Performance Analysis of Cooperative OFDM Networks Under the Constraint of Timing and Frequency Offsets

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Abstract:- *In this paper, we show the performance improvement in a cooperative Orthogonal Frequency Division Multiplexing (CO-OFDM) network employing Amplify-and-Forward & Decode-and-Forward relaying strategies under the influence of both Carrier Frequency Offset (CFO) and Timing Offsets (TO). Multiple distributed nodes in cooperative networks are generally subject to Carrier Frequency Offset and Timing Offsets. Cooperative transmission, in which a source and relay cooperate to send a message to a destination, can provide diversity against fading in wireless networks. The key idea in user-cooperation is that of resource-sharing among multiple nodes in a network. The Symbol Error Rate (SER) performance of Amplify and Forward technique (AF), Decode and Forward technique (DF) and direct communication using OFDM subcarriers in a cooperative network with a single relay between Base Station and Mobile Station is presented. The cooperative OFDM networks employing AF and DF relaying strategies show an error performance with a better correlation to theoretically calculated values after the joint compensation using ML estimation for timing and carrier frequency offsets.*

Keywords:- *AF relay, DF relay, Maximum ratio combiner, ML estimation, OFDM systems, SER performance.*

I. INTRODUCTION

In the past decades, wireless communication has benefited from a variety of technology advancements and it is considered as the key enabling technique of innovative future consumer products. In future, significantly technical achievements are required to ensure that wireless communications have appropriate architectures suitable for supporting a wider range of services and higher speed data transmission delivered to the users. The coming wireless personal communication systems are expected to provide ubiquitous, high-quality, and high-rate mobile multimedia transmission. However, in order to achieve this objective, various technical challenges need to be overcome. Signal fading due to multi-path propagation is one of the major impairments to meet the demands of next generation wireless networks for high data rate services. To mitigate the fading effects, time, frequency, and spatial diversity techniques or their combinations can be used.

Among different types of diversity techniques, spatial diversity is of a special interest as it does not incur the system losses in terms of delay and bandwidth efficiency. Spatial diversity has been studied intensively in the context of Multiple-Input-Multiple-Output (MIMO) system. Multiple-input and multiple-output (MIMO) system is a well-known technique to increase the capacity and diversity of wireless communications. However, due to the limitations on the hardware or cost, equipping devices with multiple antennas may not be possible in some wireless networks. For this reason, a class of technique known as cooperative communication has been introduced. The basic principle is to construct a virtual multiple-antenna system by sharing antennas of neighboring users in a distributed manner.

Cooperative communication [1] is one of the fastest growing areas of research, and it is likely to be a key enabling technology for efficient spectrum use in future. Cooperation is possible whenever the number of communicating terminals exceeds two is shown in Fig.1. Indeed, a vast portion of the literature, especially in the realm of information theory, has been devoted to a special three-terminal channel, labeled the *relay* channel.

User-cooperation is possible whenever there is at least one additional node willing to aid in communication. Cooperative communication is an attractive low-cost solution to combat fading in wireless communications, where multiple single antenna relay terminals receive and cooperatively transmit the source information to the destination.

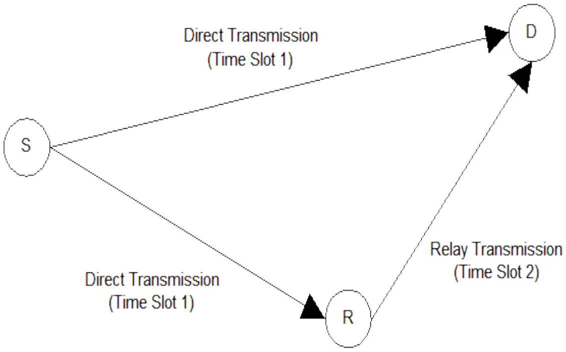

Fig.1 Three node cooperative system

In ideal settings, it has been shown that the same spatial cooperative diversity as that of *multiple-input–multiple-output* (MIMO) systems can be achieved in cooperative networks without the need for multiple antennas at each node. In conventional MIMO systems, the antenna elements are collocated on a single device, which results in a single timing and carrier offset.

However, multiple nodes in these cooperative systems [2] are not only distributed in space but also have their own oscillator, which means that there is multiple timing offset and frequency offset in cooperative transmission. These offsets may drastically undermine the diversity potential of cooperative networks. In these cooperative techniques, multiple nodes put a signal on the physical channel simultaneously. However, due to the distributed nature of the transmitter, it is often difficult to control synchronism parameters that are taken for granted in the case of co-located antennas.

In particular, significant symbol-level asynchronism can arise between the receptions of the signal from various nodes. The presence of multiple CFOs in cooperative networks arises due to the distributed nature of the network and due to simultaneous transmissions from separate nodes with different oscillators, resulting in a rotation of the signal constellation and *signal to noise ratio (SNR)* loss. The amount of SNR loss and accuracy of channel estimation is highly dependent on CFO estimation precision at the receiver. Thus, achieving frequency synchronization is key to future deployments of cooperative networks.

Relay-Assisted Transmission:

A relay is used in between source and destination. Relay communication is a technique to overcome the effects of fading in wireless networks. Relay channels and their extensions form the basis for the study of cooperative diversity because relaying and cooperative diversity essentially create virtual antenna array. The two different relaying strategies are shown in Fig.2. We consider that data is sent through three channels. Channel 1 takes little more time to reach the destination than channel 2 to reach the relay. In the simplest model, it involves the use of an extra radio, which is wirelessly connected to a transmitter and is called the relay to forward the message to a receiver.

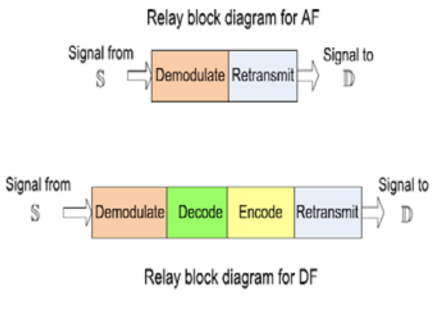

Fig.2 Relaying Strategy for AF and DF

II. Related Works

OFDM is a popular concept, which has been actively researched for the past few decades. Among the existing air-interface techniques, OFDM is a promising technique for high-bit-rate wireless communications [3]. Various methods to combat the myriad of synchronization issues involved have also been developed over the past years.

Also, the research on cooperative communication is extremely active. In Europe, the Enhanced Wireless Communication Systems Employing COperative DIVersity and NEWCOM++ are two famous international projects; include a lot of state of the art on the cooperative communication research.

Most of the existing work in the literature focuses on estimating either MCFOs while assuming perfect timing synchronization [2], [4] & [5] or MTOs while assuming perfect carrier synchronization [2] & [6]. Recently, a limited number of papers have investigated joint estimation of impairments. In [7], [8], [9] & [10], a new joint ML estimator for determining MCFOs, MTOs, and channel gains in DF cooperative networks is devised. Nevertheless, the ML estimator in [10] requires exhaustive search and is computationally very complex.

In [6], [7], [8] & [10], training and data transmission methods for both DF-and AF-relaying multi-relay cooperative networks affected by MCFOs, MTOs, and unknown channel gains are discussed. The derived closed-form FIM shows that there exist coupling between the estimation errors of MCFOs and MTOs, which establishes that these parameters must be jointly estimated at the destination.

Cooperative OFDM is a relatively nascent technology that faces more complex and critical synchronization issues. Our paper presents a simple combination of the synchronization issues and the comparison of the relative performance.

III. System Model

A communication system consists of a transmitter and a receiver connected by a channel. The channel is the actual physical medium where a signal at the channel input will produce a corresponding channel output after suffering from various distortions. The simplest wireless channel is the additive white Gaussian noise (AWGN) channel and its output signal is given by:

$$y = x + n \qquad (1)$$

where ‘x’ is the complex modulated signal transmitted through the channel and 'n' is the Additive Gaussian White Noise random variable with zero mean and variance σ^2. In this channel, the received signal is composed of an undistorted 0transmit signal infected with channel noise.

For the AWGN channel, the received signal ‘y[i]’ with timing offset ‘θ’ and frequency offset ‘ε’ expressed as

$$y[i] = x[i-\theta]e^{j2\pi\varepsilon n/N} + n[i] \qquad (2)$$

where x[i] and n[i] are the transmit signal with variance σ_x^2 and white Gaussian noise with variance σ_n^2, respectively.

Timing offset:

The objective of symbol timing or frame synchronization is to know when the first OFDM symbol starts. Timing offsets gives the phase rotation of the sub-carriers, which is largest on the edges of the frequency band. If the timing offsets ‘θ’ are small enough to keep the channel impulse response within cyclic prefix, then the orthogonality is maintained. The common methods of timing synchronization are training sequence-based and cyclic prefix-based.

Frequency offset:

The second issue is the frequency offsets in the channel caused by tuning oscillator inaccuracies and Doppler shifts. The frequency offsets causes the reduction of signal amplitudes in the output of the filters matched to each of the carriers, and introduces ICI from the other carriers that are now no longer orthogonal. The tolerable frequency offset ‘ε’ is a very small fraction of the channel bandwidth due to the OFDM carriers are inherently closely spaced in frequency compared to the channel bandwidth.

Amplify and Forward:

In this cooperative protocol, the source broadcasts message x_s in the first phase. The message is received by the destination and relays. Each relay r_i amplifies the received signal in the first phase and transmits to the destination in the second phase. The destination combines the signals received in both phases to decode the message. Specifically, the signal received by relay r_i in the first phase (denoted as y_{ri}) can be written as

$$y_{ri} = a_{sri}\ x_s + n_{ri} \qquad (3)$$

where a_{sri} is the channel gain for link s-r_i and n_{ri} denotes Gaussian noise at relay r_i. Suppose each relay normalizes the received signal before transmitting to the destination. Then, the transmitted signal can be written as

$$x_{ri} = g_{ri}\ y_{ri} \qquad (4)$$

where g_{ri} is the amplifying gain which is given by

$$g_{ri} = \sqrt{\frac{P_{ri}}{\left|a_{sri}\right|^2 P_s + N}} \qquad (5)$$

Decode and Forward:

For the decode-and-forward (DF) cooperative protocol, relay nodes apply some forms of detection and/or decoding before encoding the information and forwarding it to the destination. Such a cooperative protocol also has two phases (i.e., time slots). In the first phase, the source broadcasts the signal to the relay which subsequently detects and/or decodes it. In the second phase, the relay transmits re-encoded signal to the destination using repetition or space-time codes.

For protocols that require relays to fully decode the received signal in the first phase, the set of relays which successfully decode the signal at the end of the first phase is only a subset of all available relays. Let *D*(*s*) denote the set of successfully decoding relays which will be called a decoding set in the following. For repetition-based coding, the destination receives separate retransmission from the relay $r \in D(s)$. Hence, we write the signal from relay *ri* received at the destination *d* as

$$y_{d1} = a_{rid}\ x_{ri} + n_d \qquad (6)$$

where x_{ri} denotes the signal transmitted by relay node r_i, a_{rid} stands for the channel gain for link *ri-d*, and n_d denotes the Gaussian noise at the destination.

If space-time coding is used, the destination will receive the superimposed signals from all relay $r \in D(s)$ simultaneously. Hence, the received signal at the destination in the second phase can be expressed as

$$y_{d2} = \sum_{r_i \in D(s)} a_{rid}\ x_{ri} + n_d \qquad (7)$$

Maximum Ratio Combining:

The Maximum Ratio Combining (MRC) [11] is the method of diversity combining. The signals from both the channels are added together. The gain of the each channel is made proportional to the rms value of the signal level and inversely proportional to the mean square of the noise level in the channel. MRC is the optimal combining technique which maximizes the overall SNR at the output of the combiner. The MRC combiner requires the coherent detector that has knowledge of all channel coefficients. The SNR at the output of the MRC is the sum of the received SNRs from both the branches. The input of MRC at the destination is given by

$$m_i = y_{d1} + y_{d2} \qquad (8)$$

where y_{d1} & y_{d2} are signals received at the destination from source and relay, respectively.

The weights of the maximum ratio combiner is given as

$$a_i = \frac{y_{di}^*}{N_{di}} \qquad (9)$$

where i= 1,2., y_{di}^* is the complex conjugate of the y_{d1} & y_{d2} and N_{di} is the mean square noise power on the 1st and 2nd channel.

The MRC output signal is then given as,

$$m = \sum_{i=1}^{2} \frac{y_{di}^*}{N_{di}} m_i \qquad (10)$$

Maximum Likelihood (ML) Estimation:

The ML estimation [12] for both timing and frequency offset is done at two stages. First stage, the timing and frequency offset estimation in the first hop is performed at the relay. Secondly the ML estimation is performed at the destination after receiving the relay signal. The optimal maximum likelihood estimator for joint estimation of time and frequency offset with assumption of consecutive samples N_t + N.

The timing offset estimation $\hat{\theta}$ is given as

$$\hat{\theta} = \arg\max_{0 \le m \le N_t - 1} \left\{ \left| \gamma(m) \right| - \rho \Phi(m) \right\} \qquad (11)$$

The frequency offset estimation $\hat{\varepsilon}$ is given by

$$\hat{\varepsilon} = -\frac{1}{2\pi} \angle \gamma\left(\hat{\theta}\right) \qquad (12)$$

where,

$$\gamma(m) = \sum_{i=m}^{m+N_g-1} y[i]\, y[i+N] \qquad (13)$$

$$\Phi(m) = \frac{1}{2} \sum_{i=m}^{m+N_g-1} \left(\left| y[i] \right|^2 + \left| y[i+N] \right|^2 \right) \qquad (14)$$

and

$$\rho = \frac{\sigma_x^2}{\sigma_x^2 + \sigma_n^2} \qquad (15)$$

Thus, the joint estimation of time and frequency offset estimation is done for direct transmission, AF and DF relay protocol.

IV. RESULTS AND DISCUSSION

In this section, we present the simulation results on BER performance with the SNR for various network strategies. In all simulations, QPSK modulation is used. A cooperative network of single relay is considered. Without loss of generality, CFO and TO estimation is considered. Specifically AWGN channels are used in all simulations. We assume that fixed rate transmission at source (S) and destination (D). The packet size is also fixed.

We simulate the three node cooperative relay network using three different protocol strategies. For this, we use 1024 sub-carriers with 128 guard interval.

A) Direct transmission through the relay without and with CFO and TO

In this we send the signal in first phase to both the destination and relay. In the second phase, the relay retransmits the received signal to the destination. In this we didn't consider the effects of offset. The signal from both the relay and source is given to a MRC, which selects the signal having better SNR. This is plotted with the response to theoretical calculation as shown in Fig.3 and same performance is plotted after estimating the offset shown in Fig.4.

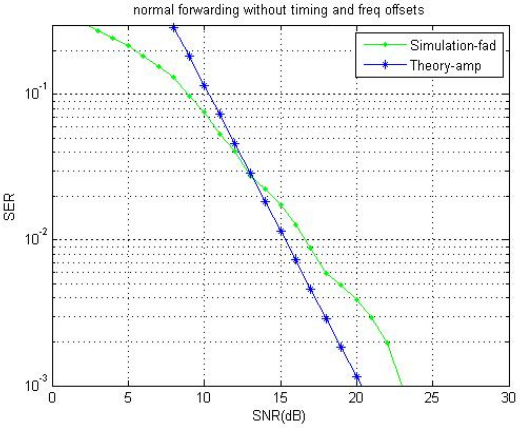

Fig.3. Forwarding without Offsets

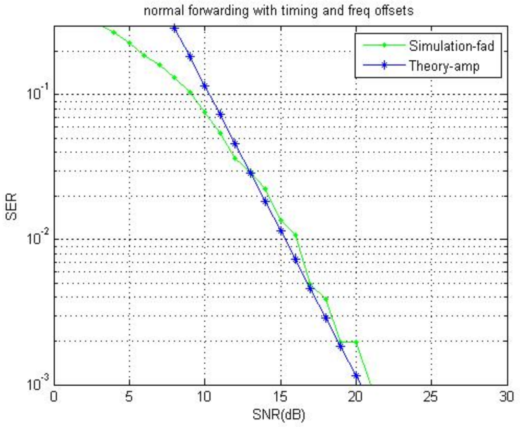

Fig. 4. Forwarding with Offsets

B) Amplify and Forward without and with CFO and TO

Considering same forwarding strategy, we use amplify and forward (AF) protocol in the relay. The relay is acting as a regenerative node, which amplifies the received signal at the relay and just forwards the amplified signal. The signal from both the relay and source is given to a MRC, which selects the signal having better SNR. This system performance is simulated and compared with the theoretical calculation without the offset as shown in Fig.5, and same performance is plotted after estimating the offset shown in Fig.6.

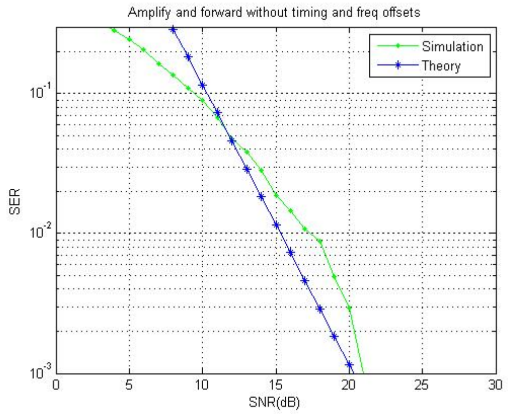

Fig.5. Amplify and Forward protocol without CFO and TO

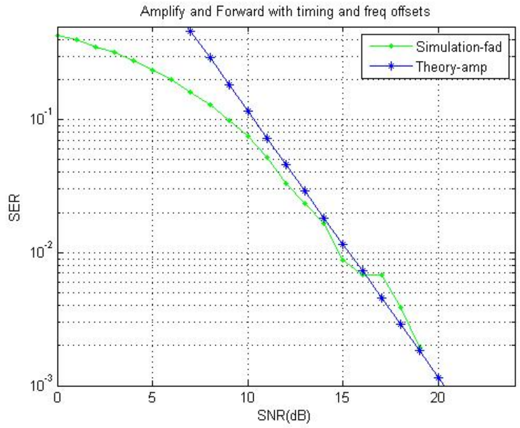

Fig.6. Amplify and Forward protocol with CFO and TO

C) Decode and Forward without and with CFO and TO

Considering same forwarding strategy, we use decode and forward (DF) protocol in the relay. The relay performs the error correction of the received signal by using cyclic check and then encodes the same signal. The encoded signal is now forwarded to the destination. The signal from both the relay and source is given to a MRC, which selects the signal having better SNR. This system performance is simulated and compared with the theoretical calculation without the offset as shown in Fig.7, and same performance is plotted after estimating the offset shown in Fig.8.

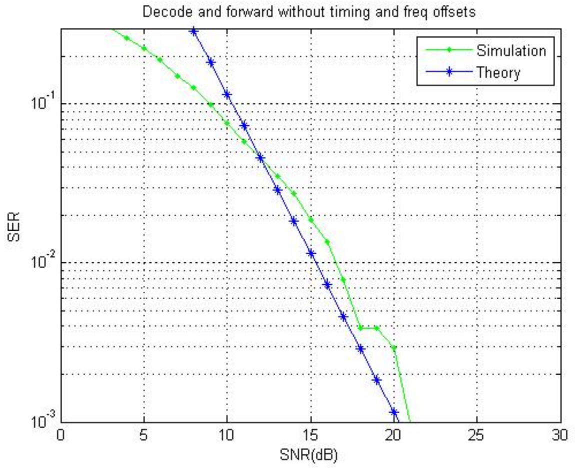

Fig.7. Decode and Forward protocol without CFO and TO

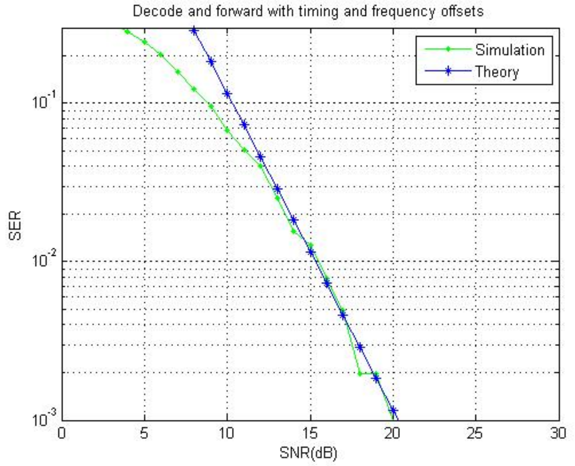

Fig.8. Decode and Forward protocol with CFO and TO

V. CONCLUSION

In this paper, performance analysis with the use of cooperative communication is intended to achieve spatial diversity similar to MIMO systems gives a better robust performance against error than a direct communication between source and destination. The effects of frequency and timing offsets provided a useful insight into the issue of synchronization in OFDM networks. The cooperative OFDM networks employing AF and DF relaying strategies show an error performance with a better correlation to theoretically calculated values after the joint compensation for timing and carrier frequency offsets.

The estimated parameters are then used to compensate for the offsets in the received signal. Maximum Ratio Combining technique was used to combine the multiple received signals into a single improved signal, thereby exploiting signal diversity resulting from cooperative communication. We intend to extend this work for multiple relay cooperative networks by jointly estimating the channel gain with timing and frequency offset.

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