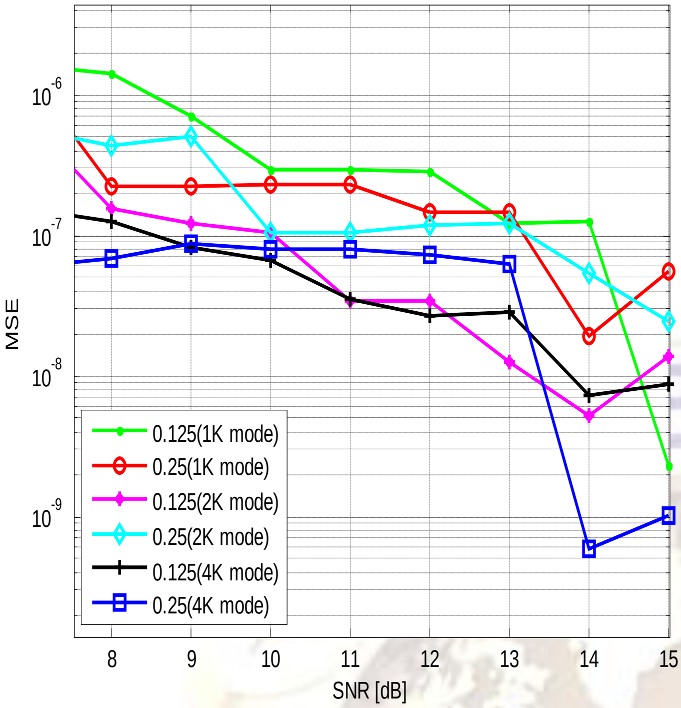

Fig. 4: Mean-squared error comparison between estimated CFO of 0.125 and 0.25 for the 1K, 2K and 4K modes.

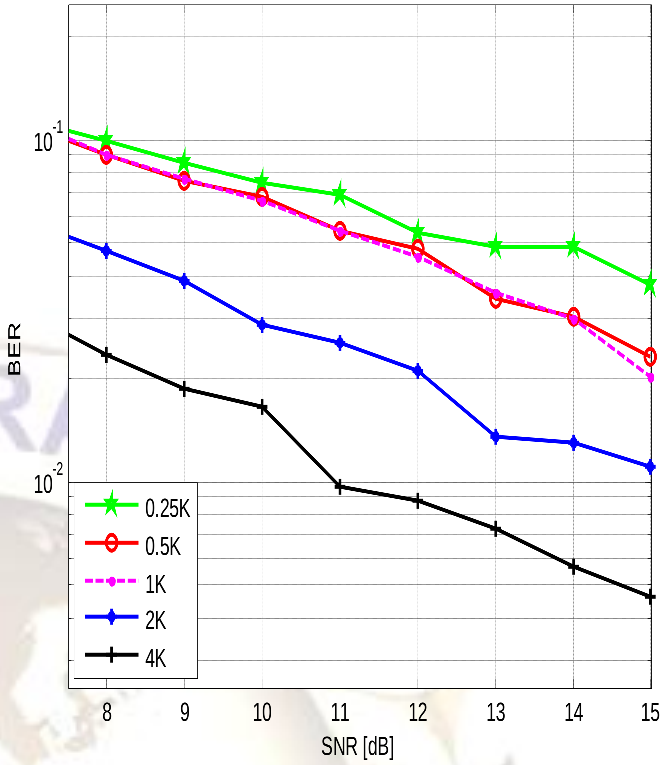

Fig. 6: Bit error rate performance for CFO of 0.25

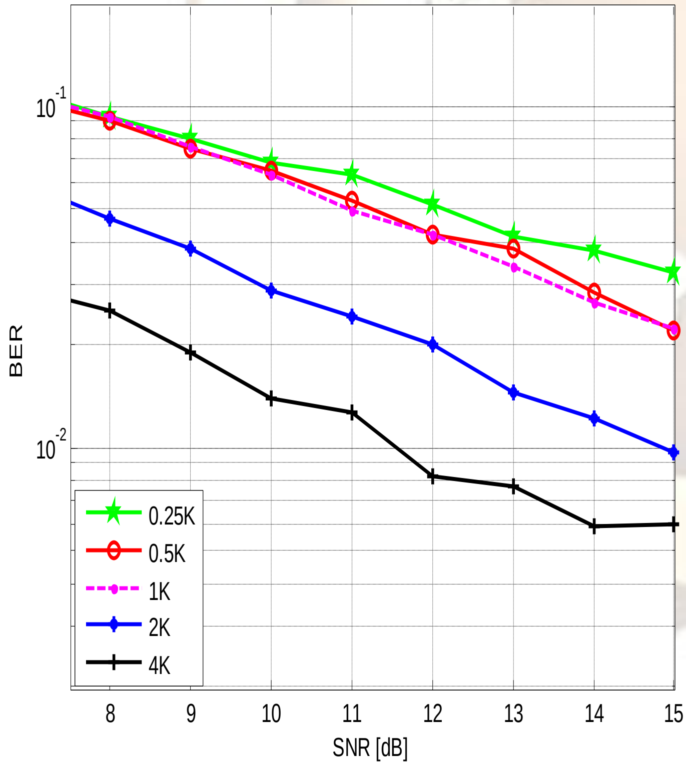

Fig. 5: Bit error rate performance for CFO of 0.125

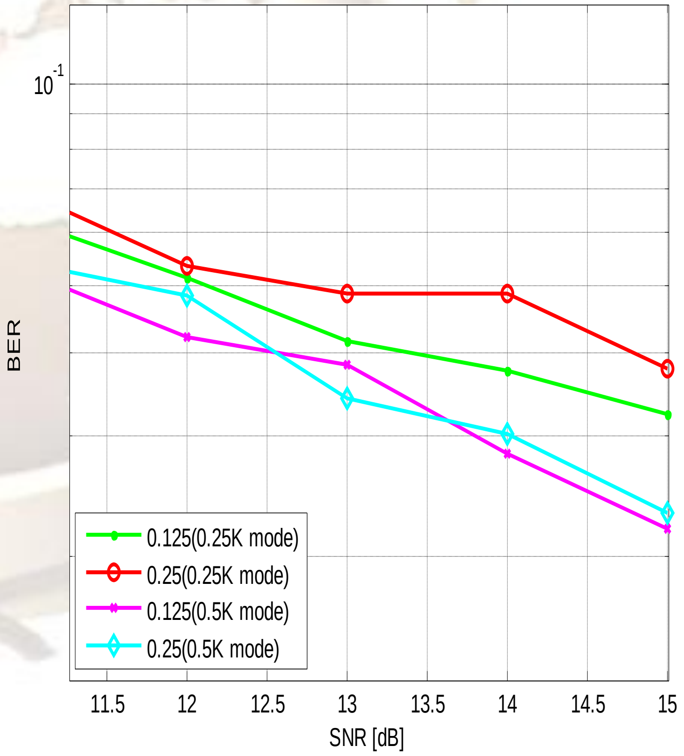

Fig. 7: Bit error rate performance comparison between CFO of 0.125 and 0.25 for the 0.25K and 0.5K modes

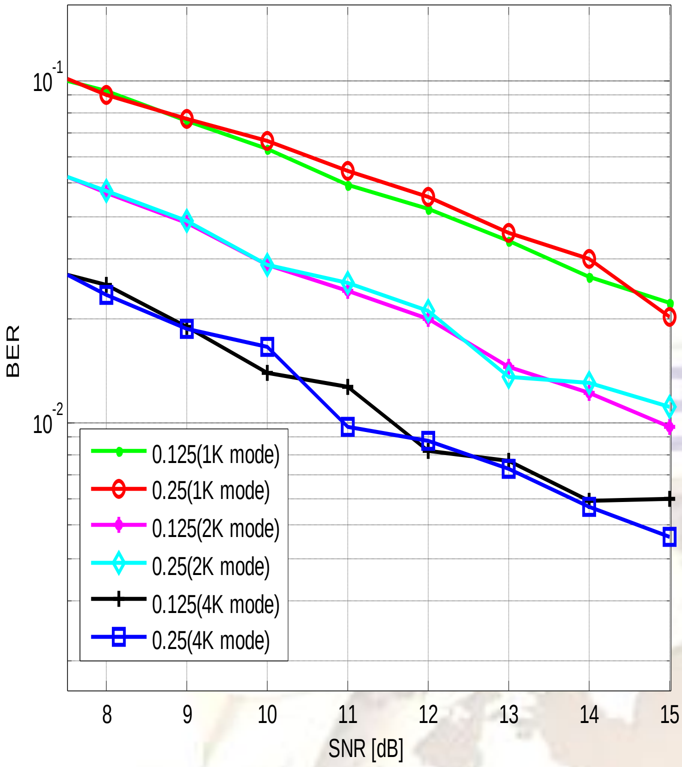

Fig. 8: Bit error rate performance comparison between CFO of 0.125 and 0.25 for the 1K, 2K and 4K modes.

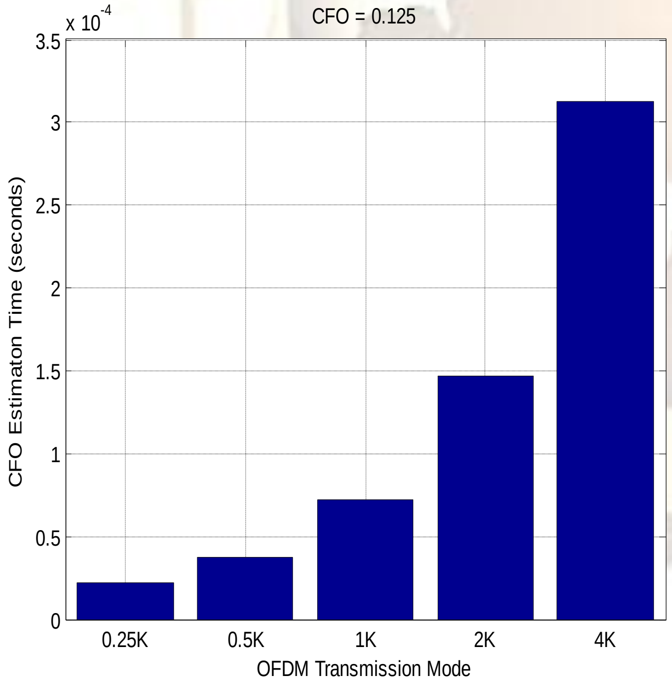

Fig. 9: Estimation time for CFO of 0.125 for the five transmission modes

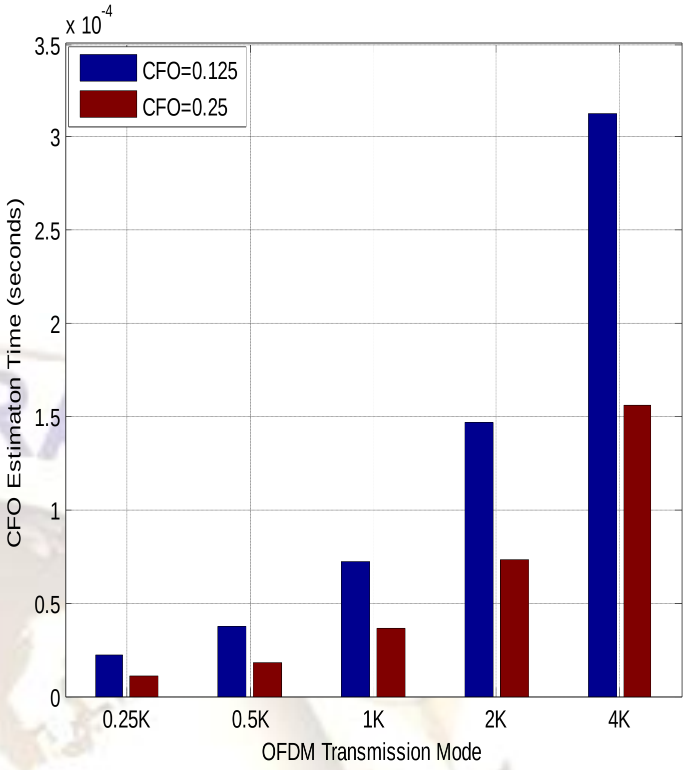

Fig. 10: Comparison of the estimation time for CFO of 0.125 and 0.25 for the five transmission modes.

5. CONCLUSION

The effect of OFDM transmission mode on the performance of the CP-based carrier frequency synchronization technique has been investigated. OFDM signal with CP-based carrier frequency synchronization technique is developed for 0.25K, 0.5K, 1K, 2K and 4K transmission modes in turn. The results are presented in terms of MSE, BER and CFO estimation time. The results reveal that the CP-based synchronization performance improves with increase in the order of transmission mode. In order words, the higher the IFFT size of an OFDM symbol the better the carrier frequency synchronization. This implies that the more the samples used for the CP the better the CFO estimation accuracy. Furthermore, from the CFO estimation times obtained, the estimation time increases with increase in the order of transmission mode. For instance, it takes the estimator shorter time to estimate the CFO in 0.25K mode and longer time to estimate in 4K mode. Moreover, for the 0.25K, 0.5K and 1K modes, the synchronizer gives better performance with CFO of 0.125 than with CFO of 0.25. However, for the 2K and 4K modes, the synchronizer gives better performance with CFO of 0.25 than with CFO of 0.125. In terms of the CFO estimation time, more time is required to estimate the CFO of 0.125 than the CFO of 0.25.

This paper has been able to show the effectiveness of the CP-based frequency synchronization technique with respect to the

OFDM transmission mode. The main advantage of this technique is that it eliminates the need for a training symbol but with a trade off of system bandwidth. This study assumed perfect timing so further investigations could consider joint timing and frequency synchronization as well as the use other synchronization techniques and higher transmission modes. The results of this paper can serve as a useful reference for researchers and designers of OFDM systems.

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