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# Estimation and Compensation for Effects of Carrier Frequency Offsets in Orthogonal Frequency Division Multiplexing Based Cooperative Networks

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***Abstract:*** *Estimation and Compensation of Carrier Frequency Offset (CFO) is regarded as major operation in the OFDM based Cooperative network. However, the presence of CFO in OFDM based cooperative networks distorts the transmitted signal from the source, this actually result to poor copy of transmitted signal at destination. Maximal Likelihood (ML) which was one of technique used to combat the effects of CFO in the system suffers from higher error as well as low bandwidth efficiency, as there was redundancy of bits for each carrier and observation of computational complex in its operation. Hence, this paper, an Extended Kalman Filter (EKF) was developed to overcome the effect of CFO in order to minimize the error in the OFDM based cooperative network The transmitting signal at the source using the Amplified and Forward protocol at different number of subcarriers and QAMs over the Rayleigh fading channel was received using Enhanced Signal to Noise Ratio Combiner (ESNRC). In the first phase, the transmitted signal was received by the relay, while the second phase of the transmission was made to amplify the transmitted signal at the relay and re-transmitted to the ESNRC where two signals from relay and source were combined for further signal transmission processes. The combined signal was made to pass through estimator and compensator block to reduce the CFO effects in order to minimize the systemic error in the OFDM based cooperative network. The performance of EKF-OFDM technique was assessed using BER and SNR, comparing it to the existing ML-OFDM technique. The simulation results showed that the developed EKF technique achieved better performance than the existing ML-OFDM as well as C-OFDM due to CFO estimation and compensation accuracy by minimizing the error and improvement in bandwidth efficiency through the EKF implementation. The developed technique can be adopted to improve the performance of the OFDM based cooperative network.*

***Keywords:*** *Orthogonal Frequency Division Multiplexing (OFDM), Cooperative network, Extended Kalman Filter (EKF), Maximum Likelihood (ML), Carrier Frequency Offset (CFO), (Quadrature Amplitude Modulation (QAM)*

## 1. INTRODUCTION

Wireless communication networks have been in existence for many years transmitting information signals to wider coverage areas. It is key enabling innovative, future beneficial technology across disciplines, supporting daily access services such as communication technology, consumers and business professional needs, multimedia communication and computer technology [1]. As a result this, wireless communications have been achieved huge growth in capacity and variety. In today's broadband system, the capacity of wireless communications is improved through the implementation of Orthogonal Frequency Division Multiplexing (OFDM which is one of technique in wireless communication purposely to achieve high data rate, high speed parallel transmission, efficient spectrum usage under the multipath condition as well as bandwidth efficiency [2,3]. Due to unique operation and performance of the OFDM, the system is integrated into Cooperative communication networks in order to increase the transmission bandwidth efficiency and mitigate the effect of the frequency-selective fading in each link of the cooperative systems, this process is known as Cooperative based OFDM [4]. Cooperative diversity is an effective way of communication technique designed to achieve spatial diversity the same as Multi-Input Multi-Output (MIMO), through the collaboration among multiple single antenna nodes, when there is no possibility of embedding an antenna array on a mobile terminal. The main difference between MIMO and cooperative diversity is the inherent asynchronization among spatially-distributed relays in the latter [5]. It is obvious that the improvement in bit rate, channel capacity, bandwidth efficiency, wider coverage areas and higher speed data transmission could be achieved with the use of a cooperative communication network [6].

However, OFDM based communication systems suffer from Carrier Frequency Offset (CFO) due to Doppler shift and frequency synchronization error at the transmitter. This drawback causes the subcarrier to lose their orthogonality which in turn lead to subcarrier leakage or Inter Carrier Interference (ICI) and Inter Symbol Interference (ISI). It becomes worst in the cooperative system. These negative effects in the OFDM based cooperative networks lead to degradation of the system performance. Hence, it is essential to perform CFO accurate estimation during the signal transmission to prevent Signal to Noise Ratio (SNR) loss [3,7,8,9,]. Therefore, this paper proposed EKF-OFDM in the OFDM based cooperative networks.

Several algorithms had been designed to estimate and compensate for the effect of CFO in OFDM based Cooperative Networks. In [10], proposed Training Prefix (T.P) technique to estimate and compensate for the CFO in OFDM based network. The paper expressed that the distance between two blocks of samples to be correlated is reduced using a new OFDM structure. The new OFDM structure enables simple equalization process with the advantage of increasing the CFO estimation range. This is because of the redundancy contained in each transmitted OFDM symbol block that enables the estimation to be updated every block. The results of the paper revealed that the estimator outperforms all of Moose, CP and Training Symbol (TS) schemes at the price of minor reduction of transmitted data rate or spectra efficiency due to the added redundancy and high computational complexity. The use of antenna diversity for CFO estimation was performed between the two points by using the combination of the received signal at all antennas in [11]. The paper revealed CFO estimation at the expense of linear increase in computational complexity and higher error. Furthermore, in [12], the Chinese remainder theorem-based CFO Maximum Likelihood Estimation (CCMLE) approach was proposed to address the effects of CFO. The technique jointly estimates the integer and fractional parts of CFO simultaneously with wide range estimation ranges up to the total number of subcarriers in high mobility OFDM system. On the design of an OFDMA-based Software-defined modem in [13], the technique designed methodology of a two-step CFO estimator that controls a specific level of estimation accuracy and computational complexity in the Software defined modem by strategically using both CPs and pilots during the coarse and fine CFO estimation. The technique requires the mutual coarse estimators and pilot estimators because the two estimators depend on each other. However, the higher error due to CFO can occur due SNR range value which determines the level of estimation range and large Doppler spread with I/Q imbalance in CFO estimation in MIMO environment. To overcome this limitation, this paper proposes EKF-OFDM to further minimize the error in OFDM based cooperative networks through the effects of carrier frequency offset. The following outlines the significant contribution of this paper:

i. Estimation and Compensation of the generated CFO in the OFDM based cooperative networks using EKF.
ii. Improvement in bandwidth efficiency through the implementation of Extended Kalman Filter algorithm.

The remainder of this paper is organized as follows: Section 2 provides a comprehensive description of the research methodology, Section 3 presents simulation results, comparing the proposed technique with existing approaches. Finally, Section 4 concludes the paper.

## 2. PROPOSED EXTENDED KALMAN FILTER OFDM

In this paper, the carrier frequency offset at the destination is estimated and compensated using the EKF technique at various subcarriers and QAMs. The multiple copies of distorted signal over the Rayleigh channel are received by ESNRC at receiver. In this case, CP is removed to obtain the data in the discrete time domain and then processed using the FFT for data recovery. In the presence of time dispersive channel, additive noise, and carrier frequency offset, the OFDM signal at the receiver is now,

$$P(k) = H(k) * x(k - \emptyset) + u(k) \tag{1}$$

where,
$x(k-\emptyset)$ = Transmitted data symbol
$H(k)$ = Channel impulse
$u(k)$ = White Gaussian Additive Noise
$*$ = Linear convolution

When time deviation ($\emptyset$) between the transmitter and receiver, it is assumed to be zero and the equation becomes

$$P(k) = H(k) * x(k) + u(k) \tag{2}$$

### 2.1 CFO Estimation

To estimate the quantity $\varepsilon(a)$ carrier frequency offset using an EKF frame. The OFDM signal at the receiver is given as:

$$P(a) = H(a) * x(a)\ell^{\frac{j2\pi s\varepsilon(a)}{N}} + u(a) \tag{3}$$

Assuming the preceding data symbols in each frame are used as a training sequence and the variance of the AWGN u(k) is stationary. The computation procedure is described as follows.

i. Determine the initial value for $\hat{\varepsilon}[0]$and error covariance $T(0) = \sum_{0|0}$
ii. Compute the value of $H(a)$ at the point $\hat{\varepsilon}(a-1)$ which is the frequency offset estimation in the previous step.

$$H(\varepsilon[a]) = x[a]\exp\left(\frac{j2\pi s\varepsilon(a)}{N}\right) \tag{4}$$

iii. Compute Kalman filter gain $G(a)$ using

$$T(a-1) = (\textstyle\sum_{a|a-1} = \sum_{a-1|a-1}) \text{ and } H(a) \tag{5}$$

$$G(a) = T(a-1)H(a)H'(a)T(a-1)H(a) + R(a)^{-1} \tag{6}$$

iv. Compute the value of $H(a)$ using $x(a)$ and $\varepsilon(a-1)$ Then determining the error between $P(a)$ and $H(a)$

$$\widehat{H}(a) = H(a) * x(a)\ell^{\frac{j2\pi a\hat{\varepsilon}(a-1)}{N}} \tag{7}$$

v. Update the value of $\hat{\varepsilon}(k)$ using

$$\hat{\varepsilon}(a) = \hat{\varepsilon}(a-1) + G(a)\left[P(a) - \widehat{H}(a)\right] \tag{8}$$

vi. Then update the new value of error covariance T(a)

$$T(a) = [1 - G(a)H'(a)T(a-1)$$

vii. Return to step 1.

### 2.2 CFO Compensation

The signal distortion in the data symbol x(k) that follow the training sequence can then be mitigated by multiplying the received data symbols P(k) with a complex conjugate of the estimated frequency offset and applying FFT. The expression is given as

$$X(a) = FT[P(a)]\ell^{\frac{j2\pi a\prime\varepsilon}{N}} \tag{10}$$

$$X(a) = FT[H(a) * x(a)\ell^{\frac{j2\pi\varepsilon(a)}{N}} + u(a)]\ell^{\frac{j2\pi\varepsilon(a)}{N}} \tag{11}$$

Received data symbol $X(a)$ was determined by using equation 11

### 2.3 Bit Error Rate for the proposed technique

In order to compare Maximum Likelihood and Extended Kalman Filter, Bit Error Rate (BER) is used as the performance metric to evaluate the performance of each scheme. Probability of receiving erroneous bits for the developed technique is the BER and expressed as

$$BER_{EKF} = \Pr(X(a) \neq 0 \tag{12}$$

Where X(a) is the estimated received data symbol
Substituting Equation 11 into 1

$$BER_{EKF} = \Pr\left(FFT\left[H(a) * x(a)\ell^{\frac{j2\pi\varepsilon(a)}{N}} + u(a)\right]\ell^{\frac{j2\pi\varepsilon(a)}{N}} \neq 0\right) \tag{13}$$

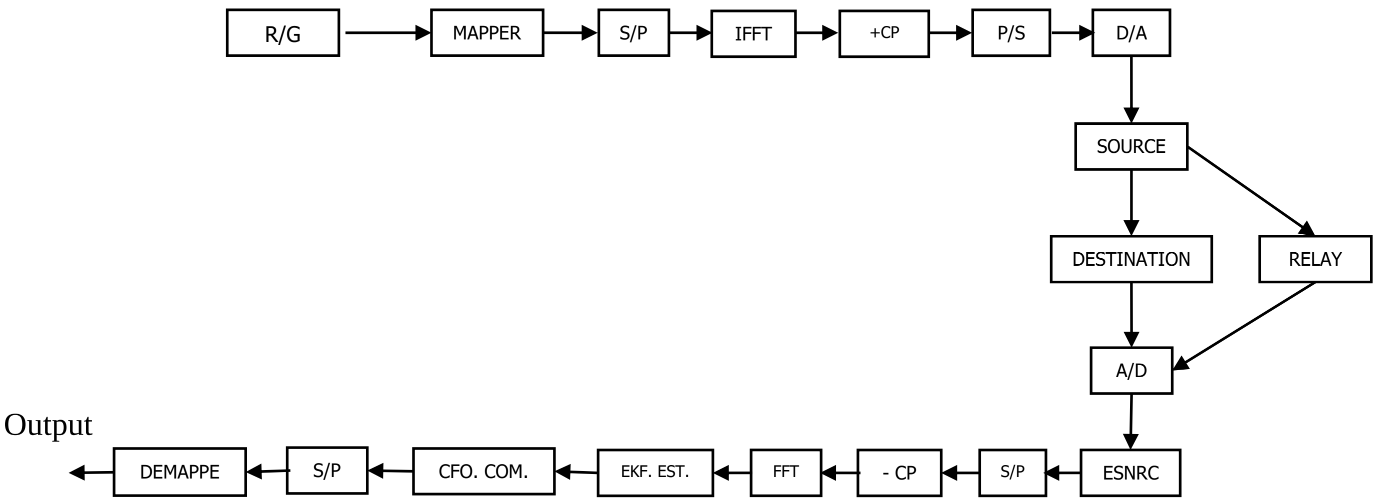


Figure 1: OFDM based cooperative model

## 3. SIMULATION RESULTS AND DISCUSSION

This paper presents simulation model for the research which comprises of Source node, relay node, Rayleigh fading channel and the destination. The data was obtained from the random integer generator, which is available within the MATLAB software. Figure 1 illustrates OFDM based Cooperative Model while Table 1 summarizes the simulation parameters. The BER was employed for the performance metrics to access the performance of the proposed EKF-OFDM operating over Rayleigh fading channel. The BER values at different subcarrier numbers and QAM values were obtained and compare with the existing Wei, H.*et al.* (2023). Figure 2 presents the BER against SNR for EKF-OFDM, C-OFDM and ML-OFDM technique at 128-QAM for 64 subcarriers. The BER value obtained for EKF-OFDM, C-OFDM and ML-OFDM at SNR of 10 dB were $7.360\times10^{-11}$, $5.08\times10^{-9}$ and $2.586\times10^{-10}$, respectively. The results obtained revealed that EKF has better performance compare with both C-OFDM and ML. This is due to the accurate estimation and compensation of CFO by the developed technique, for this reason the error minimization was recorded. Also, it was observed that lower BER was obtained with EKF technique at SNR of 10 dB

Figure 3 depicts the BER for the three techniques, which are EKF-OFDM, C- OFDM and ML-OFDM at 64-QAM for 128 subcarriers. At SNR of 8dB, the BER obtained were $3.21\times10^{-09}$, $2.21\times10^{-07}$ and $3.42\times10^{-08}$. In this simulation result, the BER at 64-QAM has lower error values in comparison with 128-QAM implying the better performance with specified QAM value. Considering all the three techniques, it was showed that EKF has the best performance in error reduction.

Table 1: System simulation parameters for the proposed model

| **Parameters** | **Specifications** |
| --- | --- |
| Number of carriers | 64, 128 and 256 |
| Modulation | 32-QAM, 64-QAM and 128-QAM |
| Frequency Offset | 0.10 |
| No. OFDM symbols | 256 |
| Bits per OFDM symbols | $N * log^2(M)$ |
| IFFT size | 1024 |
| Signal Combining Scheme ESNRC | |

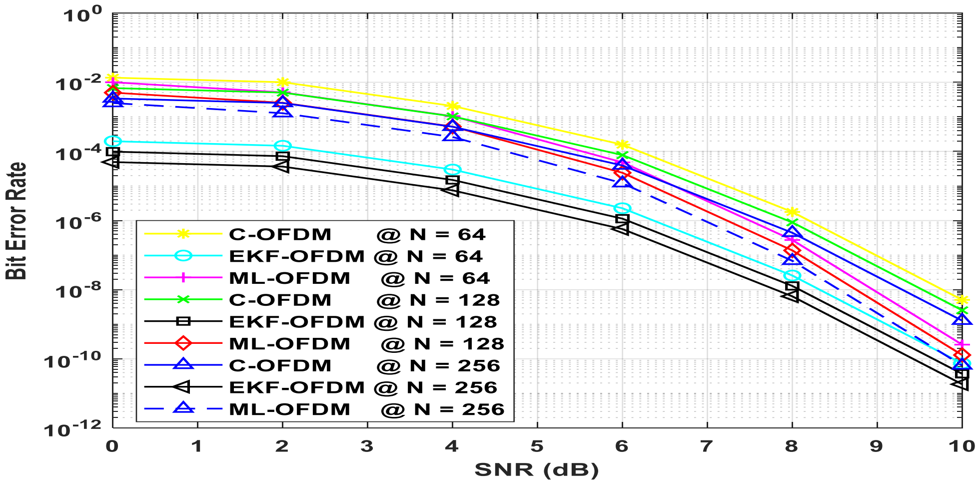


Figure 2: System performance of OFDM Cooperative system at 128-QAM

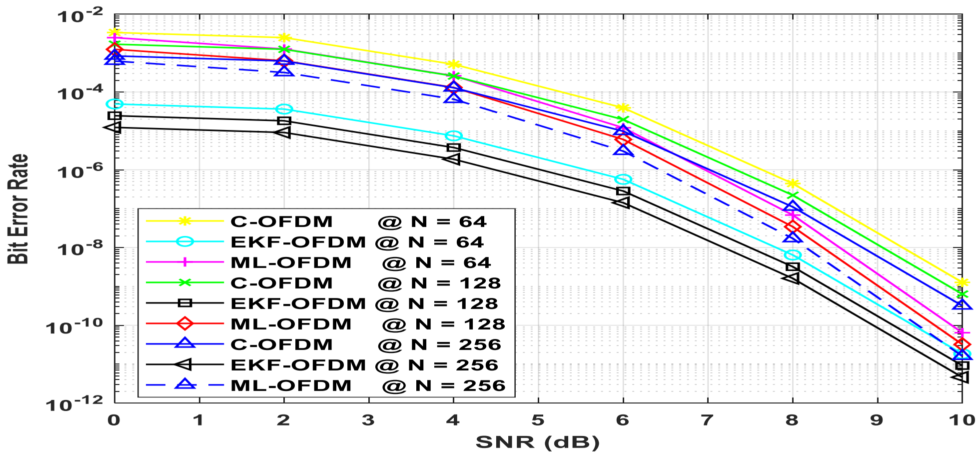


Figure 3: System performance of OFDM cooperative system at 64-QAM

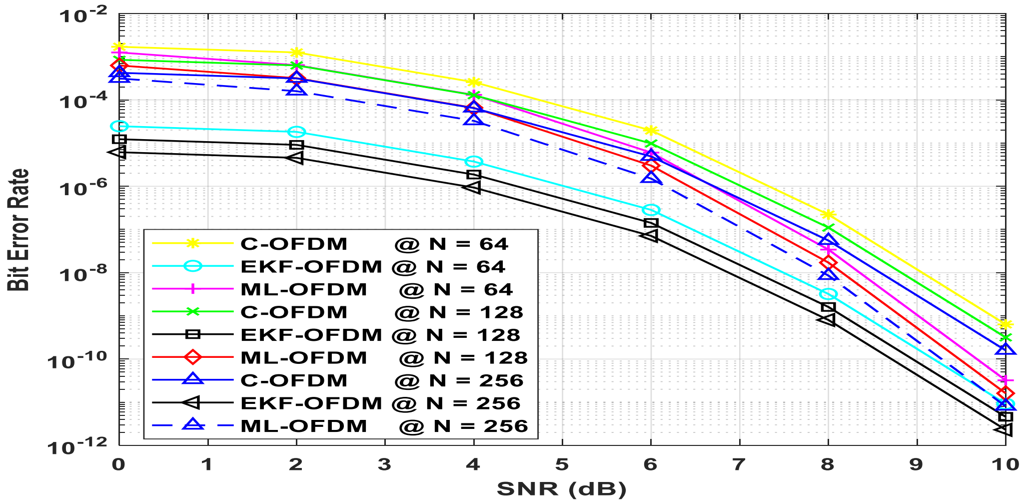


Figure 4: System performance of OFDM cooperative system at 32-QAM

From the simulation result in Figure 4, at SNR of 6dB for 32-QAMwith 256 subcarriers, the three techniques which are EKF-OFDM, C-OFDM, and ML-OFDM were able to produce the BER results as $7.08\times10^{-08}$, $4.89\times10^{-06}$ and 1.50 $\times10^{-06}$. The BER recorded in these results revealed that Figure 3 has better error reduction than Figure 4. This can be attributed to the value of QAM, and number of subcarriers as well as effective CFO estimation accuracy. The ML technique showed the possibility of the system to perform at wider estimating range with higher number of subcarriers. Meanwhile, in all results with EKF technique, there is an improvement in system performance compare with other technique due to the BER value recorded in each case.

Different BER values with QAMs were presented in order to evaluate the performance level at various techniques. The simulation results in Figure 5 showed the graphical representation of all techniques including BER plot against SNR with different SNR values. At SNR of 10 dB, the BER results for three technique were obtained as $1.84\times10^{-11}$ for EKF-OFDM, $1.27\times10^{-09}$ for C-OFDM and $6.44\times10^{-11}$ for ML-OFDM at 64 subcarrier with 64-QAM. These results revealed that EKF has better systemic performance than other techniques in terms of BER. The implementation of the developed technique provides the better system performance with the improved bandwidth efficiency. Furthermore, the integration of EKF into the cooperative based communication with ESNC combiner was used to address the noise and error reduction in wireless communication system.

Figure 6 showed the BER results at SNR of 8 dB for 128 subcarrier with 64-QAM where three techniques were EKF-OFDM, C-OFDM and ML produced the results as $3.21\times10^{-09}$, $2.21\times10^{-07}$ and $3.42\times10^{-08}$. Considering the number of subcarriers, EKF possesses lower BER, this indicates that higher estimation range of CFO is possible at lower SNR values in compare with other techniques.

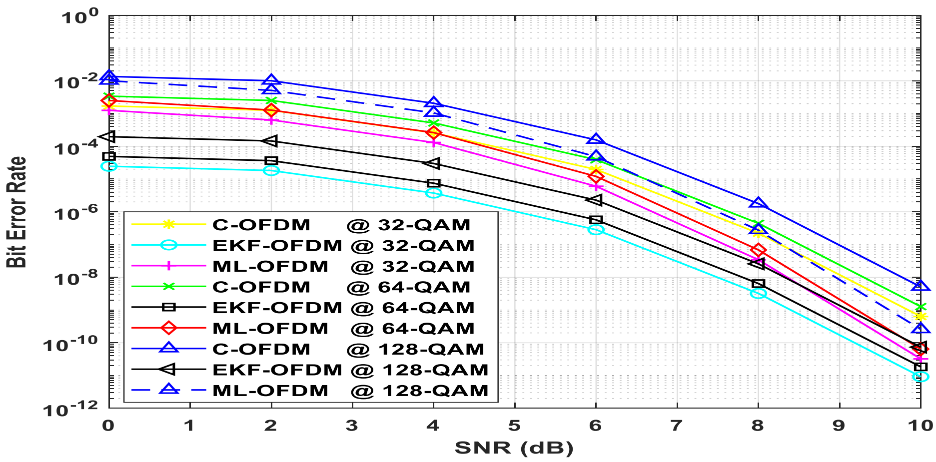


Figure 5: System performance with 64 subcarriers

Figure 7 displayed the increase in BER values in all techniques at SNR of 6 dB for 256 subcarriers with 128-QAM. These can be confirmed as $5.67\times10^{-07}$ for EKF-OFDM, $3.91\times10^{-05}$ for C-OFDM and $1.20\times10^{-05}$ for ML-OFDM. The change in BER values occurred as a result of number of subcarriers and QAM values when compare with Figure 6. Therefore, the requirement for the number of subcarrier and QAM values must be considered for effective estimation of

CFO in order to minimize the level of error. Also, the results confirmed that the performance of EKF technique is exceptional in term of adequate error controls in the OFDM based Cooperative system due to adequate estimation and compensation of CFO compare to other techniques. Furthermore, the use of lower SNR values with EKF technique does not deteriorate the system performance in terms of BER, meanwhile this can not be achieved with the ML technique because the effective performance of the system starts from above SNR of 12 dB.

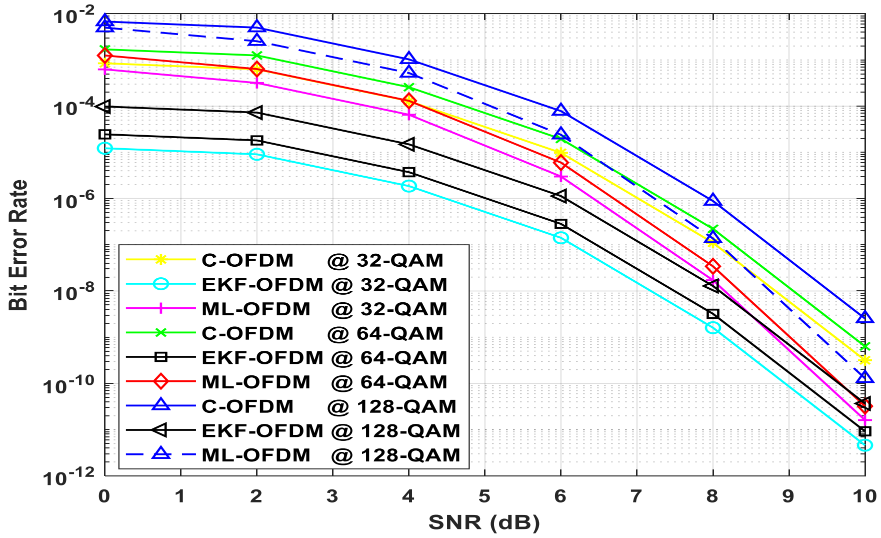


Figure 6: Performance of the system with 128 subcarriers

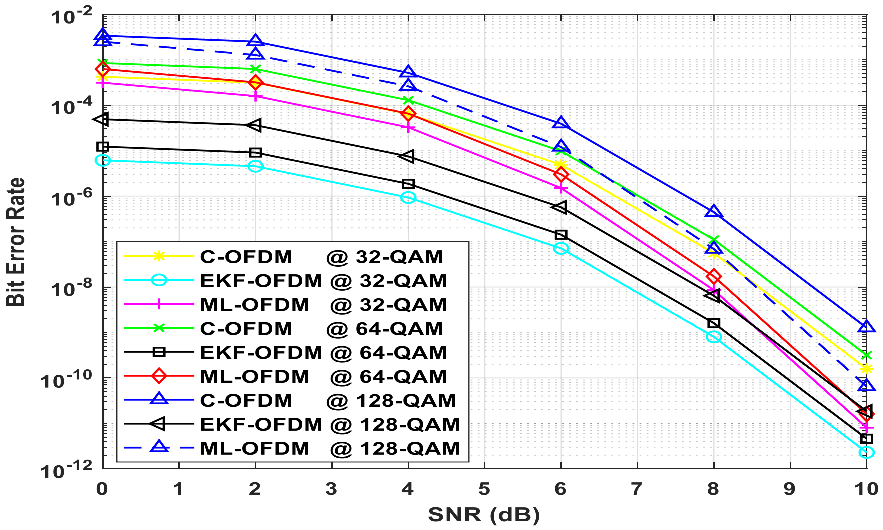


Figure 7: Performance of the system with 256 subcarriers.

## 4. CONCLUSION

This paper proposes EKF-OFDM technique over Rayleigh fading channels to perform CFO estimation and compensation in order to minimize the error in OFDM based cooperative networks. The system comprises source, relay and destination, the transmitting signal at the source using the Amplified and Forward protocol at different number of subcarriers and QAMs over the Rayleigh fading channel is received using Enhanced Signal to Noise Ratio Combiner (ESNRC). In the first phase, the transmitted signal is received by the relay, while the second phase of the transmission is made to amplify the transmitted signal at the relay and re-transmitted to the ESNRC where multiple copies of distorted signals from relay and source are combined for further signal transmission processes. The combined signal is made to pass through estimator and compensator block. Bit Error Rate (BER) and Signal to Noise Ratio (SNR) are used to evaluate system performance, Rayleigh fading channels are modeled for both source-to-destination and relay-to-destination links with Additive White Gausian Noise (AWGN). Simulation are conducted at various values of SNR, QAMs with different number of subcarriers. Due to this, the performance of the developed EKF-OFDM technique is compared with C-OFDM and ML-OFDM. The EKF-OFDM technique outperforms the both C-OFDM and ML-OFDM due to better reduction of systemic error through accurate estimation and compensation of CFO and improvement in bandwidth efficiency by the implementation of Extended Kalman Filter (EKF). In essence, this paper demonstrates the effectiveness in minimization of error through the CFO estimation and compensation in OFDM based cooperative networks.

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