Mitigating the Effects of Mobility and Synchronization Error in OFDM Based Cooperative Communication Systems

Yetera B. Bereket, Philip K. Langat, and Edward K. Ndungu

***Abstract*— An Orthogonal Frequency Division Multiplexing based mobile wireless network with a sender, a destination and a third station acting as a cooperating node is modelled and analyzed. The length of cyclic prefix in the orthogonal frequency division multiplexed symbols is made to vary depending on the channel conditions and maximum likelihood estimator is used at the receiver in order to compensate for the carrier frequency offset that occurs during transmission. Simulation results show that maximum likelihood estimator has better performance than self-cancellation estimations. The channels between the source, the cooperating node and the destination are modelled containing thermal noise, Rayleigh fading, Rician fading and path loss. Amplify-and-Forward cooperation protocol is used at the cooperating node when the system is in cooperation mode. For a relatively short distance between the cooperating nodes, when compared to the distance between them and the base station, amplify and forward cooperation protocol has a better performance than decode-and forward protocol, unless an error correcting code is simulated. The cooperating node turns its cooperation mode switch ON or OFF depending on the channel state between the source and the cooperating nodes. The performance of different combination protocols at the receiver is simulated and maximum ratio combining is found to have better performance. However, for immobile wireless sensor networks Extended SNR (ESNR) combiner has also better performance. The system has also showed that with any kind of combination protocol at the receiver it is possible to achieve second order diversity when there is only one cooperating node in the system.**

***Keywords*— OFDM, CFO, ICI, cyclic prefix, cooperative communication, BER, SNR, maximum ratio combiner, amplify-and forward, decode-and-forward, subcarriers, maximum likelihood.**

I. Introduction

During the last two decades, the wireless communications have experienced a huge growth in both capacity and variety. This growth has been possible to achieve due to some advancement and new discoveries of communication technologies, techniques and protocols. The mere motivation that stimulated intense interest to the advancement of existing technologies in wireless communication systems is an increased demand for services that need higher data rate and higher capacity. It has been seen and still expected that the wireless communication systems of the near future will require data rates up to few hundreds of mega bits per second (Mbps), which are able to deliver bandwidth hungry applications such as online gaming, virtual class room, and video streaming. The required data rate of the next generation wireless communication systems will be achieved by efficiently increasing the amount of the allocated bandwidth and using more advanced technologies, both in hardware and software.

One of the major themes in today's broadband systems is the use of orthogonal frequency division multiplexing (OFDM). Orthogonal frequency division multiplexing is a modulation scheme suitable for frequency selective channels and for providing high speed data transmission, which makes it one of the promising solutions for the next generation wireless communications. OFDM mitigates the effect of multipath channel by essentially dividing the source spectrum into many narrow sub-bands that are transmitted simultaneously. In OFDM system, the source bit-stream to be transmitted over the air link is split into N parallel streams, which are later going to be modulated using N sub-carriers. Because of using many sub-carriers, the symbol duration T_s becomes N times larger. This reduces and even totally averts the effect of inter symbol interference (ISI) in multipath channels, and thereby reduces the equalization complexity. However, there is a need for more developments of OFDM systems in terms of complexity reduction and adaptation, therefore reconfigurable solutions are needed to achieve the user requirements. This is necessary because the end users require lightweight, compact size and power efficient devices besides the high bit rate capabilities.

Furthermore, combining OFDM transmission technique with the new techniques such as multiple-input-multiple-output (MIMO) or cooperative communication can also enhance the capacity and the bit rate of the emerging wireless communication systems. Also MIMO transmissions have been extensively studied as a means to improve spectral efficiency in wireless networks. While MIMO techniques offer tremendous advantages, its performance strongly depends on the number of antenna elements, spatial fading correlations between antennas, the presence of line of sight component, etc. Especially, multiple antennas at small handsets/cellular phones are unattractive for the achievement

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of transmit/receive diversity due to the limitation on size, power, hardware and price. The advantages of MIMO techniques can be achieved via cooperative communication. However, carrier frequency offset plays an important role when OFDM is integrated into cooperative communication systems [1]. Carrier frequency offset (CFO) arises either due to mobility that results in different Doppler shifts for each relay, or due to oscillator instabilities that result in slightly different carrier frequencies for every relay. This CFO leads to inter carrier interference, which is the leakage of signal power, in any OFDM based communication system.

In the context of addressing CFO issues surrounding cooperative communication systems based on OFDM, much of the work to date has focused on cooperative relaying techniques that utilize orthogonal space-time codes. For instance, in [1], [2] the authors design appropriate receivers to handle frequency offsets. In [1], the authors develop a frequency synchronization algorithm that exploits the structure of the cooperation protocol. In [2], the authors utilize a long cyclic prefix to mitigate the impact of carrier frequency offsets. This technique reduces the transmission bit rate. One mechanism of simplifying the receiver and transmitter design is to assign orthogonal subcarriers to each relay. The design of frequency offset estimation algorithms were considered in [3] from a multiuser perspective whereby each user is assigned a unique set of subcarriers. The other widely known carrier frequency offset mitigation technique is the self-cancellation (SC) technique [4]. The main idea in self-cancellation is to modulate one data symbol onto a group of subcarriers with predefined weighting coefficients to minimize the average carrier to interference ratio (CIR). This is the main drawback of this method because it utilizes half of the available subcarriers for CFO estimation and hence, inter carrier interference reduction.

Cooperative communication networks [5, 6 and references therein] are created via the help of cooperating terminals which are willing to help the communication of any source-destination pair. End to end spectral efficiency of a wireless network can be increased with the aid of cooperative strategies. The concept of node cooperation brings a new form of diversity. Transmit and/or receive diversity can be achieved even with single antenna terminals [7]. By this way, the need for costly multiple transceiver circuitry diminishes. Furthermore, spatial fading correlation of a cooperative diversity scheme is expected to be much less than spatial fading correlation of multi-antenna arrays co–located at a terminal.

In a cooperative communication system, each wireless user is assumed to transmit data as well as act as a cooperative agent for another user. One of the key components in such a cooperative relay network is a forwarding method used by a relay terminal. Amplify-and-Forward (AAF) and Decode-and-Forward (DAF) are the main forwarding protocols which can be used in the cooperative relay networks [7]. A relay terminal using the AAF scheme amplifies and forwards the signal received from its immediate predecessor (the source node) in the network. A relay terminal using the DAF protocol decodes, re-encodes and forwards the signal received from its immediate predecessor in the network. The use of either AAF or DAF at a relay terminal achieves different performance results under given Signal to Noise Ratio (SNR) conditions. But when the cooperating node gets the line-of-sight signal from the source node, AAF cooperation protocol is preferable than the DAF protocol because of its simplicity and it also doesn't incur system losses in terms of introducing processing delay.

With an intent to integrate the benefits of both cooperation as well as OFDM, OFDM based cooperative communication networks have been intensely investigated [8]-[13]. In [8], [9] Gui and Cimini Jr devise bit loading algorithms for cooperative OFDM systems with decode-and-forward (DF) cooperation protocol, considering a single source-destination pair and multiple cooperating nodes. In [10], the authors proposed an OFDM-based selective relaying scheme in a multihop cooperative network, where the relay selection at each hop is performed on a per-subcarrier basis and joint selection is adopted at the last two hops. In [11], Jamshidi *et al*. derive exact expression and tight lower bound for the outage probability of space-frequency coded cooperative OFDM system. Effect of carrier frequency offsets on the relay-to-destination links in cooperative OFD is investigated in [12]. In [13], interference mitigation techniques to alleviate the effect of inter-symbol interference (ISI) and inter-carrier interference (ICI) caused due to frequency selectivity of the channel and violation of 'quasi-static' assumption in space-frequency block coded cooperative OFDM are presented and analyzed for amplify-and-forward (AAF) and decode-and-forward (DAF) cooperation protocols.

In this paper an OFDM based cooperative communication system with AAF protocol is developed. In order to completely avert the effect of ISI from occurring some redundant information are added into the OFDM symbols before transmission. This added redundant information is called cyclic prefix (CP). Maximum likelihood (ML) estimation is used to estimate the CFO and compensate for its effect that occurs due to the Doppler shift and transmitter-receiver carrier frequency offset. ML estimation is compared with the self-cancellation (SC) estimation series and is found to be better in many aspects. The cooperating node is assumed to get line-of-sight signal from the source and hence, the channel between the cooperating nodes is assumed to have Rician fading characteristics. The channels between the source node and the receiver and the cooperating node and the receiver as well are assumed to be frequency selective and Rayleigh fading. We also assumed the cooperating node to be only a few meters apart (up to 10 meters) from the source node. This is due to the fact that the cooperating nodes need to be a few wavelengths apart in order to create a virtual MIMO system through spatial diversity. In most cases, if the distance between the source and cooperating nodes is longer than 10 meter the level of the noise added to the transmitted signal will become pronounced and eventually surpass the threshold value. In addition to this, by limiting the distance between the two cooperating nodes to 10 meter, the channel characteristics of source node to destination and cooperating node to destination will be nearly the same. Hence, the carrier frequency offset estimated at the receiver upon the arrival of a signal from the source node will be used to compensate for the effects of CFO on both channels, the channel between the source node and the destination and the channel between the cooperating node and the destination. Meaning, there is no need to estimate the CFO that occurs over the cooperating node to destination channel. This minimizes computational time and complexity at the receiver side.

Our contributions are three-fold. First, we show through simulation results that cooperative communication systems with amplify and forward cooperation protocols are not affected by the carrier frequency offset of the relaying nodes when the distance between the cooperating nodes is limited to be in the range of 10 meter. That is, the final received signal at the destination is only affected by the carrier offset between the source and destination, much like relay-less system. This is significant finding which shows that from the point of view of the destination, it can use a receiver built for a conventional multiple antenna transmissions without employing a multiuser-like front-end to handle non coherent transmissions from multiple nodes.

The second contribution is that when the distance between the cooperating nodes is limited to 10 meter range, there will be no need to deal with the issues of imperfect timing synchronization. Hence, in these types of cooperative communication systems, perfect timing synchronization can be assumed between the cooperating nodes. And, since the cooperating node is located far enough from the source node, there will be no spatial fading correlation between the channels from the source to the destination and from cooperating node to the destination. These reduce computational complexity at the cooperating node and at the intended destination.

Lastly, we analyzed, and build a fully functional amplify-and-forward cooperative communication system which is based on an OFDM transmission technique. We have come up with new threshold value at the cooperating node based on which the cooperating node decides whether to cooperate with the source node. In most OFDM cooperative networks to date, the cooperating node amplifies and retransmits the received signal together with the noise added to the signal. In such cases the original message signal will be overshadowed by the noise signal when it reaches the intended destination and it will have no meaning. Through the simulation results, we have also shown how the performance of such systems improves when the cooperating node gets the line-of-sight signal from the source node.

Generally, the solutions developed in this paper to mitigate the effects of CFO in a cooperative OFDM system have shown an advantage of improving system performance in terms of bit error rate (BER) against signal-to-noise ratio (SNR). To validate the achieved results, section VI compares the performances of the system developed in this paper with the widely known and used cooperative OFDM system with self-cancellation CFO estimator.

II. Signal Model

The signal to be transmitted over the wireless channel must first be converted into OFDM symbols. In OFDM system with N subcarriers, N information symbols are used to construct one OFDM symbol. Each of the N symbols is used to modulate a subcarrier and the N modulated subcarriers are added together to form an OFDM symbol. Orthogonality among subcarriers is achieved by carefully selecting the carrier frequencies such that each OFDM symbol interval contains integer number of periods for all subcarriers. Using discrete-time baseband signal model, one of the most commonly used schemes is the IDFT-DFT based OFDM systems [14]. Guard time, which is cyclically extended to maintain inter-carrier orthogonality, is inserted that is assumed longer than the maximum delay spread to totally eliminate inter-symbol-interference [15]. In the presence of virtual carriers, only M out of N carriers is used to modulate information symbols. Without loss of generality, we assume that the first M carriers are used to modulate information symbol, while the last $N - M$ carriers are virtual carriers. With symbol rate sampling, the discrete time OFDM model is:

$$s(n) = \frac{1}{\sqrt{N}} \sum_{k=0}^{N-1} d_k \mathrm{e}^{j2\pi nk/N} \, , \tag{1}$$

where each d_k is used to modulate the subcarrier $\mathrm{e}^{j2\pi nk/N}$. Written in matrix form, we have:

$$s = \mathbf{Wd} \, , \tag{2}$$

where $\mathbf{W}$ consists of the first M columns of the IDFT matrix and $d = [d_0, \ldots, d_{M-1}]$ is the symbol vector. In the presence of time dispersive channel, additive noise, and carrier frequency offset, the OFDM signal at the receiver is now:

$$x(n) = \frac{1}{\sqrt{N}} \sum_{k=0}^{N-1} d_k H(k) \mathrm{e}^{j(2\pi k/N + \Delta\omega T_s)n} + z(n) \, , \tag{3}$$

where $H(k)$ is the channel frequency response corresponding to subcarrier k, $z(n)$ is additive complex Gaussian noise, and $T_s = T/N$ is the symbol interval with T being the IDFT interval (or OFDM symbol interval, excluding the guard time, as often termed in the literature). Here the initial phase due to frequency offset is assumed to be zero (equivalently, the initial phase can be absorbed into $H(k)$). Notice if we define $\varphi = \Delta\omega \cdot T_s$, then φ and the frequency offset $\Delta\omega$ differ only by a constant scalar, hence estimation of $\Delta\omega$ is equivalent to estimation of the normalized phase shift φ.

III. III. OVERALL SYSTEM MODEL

Consider a three node OFDM based cooperative communication network with source node (SN), cooperating node (CN) and receiving node (RN). The SN broadcasts its signal over the fading wireless communication channel and both the CN and RN receive the signal. The CN amplifies and re-transmits the received signal depending up on the link state between its node and the SN and also if the cooperating switch is on ON state by the time the signal arrives. It is assumed that the source and cooperating nodes are always near to each other and the cooperating node gets the LOS signal from the source node. Hence, the channel between the source node and the cooperating node assumed to have Rician fading characteristics. The channels between the source node and the receiving node and between the cooperating node and the receiving node are assumed to be frequency selective and Rayleigh fading.

Consider N OFDM subcarriers. In the first time slot, SN transmits one OFDM frame of duration $(N + N_g)T_s$, where T_s is one sample duration and N_g is the cyclic prefix (CP) length. The transmitted OFDM frame consisting of data symbols $X[k]$, $k = 0,1,\ldots,N-1$, is given by:

$$x[n] = \frac{1}{N}\sum_{k=-N_g}^{N-1} X[k]e^{j2\pi kn/N} \; ; \; -N_g \le n \le N-1. \quad (4)$$

Let $h_{sc}[n]$, $h_{sr}[n]$ and $h_{cr}[n]$ denote the channel impulse responses (CIR) of the source node to cooperating node, the source node to the receiving node and the cooperating node to the receiving node links, respectively. The received OFDM symbols at the cooperating and receiving nodes, during the first phase (time slot), will be:

$$y_{sc}[n] = x[n] * h_{sc}[n] + n_{sc}[n], \quad (5)$$

$$y_{sr}[n] = x[n] * h_{sr}[n] + n_{sr}[n], \quad (6)$$

where $*$ indicates linear convolution, $n_{sc}[n]$ is the white Gaussian noise signal at the cooperating node, and $n_{sr}[n]$ is the white Gaussian noise signal at the receiving node, both white Gaussian noises with variance N_o; $y_{sc}[n]$ is the signal received at the cooperating node from the source node and $y_{sr}[n]$ is the signal received at the destination from the source node. During the second time slot (or cooperation phase), the cooperating node will amplify the received signal by gain β and re-transmits it to the receiving node. Hence, the received signal at the receiving node, $y_{cr}[n]$, in this second phase is:

$$y_{cr}[n] = \beta y_{sc}[n] * h_{cr}[n] + n_{cr} = \beta\left(x[n]*h_{sc}[n] + n_{sc}[n]\right) * h_{cr}[n] + n_{cr}, \quad (7)$$

where $*$ indicates linear convolution and n_{cr} is the white Gaussian noise over the cooperating and receiving nodes link with variance N_o. The magnitude of the amplifying factor is determined based on the transmitted signal energy and the received signal energy. Let $\xi = E[|x[n]|^2]$, then the energy of the signal received at the cooperating node is:

$$E[|y_{sc}[n]|^2] = E[|h_{sc}[n]|^2]E[|x[n]|^2] + E[|n_{sc}[n]|^2] = E[|h_{sc}[n]|^2]\xi + 2N_o. \quad (8)$$

To re-transmit the data with the same power as the source node did, the cooperating node needs to amplify the received signal by a factor of:

$$\beta = \sqrt{\frac{\xi}{E[|h_{sc}[n]|^2]\xi + 2N_o}}. \quad (9)$$

The system developed in this paper supports cooperation if and only if $\xi >> E[|h_{sc}[n]|^2]\xi + 2N_o$, otherwise the cooperating node turns its cooperation mode switch to OFF state. Therefore, the received signal at the receiving node in two time slots is:

$$\begin{aligned} y[n] &= y_{sr}[n] + y_{cr}[n] = \\ &= \left(x[n]*h_{sr}[n] + n_{sr}[n]\right) + \\ &\quad + \beta\left(x[n]*h_{sc}[n] + n_{sc}[n]\right)*h_{cr}[n] + n_{cr} = \\ &= x[n]*h_{sr}[n] + \beta x[n]*h_{sc}[n]*h_{cr}[n] + \\ &\quad + \beta n_{sc}[n]*h_{cr}[n] + n_{sr}[n] + n_{cr}[n]. \end{aligned} \quad (10)$$

Using distributive property of convolution and defining $w[n]$ as $w[n] = \beta n_{sc}[n]*h_{cr}[n] + n_{sr}[n] + n_{cr}[n]$, the eqn. (10) can be written as:

$$y[n] = x[n]*\left(h_{sr}[n] + \beta h_{sc}[n]*h_{cr}[n]\right) + w[n]. \quad (11)$$

The output on the k^{th} subcarrier is given by performing the discrete Fourier transform on the above equation (11).

Defining $h_r[n] = h_{sr}[n] + \beta h_{sc}[n]*h_{cr}[n]$, then (11) becomes $y[n] = x[n]*h_r[n] + w[n]$. Then:

$$Y[k] = X[k]H_r[k] + W[k], \quad (12)$$

where $H_r[k] = H_{sr}[k] + \beta H_{sc}[k]H_{cr}[k]$, whereas $H_{sr}[k]$ and $H_{sc}[k]$ being the N-point DFTs of $h_{sr}[n]$ and $h_{sc}[n]$, respectively. Equation (12) shows the amplitude of the transmitted signal is attenuated by a factor of $H_r[k]$ and interfered by a signal $W[k]$. To reduce this reduction in amplitude and mitigate the interference at the destination this paper used different type of combiners and analysed the performance of each combiner.

The schematic diagram in Fig. 1 shows the overall system followed by its description. The transmitting node should always perform signal modulation whenever it has a signal to transmit. Hence the bit stream will be converted into symbols. Then the source node performs serial to parallel conversion. The number of parallel symbols should coincide with the number of available subcarriers. After the conversion, IFFT is performed to obtain OFDM symbol. The cyclic prefix (CP) is lastly added before transmission to completely avert inter-symbol interference (ISI) and minimize Inter Carrier Interference (ICI) at the receiving end. Then the transmitter in the source node converts the parallel data into serial data and transmits it over the air link to the cooperating node and the receiving node. In this first phase, the cooperating node performs amplification of the received signal for re-transmission if the received signal passes the threshold quality for re-transmission. The cooperating node decides to cooperate depending on the state of the channel between the source and cooperating nodes. In the second phase, the receiver receives another copy of the signal from the cooperating node and combines it with the signal received from the source node directly using maximum ratio combiner (MRC). In this paper we have checked and tested different combiners under different conditions. After obtaining the received signal by combining the direct signal and the signal from the cooperating node by maximum ratio combiner, the process that was undertaken in the main transmitting node is reversed to obtain the decoded data. The CP is removed to obtain the data in the discrete

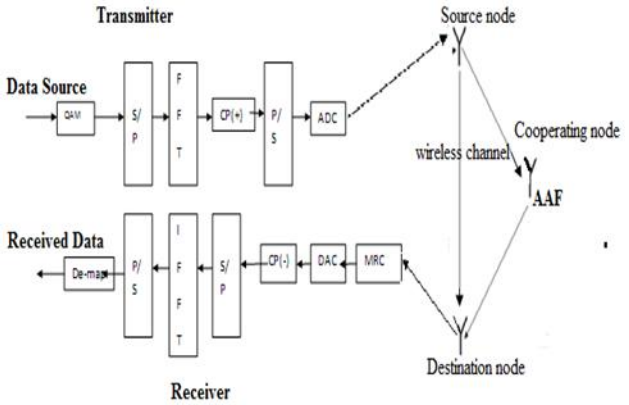


Figure 1: OFDM based Cooperative communication system diagram.

time domain and then processed using the FFT for data recovery. Since the wireless channel is known to be fading and to introduce Doppler shift, the ML estimator that comes immediately after the FFT block in the system is used to perform CFO estimation. Then using the estimated values of CFO, the ICI that occurs during transmission will be compensated. Finally the symbols pass through the de-mapper (demodulation) in order to regenerate the received bit stream.

IV. Maximum Likelihood Estimation for CFO at the Receiver

In this paper the source node and the cooperating node are assumed to be separated only few meters apart (up to 10 meters maximum) and the cooperating node gets the LOS signal from the source node. Hence, it is also assumed that the channel characteristics between the cooperating node and the receiver are the same with the channel characteristics of the source node to the receiver, except for simulation less Doppler frequency for the cooperating node-to-receiver channel is used. This is due to the fact that only a node with lower speed will be chosen for cooperation. Therefore, the CFO estimated at the receiver for the signal coming from the source node will be used to compensate both the signal from the source and cooperating nodes. That means, there is no need to do CFO estimation for the signal arriving at the receiver from the cooperating node.

This method has been presented in several papers in slightly varying forms [16, 17]. The training information required is at least two consecutive repeated symbols. The IEEE 802.11a preamble satisfies this requirement for both the short and long training sequence. Let the transmitted baseband signal be s_n, then the complex baseband model of the passband signal y_n is:

$$y_n = s_n \mathrm{e}^{j2\pi f_{tx} n T_s}\,, \tag{13}$$

where f_{tx} is the transmitter carrier frequency and T_s is the sampling interval. After the receiver down-converts the signal with a carrier frequency f_{rx}, the received complex baseband signal r_n is:

$$r_n = s_n \mathrm{e}^{j2\pi f_{tx} n T_s} \mathrm{e}^{-j2\pi f_{rx} n T_s} + w_n = s_n \mathrm{e}^{j2\pi \Delta f n T_s} + w_n\,, \tag{14}$$

where $\Delta f = f_{tx} - f_{rx}$ is the carrier frequency offset and w_n the white Gaussian noise with variance N_o.

Let D denote the delay between the identical samples of the two repeated symbols. Then the frequency offset estimator is developed as follows: The cross-correlation of the two consecutive symbols is computed as:

$$\begin{aligned} c &= E\left[\sum_{n=0}^{N-1} r_n r_{n+D}^{*}\right] = \\ &= E\left[\sum_{n=0}^{N-1}\left(s_n \mathrm{e}^{j2\pi\Delta f n T_s} + w_n\right)\left(\left(s_{n+D}\mathrm{e}^{j2\pi\Delta f(n+D)T_s} + w_{n+D}\right)^{*}\right)\right]. \end{aligned} \tag{15}$$

Since w_n is an additive white Gaussian noise white mean zero and covariance σ^2, the above equation will reduce to:

$$\begin{aligned} c &= \sum_{n=0}^{N-1} s_n s_{n+D}^{*} \mathrm{e}^{j2\pi\Delta f n T_s} \mathrm{e}^{-j2\pi\Delta f(n+D)T_s} = \\ &= \mathrm{e}^{-j2\pi\Delta f D T_s} \sum_{n=0}^{N-1} s_n s_{n+D}^{*} = \mathrm{e}^{-j2\pi\Delta f D T_s} \sum_{n=0}^{N-1} \left|s_n\right|^2. \end{aligned} \tag{16}$$

Hence, the maximum likelihood estimate gives us the frequency offset estimation as:

$$\Delta f = \frac{\arg(c)}{2\pi D T_s}\,. \tag{17}$$

The ML estimation of frequency offset can also be derived after the discrete Fourier Transform (DFT) processing (i.e. in frequency domain). The received signal during two repeated symbols is (ignoring noise for convenience):

$$r(n) = \frac{1}{N}\left[\sum_{k=-K}^{K} X_k H_k \mathrm{e}^{j2\pi n(k+f_r)/N}\right], \text{ for } n = 0,\ldots 2N-1 \tag{18}$$

where X_k's are the transmitted data symbols, H_k is the channel frequency response for the k^{th} subcarrier, K is the total number of subcarriers, and f_r is the relative frequency offset to the subcarrier spacing. The DFT of the first symbol and for the k^{th} subcarrier is:

$$R_{1,k} = \sum_{n=0}^{N-1} r_n \mathrm{e}^{-j2\pi kn/N}\,,\ k = 0,1,\ldots N-1\,. \tag{19}$$

The DFT of the second symbol is derived as:

$$R_{2,k} = \sum_{n=N}^{2N-1} r_n \mathrm{e}^{-j2\pi kn/N} = \sum_{n=0}^{N-1} r_{n+N} \mathrm{e}^{-j2\pi kn/N}\,,\ k = 0,\ldots N-1\,. \tag{20}$$

But from (14) the received signal at the index of $n + N$, $r(n + N)$, is given as:

$$\begin{aligned} r(n+N) &= \frac{1}{N}\sum_{k=-K}^{K} X_k H_k \mathrm{e}^{j2\pi(n+N)(k+f_r)/N} = \\ &= \frac{1}{N}\sum_{k=-K}^{K} X_k H_k \mathrm{e}^{j2\pi n(k+f_r)/N} \mathrm{e}^{j2\pi(k+f_r)}. \end{aligned} \tag{21}$$

Since $\mathrm{e}^{j2\pi(k+f_r)} = \mathrm{e}^{j2\pi k}\mathrm{e}^{j2\pi f_r}$ and $\mathrm{e}^{j2\pi k} = 1$ for all integer values of k, eqn. (21) can be rewritten as:

$$\begin{aligned} r(n+N) &= \frac{1}{N}\sum_{k=-K}^{K} X_k H_k \mathrm{e}^{j2\pi n(k+f_r)/N} \mathrm{e}^{j2\pi f_r} = \\ &= r(n)\mathrm{e}^{j2\pi f_r},\ n = 0,1,\ldots 2N-1. \end{aligned} \tag{22}$$

Substituting equation (22) into equation (20) yields:

$$R_{2,k} = \sum_{n=0}^{N-1} r(n) e^{j2\pi f_r} e^{-j2\pi kn/N} = \\ = e^{j2\pi f_r} \sum_{n=0}^{N-1} r(n) e^{-j2\pi kn/N} = \\ = R_{1,k} e^{j2\pi f_r}, \quad k = 0, 1, \ldots N-1. \tag{23}$$

This, therefore, shows us that every subcarrier experiences the same shift that is proportional to the frequency offset. The cross-correlation of the two subcarriers is obtained as follow:

$$C = \sum_{k=-K}^{K} R_{1,k} R_{2,k}^{*} = \sum_{k=-K}^{K} R_{1,k} \left(R_{1,k} e^{j2\pi f_r} \right)^{*} = \\ = e^{-j2\pi f_r} \sum_{k=-K}^{K} R_{1,k} \left(R_{1,k} \right)^{*} = e^{-j2\pi f_r} \sum_{k=-K}^{K} \left| R_{1,k} \right|^{2}. \tag{24}$$

Thus, the frequency offset estimator governing equation is:

$$f_r = -\frac{1}{2\pi} \arg(C), \tag{25}$$

$$\Delta f = -\frac{f_{sc}}{2\pi} \arg(C), \tag{26}$$

which is quite similar in form to the time domain version of the ML estimation in (17).

This CFO estimation is used at the receiver to estimate the carrier frequency offset, that occurs due to Doppler shift and frequency synchronization error of the transmitter and receiver. Then this estimated CFO values will be used to compensate both the signals from the source node and the cooperating node at the receiver node.

V. Simulation Results and Discussion

For simulation, quadrature amplitude modulation (QAM) scheme with $M = 4$ is chosen and the total number of subcarriers is set to 64. These parameters are chosen because the current wireless communication systems, 3G and beyond, are based on them. The fading channel between the source node and the receiver and the fading channel between the cooperating node and the receiver are set to have six different signal propagation paths with 100 Hz and 80 Hz Doppler frequency, respectively. The 100 Hz Doppler shift between the source node and the base station is the worst case in wireless communication system. The reason we chose 80 Hz Doppler frequency between the cooperating node and the base station is that the source node is always assumed to select a cooperating node with relatively lower speed. Figure 2 shows the transmitted and received signal. Figure 3 shows the performance of the system when there is no cooperation, meaning, when there is no diversity. The broken curve in red color shows the system performance when there is no CFO. But, the broken curve in green color shows the effect of CFO with value of 0.2 in the system performance. The system performance, for instance, at 40 dB SNR is less that 10-4 when the system is CFO free.

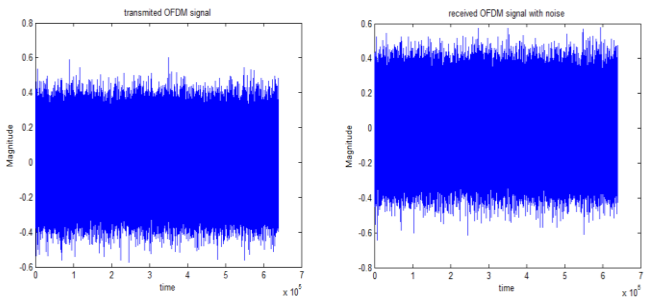


Figure 2: Transmitted and received signal, when there is no cooperation.

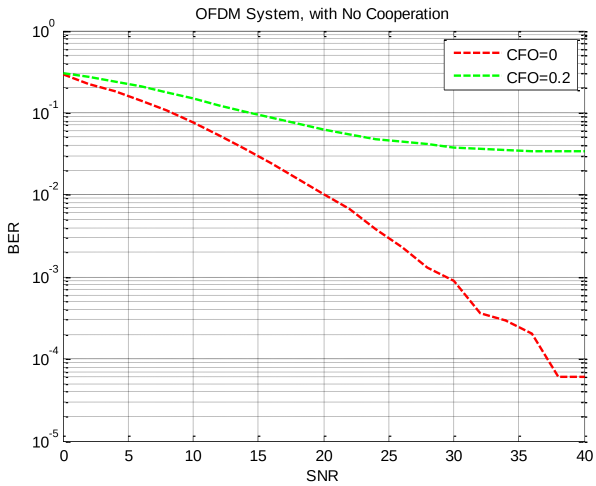
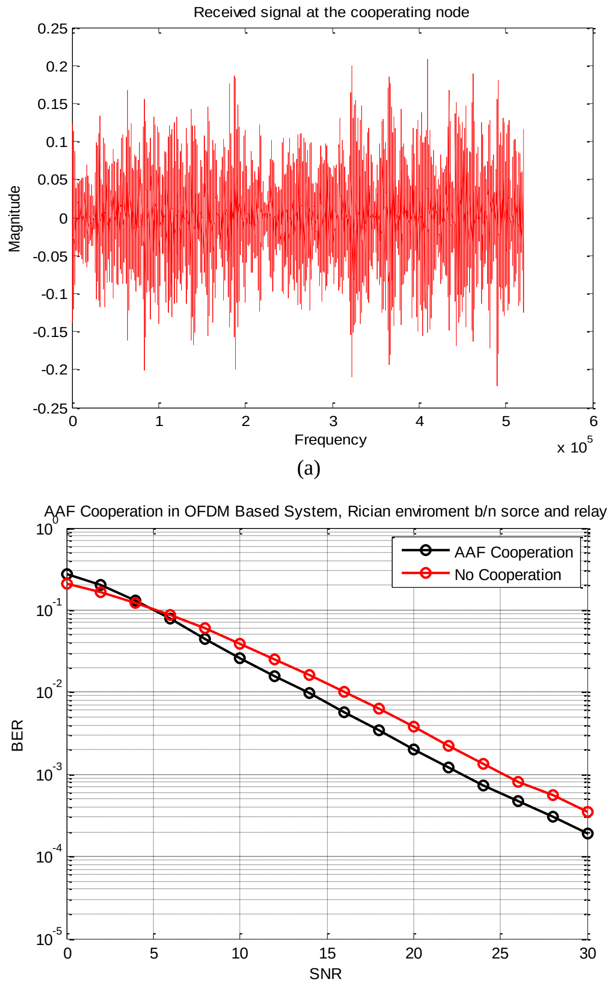


Figure 3: System performance of OFDM system with no cooperation.



(a)

(b)

Figure 4: (a) Signal received at the cooperating node from the source node, 20dB SNR, (b) Ideal OFDM based Cooperative communication system performance

But, the system performance deteriorates to nearly 10^{-1} for the CFO value of 0.2. The Figure 3 shows the bit error rate (BER) deteriorating as the system introduces more carrier frequency offset. However, the system performance should improve when carrier frequency estimation technique is incorporated at the receiver side of the system.

Figure 4a shows the signal received at the cooperating node from the source node and Figure 4b shows the performance of an ideal OFDM based cooperative communication system, where there is no CFO in the system and hence, no need of mitigating the effects of mobility and frequency synchronization error. From the simulation result in Figure 4b, the BER of the system with cooperation improves as the SNR increases starting from 5 dB. Hence, it can be concluded that at higher level of SNR cooperation results in a very improved system performance in terms of BER.

Figure 5 shows the effects of carrier frequency offset (CFO) deteriorating the performance of OFDM based second-order diversity cooperative communication system. Therefore, maximum likelihood estimation developed in the above session in chapter three to mitigate the effects of CFO is used to soothe the severity of CFO in the system. The simulation result shows how the system performance deteriorates for CFO = 0.2.

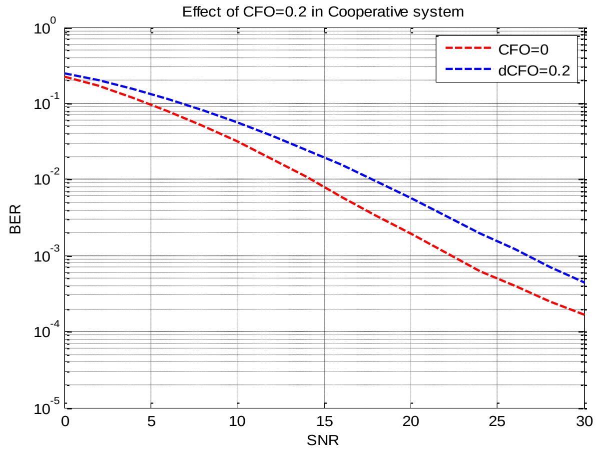


Figure 5: OFDM based cooperative system with CFO effects for CFO=0.2.

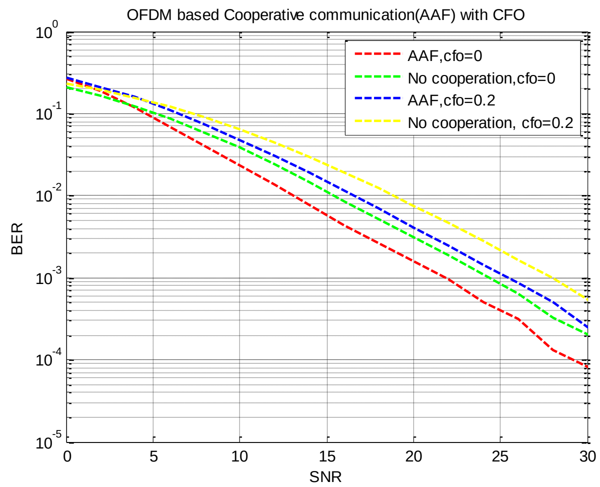


Figure 5: ML estimation of CFO in cooperative communication system.

Figure 6 shows how the integration of ML estimation into the system improved the system performance. The simulation result compares the performance of the system with and without cooperation for CFO values of 0 and 0.2. The performance of the system with AAF cooperation in the environment where 0.2 carrier frequency offset introduced to the system has nearly the same performance with the system without cooperation and carrier frequency offset value of 0. This result shows how cooperation in wireless communication systems can significantly improve the performance in terms of BER against SNR.

VI. Validation of the Simulation Results

The simulation results in Figure 7 and Figure 8 show how the performance of developed cooperative communication system with ML estimation technique overrides the performance obtained from cooperative communication system with self-cancellation (SC) estimation technique.

The comparison between the ML estimation technique and the SC estimation technique is made for CFO values of 0.15, and 0.3 and for modulation types of QAM-4, and QAM-16. In all of the simulation scenarios ML estimation and compensation techniques have shown better performance. The maximum likelihood method gives the best overall results.

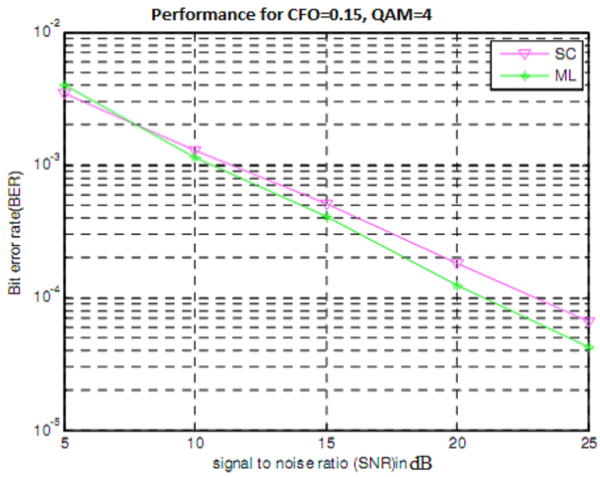


Figure 7: Comparison of ML with SC for CFO= 0.15and 4-QAM

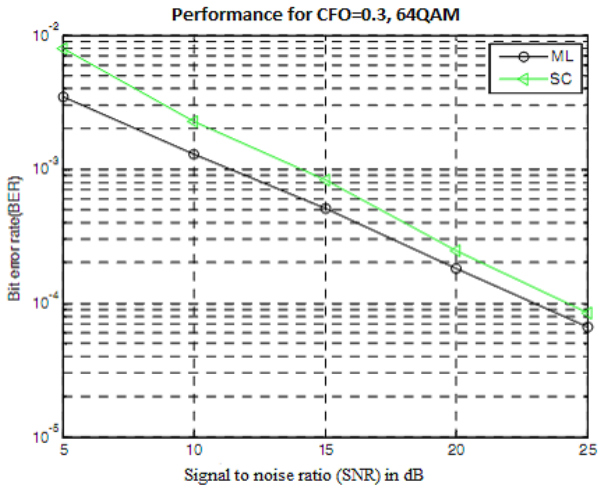


Figure 8: Comparison of ML with SC for CFO=0.3 and 64-QAM.

Figure 7 shows simulation result of the cooperative communication systems based on ML and SC methods for carrier frequency offset value of 0.15 and 4-QAM modulation. The purple colored curve represents the performance curve of cooperative system with self cancellation CFO estimator and the green colored curve represents the performance of cooperative system with maximum likelihood CFO estimator. For these carrier frequency offset value and modulation type, the two methods showed nearly the same performance for SNR values of up to 10 dB. But, thence the performance obtained from the ML method showed better performance in terms of BER.

For CFO value of 0.3 and modulation scheme of QAM-64, the ML based cooperative system shows better performance for the entire range of SNR values. This is shown in Figure 8.

Hence, the system developed in this paper shows better performance when it is compared with the widely studied and previously developed OFDM based cooperative communication systems.

VII. Conclusion

The paper considered the most practical scenarios in cooperative communication systems where the cooperating node gets line-of-sight signal from the source node. It has also investigated the effects of carrier frequency offset in amplify and forward cooperative communication system and how these effects are mitigated by using multi-carrier transmission along with maximum-likelihood estimation of CFO. The simulation results of the developed structure have also proved that better BER can be achieved if the cooperating node is restricted to be in a limited range of distance from the source node.

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