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Timing and Carrier Synchronization by Offset Estimation for Cooperative Relay Networks

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Abstract

Cooperative communication combats the effects of fading without the need for multiple antennas. The cooperative networks use multiple distributed nodes that virtually behave like multiple antennas each having their own local oscillators. But the oscillators cause multiple Carrier Frequency Offsets (CFO), unknown channel gains and Multiple Timing Offsets (MTO). For a good performance of the system perfect synchronization is needed which is achieved by estimation and compensation of multiple offsets. Also, the coverage and capacity can be improved by employing intermediate nodes called relays within cooperative networks. These cooperative relay networks can perform in a better manner even when considering MCFOs, MTOs and unknown channel gains by having more computationally efficient decoders that can use Maximum Likelihood (ML) estimation subject to the Cramer-Rao Lower Bound (CRLB) on the variance of any impartial estimate. The simulation results show that frequency offset still exist after Amplify and Forward (AF) relaying. The performance of a conventional cooperative network seems to have improved with respect to Bit Error Rate of the system when an AF relay is hosted. The estimate of the frequency offset is chosen such that it gives the signal, a high probability of occurrence using ML estimator. In ML estimate, since the bias and variance is difficult to compute, a lower bound called the CRLB on the variance of any unbiased estimate is derived which is satisfied by the ML estimator.

Keywords: AF, Cooperative Communication, CFO, ML Estimation and Compensation, OFDM

1. Introduction

A wireless system can be considered as a group of nodes that can communicate with each other without being connected by wires. Because the wireless channels are broadcasting in nature, those nodes act as antennas in the wireless system. When there are multiple nodes or users the available channels must be shared among them. To support multiple users in the network, each user must be allocated with different signal space. This allocation of different signalling magnitudes to different users is called multiple access. Some of the multiple access techniques are: Time Division Multiple Access (TDMA), Frequency Division Multiple Access (FDMA) or Code Division Multiple Access (CDMA) and each of these techniques perform differently in different multi-user channels. Depending on the system requirements, characteristics as well as complexity and cost of the system, an appropriate accessing technique can be chosen.

Any signal through a wireless channel is subject to conditions or factors that degrade or distort signals as they are transmitted through the channel from source to destination and these factors are called Channel impairments. Some of the channel impairments are: Path Loss,

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Noise, Inter-symbol Interference, Fading, etc.

In the history of wireless communication, there are several challenges that still contribute to today's research. Some of them are: multipath fading, shadowing, and path loss effects of wireless channels. These effects lead to random variations in time, frequency, and space dimensions of the channel that make conventional wire line communication techniques too difficult to be employed in the wireless environment. The use of diversity technology provides a separate fading path to the transmitted signals so that different channel dimensions, such as time, frequency, and space can be efficiently utilized which improves the diversity gains and hence performance of the wireless communications. Moreover, the Multiple-Input Multiple-Output (MIMO) technology has allowed the use of multiple antennas to achieve diversity. But having several antennas on a particular node is unrealistic because of the size and cost constraints on wireless devices such as in wireless sensor networks or in cellular phones. In such cases, a virtual MIMO environment can be created by making the nodes to share their antennas in a distributed. This scheme is followed in the cooperative communication systems.

2. Related Works

The inverse effects of the multiple frequency and timing offsets having unknown channel gains are mitigated by the use of Distributed Space-Time Block Code (DSTBC) based Amplify-and-Forward (AF) cooperative networks at the destination side. After receiving the superimposed signals broadcasted from the relay node, the user nodes estimate the impairments using known training signals. A Maximum Likelihood (ML) or Differential Evolution (DE) based estimator is used for this purpose. Then, the users employ a Minimum Mean-Square Error (MMSE) receiver in combination with the estimated impairments to decode the received signal. The estimated values are subjected to Cramer-Rao Lower Bounds (CRLBs) to measure the performance of synchronization and channel estimation in AF Two Way Relay networks[1].

The symbol timing offset in an OFDM system having cooperative diversity is removed even in a Rayleigh fading channel, with a good probability of detection of synch. The timing estimation for independent and orthogonal channels can also be evaluated using Monte Carlo simulations[2].

The CRLBs are derived for various probability distribution functions especially for the Gaussian distribution and its variants to be used on the ML estimation of offsets. The derivation of these Cramer-Rao Lower bounds is carried out using Fisher information matrix[3].

The estimation of multiple timing offsets and the unknown channel parameters significantly depends on the training sequences. Hence the training sequences must be optimally designed for an efficient offset estimation. The unknown channel parameters and the MTOs can be jointly estimated by using a Hybrid CRLB (HCRB) which is derived as a function of training sequences. Three conditions are imposed on designing the appropriate training sequences. The accuracy of estimation can be improved by enforcing these conditions on HCRB to obtain a tighter lower bound on the estimates, known as the conditional Cramer-Rao Lower Bound (ECRB). By applying the training sequences that satisfy the ECRB, the bit error rate performance of the cooperative relay networks can be lowered[4].

3. System Model

In cooperative networks, MCFOs, MTOs and unknown channel gain occur due to the presence of multiple nodes and their own local oscillator. These offsets lead to losses at the receiver, which can be overcome by synchronization. For synchronization, the offset in the signals must be estimated. These estimated values must be used for compensation at the receiver.

Carrier frequency offset contributes to Common Phase Shift (CPS). This CPS rotates the desired signals and does not change within one OFDM symbol. It also causes intercarrier interference that destroys the orthogonality between OFDM sub carriers.

In an OFDM system, inverse and forward Fourier transforms are carried out during the modulation and demodulation at the transmitter and receiver, respectively. Those samples of the transmitted signal which make up the OFDM symbol are needed for these operations. Such exact samples may not be available due to Carrier Timing Offset (CTO). Therefore a synchronization of the symbols must be performed for the exact detection and reconstruction of the samples. Apart from phase distortion, the carrier timing offset also causes Inter Symbol Interference (ISI) in OFDM systems. So to improve its performance, the timing offset must be accurately estimated so that the beginning of OFDM symbols can be easily determined at the receiver[5].

All these offsets that are discussed above occur due to the presence of multiple distributed nodes in the cooperative networks and also in the channels with unknown gains[6].

3.1 Cooperative Communication Protocols

The Cooperative Communication Protocols define how the incoming data is processed at the relays before onward transmission to the destination. Some of cooperative communication protocols are: Amplify and Forward (AF), Decode and Forward (DF) protocols, Detect-and-Forward (DtF).

Amplify and Forward (AF) is a signalling method where each user amplifies the received noisy version of the signal that is transmitted and again retransmits the amplified version to the base station. The base station combines the two independently faded versions of the signal that is received so that information detection can be made easy.

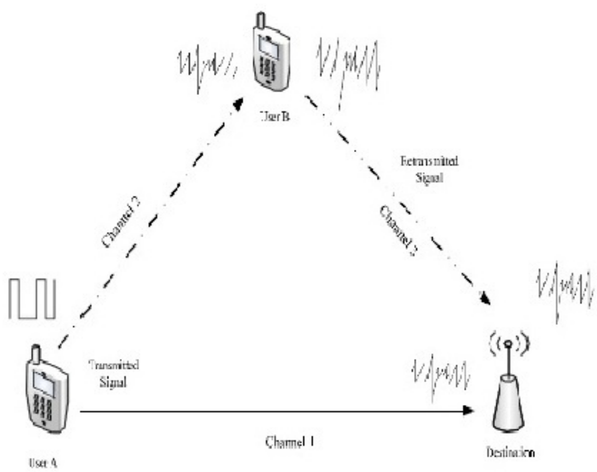

Figure 1. Amplify and Forward relay network.

The amplification factor of the relay is given by equation (1).

$$\beta = \sqrt{\frac{\xi}{(\square\, | h_{s,r} | \xi + 2\sigma_{s,r}^{2})}} \quad (1)$$

Decode and Forward (DF) strategy says that the intermediate node should decode the received signal from the transmitter node, receives the signal from the transmitter node and checks for any errors and corrects them. The error-corrected signal will be encoded and it will be forwarded to the receiver node[7].

In Detect-and-Forward (DtF), the signal is demodulated/detected by the relay and sent to the destination but the channel encoded signal is not fully decoded by the relay. It can be concluded that this scheme is less complex when compared to the Decode and Forward (DF) protocol. The DtF protocol is also termed as fixed DF.

It has been observed from simulation results that the above discussed multiple offsets still exist even after relaying with any of the protocols like AF, DF or DtF. So these offsets must be compensated at the receiver so that it is synchronised with the transmitter. For the compensation of the offsets, those offsets must be estimated to be used at the receiver for compensation. Various estimators available are:

- ML Estimator
- DE Estimator

The entire scheme of joint estimation and compensation of the multiple carrier frequency and timing offsets is depicted in Figure 2.

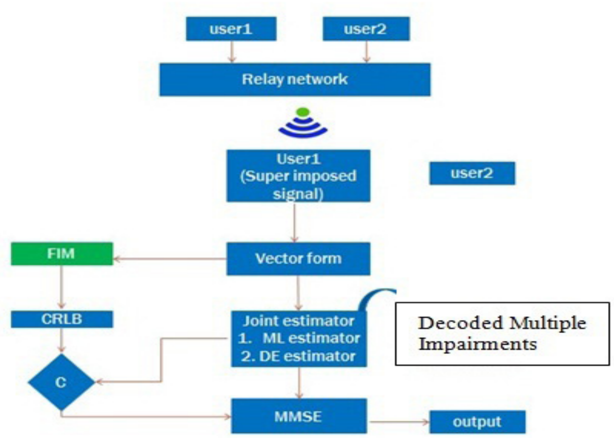

Figure 2. Joint estimation and compensation.

3.1.1 Maximum Likelihood Estimation

In general, the parameters of a statistically modelled system can be estimated such that the values have the maximum probability of occurrence. This method is called the Maximum-Likelihood Estimation (MLE). For a given statistical model, the ML estimator provides the estimated values of the parameters that are close to the actual values[8].

3.1.2 Cramer-Rao Bound

The estimated values from an ML estimator are quite accurate and hence the bias and variance of the estimate are difficult to compute. The problem is tackled by deriving a lower bound for the variance of the estimate, then comparing the variance of the ML estimate of this lower bound[9].

The following assumptions are made during the simulations for analysis of AF relay networks.

- Complex Gaussian Channel.
- Input sequence length: 80bits.
- Multiple Access Technique: OFDM.
- Frequency offset: (-200 to 200) kHz.
- Amplification Factor,

$$\beta = \sqrt{\frac{\xi}{(\square \mid h_{s,r} \mid \xi + 2\sigma_{s,r}^2)}} = 1.2$$

where,
ξ is the energy of the transmitted signal,
$\sigma_{s,r}$ is the total attenuation i.e., channel response.

- Average channel gain, |hs,r|= 0.8

4. Results and Discussion

A cooperative relay network is given an arbitrary input sequence and the behaviour of the system having an Amplify and Forward relay as the intermediate node is analysed.

AF relay is chosen because it does not take much time at the relay node where it operates in a particular time-slot, as well as there is no need of error correction at the relay part.

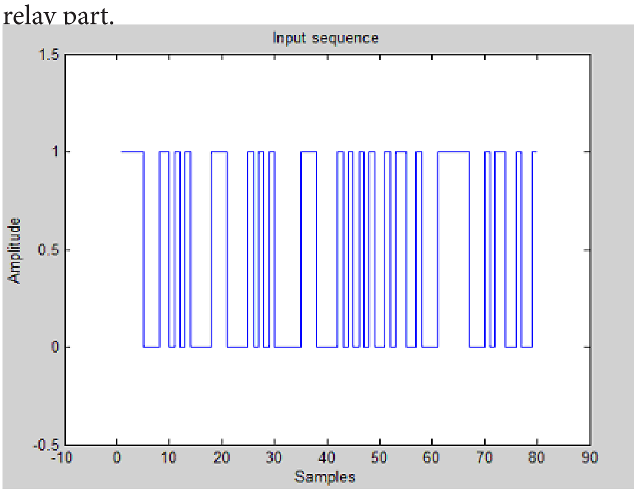

Figure 3. Input sequence.

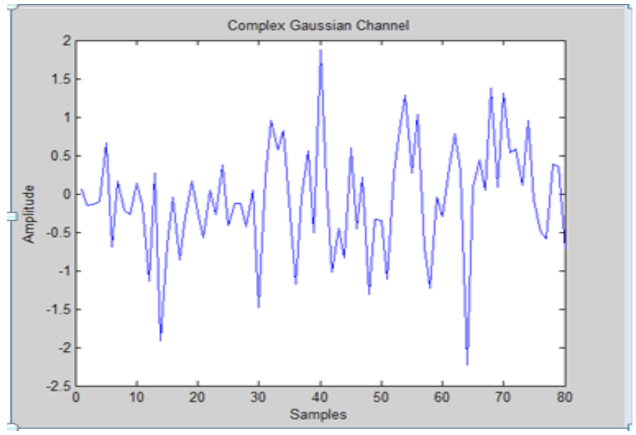

Figure 4. Complex channel gain.

Cooperative AF network performance using QPSK.

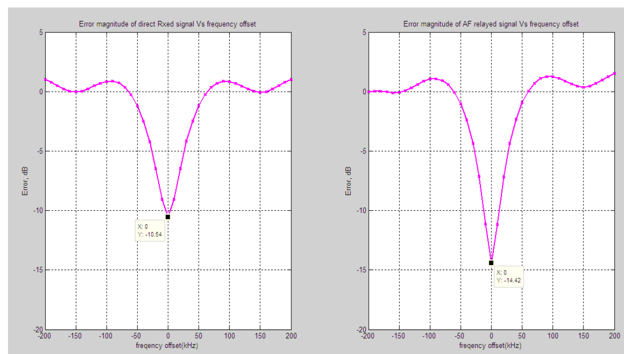

Figure 5. MSE vs. Frequency offset for direct path and AF relayed path.

In both the paths, the MSE is increasing for a positive and a negative increasing frequency offset and is the minimum for a zero frequency offset. This clearly shows the necessity of frequency offset compensation at the receiver for a better error performance.

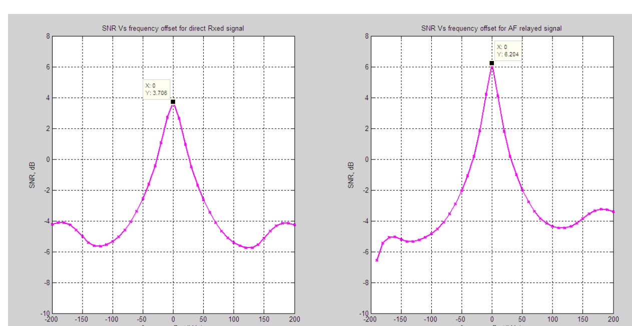

Figure 6. PSNR vs. Frequency offset for direct path and AF relayed path

4.1 Simulation Parameter: Different Modulation Schemes

Though the OFDM channel treats all the modulation schemes similarly, the received signal after relaying by the AF relay has some metrics that are more desirable for some modulation schemes and below that required for communication in other modulation schemes. So the same transmission from source to destination across the direct path and the AF relayed path are observed and the observations are tabulated.

Table 1. MMSE for various modulation schemes

Modulation Techniques	MMSE(dB)	
	Direct Path	Amplify and Forward
BPSK	-10.62	-14.56
QPSK	-10.54	-14.42
16-QAM	0.7343	-3.281
32-QAM	4.094	0.07461
64-QAM	8.648	4.614

The MMSE is lesser in the amplified and forwarded path, than in the direct source-to-destination path, for all modulation schemes. This is because the OFDM channel treats every modulation technique in the same way except for the number of bits required to represent a symbol.

Table 2. PSNR for various modulation schemes

Modulation Techniques	PSNR(dB)	
	Direct Path	Amplify and Forward
BPSK	3.762	6.287
QPSK	3.706	6.204
16-QAM	3.802	6.428
32-QAM	3.804	6.435
64-QAM	3.817	6.457

The SNR is higher in the amplified and forwarded path, than in the direct source-to-destination path, for all modulation schemes. This is because the OFDM channel treats every modulation technique in the same way except for the number of bits required to represent a symbol. QAM techniques provide higher SNR range since it gives better BER performance.

4.2 Simulation Parameter: Different Values of Average Channel Gain

It is known that the amplification factor of the amplify-and-forward relay is dependent on the average channel gain, |hs,r|.

Thus varying the average channel gain changes the amplification factor, β and hence the PSNR and MMSE values of the relayed signal. So the transmission from source to destination in the direct path and the AF relayed path are observed and the observations are tabulated. QPSK modulation scheme has been considered.

Table 3. PSNR and MMSE values for various Average channel gain values

Average Channel Gain	PSNR(dB)		MMSE(dB)	
	Direct Path	AF Path	Direct Path	AF Path
0.78	3.706	6.86	-10.54	-15.54
0.79	3.706	6.602	-10.54	-15.09
0.80	3.706	6.204	-10.54	-14.42
0.81	3.706	6.124	-10.54	-14.28
0.82	3.706	5.902	-10.54	-13.91

5. Conclusion and Future Work

The aim of this project is to design less complexity decoders for single relay cooperative networks with MCFOs, MTOs and unknown channel gains.The observations made using an AF relay network in this phase show that:

1. Offsets exist even after relaying.
2. Offsets are inter-dependant.

i.e., the relayed signal power depends on the amount of frequency offset introduced by the channel and also on the average channel gain. This also suits to timing offsets introduced by the channel, which means that estimating any of these offsets individually requires the others to be assumed constant or synchronized. But this is not valid in any of the practical scenarios as seen. So the joint estimation of these offsets is necessary, which can be performed using ML estimators. But the variance and bias of an ML estimator is very difficult to compute. Hence, the estimated offset values will be subjected to some lower bounds like the Cramer-Rao Lower Bound (CRLB) and those values that satisfy this bound are to be chosen as the optimum estimates of the offsets. These estimated offset values are compensated at the receiver so that synchronization can be achieved ensuring an efficient operation even if multiple carrier frequency and timing offsets are present.

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