OPPORTUNISTIC MULTIPLE RELAYING IN WIRELESS AD HOC NETWORKS

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ABSTRACT

OPPORTUNISTIC MULTIPLE RELAYING IN WIRELESS AD HOC NETWORKS

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Cooperative relaying systems aim to improve weak communication links by exploiting the spatial diversity obtained by the statistically independent channels between relays and the destination. In this thesis a cooperative relaying scheme called the Opportunistic Multiple Relaying (OMR) is proposed with its special receiver structure. Unlike most relaying schemes in the literature, multiple relay nodes are allowed to transmit in nonorthogonal channels in OMR without requiring any control overhead for relay coordination. OMR is compared to a benchmark scheme called the Selection Relaying (SR) in which the relay node is preselected by the source before transmission according to the average channel quality information. It is observed that OMR performs significantly better than SR in terms of error performance.

Keywords: Cooperative Relaying, Opportunistic Relaying, Relay Selection, Selection Relaying, Joint Channel and Sequence Estimation, CFO Estimation

ÖZ

TASARSIZ KABLOSUZ HABERLEŞME SİSTEMLERİNDE ESNEK ÇOKLU RÖLELEME YÖNTEMİ

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İşbirlikli haberleşme, farklı röleler ile hedef arasında oluşan bağımsız kanalları kullanarak uzaysal çeşitlilikten yararlanmayı ve böylece kanal kalitesi yetersiz iki düğümü birbiriyle haberleştirmeyi amaçlar. Bu tez çalışmasında, literatürdeki birçok işbirlikli haberleşme yönteminden farklı olarak aktarıcı düğümlerin ortak bir kanalda haberleşme verimini düşürmeden yayın yapmalarına imkan veren bir röleleme yöntemi olan Esnek Çoklu Röleleme (EÇR) yöntemi ve bu yönteme uygun bir alıcı yapısı önerilmiştir. Önerilen EÇR yönteminde herhangi bir önseçime gerek duyulmadığından röleler arası kontrol haberleşmelerine olan gereksinim de azalmıştır. Tez kapsamında önerilen bu röleleme yöntemi ortalama kanal kalitesi bilgisi ile aktarıcının seçildiği önseçimli röleleme yöntemi ile karşılaştırılmış ve önerilen EÇR yönteminin tek ünite üzerinden yönlendirmeye denk olan önseçimli röleleme yönteminden hata başarımı açısından çok daha üstün olduğu gösterilmiştir.

Anahtar Kelimeler: İşbirlikli Aktarıcılık, Aktarıcı Seçimi, Kör Tabanlı Kanal ve Dizi Kestiricileri, Taşıyıcı Frekans Hatası Kestirimi

To my family

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CHAPTER 1

INTRODUCTION

Signal fading due to the random nature of the channel is one of the major problems in wireless communication systems. A fraction of the links in any system experience more severe fading in comparison to others as a result of the geographical conditions. Relaying is one of the methods aiming to improve reliability of such links. By relaying, two new communication channels are introduced to the system which are between source and relay, relay and destination. Utilizing these newly introduced channels may increase the probability of reliable transmission from a source to a destination.

In relaying systems, the destination processes the signals coming from the source and also from the relays in order to gain from the same advantages of MIMO (multiple-input multiple-output) systems. This kind of relaying in which communicating nodes help each other to improve communication capacity, speed and performance is referred to as *cooperative relaying* and is first proposed in [1, 2]. In MIMO systems, the received signal quality and data communication speed is increased by using signal processing techniques to combine the transmitted signals from multiple wireless paths created by the use of multiple receive and transmit antennas. However, using multiple antennas on the transmitter and receiver is usually impossible for small-size communication devices, since different antennas should see independent channel fades to gain from the spatial diversity. Therefore, considering cooperating relay nodes as different transmitter antennas of a MIMO system, it is more probable for a cooperative relaying system to obtain full spatial diversity since relay nodes are almost always several wavelengths distant from the source and each other.

Cooperative relaying can be done by using fixed relaying or adaptive relaying techniques according to the communication needs of the system [3, 4]. In fixed relaying, relays are dedicated and fixed nodes and they are placed strategically to increase link success between source and destination. This kind of relaying is easy to implement. However, it has a low bandwidth efficiency and usually half of the bandwidth is allocated to the relay nodes. For example, when the source-destination channel condition is sufficiently good and most of the packets transmitted by the source can be received by the destination then relay's transmissions would be mostly wasted. Moreover, such relaying schemes are not suitable for ad hoc systems where such a static and dedicated relay unit cannot be found. Adaptive relaying tries to overcome this problem by selecting the relay only when there is a need for relaying.

In both adaptive and fixed relaying, the processing at relay nodes differs according to the employed protocol [4]. In the amplify-and-forward (AF) relaying protocol, the relay node only scales the received signal and transmits the amplified version of the received signal. Another option in the relay node is to decode the received signal and then retransmit after re-encoding. This kind of relaying protocol is referred as decode-and-forward (DF) relaying.

In this thesis study, adaptive relaying schemes in which any node of an ad hoc network can be employed as a relay node is considered. In adaptive relaying schemes, relaying can be done by using only one node or multiple nodes. In both situations, selection of the relay nodes is a critical problem. Selection can be performed by using the instantaneous channel quality metrics or average channel quality metrics based on the previous knowledge about the channel. Relay selection based on instantaneous channel quality requires the channel state information (CSI) at source and relay nodes as in [5, 6]. However, considering fast varying channels due to high mobility or frequency hopping, CSI should be updated frequently to gain from the spatial diversity of the channel. Therefore, requiring frequent updates of CSI and so a high control overhead makes this kind of relay selection method inappropriate for communication systems with low bit-rate. On the other hand, relay selection schemes that use the average of the previous channel quality metrics or location information (e.g. obtained by GPS) do not guarantee obtaining the maximum spatial diversity possible, since the selected relay can experience worse channel conditions due to instantaneous fading.

Multi-node relaying can be considered as an alternative to selection relaying, since selecting the best relay requires a considerably high control information in selection based relaying schemes. Most of the multi-node relaying schemes studied in the literature employs orthogonal time or frequency channels to achieve full diversity order of the system by employing one of the well known diversity combining techniques [4, 7]. The diversity combining methods to be used at the receiver can be selected such as Maximal-Ratio-Combining (MRC), Equal Gain Combining (EGC) or Selection Combining (SC) which are described in detail in [8]. However, since relay nodes use orthogonal time or frequency channels, the spectral efficiency of the system is inversely proportional to the number of relays. Therefore, Distributed Space Time Coding (DSTC) is proposed to enable multi-node relaying in the same channel [9, 10].

DSTC is a type of space-time coding (STC) where space time coding is done over different relay nodes. DSTC has the advantage of reducing the data rate loss due to orthogonal transmission of relay nodes without sacrificing diversity order. However, DSTC is adapted from STC of MIMO and it requires accurate synchronization among nodes. Most of the work on cooperative communications assume perfect synchronization between relay nodes which is quite impossible in practice since all relay nodes should have the same timings, carrier frequencies and propagation delays. Therefore, in the literature some DSTC techniques not requiring perfect synchronization are also proposed [11, 12]. The method proposed in [11] requires guard intervals between different relays' transmissions which are orthogonalized in smaller time slots than the time slot used for a standard transmission. In this technique the source should know the relay nodes before transmission and each relay nodes should know when and which part of the coded packet it should relay. This technique leads to an increase in control messaging and hence an increased overhead for the system. Additionally, the guard intervals required will result in a loss in transmission efficiency. In another study [12], multiple relays are not required to be known by the nodes and they are allowed to transmit in the same time by employing a similar coding technique to Alamouti coding. However, this method also requires guard intervals between the transmissions in consecutive time slots. Hence, it is costly to implement in systems with small slot durations.

Cooperative beamforming is another method in which multiple relays transmit in nonorthogonal channels. In this method, relay nodes transmit their messages by phase aligning and power controlling according to their instantaneous channels to the destination [13]. However, such a method requires channel information at relay nodes and as well as perfect synchronization among relay nodes. Therefore, it is difficult to use in practical systems where all nodes have different clocks.

In this thesis, a cooperative relaying scheme which is called the Opportunistic Multiple Relaying is proposed. This scheme enables multiple nodes to operate as relays in a nonorthogonal manner without requiring accurate synchronization and channel information among the nodes of the system. The scheme also includes a special receiver structure which aims at responding to these requirements by a joint channel and data sequence estimator. Although fine synchronization is not crucial for the proposed scheme, a synchronization sufficient enough to enable nodes to transmit using a Time Division Multiple Access (TDMA) medium access protocol is assumed throughout the work.

There are studies in the literature similar to ours in which multiple nodes are allowed to relay the source's signal in the same time and frequency slot without employing a DSTC. One of these studies found in the literature is [14]. However, this study differs from our study in that it ignores the different timing inaccuracies and different propagation delays experienced by different relays under the assumption of narrowband communication. However, in our study we have observed the timing inaccuracies and propagation delays of the nodes causes Inter-Symbol-Interference (ISI) at the destination even for narrowband communications. Therefore, we consider the problem under a more realistic set of assumptions. Another study found to be similar to ours is given in [15]. This study also considers the timing inaccuracies and propagation delays for different relay nodes and proposes to use a decision feedback equalizer assuming channel state information at the destination. However, in our case due to the absence of channel information at the destination and severe bandwidth limitation we focused on a near blind channel estimator and equalizer which needs only a limited number of training symbols for the destination.

The rest of this thesis is organized as follows. Chapter 2 describes the related theoretical background information for the wireless channel models used throughout the work. Chapter 3 presents the proposed scheme OMR in more detail, and describes the proposed receiver structure for the destination nodes of this scheme. The *selection relaying* (SR) scheme which is used to compare the performance of OMR is also introduced in this chapter and the simulation results showing performance of both schemes are presented. In Chapter 4, the carrier frequency offset (CFO) problem is taken into consideration and methods proposed to reduce the effect of CFO at nodes of the system are given. The comparison of the schemes under CFO can also be found in this chapter. The thesis is concluded in Chapter 5.

CHAPTER 2

MODELING WIRELESS CHANNELS

This chapter provides necessary background related to wireless communication channel models for better understanding of the concepts that will be presented in the subsequent chapters of the thesis.

2.1 Wireless Channels

Wireless communication systems suffer from many challenges such as noise, fading, and interference. These impairments are usually modeled in a statistical fashion as random variables with parameter values that are based on the measurements made for specific communication systems or frequency spectrum. The main impairments considered here that affect the signals are *noise*, *large-scale propagation effects*, and *small-scale propagation effects*.

2.1.1 Noise

In communication systems, the received waveform is usually categorized into the desired part which contains the information and the undesired part. The desired part is the signal and the undesired part is either the *noise* or the *interference*, which are modeled as additive impairments. Throughout the thesis study it is assumed that no other sources interfere the desired signal and noise is the only source of the additive impairment.

Noise is assumed to be the sum of many undesired components in communication systems and it is generally modeled as a Gaussian variable according to the central limit theorem. Additionally, noise is usually assumed to have a constant power spectral density (PSD) at least over the communication band, therefore, it is also assumed as a white process in the band of communication. As a result, in most of the communication models the noise is assumed to be an additive white gaussian noise (AWGN) with proper filtering, sampling, etc.

In this thesis study, we assume the noise at the receiver is caused by the thermal noise sources. Noise performance of the receivers are characterized by *noise figure* (NF), which is a parameter given by the receiver manufacturer in dB scale and used as a figure of merit for the receivers [16]. By using NF, signal bandwidth W in Hz, receiver temperature T in Kelvins and the Boltzman constant k, the noise power and the spectral density (N_o) of the noise at the receiver can be calculated by equation (2.1) as given below:

$$N_o = 10^{NF/10} kT. \tag{2.1}$$

If the symbol duration T_s is set to $1/W$, E_s/N_o, which is the ratio of the energy per symbol to the noise spectral density at the receiver, is given by

$$E_s/N_o = \frac{P_{rec} T_s}{N_o} = \frac{P_{rec}}{10^{NF/10} kTW}, \tag{2.2}$$

where P_{rec} is the received signal power at the receiver.

2.1.2 Large-scale propagation effects

Large-scale propagation effects are the impairments which are noticeable over long distances. They contribute to the total signal impairment by reducing the signal power. Two large-scale propagation effects are path loss and shadowing.

Path loss is the attenuation suffered by a signal as it propagates from the transmitter. It is measured as the value of the ratio between the transmitted power and received power in decibels. Typically, path loss can be modeled by using one of the models below:

- Free space path loss formula,
- Ray tracing methods,
- Empirical path loss models.

Empirical path loss models are used for more realistic simulations. Empirical models are derived from a very large number of measured data for a given distance, frequency band and geographical area or building. Simulations done for this thesis study uses the *Hata model* [17], which is an empirical path loss model. The Hata model, aims to predict the path loss by a closed form expression which is obtained by fitting the empirically observed path loss values [8], therefore, it is a practical model to use for simulation purposes. The Hata model is valid over frequencies between 150 – 1500 MHz and its standard form is for urban areas. However, the model can also be extended to suburban or rural areas.

The standard formula for urban areas is given by,

$$P_{L,urban}(d) = 69.55 + 26.16\log_{10}(h_t) - 13.82\log_{10}(h_t) - a(h_r) + (44.9 - 6.55\log_{10}(h_t))\log_{10}(d), \tag{2.3}$$

where $P_{L,urban}(d)$ is the received power in dB at a distance of d and $a(h_r)$ in eqn. (2.3) is calculated by

$$a(h_r) = (1.1\log_{10}(f_c) - 0.7)h_r - (1.56\log_{10}(f_c) - 0.8). \tag{2.4}$$

In equations (2.3) and (2.4), the variables h_t and h_r are transmitter and receiver antenna heights in meters, respectively, d is the distance between the transmitter and the receiver in kilometers and f_c is the carrier frequency of the signal in MHz.

Since ad hoc tactical networks under consideration are usually used in rural areas, the rural extension to the standard model is used in simulations. The path loss in rural areas is calculated by

$$P_{L,rural}(d) = P_{L,urban}(d) - 4.78[\log_{10}(f_c)]^2 + 18.33\log_{10}(f_c) - K, \tag{2.5}$$

where K is a constant and should be selected in the range from 35.94 (countryside) to 40.94 (desert) [8].

Shadowing is the other large scale propagation effect. The path losses of two receive antennas situated in the same distance from the transmit antenna do not experience the same received power due to the shadowing loss which models the different obstacles located between transmitter and receiver antennas. The obstacles between transmit and receive antennas cannot be known in advance, therefore, shadowing effect is modeled by a random variable and usually assumed to be a zero mean gaussian random variable in decibels with standard deviation σ_{dB}. Therefore, it has a log-normal distribution in linear domain.

2.1.3 Small-scale propagation effects

Small-scale propagation effects result in a difference in the received signal due to small displacements of transmitter or receiver. These small displacements can be on the order of wavelength of the signal so that multipath components of the signal varies with distance in the received signal. The multipath components of the signal are multiple copies of the same signal reflected, scattered and attenuated over different paths between transmitter and receiver. These copies are added at the receiver either in a constructive or destructive manner with each other so that the *fading* phenomenon occurs. For instance, when the transmitted signal $x(t)$ is received as $y(t)$ at the receiver, the relation between them can be written as

$$y(t) = \sum_{i=1}^{L} h_i(t)x(t - \tau_i(t)), \tag{2.6}$$

where h_i is the attenuation of the i_{th} path at time t and $\tau_i(t)$ is the corresponding path delay with L being the number of resolvable paths. The channel impulse response can then be written as

$$h(t) = \sum_{i=1}^{L} h_i(t)\delta(t - \tau_i(t)). \tag{2.7}$$

If it is assumed that channel impulse function $h(t)$ does not change during transmission, dependency on t in (2.6) can be omitted so the received signal $y(t)$ can be written as

$$y(t) = \sum_{i=1}^{L} h_i x(t - \tau_i), \tag{2.8}$$

that leads to the channel impulse response

$$h(t) = \sum_{i=1}^{L} h_i \delta(t - \tau_i). \tag{2.9}$$

Channel impulse responses can be classified into two according to their time dependency as shown in equations (2.7) and (2.9) as time-dependent and time-independent channels, correspondingly.

Channels can also be characterized according to the length of their impulse responses and spectral properties. Defining the *channel delay spread* as $\sigma_{T_m} = \tau_L - \tau_1$, if the symbol duration T_s has the relation $T_s < \sigma_{T_m}$ then the symbols will suffer severe inter-symbol interference (ISI) and the channel in that condition is referred to as an ISI channel. If $T_s >> \sigma_{T_m}$ then the system will experience negligible ISI.

The *coherence bandwidth* is another measure used in classification of channels. It is the range of frequencies over which the complex amplitude of two spectral components of the channel response are correlated. If the bandwidth of the transmitted signal is smaller than the coherence bandwidth then the signal will experience approximately the same amplitude and phase in frequency domain. Such a channel is referred to as a *flat fading* or *narrowband channel*. Otherwise some spectral components of the signal will experience different attenuations, in this case the channel is called a *frequency selective* or *broadband channel*.

The channels are also classified according to their second order statistics such as the autocorrelation of the channel. The parameter *coherence time* denotes the time for which the channel decorrelates. If channel coherence time is smaller than the symbol duration then the channel observed by the signal will vary in a symbol duration and in this case the channel is called as fast fading channel. Otherwise, when the coherence time of the channel is larger than the symbol duration the channel is termed as a slow fading channel it is assumed to static for several symbol durations.

It should be noted here that, a narrow band, slow fading channel is assumed in the remainder of the thesis.

CHAPTER 3

RELAYING SCHEMES

3.1 Introduction

A wireless *ad hoc* network is an autonomous system of mobile nodes connected by wireless links without any static structures. Since all the nodes are mobile, unpredictable changes in the network may occur in any time, therefore ad hoc systems should handle such changes. Nodes can join or leave the network at any time as an advantage of the decentralized network structure as a result ad hoc networks are suitable especially for tactical communication systems and sensor networks. Specifically, tactical ad hoc communication systems are the main consideration for this thesis study.

The channel conditions between the nodes of an ad hoc network depend on the distance between nodes and also to the geographical conditions. As a result, two nodes trying to communicate may experience severe fading. In the absence of a centralized unit, relaying by employing any node of the network is a solution to mitigate these challenges and increase the communication range of the system. In ad hoc networks relaying can be done by any node of the network which is located at an advantageous location for both to the source and the destination.

As stated in Chapter 1, the relaying protocols are classified into two according to the processing done by the relay node, as amplify-and-forward (AF) and decode-and-forward (DF). In this thesis the relays employ DF protocol with an error detection mechanism such as cyclic redundancy check (CRC) to avoid error propagation. The error detection is assumed to be perfect at the relay nodes.

Additionally, in this thesis the relay nodes operate in half-duplex mode in which the relays cannot receive and transmit at the same time.

3.2 System Model

In this subsection, the details of the communication system for which the cooperative relaying schemes are proposed will be presented.

The communication system considered in this thesis is a narrowband wireless ad hoc tactical network. It is assumed that N network nodes are distributed randomly in a $D \times D$ area. All the nodes make their transmissions in time slots which are assumed to be organized by a Time Division Medium Access (TDMA) Medium Access Control (MAC) protocol as shown in Fig. 3.1. The TDMA protocol allows many users in the network to share the same frequency band by allowing them to transmit only in their own *time slots*. In order the nodes to transmit in the correct time slots, a coarse synchronization among the nodes is assumed to be enabled by a network time synchronization algorithm.

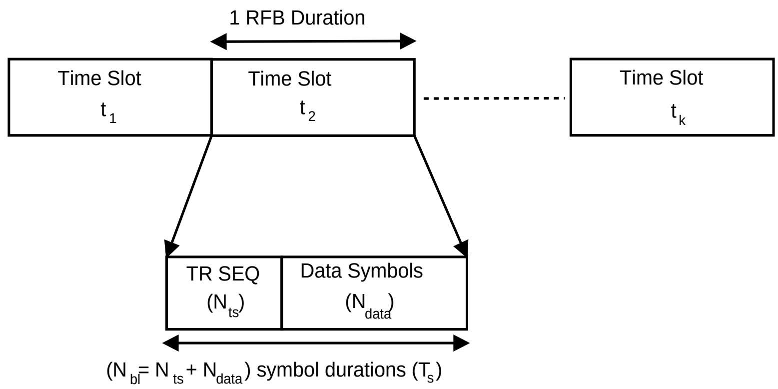

Figure 3.1: TDMA slots and RFB structure

As shown in Fig. 3.1, the transmission by a node in a time slot is called a Radio Frequency Burst (RFB). As stated before, the cooperative relaying schemes in this thesis is proposed especially for tactical networks which mostly employ frequency hopping in order to be more robust against jamming. In this study, although the transmissions are over a constant carrier frequency f_c, the utilized system parameters are inspired by limitations for fast frequency hopping and narrow band communication. Frequency hopping is fast in the respect that each RFB has a small number symbols which also makes it more costly to include pilot symbols in an RFB. Each RFB spans a bandwidth of W, which is assumed to be narrow enough to experience a flat fading channel during transmission. For the flat fading assumption, the baseband relation between the transmitted RFB and received signal $y(t)$ is given in eqn. (3.1) for a transmission from node-i to node-j by

$$y(t) = \alpha_{ij} \sum_{k=0}^{N_{bl}-1} s_k g(t - kT_s) + n(t), \tag{3.1}$$

where α_{ij} is the channel gain obtained by

$$\alpha_{ij} = X_{PL} X_s X_r \sqrt{P_t}, \tag{3.2}$$

where X_{PL} is a deterministic path loss component and modeled according to the rural area extension of the Hata model which was introduced in Section 2.1.2. The variable X_s represents log-normal shadowing with a given standard deviation value σ_s in dB, X_r denotes the small scale Rayleigh fading component and P_t the transmitter power. In eqn. (3.1), N_{bl} denotes the number of symbols in an RFB, s_k is the kth symbol of the RFB, $g(t)$ is (without loss of generality) the impulse response of the unit power Root Raised Cosine (RRC) pulse shape filter which is over-sampled by rate F_S and truncated to $[-N_{RRC}T_s, N_{RRC}T_s]$ with the roll-off factor β. The symbol duration T_s is equal to $1/W$, where W is the bandwidth spanned by an RFB and $n(t)$ denotes the complex white Gaussian noise with flat power spectral density $N_o/2$.

The RFB Structure of the communication system is also shown in Fig. 3.1. In this figure N_{data} denotes the number of data symbols in an RFB, each of which is transmitted in a time duration of T_s and N_{ts} denotes the number of training symbols inserted at the front of the data symbols of each RFB. The training symbols are used for channel and carrier frequency estimation purposes and also to function as the pilot sequence for frame synchronization.

At the receiver side a frame synchronizer is employed in order to estimate the initial sampling instant. This estimation is done by filtering the received signal with the matched filter of the training sequence $f_{MF}(t)$ and finding the peak point of the filtered stream around the ideal sampling instant. The matched filter impulse response can be expressed as follows

$$f_{MF}(t) = \sum_{k=0}^{N_{ts}-1} s_{N_{ts}-k-1} g(t - kT_s), \tag{3.3}$$

where s_k denotes the kth symbol of the training sequence, N_{ts} is the number of training symbols included in a single RFB, and $g(t)$ is the pulse shape filter as introduced before. By using the matched filter, $\hat{T}$ which is the frame synchronizer output for the initial sampling point can be expressed mathematically as,

$$\hat{T} = \underset{t}{\operatorname{argmax}}(|f_{MF}(t) * y(t)|), \quad (N_{ts} + N_{RRC} - N_{sync})T_s \leq t \leq (N_{ts} + N_{RRC} + N_{sync})T_s \tag{3.4}$$

where $|\cdot|$ operation denotes the absolute value and $*$ denotes the convolution operation. In eqn. (3.4) the variable N_{sync} denotes the distance between the ideal sampling instant and the search interval in T_s units where $(N_{ts} + N_{RRC})T_s$ is the ideal result of eqn. (3.4) when there is no propagation delay or local timing errors between the units. The initial sampling instant is obtained by using the result ($\hat{T}$) of eqn. (3.4) in

$$T_{samp} = \hat{T} - (N_{ts}T_s), . \tag{3.5}$$

3.3 Opportunistic Multiple Relaying (OMR)

The Opportunistic Multiple Relaying scheme offers an option to improve weak communication links with low SNR in a wireless ad hoc communication system without additional need for any control overhead to coordinate relay nodes. OMR is advantageous in comparison to previously proposed schemes, since it requires neither perfect channel state information nor perfect synchronization at nodes of the network.

The OMR scheme spans two time slots for communication. As given in Fig. 3.2, the source node transmits and all other nodes in the network listen in the first time slot ($t1$). In the second time slot ($t2$), assuming that an error detection mechanism such as CRC is used by the nodes, the nodes which receive the source's transmission successfully decode and forward (DF) the source's transmission to the destination, in the same time and frequency channel without employing a space time coding among relays. As stated previously, as opposed to the OMR, schemes employing space time coding requires accurate synchronization and also relay coordination among nodes therefore space time coding is not suitable for the considered system. In slot $t2$, the destination receives the sum of scaled and delayed versions of the same RFB transmitted by multiple relay nodes. Therefore, an inter-symbol interference (ISI) channel is expected to be observed at the destination, since propagation delay and timing inaccuracies between nodes can be larger than or comparable with the symbol duration T_s.

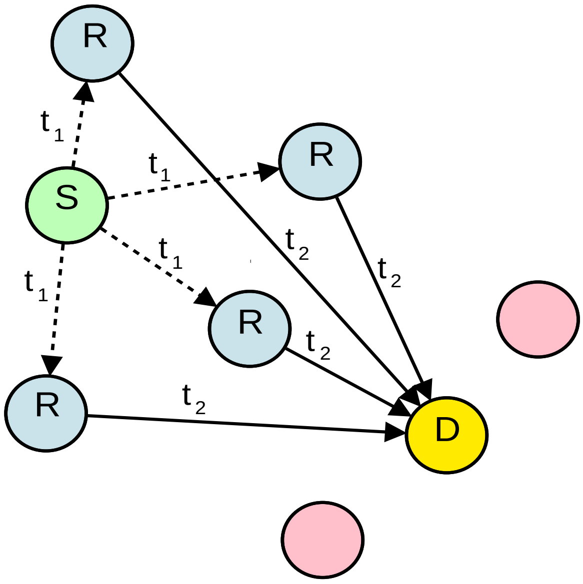

Figure 3.2: Description of OMR scheme: t_1 and t_2 represent the transmissions in the first and second time slots, respectively

The signal received from multiple relay nodes at the destination is expressed by

$$y(t) = \sum_{R_i \in R_{set}} \alpha_{R_i-D} \sum_{k=0}^{N_{bl}-1} s_k g(t - kT_s - \tau_{R_i-D}) + n(t). \tag{3.6}$$

where R_{set} is the set of relay nodes. The α_{R_i-D} is the channel gain between relay node R_i and destination D and is as modeled in eqn. (3.1). The variable τ_{R_i-D} models the timing errors and propagation delays between R_i and D and is calculated by

$$\tau_{R_i-D} = t_{offset,R_i} - t_{offset,D} + t_{prop,R_i-D}, \tag{3.7}$$

where $(t_{offset,i})$ is the timing offset error of node-i relative to the perfect clock and is modeled by a random variable that is uniformly distributed between $\pm T_{max}$. The variable (t_{prop,R_i-D}) is the propagation delay between nodes R_i and D and is calculated by $t_{prop,R_i-D} = \frac{d_{R_i-D}}{c}$ where

d_{R_i-D} is the distance between node-R_i and node-D, and c is the velocity of light.

The signal model for the OMR scheme can be seen in Fig. 3.3.

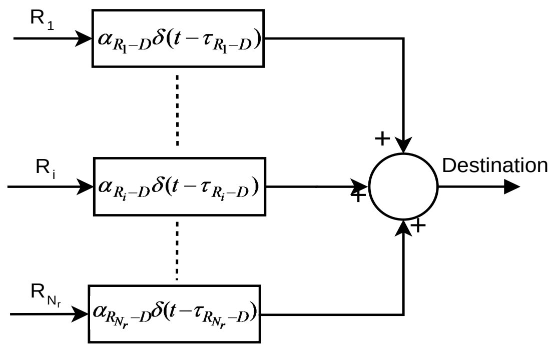

Figure 3.3: OMR scheme signal model from relays to destination

Due to the ISI observed at the destination as the result of the multiple transmissions from network nodes as shown in Fig. 3.3, the receiver in this scheme should equalize the ISI channel to avoid the performance degradation. Therefore, we propose a special receiver structure for the networks employing OMR. As stated in Section 3.2, the narrowband system under consideration may also employ fast frequency hopping due to the needs in tactical field. For meeting such a strict requirement, we assume a small number of symbols in an RFB which eliminates the channel estimation and equalization alternatives requiring long training sequences.

The proposed estimator is a modified version of the estimator which was first introduced in [18] where modulated symbols, channel and noise are assumed to be real. We generalize the technique in [18] to M-PSK modulations with a complex constellation and also to complex channel and noise.

The proposed channel and sequence estimator originating from [18] is described in the following subsection in more detail.

3.3.1 Joint Channel and Data Estimator for OMR

The maximum likelihood estimation for a channel can be obtained by estimating the channel for all possible data sequences and then selecting the estimates for channel and data sequence giving the sum of smallest absolute error squares. However, this kind of an estimator has a computational complexity that increases exponentially with the data sequence length. Therefore, a suboptimal method given in [18] is modified and used in the OMR scheme. This estimator jointly estimates the channel and the transmitted data sequence by a blind trellis search algorithm and will be denoted by joint channel and sequence estimator (JCSE) in the remainder of this thesis. The estimation algorithm follows the steps given below which are valid under the assumption of a two tap channel $\mathbf{h}$ with channel taps $\mathbf{h} = [h_1 h_2]^T$ and a BPSK modulation with alphabet ∓ 1. The operator $[\cdot]^T$ in $\mathbf{h} = [h_1 h_2]^T$ denotes the transposition operation.

1. The received sequence is $\mathbf{y} = y_{k=0}^{N_{bl-1}}$.

2. **Initialization:** Since the channel has two taps and the modulation alphabet size is 2, initialize the estimator with 2 states: $+1$ and -1. Assuming $+1$ is the initial state, assign zero for the initial state metric and infinity for the other state, i.e., $J_0(+1) = 0$ and $J_0(-1) = \infty$. Assign initial channel estimates for state $+1$ as $h_0(+1) = 0$ where subscript denotes the time.

3. **Accumulated Metric Calculation:** Assuming $j = \mp 1$ is the next state at time k, the accumulated metric at the next state j is calculated by

$$J_k(j) = min(J_{k-1}(+1) + |e_k(+1, j)|^2, J_{k-1}(-1) + |e_k(-1, j)|^2), \quad (3.8)$$

   where $|\cdot|$ refers to the *norm* operation and $e_k(\pm 1, j)$ denotes the error for the transition from initial states $+1$ or -1 to next state j.

4. **Channel Update:** Channel updating is done for the state transition for which the minimum accumulated metric is obtained in the previous step. For instance, let the transition from state -1 to state $+1$ at time k has the minimum accumulated metric. Then the channel update for state $+1$ at time k is calculated according to the Least Mean Squares (LMS) criterion as given by

$$\mathbf{h}_k(+1) = \mathbf{h}_{k-1}(-1) + \Delta e_k(-1, +1) \begin{bmatrix} +1 & -1 \end{bmatrix}^H, \quad (3.9)$$

   where $[\cdot]^H$ refers to conjugate transpose, Δ is the step size for LMS and $e_k(-1, +1)$ is the error for the transition from the initial state -1 to the next state $+1$ and is calculated by

$$e_k(-1,+1) = r_k - \mathbf{h}_k(-1)\begin{bmatrix} +1 & -1 \end{bmatrix}^T. \tag{3.10}$$

The algorithm given in the steps above are repeated M times for each state transition, because apart from the classical Viterbi algorithm $M \geq 1$ states are allowed to survive after path eliminations at the reached state as shown in Fig. 3.4. This modification to the Viterbi algorithm enables the estimator not to eliminate the correct paths due to the unreliable channel estimations especially at the beginning of decoding. The recursive channel estimation method LMS is chosen for the channel updates during the transitions for its low complexity. Channel estimations can also be done over all the surviving sequences to each reached state according to the Least Squares (LS) criterion. However, this will be a much more complex solution.

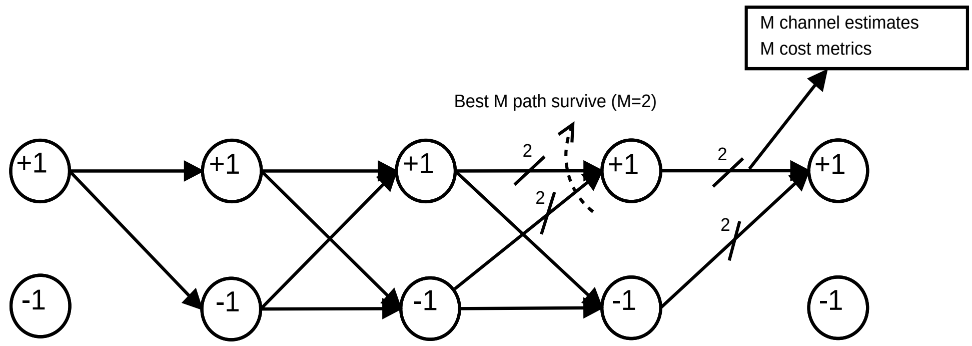

Figure 3.4: State transitions for $M = 2$ from $k = 0$ to $k = 4$

In the proposed blind estimator the rotated versions of the channel and the sequence can also be obtained at the output, since the blind estimator is prone to phase ambiguity. This problem can also be observed in the absence of noise. In the absence of noise, the decoded sequence $-1, +1, -1$ and the channel estimate $+0.5$ will have the same cost with the decoded sequence $+1, -1, +1$ for the channel estimate of -0.5. If there is no information about the channel before decoding by the estimator phase ambiguity in the decoded sequence can be observed and differential encoding may have to be used since the phase difference between decoded symbols will remain the same when such phase ambiguities occur.

Additionally, due to the small number of symbols in an RFB and the slow convergence of the LMS algorithm, the channel estimate obtained at the end of the decoding process may not be so reliable. In order to get rid of the slow convergence and the phase ambiguity problem of this decoder, we initiated the decoder with a channel estimate over a few pilot symbols inserted at the beginning of the RFB. As a result, there is no phase ambiguity on the initial channel estimate, hence differential encoding is not useful in this case. In the following subsection, the channel estimation performed over these pilot symbols is explained in detail.

Instead of the LMS algorithm, the recursive least squares (RLS) algorithm can also be used for channel estimate updates in JCSE. The channel update equations of the RLS algorithm can be found in [19]. The performance difference between RLS and LMS will be discussed in Section 3.5.6.

3.3.2 Least Squares Channel Estimation Over A Known Sequence

The channel estimation in the joint channel and sequence estimator (JCSE) is done by the LMS algorithm. Although the LMS algorithm has a low complexity and is suitable for use in the Viterbi algorithm for channel updates, it has a slow convergence. Therefore, in order to initiate the JCSE introduced in Section 3.3.1 with an initial channel estimate, the Least Squares (LS) algorithm which aims to minimize the sum of the square of the error is used for the channel estimation over the pilot sequence transmitted in the RFB. The received signal at the destination is written as

$$\mathbf{y} = \mathbf{S}\mathbf{h} + \mathbf{n}, \tag{3.11}$$

where the complex channel impulse response $\mathbf{h}$ is expressed as

$$\mathbf{h} = [h_0 h_1 \cdots h_{L-1}]^T, \tag{3.12}$$

and $\mathbf{n}$ denotes the noise samples. The pilot sequence $\mathbf{s}$ is given by

$$\mathbf{s} = [s_0 s_1 \cdots s_{N_{ts}-1}]^T, \tag{3.13}$$

where each s_i is selected from the alphabet ± 1, the corresponding convolution matrix S, assuming no transmission before training symbols, can be expressed as

$$\mathbf{S} = \begin{bmatrix} s_0 & 0 & 0 & \cdots & 0 \\ s_1 & s_0 & 0 & \cdots & 0 \\ s_2 & s_1 & s_0 & \cdots & 0 \\ \vdots & \vdots & \vdots & & \vdots \\ s_{N_{ts}-1} & s_{N_{ts}-2} & s_{N_{ts}-3} & \cdots & s_{N_{ts}-L} \end{bmatrix}. \tag{3.14}$$

The LS channel estimates can be found by minimizing the squared error metric

$$\hat{\mathbf{h}} = \underset{\hat{\mathbf{h}}}{\operatorname{argmin}} \|\mathbf{y} - \mathbf{S}\mathbf{h}\|, \tag{3.15}$$

where $\|\cdot\|$ denotes the *Euclidian norm* operation and the solution for channel estimation which is given in [20] can be obtained as

$$\hat{\mathbf{h}} = (\mathbf{S}^H\mathbf{S})^{-1}\mathbf{S}^H\mathbf{y}. \tag{3.16}$$

The training sequence with N_{ts} symbols is selected by using the results of [21] where training sequences having the best LS channel estimation performance are listed.

3.3.3 Channel Length Considerations For OMR

Due to the transmission of the same RFB by different relay nodes in OMR, ISI is observed at the destination. Pulse shape used by communication systems is assumed to have infinite length in time due to finite bandwidth occupied by the system. Even though the pulse shape is chosen to be satisfying Nyquist criterion [22], the delay of the RFBs which is introduced by relay nodes and is not an integer multiple of the symbol duration, results in the observed ISI channel to be of infinite length. Assuming a finite length channel by only considering the taps with significant power will cause performance loss for the system, as the neglected channel taps will interfere with the signal and increase the noise level. Additionally, selecting a large expected channel length (L_{ch}) parameter for the system will increase the complexity of JCSE which was introduced in Section 3.3.1 since the number of states is dependent on the number of channel taps. Therefore, selecting an appropriate L_{ch} for the system is crucial and performance results with different L_{ch} assumptions will be presented in Section 3.5.2.

3.3.4 The Overall Receiver Structure for OMR

In the OMR scheme, due to the ISI channel effect of multi-node transmission in the same time slot, a receiver structure including the parts introduced in Sections 3.2, 3.3.1, 3.3.2 is proposed for the destination node. The overall receiver structure is presented in Fig. 3.5.

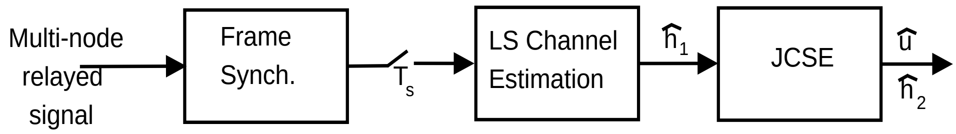

Figure 3.5: Proposed receiver structure for destination node in OMR

3.4 Selection Relaying (SR)

The Selection Relaying (SR) scheme is used as a benchmark in order to compare the performance of the proposed OMR scheme with its special receiver structure. SR is selected as the benchmark, since it also uses two time slots for transmission as in the case of OMR, so that both schemes have the same bandwidth efficiency.

In SR, source selects the relay node according to the average channel qualities between nodes. Average channel quality is a kind of information that can be obtained by averaging the previously observed link qualities between nodes. In SR, as opposed to OMR, only one relay is employed and there is no need to use special equalization techniques under the assumption of flat fading channel. Consequently, SR is an easy to implement scheme for practical systems and can be an alternative for the OMR scheme. SR actually corresponds to a two-hop routing scheme which can represent state of the art for ad hoc networks.

In the SR scheme the relaying operation shown in Fig. 3.6 is executed as described below:

1. By knowing the average channel quality information (average SNR in our case) between nodes, the source selects a relay node and transmits its RFB to this selected relay (t1). The selection is done by calculating RFB success rate of each source-potential relay-destination routes. The potential relay giving the highest RFB success rate is selected. This calculation will be described in detail in Section 3.5.4 where simulation

model of SR is described.

2. The selected relay node decodes the data received from the source. Assuming an error detection mechanism is used by the relay, the relay forwards the source's data to the destination (t2) if decoding is successful. Otherwise the relay will be idle.

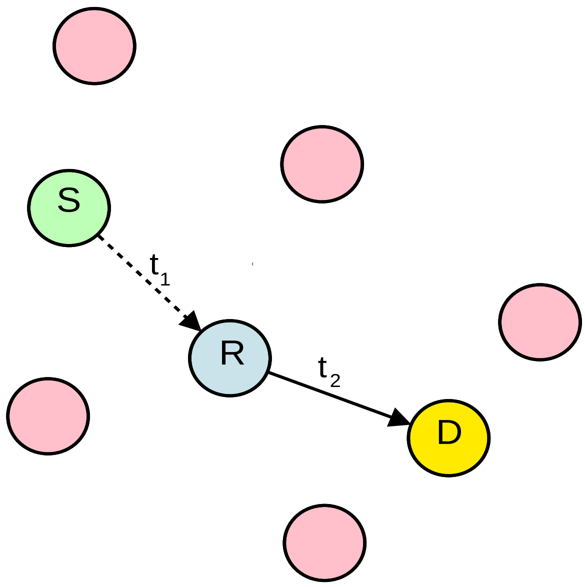

Figure 3.6: Description of SR scheme: t_1 and t_2 represent the transmissions in the first and second time slots

The received signal $y(t)$, from the relay node R_i can be expressed by

$$y(t) = \alpha_{R_i-D} \sum_{k=0}^{N_{bl}-1} s_k g(t - kT_s - \tau_{R_i-D}) + n(t). \tag{3.17}$$

For the SR scheme expressed above, the average channel quality information between the nodes should be known by the nodes for relay selection, which will require more control information than needed for OMR. Moreover, informing the selected nodes for relaying requires an additional coordination which is another reason for the increase in control messages in this scheme.

In addition to the increased control message needs, the scheme also has other drawbacks that is caused by the relay selection made over the average channel information. The relay selections will not be good in the case that nodes have high mobility, employ frequency hopping or do not have enough observation for the average channel quality information. Also, small-scale propagation effects introduced in Section 2.1.3 can change the communication channel due to the small displacements of the nodes. Therefore, SR does not guarantee to achieve the maximum diversity gain that the system offers since selecting the instantaneously best relay is not guaranteed in this scheme.

3.5 Simulation Studies

3.5.1 Simulation Model

In all simulations performed in this thesis, the SNR metric is selected to be average Es/No at a constant distance (d) of 10 kms, which is calculated by counting only the path loss as

$$Es/No@(d = 10km) = \frac{P_t}{(X_{PL}(10))^2 P_n}, \tag{3.18}$$

where P_t is the transmitted power, $X_{PL}(10)^2$ is the path loss at a distance of 10 kms and P_n is the average noise power at the receiver. The reason for selecting such an SNR metric as given in eqn. (3.18) is the variation of the received power at the destination according to the random location and number of transmitting nodes.

In Tables 3.1, 3.2 and 3.3 the parameters related to the channel and noise models, pulse shape and the simulation environment are given respectively. The values in the tables are representative of what typically arise in tactical field.

Table 3.1: Channel and noise parameters used in simulations

Parameter	Description	Value
f_c	Carrier Frequency in MHz	200
K	Hata Model Parameter	37
h_t	Transmitter Antenna Height (meters)	2
h_r	Receiver Antenna Height (meters)	2
σ_s	Shadowing Standard Deviation in dB	7
σ_r	Rayleigh Fading Parameter Variance	1
NF	Noise Figure of the Receiver in dB	7
T	Receiver Temperature in Kelvins	400
W	Signal Bandwidth in KHz	25

Table 3.2: Pulse shape parameter values used in simulation

Parameter	Description	Value
T_s	Symbol Duration in μs	40
F_s	Upsampling Rate	64
β	Roll-off factor	0.3
N_{RRC}	Pulse shape truncation parameter	7

Table 3.3: Parameters related to the simulation environment and the Viterbi estimator

Parameter	Description	Value
N	Number of Nodes	12
T_{max}	Timing offset in μs	25
D	Area dimension (km)	30
Modulation		BPSK
N_{ts}	Training sequence length	7
M	Number of survivors per state	1

As can be seen in Table 3.3, the number of survivors per state (M) is selected as 1 for the JCSE throughout the simulations. In Section 3.3.1, it is stated that the number of survivor paths in JCSE may be larger than one in order to avoid wrong path eliminations which may occur as a result of the absence of channel information. However, in our study we have initiated the JCSE with the channel estimate obtained by the LS channel estimator. The initial channel estimate is relatively reliable in this case as will be shown by numerical results in Section 3.5.3. Consequently, we have set M equal to one throughout this study.

3.5.2 Simulation Results For Identifying The Channel Length (L_{ch}) In OMR

Since multiple nodes forward the same RFB in OMR, propagation delays and timing errors of the nodes will result in ISI channel at the destination. The length of the ISI channel is infinite, since the pulse shape used for transmission is of infinite length in time and all the RFBs are not received by delays those are an integer multiple of the symbol duration T_s. The finite bandwidth limitation in communication systems requires the pulse shape to have infinite length in time domain. However, most of these ISI effects will be negligibly small. In order to see the number of channel taps that should be estimated by the receiver, the receiver channel length (L_{ch}) is varied from 1 to 4 while assuming that the receiver has the perfect channel state information (CSI) for maximum power L_{ch} taps of the actual channel. Since perfect CSI is assumed in these simulations, the LMS update parameter (Δ) is set to 0, therefore the joint channel and sequence estimator (JCSE) has turned into a classical Viterbi decoder. In these simulations, it is also assumed that a constant number of 5 randomly selected relays transmit to the destination. The channel observed by the destination is obtained by the following simulation models enlisted below:

- Select 5 relay nodes randomly.
- Calculate instantaneous channel gains (α_{R_i-D}) and delays (τ_{R_i-D}) between selected relays and the destination.
- Each relay node transmits N_{ts} training symbols with the calculated channel gains and delays.
- By receiving the relayed N_{ts} training symbols, destination estimates the initial sampling instant by employing the frame synchronizer introduced in Section 3.2.
- With the same calculated channel gains and delays, relay nodes transmit the symbol +1.
- Receiver samples the received signal starting from the estimated initial sampling instant. Here, in order to consider the precursor channel terms the instants before initial sampling point are also sampled.
- The obtained samples give the instantaneous channel impulse response observed by the destination for the current topology.
- The maximum power L_{ch} taps of the observed channel is fed to the JCSE in order to decode the RFB received from the same relays with same channel gain and delay values used to obtain the impulse response.

The resulting bit error rate (BER) and packet error rate (PER) performances are shown in Figures 3.7 and 3.8, respectively.

In order to obtain reliable results, the simulations are run until observing at least 100 erroneous RFBs.

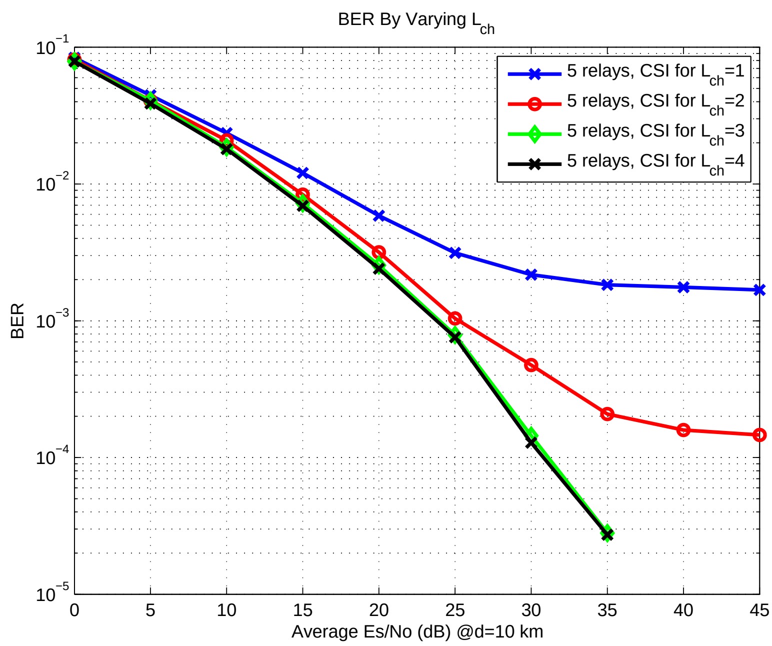

Figure 3.7: BER by varying L_{ch}, assuming perfect CSI for max. power L_{ch} taps

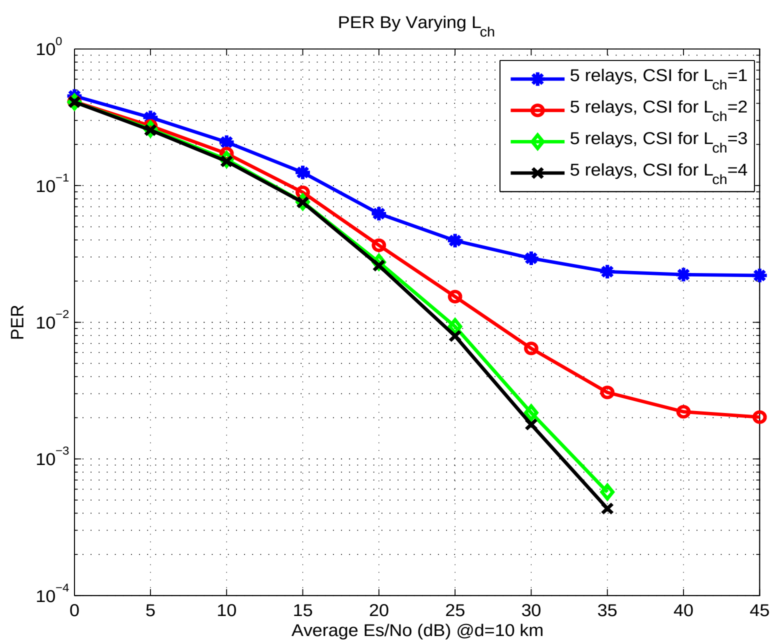

Figure 3.8: PER by varying L_{ch}, assuming perfect CSI for max. power L_{ch} taps

As can be seen from the Figures 3.7 and 3.8, selecting $L_{ch} = 1$ and $L_{ch} = 2$ result in a severe performance degradation. This observation validates the requirement of multi-tap channel estimation and equalization for OMR scheme. Additionally, it can also be seen by the related figures that setting L_{ch} to 3 or 4 results in a negligibly small BER and PER performance difference for the system. Therefore, by also considering the computational complexity increase for the JCSE for larger channel lengths, L_{ch} is taken as 3 in further simulations.

3.5.3 Simulation Results For Observing the Effect of Receiver Parameters

These simulations are done in order to observe the performance of the receiver structure proposed for the OMR scheme by varying some receiver parameters, namely, the LMS update parameter (Δ), and the number of iterations (N_{iter}) of the JCSE. Since the main objective is to investigate the performance of the receiver, in these simulations a constant number of 5 relay nodes transmit to the destination assuming that they all decode the source's RFB successfully.

In order to obtain reliable results, the simulations are run until observing at least 100 erroneous RFBs.

In Figures 3.9 and 3.10 the performance results obtained by varying the LMS channel update parameter Δ is shown. The performance obtained by iterating the JCSE twice ($N_{iter} = 2$) by using the channel estimate obtained at the end of the first iteration in second iteration is also presented. In this case, the different LMS channel update parameters used are denoted as Δ_1 and Δ_2 for the first and second iteration, respectively. All figures obtained for different Δ values and number of iterations are compared to the performance obtained when perfect channel state information is available for $L_{ch} = 3$ at the destination.

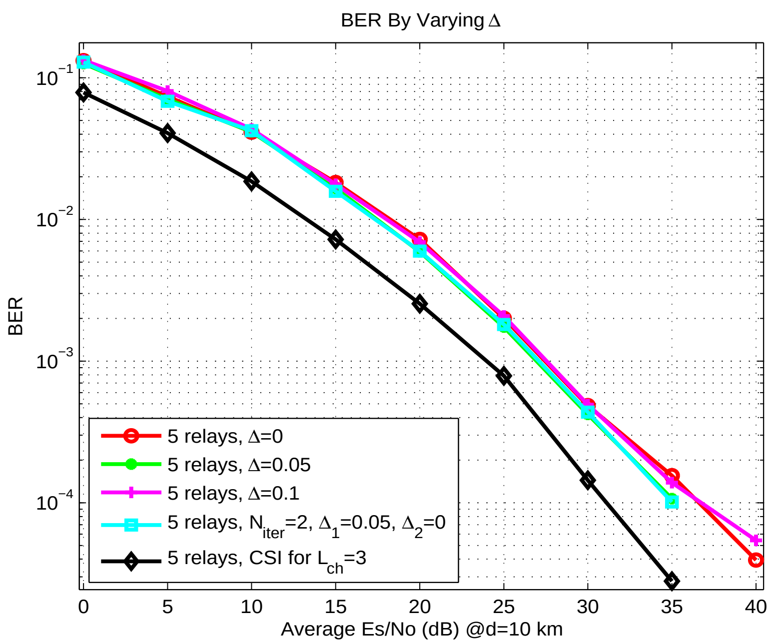

Figure 3.9: BER obtained by varying Δ values

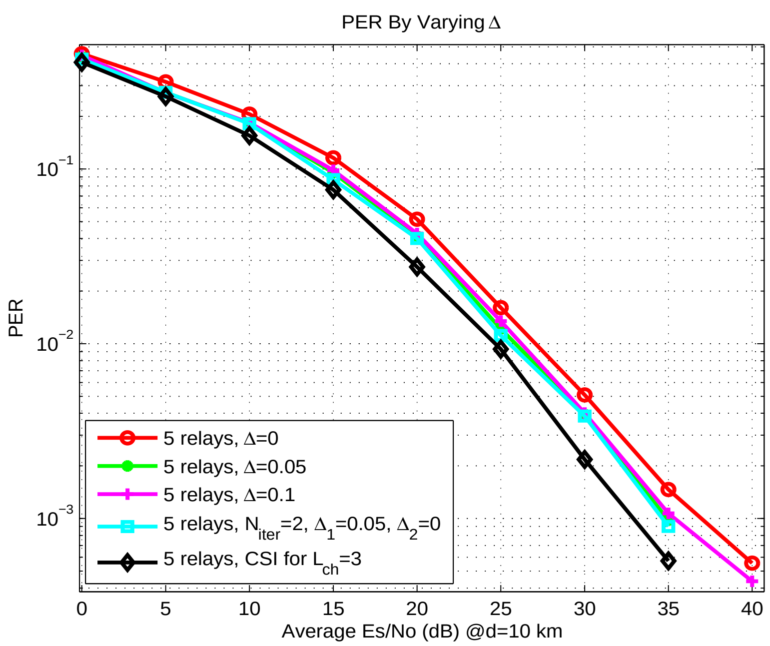

Figure 3.10: PER obtained by varying Δ values

As can be seen from the Figures 3.9 and 3.10, if the receiver is iterated once, a Δ value of 0.05 results in a slightly better performance than obtained with other Δ values. When the receiver is iterated twice by using the channel estimate obtained at the end of the first iteration and by setting Δ_2 to 0 in the second iteration, the performance can also be slightly improved. The result of this performance improvement is using a more reliable channel estimate in the second iteration. Because, the channel estimate at the end of the first iteration is obtained first by least squares channel estimation over training symbols and then by updating this estimate with LMS channel updates in the JCSE.

By using the results obtained by these simulation, in further simulations Δ_1 is selected as 0.05 and the JCSE is iterated twice by using the channel estimate of the first iteration and setting $\Delta_2 = 0$ in the second iteration.

It can also be concluded by observing Figures 3.9 and 3.10 that for a target PER value of 0.01 the channel updates done in JCSE improve the system performance by around 2 dB. This performance improvement obtained by channel estimate updates in JCSE is expected to be larger for the case when initial channel estimate is less reliable due to smaller number of training symbols used for LS channel estimation or when channel observed is time varying due CFO that is present among nodes. Additionally, in the case when the the modulation alphabet size is larger, a more reliable channel estimate will be required. Correspondingly, the channel updates in JCSE will be even more critical for the system performance.

3.5.4 Simulation Results For Performance Comparison Of OMR And SR

In this section the results of simulations which are done in order to compare the schemes OMR and SR will be presented. The simulation model for comparing OMR and SR schemes is as follows:

- Place N nodes randomly in a $D \times D$ area each having different timing offset errors.
- Select a random source - destination pair.
- If the scheme is OMR:
  - According to the instantaneous SNRs between the source and potential relays,

calculate theoretically the RFB error probability for the selected modulation assuming flat fading channel is known by the potential relays.

  - Generate a binary random variable with probability of zero set equal to the theoretical RFB error probability. If the random variable is equal to 1, select the node for relaying.
  - Calculate the instantaneous losses and delays from the relays to the destination. Obtain the received signal at the destination.
  - The destination estimates the data symbols transmitted by the source by using the receiver structure of Fig. 3.5.

- If the scheme is SR:
  - Calculate large-scale losses among nodes of the network and select the relay resulting in the highest average end-to-end RFB success probability calculated by multiplying theoretical RFB error probabilities for source-relay and relay-destination links. Since nodes only have the information about average SNR of the links, the theoretical RFB error probability is calculated by using only the large-scale losses which are path loss and shadowing.
  - For the selected relay, calculate the instantaneous SNR for the source-relay and relay-destination links. Calculate RFB error probability for source-destination transmission based on the instantaneous source-relay SNR assuming flat fading channel between source and relay is known by the relay.
  - Generate a binary random variable with probability of zero set equal to the theoretical RFB error probability. If the random variable is equal to 1, select the node for relaying.
  - The destination decodes the received signal assuming perfect knowledge of the flat fading channel.

- After decoding the received data at the destination, calculate the number of bit errors and increment the RFB error counter if there is at least a bit error in the decoded RFB .

- In order to obtain reliable results run the simulations until observing at least 100 erroneous RFBs.

- PER is calculated by counting the erroneous RFBs and also the RFBs that cannot be transmitted due to not finding a suitable relay node. Hence, PER is the ratio of unsuccessful transmissions from the source to the destination. However, for BER we only counted the erroneous bits for the transmitted RFBs, therefore the BER results do not give any information about the unsuccessful transmissions due to not finding a relay node.

The simulation results obtained by following the simulation model introduced above is given in Figures 3.11 and 3.12.

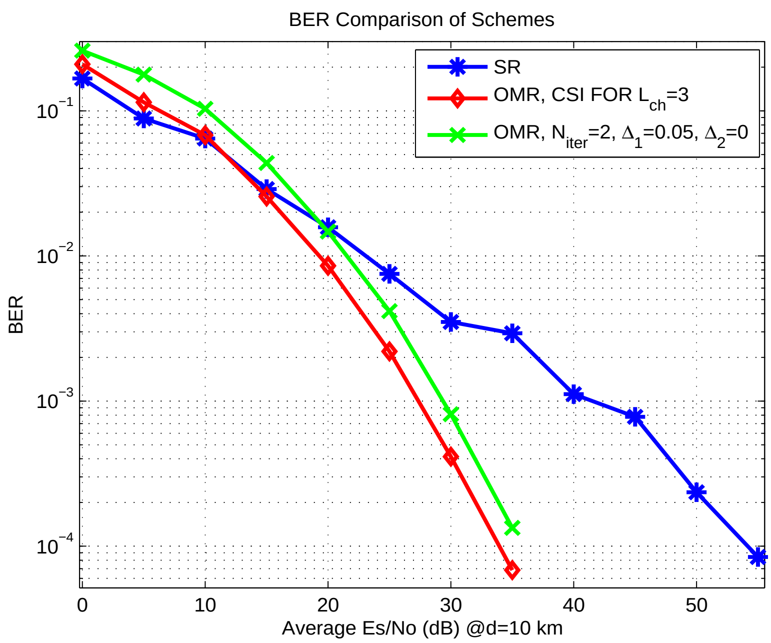

Figure 3.11: BER comparison of both schemes

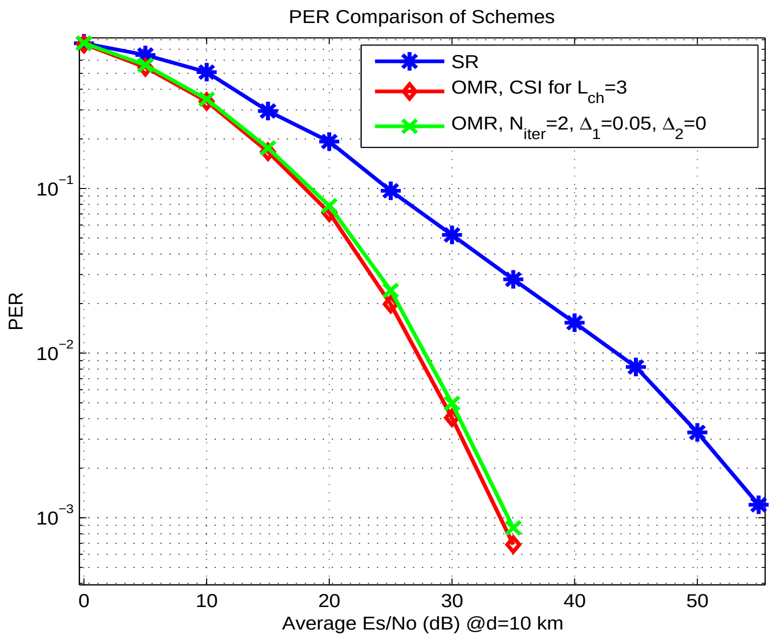

Figure 3.12: PER comparison of both schemes

As can be seen from the Figures 3.11 and 3.12, the OMR scheme performs favorably compared to the benchmark scheme SR without requiring any control overheads and channel quality information for relay selection and decoding done in the destination. In this comparison, it should also be noted again that in the SR scheme as opposed to OMR, destination is also assumed to have perfect channel information for the one tap channel gain between relay and destination. In practice, since this channel cannot be perfectly estimated, the SR scheme will perform worse than presented in Figures 3.11 and 3.12.

The OMR scheme has a significant performance advantage compared to the SR scheme since OMR employs multiple relay nodes which are selected according to their instantaneous source-relay SNR's which is done inherently in the OMR scheme without requiring channel information at the source side for relay selection. The nodes, which cannot decode the source's RFB successfully are not allowed to operate as relays. However, in SR, relay selection is based on the average channel conditions, i.e., large-scale propagation effects, therefore in the case of severely faded channels due to small-scale propagation effects, transmission probability will decrease. Additionally, it can also be concluded from the figures that the performance difference between the schemes is more significant if PER performance is considered. However, the difference gets closer for BER, which shows the fact that the estimation errors of the ISI channel causes large number of bit errors for an erroneous RFB in the OMR scheme. The difference in BER and PER performances is also resulted from the PER definition which also counts the cases when no relay is found as an error.

3.5.5 Simulation Results For Different Channel Update Algorithms Used in JCSE of OMR

In this section, the performance of the OMR scheme is simulated for different channel update algorithms that are used in the JCSE. In the JCSE introduced in Section 3.3.1, the LMS algorithm is proposed to be used for channel estimate updates taking place in the special Viterbi decoder. However, we focus here on using different channel update algorithms in JCSE which are listed as follows:

1. Use LMS channel update algorithm as in the proposed JCSE of Section 3.3.1, while keeping only one channel estimate per transition time. This survived channel estimate is the estimate corresponding to the state with the smallest accumulated metric for all the reached states in a state transition time.

2. Use the recursive least squares (RLS) algorithm for channel updates and keep the channel estimates for all the survived paths as in JCSE.

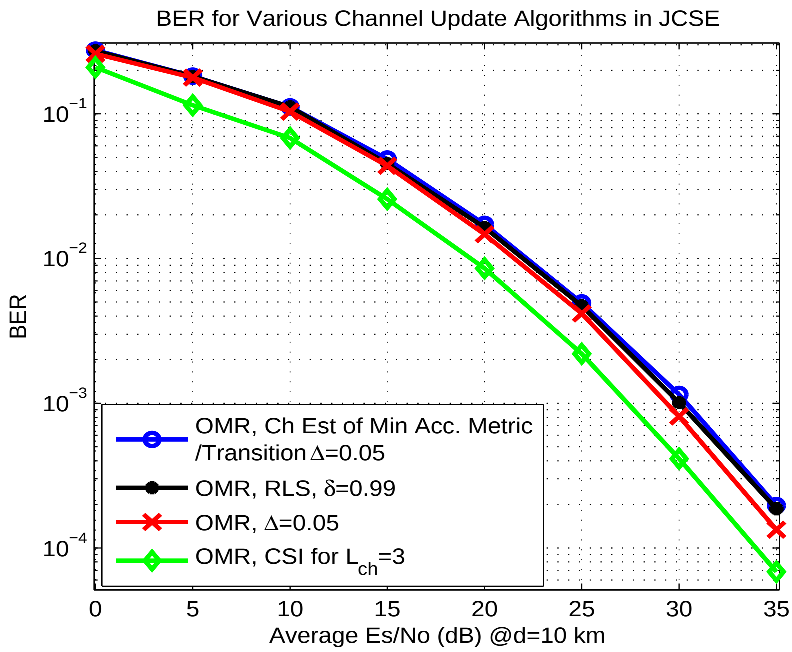

Figure 3.13: BER comparison for various channel update algorithms used in JCSE

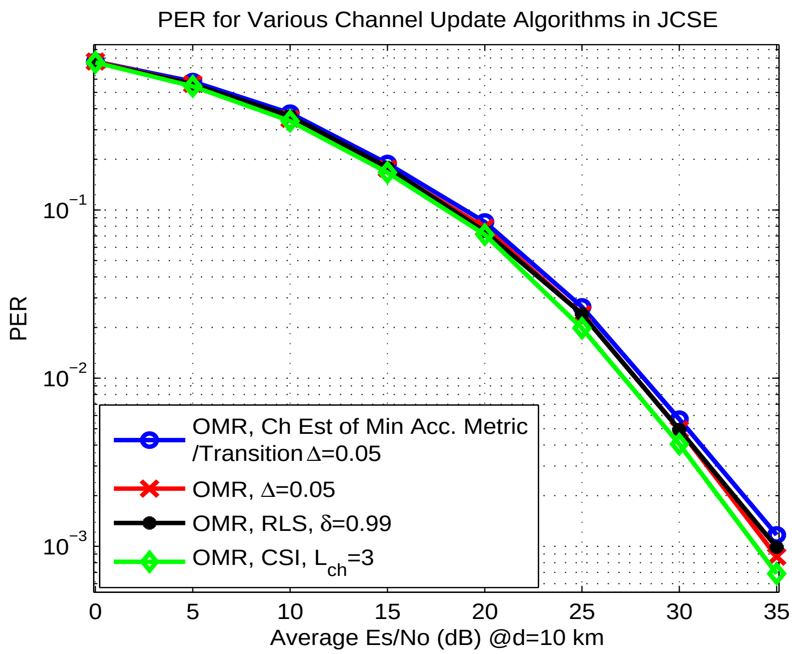

Figure 3.14: PER comparison for various channel update algorithms used in JCSE

The resulting Figures 3.13 and 3.14 are obtained by iterating the JCSE twice apart from the channel update algorithm used. In the second iteration, no channel update is done and the channel estimate obtained at the end of the first iteration is used. The forgetting factor δ of RLS is selected as 0.99 which is seen to be the best according to the results of simulations that are not reported here.

By examining Figures 3.13 and 3.14 it can be observed that three different channel update algorithms perform very close to each other according to their PER performances. The reason for this phenomenon can be thought as the good initial channel estimate obtained by the LS channel estimator that uses the training symbols for initial channel estimation. Both algorithms begin with a good channel estimate as a result, the difference resulting from the convergence properties of the algorithms is not so significant. Additionally, the performance of the RLS algorithm is affected by the selection of the initialization parameters of the algorithm. As observed in Fig. 3.14, all the algorithms perform quire close to the perfect CSI case. Since the gains through optimization of the RLS parameters are minute, we do not pursue such an optimization.

3.5.6 Simulation Results For The Number Of Participating Nodes In OMR

Number of relays participating in relaying in the OMR scheme is proportional to the average SNR between source and relays. Therefore, as the SNR increases the performance of OMR scheme improves due to the SNR increase and also due to the increased number of relays. Increase in the number of relays also improves the probability of finding the relay nodes that are in advantageous locations for the destination. In this simulation the variation in the number of relays and the probability of finding a relay node are being investigated and the results obtained by Monte-Carlo simulations are shown in Figures 3.15 and 3.16.

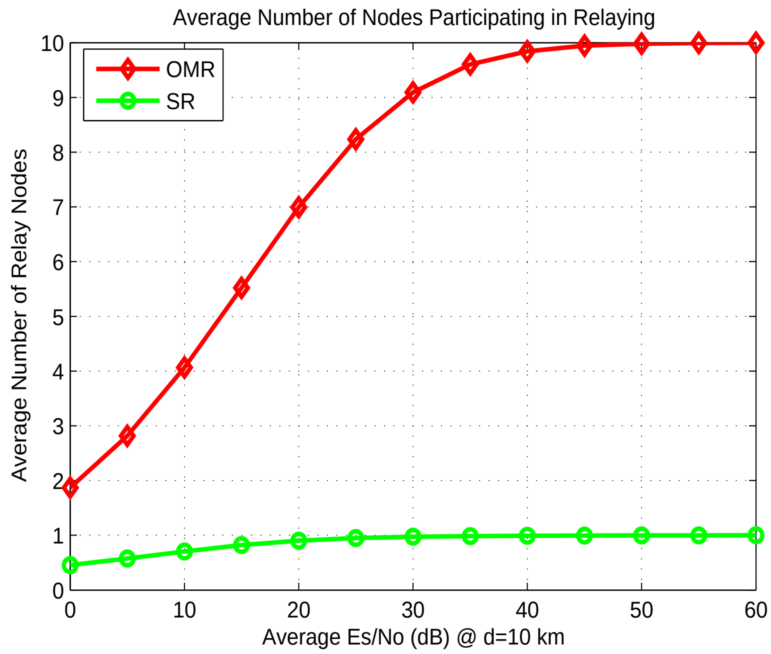

Figure 3.15: Number of selected relays according to SNR in Schemes

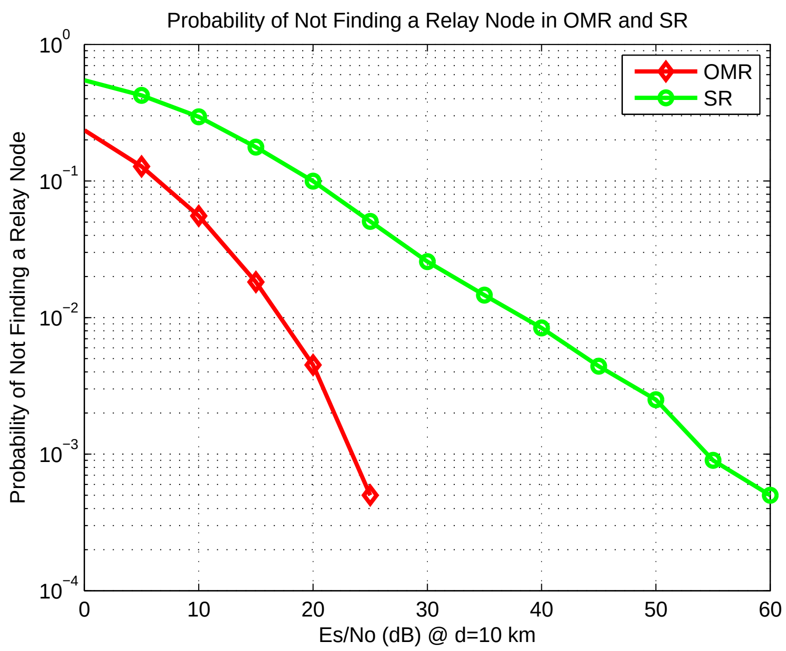

Figure 3.16: Probability of not finding a relay node in OMR and SR

The change of number of relay nodes as shown in Fig. 3.15 increases linearly the total energy consumed for a transmission in the OMR scheme. The communication system under consideration is being designed for a tactical ad hoc network, therefore, the energy consumption may not be the main consideration of this communication system. Additionally, by examining the PER performance comparison Figure 3.12 of the schemes, for a target PER value of 0.01, the performance improvement obtained by the OMR scheme is approximately 16 dB. For the SNR value of 28 dB when the target PER is reached by the OMR scheme an average number of 9 nodes are employed as relay, which can be seen in Fig. 3.15. Therefore, the total energy required for the OMR scheme including the transmission of the source is 5 times the required energy in SR scheme, which corresponds to an increase in the energy consumption of approximately 7 dB. However, considering the 16 dB performance improvement of the OMR scheme, it can be concluded that the OMR scheme performs roughly 10 dB better than SR also in terms of transmission energy efficiency.

In Fig. 3.16, the probability of finding a relay node which is the ratio of the number of transmissions with at least one relay node to the number of all transmissions is plotted with increasing transmitted power. As can be concluded from Fig. 3.16, it is more probable to find a node to use as a relay in OMR, since the instantaneous channel conditions are used in this scheme inherently and the source relay links are evaluated according to their actual SNR. The relay selection criterion is over the average SNR of the links in SR as a result, the node having instantaneously the best channel conditions between source and the destination may not be selected as the relay.

CHAPTER 4

CARRIER FREQUENCY OFFSET IN RELAYING SCHEMES

In this section, the effect of carrier frequency offset (CFO) originating from the imperfections of the local oscillators of different nodes is investigated for the OMR and SR schemes studied in the thesis. First, the system model of both schemes under CFO will be presented. CFO estimation methods proposed for the OMR and SR schemes will be introduced and the performance comparisons obtained by employing the CFO estimators will be shown.

4.1 System Model Under CFO

All communication devices include a clock (oscillator) which keeps the time and generates reference frequency signals for various purposes. However, oscillators do not create the required frequencies which cause carrier frequencies to differ at different nodes. As a result, the received signal is down converted by the carrier frequency generated by the receiver, which is not exactly equal to the transmission frequency f_c. Additionally, mobility causes the carrier frequency of the signal to introduce Doppler shifts as another source of CFO.

For the communication system studied here, it was stated that a network-wide synchronization is available among the nodes to enable them to transmit according to the TDMA structure. However, after such a synchronization CFO errors may still remain and degrade the system performance.

We define Δ_{max} as the maximum absolute clock error in ppm (parts per million) that one node can have after the network synchronization. The maximum carrier frequency error between two nodes is expressed as

$$\Delta f = 2\Delta_{max} f_c 10^{-6}, \tag{4.1}$$

where all frequencies are in Hz.

When the transmitter node i has a frequency error of Δf_{ij} relative to the receiver node j, the received signal, assuming flat fading between nodes, can be expressed by

$$y(t) = \Re\{e^{j2\pi(f_c+\Delta f_{ij})t}\alpha_{ij}\sum_{k=0}^{N_{bl}-1} s_k g(t-kT_s)\}, \tag{4.2}$$

where $\Re\{\cdot\}$ denotes the $real(\cdot)$ operation, and α_{ij} is the channel gain between node i and j, which includes all the path loss components introduced in Section 3.2. Assuming that the filters do not distort the signal from the RF front end to the baseband section due to the mismatch of the carrier frequency, the signal obtained after down-conversion by the mismatched carrier frequency $f_c + \Delta f_{ij}$ can be expressed as

$$y(t) = e^{j2\pi\Delta f_{ij}t}\alpha_{ij}\sum_{k=0}^{N_{bl}-1} s_k g(t-kT_s) + n(t). \tag{4.3}$$

After sampling with period T_s, the received signal $y(t)$ is expressed in the discrete baseband equivalent form by

$$y_k = e^{j\theta_{ij}k}\alpha_{ij}s_k + n_k, \quad 0 \leqslant k \leqslant N_{bl}-1, \tag{4.4}$$

where θ_{ij} is the relative CFO error between nodes i and j in radians, s_k is the k^{th} transmitted symbol and n_k is the complex white Gaussian noise with flat power spectral density N_o. As can be seen from eqn. (4.4), as the symbol index k increases the effect of phase rotation due to CFO mismatch becomes larger. Therefore, a counter measure should be taken in order to avoid performance degradation due to CFO as will be presented in the following sections.

4.1.1 CFO Estimation in OMR

In the OMR scheme, multiple nodes receiving the source's RFB successfully are responsible for relaying the RFB using the same slot as stated in Section 3.3. Due to the different CFO's between relay nodes and the destination, the destination will observe a time dependent ISI channel which will require the estimator at the destination to be more complex. Therefore, we focused on a solution that aims to synchronize the relay nodes and thus enable them to have the same CFO at the destination. In the ideal case when relays perfectly synchronize with the source, the CFO problem at the destination node will turn into the problem of CFO estimation under an ISI channel.

The CFO estimation at the relay nodes and the destination is done by employing the maximum likelihood (ML) CFO estimator given in [23]. The proposed CFO estimation algorithm executed in two time slots of the OMR scheme is summarized in the following steps below:

1. Assuming differential modulation, the nodes hearing the source try to demodulate the source's RFB. If demodulation is successful then the nodes estimate the CFO by using the ML estimator while employing all symbols as a training sequence (t1).
2. By synchronizing their clocks to the source's clock the nodes transmit the data symbols in a common time slot (t2).
3. After receiving the RFBs transmitted by multiple relay nodes, which are assumed to be synchronized among themselves in Step-2, we propose three different solutions for the CFO problem at the destination.
    - **Solution 1:** The CFO at the destination can be tracked by LMS channel updates which are done by using a suitable channel update parameter Δ in JCSE. The simulation results obtained with this estimator are given in Section 4.2.2.
    - **Solution 2:** The CFO tracking proposed in the second solution can also be done by using the RLS algorithm with a suitable forgetting factor (δ) value in JCSE. The corresponding results are given in Section 4.2.2.
    - **Solution 3:** The CFO at the destination can be first estimated by ML CFO estimator over the training symbols and then the remaining CFO error can be tracked by the channel updates in JCSE by using an appropriate channel update constant. This method can be iterated twice by using all the estimated sequence as a training sequence at the end of the first iteration to have a more reliable CFO estimate. This estimate can then be used at the beginning of the second iteration to correct the CFO. Simulation results of this solution are given in Section 4.2.3.

In Step-1 of the proposed CFO estimation algorithm for OMR, a coherent modulation can also be used instead of using a differential modulation and the CFO estimation at the relays can be executed over the N_{ts} training symbols included in the RFB. However, N_{ts} is expected to be a small number due to the limitations of the system, as a result, such a CFO estimation will perform worse than the estimation obtained by Step-1. Therefore, we have focused on using differential modulation to mitigate the CFO problem in source to relay transmissions. When the relay nodes have different CFOs relative to the destination, the observed channel taps will be time varying and complicated channel estimation and equalization techniques will be required. As a result, the synchronization among relay nodes is critical for the OMR scheme. The performance of the ML CFO estimation over training symbols will be presented in the simulation results of Section 4.2.3.

The modulation used during the transmission mentioned in Step-2 of the proposed CFO estimation algorithm can be differential or coherent. However, the JCSE, which uses a modified form of the Viterbi algorithm, works in a coherent manner. Therefore, using differential or coherent modulation techniques will not affect the performance.

4.1.2 CFO in SR

In SR, some alternatives against the CFO problem are enlisted below:

1. Estimate CFO over N_{ts} training symbols transmitted in each RFB. After correcting the received signal, demodulate coherently.
2. Estimate CFO by using N_{ts} training symbols, correct the received signal with this estimate. Then employ the JCSE assuming one tap channel and take the advantage of JCSE's tracking capability of phase rotations caused by the residual CFO estimation errors.
3. Use differential modulation for the source to relay and relay to destination transmissions. In this case, there is no need to estimate CFO. However, differential demodulation is known to have a worse BER performance than that of coherent demodulation.

Although we have described three different algorithms for the CFO problem in the SR case, we have assumed that in our simulations CFOs in both transmissions are perfectly known by the receivers of this scheme which are the relay and the destination, respectively. We will see that even SR with perfect channel information cannot surpass the performance of OMR with channel estimation and CFO.

4.2 Simulation Results

In this section, the results of the simulations where the nodes have CFO are presented. The simulation model parameters, except for the CFO and modulation are the same as given in Section 3.5.1. The maximum CFO at the nodes is set to be $\pm\Delta_{max}$ in ppm assuming a network synchronization that is done before the transmissions. The maximum phase rotation (in degrees) between consecutive symbols for a transmission between nodes i and j is calculated by

$$\phi_{max} = 2\Delta_{max,ppm} f_c T_s 360. \tag{4.5}$$

Assuming Δ_{max} is 1 ppm after network synchronization, ϕ_{max} is calculated as 5.76 in degrees using the parameter values of Section 3.5.1. Since ϕ_{max} is a considerable rotation value, the performance degradation due to CFO will be significant in ISI channels if no additional estimation techniques are used. However, in terms of the frame synchronization performance, we have observed that by using a sufficient amount of training symbols for frame synchronization, which is the case in this study, the maximum CFO of the system considered here does only have a negligible effect on the frame system performance. If the CFO values are larger, some precautions should also be taken against the CFO effect in frame synchronization.

By the definition of ϕ_{max}, the CFO estimate search in the ML estimator is done between the angles $(-\phi_{max}, \phi_{max})$, therefore the maximum error of the CFO estimation is bounded.

The simulations under CFO are done in two phases which are:

1. In the first phase of simulation studies, we have assumed that the source and the destination are perfectly synchronized, however, the relay nodes have CFO.

2. In the second phase of simulation studies, we have assumed that source and relays are perfectly synchronized and CFO is present only for the transmissions between relays

and the destination. The reason for this assumption is the observed negligible performance loss revealed by the results of simulations of Phase-1.

4.2.1 Simulation Results For CFO Present Only In Source-Relay Links of OMR

The simulations presented here are conducted in order to observe the effect of CFO in source-relay links. The steps listed below take place in the order they are presented in simulations.

- Locate N nodes randomly in a $D \times D$ area each having different timing offset errors.
- Select a random source and destination pair.
- Assign CFO to each relay node by generating random variables that are distributed uniformly in $[-\phi_{max}/2, \phi_{max}/2]$. Assign a CFO to source and destination by again generating a random variable uniformly distributed in $[-\phi_{max}/2, \phi_{max}/2]$.
- If the scheme is OMR:
  - According to the instantaneous SNR between source and potential relays, theoretically calculate the RFB error probability for the selected differential modulation.
  - Generate a binary random variable with probability of zero is set equal to the theoretical RFB error probability. If the random variable is equal to 1, select the node for relaying.
  - Since selected nodes decode the RFB received from the source successfully, they estimate the CFO by the ML estimator using all the RFB symbols and correct their clocks according to the estimated CFO.
  - Calculate instantaneous losses and delays for relay to destination transmissions and obtain the received signal at the destination.
  - Destination estimates the data symbols transmitted by the source by using the receiver structure in Fig. 3.5 without changing its parameters which are found to be appropriate for the case when CFO is not present.
- After estimating the received sequence at the destination, calculate the number of bit errors and if there is at least one bit error in the decoded RFB, increment the packet error counter and bit error counter.

- Continue simulations until observing at least 100 erroneous RFBs.

- Increment packet error counter also for the situations when none of the potential relays decode the sources RFB successfully, which is another reason for unsuccessful RFB delivery to the destination.

The results shown in Figures 4.1 and 4.2 are obtained by executing the simulation model described.

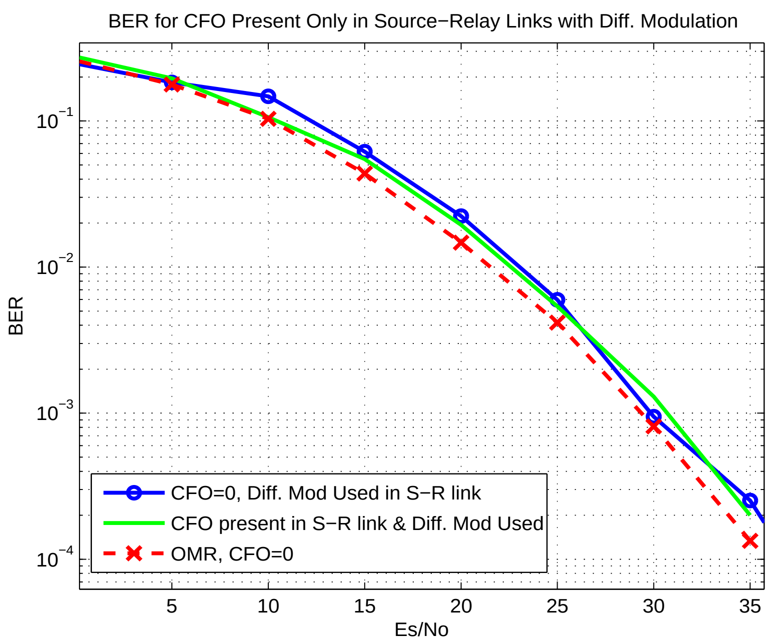

Figure 4.1: BER for CFO present only in source-relay links with differential modulation is used in source-relay Links

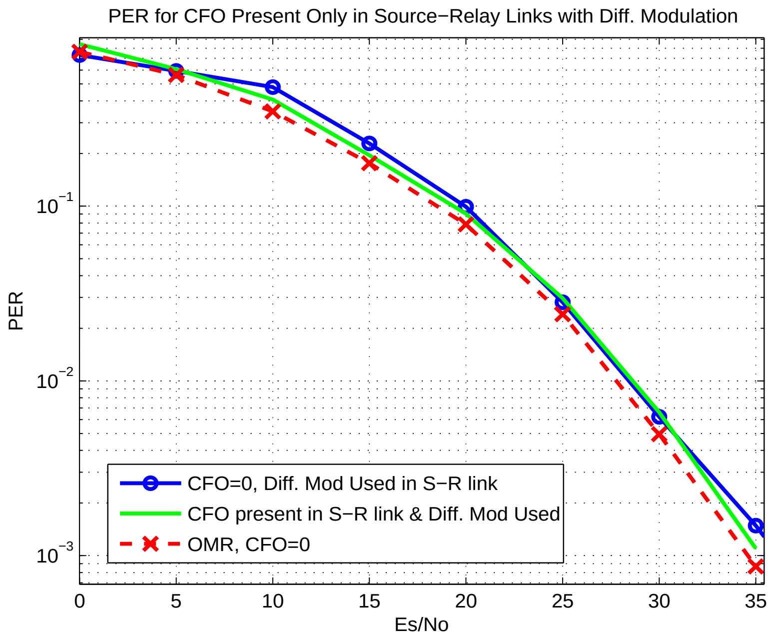

Figure 4.2: PER for CFO present only in source-relay links with differential modulation is used in source-relay Links

It can be seen from the Figures 4.1 and 4.2 that the performance difference for the CFO present case is negligibly small as a result of the good CFO estimates, which are obtained by ML CFO estimation over all N_{bl} symbols of the RFB. Therefore, we have done our further simulations with CFO presence only between relay and destination, assuming differential modulation is employed between source and relay links, and source and relays are perfectly synchronized among themselves.

By examining the Figures 4.1 and 4.2 it can be concluded that using differential modulation results only in a small SNR loss in the OMR scheme. This is because of the fact that the number of selected relays determines the performance of the OMR scheme and using differential modulation between source and relays results in a small decrease in the number of relay nodes which is shown in the Figure 4.3.

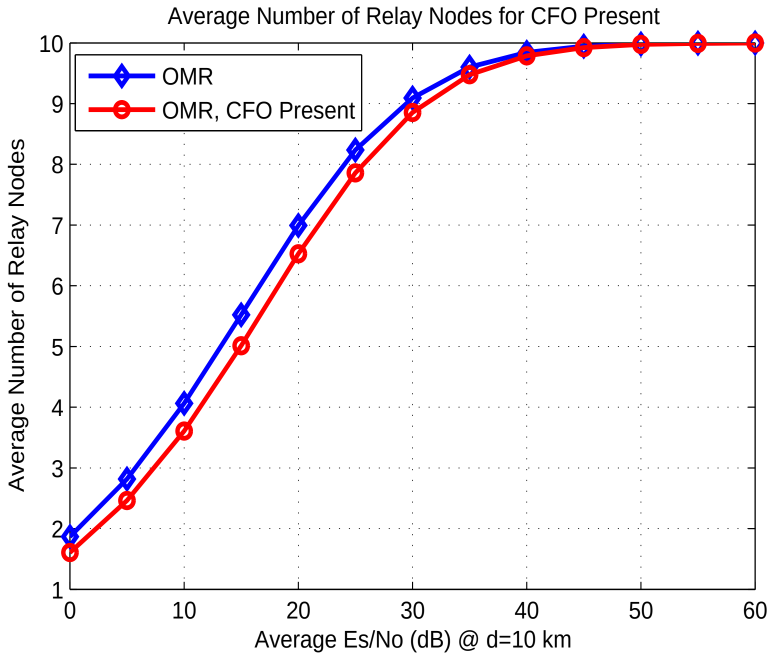

Figure 4.3: Average number of selected relay nodes

4.2.2 Simulation Results For CFO Present In Relay-Destination Links of OMR and Being Tracked by LMS and RLS Channel Updates in JCSE

The simulations done in this part aims to investigate the performance loss when CFO is present only for the relay to destination links and being tracked by the channel updates done in JCSE. The results obtained correspond to the proposed Solution-1 and Solution-2 which are introduced in Section 4.1.1. The modifications made to the previous simulation model of Section 4.2.1 are listed below.

- Assign a CFO by generating random variables that are distributed uniformly in $[-\phi_{max}/2, \phi_{max}/2]$ to the destination.
- Assign the same CFO to all the other nodes by generating a random variable that is also distributed uniformly in $[-\phi_{max}/2, \phi_{max}/2]$.

The results obtained for the proposed Solution-1 by applying the simulation model above are given in Figures 4.4 and 4.5.

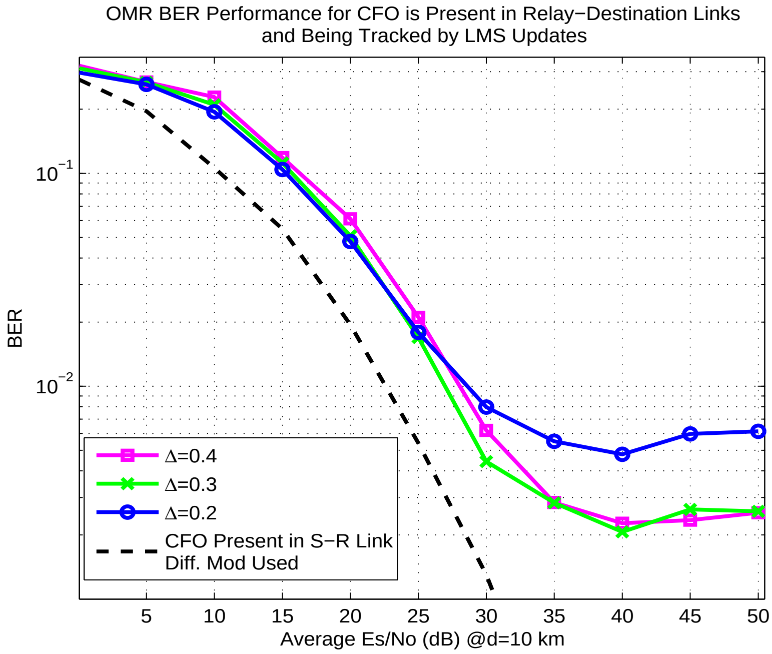

Figure 4.4: BER for CFO present only in relay-destination links and being tracked by LMS updates

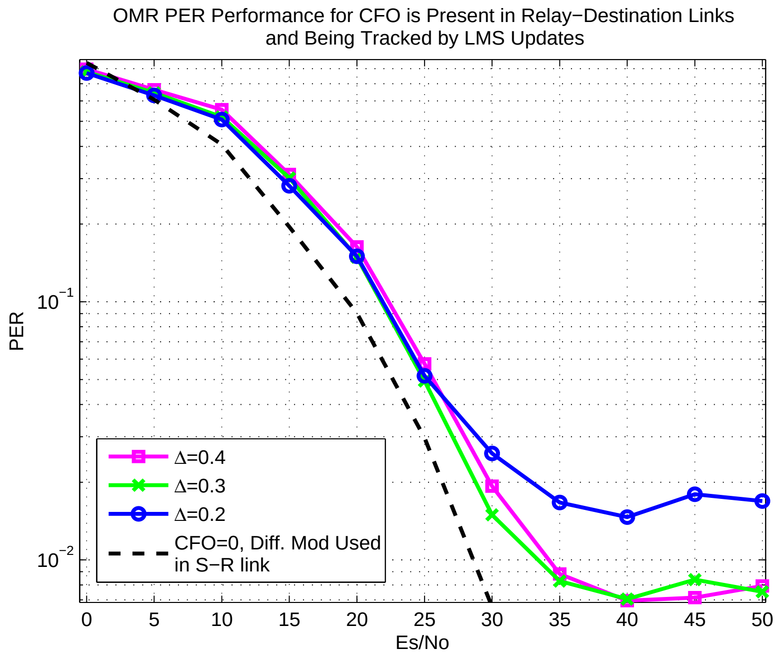

Figure 4.5: PER for CFO present only in relay-destination links and being tracked by LMS updates

As can be seen from Figures 4.4 and 4.5, it is possible to lessen the effect of CFO by only varying the channel update parameter Δ of LMS algorithm, without making a CFO estimation. The instantaneous CFO and channel are not known by the JCSE. As a result the estimates obtained by such a method are not so reliable even by using the most appropriate Δ value found by simulations. The system performance at a PER value of 0.02 remains 3 dB away from the case when CFO is absent in relays to destination links.

Instead of using the LMS algorithm for channel updates in JCSE, RLS can also be employed. This corresponds to the proposed Solution-2 and the results including the comparison of the RLS algorithm to no CFO case and the LMS case are given in Figures 4.6 and 4.7.

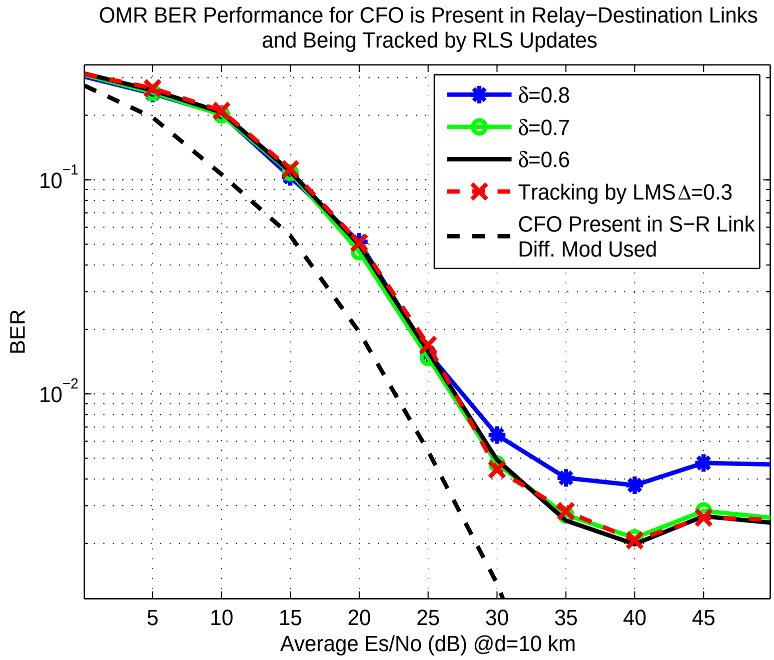

Figure 4.6: BER for CFO present only in relay-destination links and being tracked by RLS updates

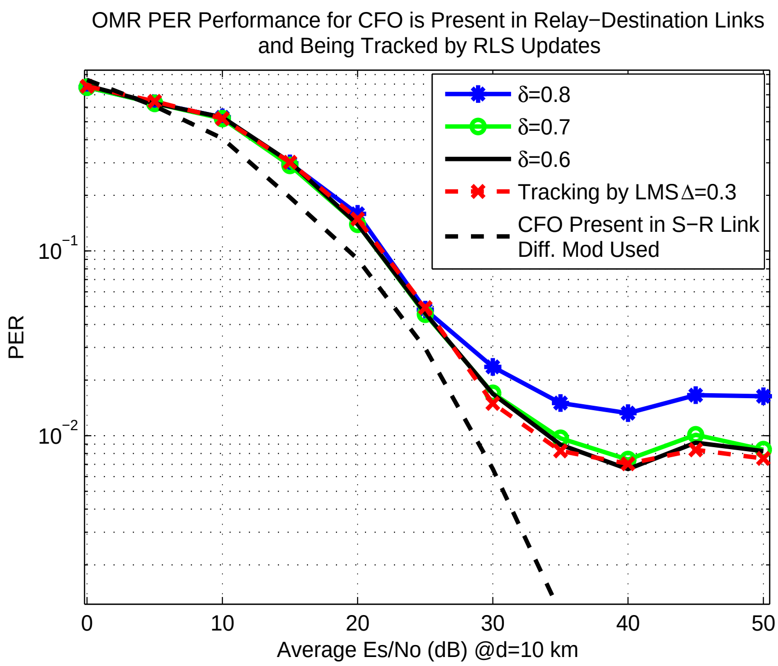

Figure 4.7: PER for CFO present only in relay-destination links and being tracked by RLS updates

As can be seen from the Figures 4.6 and 4.7, doing channel updates with RLS algorithm has a very close performance to the LMS algorithm. The best performance under CFO case is obtained with a forgetting factor (δ) value of 0.6 which is a smaller value than that is used in the absence of CFO. The reason for this is thought to be that RLS also uses the past information of the received symbols for the channel update calculation. However, in CFO case since the channel can be thought as a time dependent channel, the dependency on the previous symbols should be decreased in order the channel updates to track the changes in the channel due to CFO. In fact at high SNR assuming channel is reliably estimated by the LS estimator over N_{ts} training symbols, the channel updates will only aim to track CFO. In this case the LMS update algorithm is expected to perform better since the channel update calculated over the instantaneous error will be only resulted by the phase rotation of the channel due to CFO.

The results obtained in this section have revealed that the performance degradation due to CFO is still significant although the tracking capability of the JCSE lessens this effect. Therefore, it is decided to estimate the CFO at the destination by employing the proposed Solution-3 in Section 4.1.1.

4.2.3 Simulation Results For CFO Present In Relay-Destination Links of OMR and Being Estimated by ML estimator

The simulations done in this part aims to investigate the performance loss when CFO is present only for the relay to destination links and being estimated over N_{ts} training symbols by the ML estimator. The method simulated here corresponds to Solution-3 that is introduced in Section 4.1.1. The simulation model used is the same as used in 4.2.2 and by applying this model the results shown in Figures 4.8 and 4.9 are obtained.

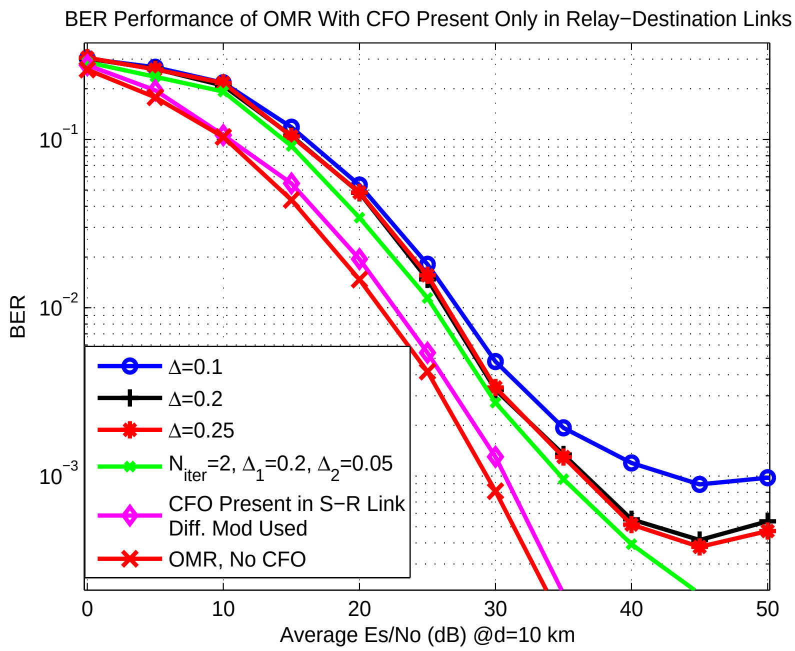

Figure 4.8: BER for CFO only present in relay-destination links and being estimated by the ML estimator

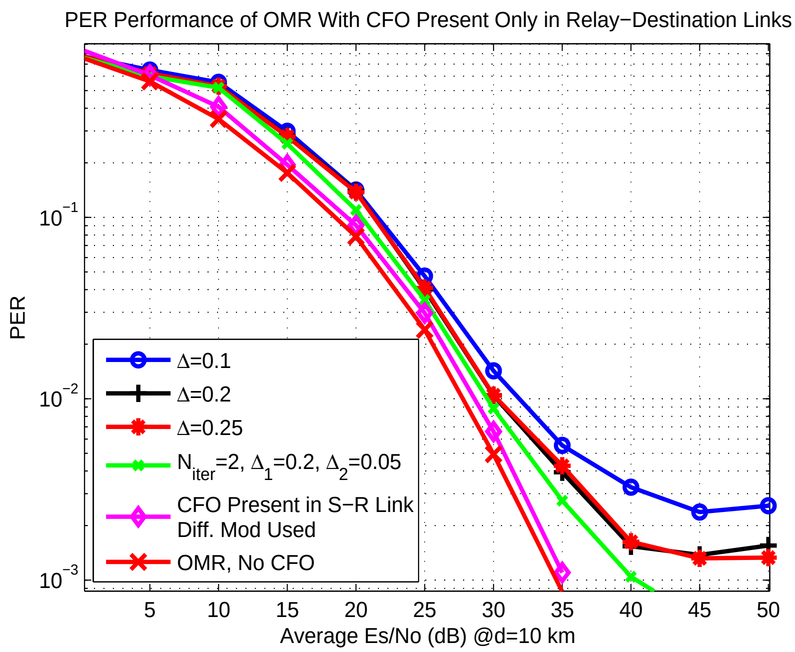

Figure 4.9: PER for CFO only present in relay-destination links and being estimated by the ML estimator

It can be concluded by inspecting Figures 4.8 and 4.9 that when CFO is present between relays and the destination for a target PER value of 0.01 approximately 2 dB of PER performance loss is observed by using the proposed Solution-3 with 2 iterations. It can also be seen from the figure that about 1 dB of this loss results from the differential demodulation used in links between source and relays. Hence, it can be concluded that the CFO estimation done in this step results in a small performance loss for the system. As can also be seen from the figures, when the JCSE is not iterated twice or when Δ is not selected appropriately, the loss in comparison to the performance obtained in the absence of CFO, increases up to $\sim$ 4 dB. The performance loss with the decreasing Δ results from the estimation errors of the ML CFO estimator, since small Δ values as 0.1 has been shown to be appropriate for the case when CFO is not in present among nodes in Section 3.5.3.

4.2.4 Simulation Results For Comparison of OMR and SR With CFO in Relay Destination Links

In Section 4.2.1, we have observed that differential demodulation between source and relays is sufficient to synchronize the relays with the source. By using the results of Sections 4.2.3 and 4.2.2, the most appropriate CFO estimation method for OMR turn out to be Solution-1 with 2 iterations that is proposed in Section 4.1.1.

In SR case we have assumed that flat fading channel and CFO's are perfectly known and corrected by the receivers of each transmission which are the relay and the destination, respectively. The corresponding simulation results are presented in Figures 4.10 and 4.11.

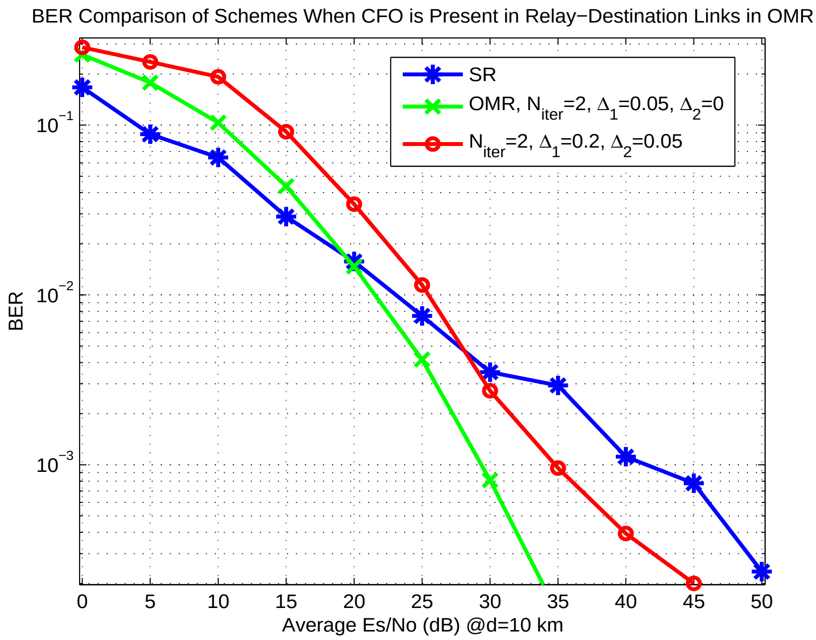

Figure 4.10: BER comparison of OMR and SR for CFO present in relays to destination links of OMR

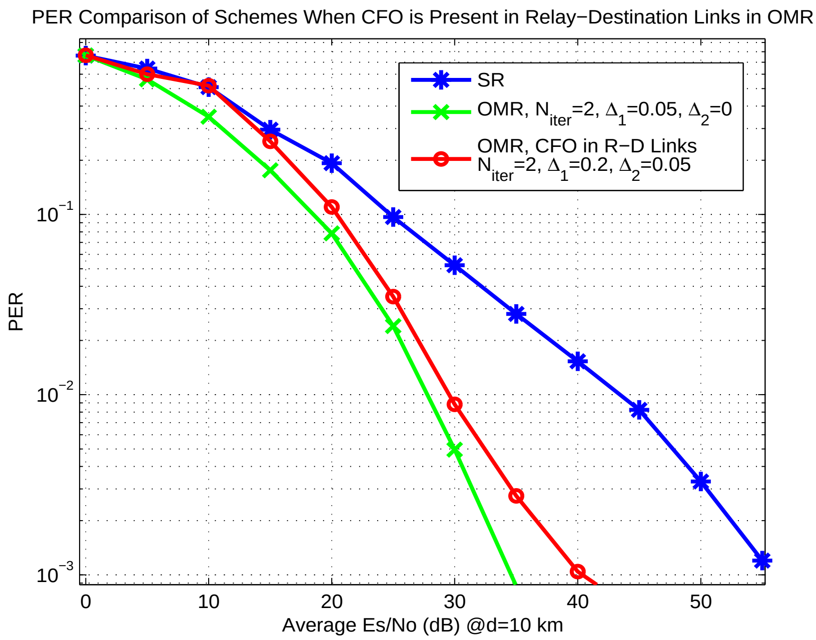

Figure 4.11: PER comparison of OMR and SR for CFO present in relays to destination links of OMR

It can be concluded from Figures 4.10 and 4.11 that although CFO imperfections are not included in SR simulations, the OMR scheme performs significantly better compared to SR in terms of PER performance. The imperfections due to CFO and channel estimation in SR will enlarge this gap. However, the BER performance difference between two schemes is not as large as it is in the case of PER, which is a result of the fact that erroneous RFBs in OMR tend to have larger number of bit errors. Since PER performance also includes the RFB errors resulting from the situations when there is no possibility of finding a relay node, the difference between PER and BER performances also shows that the probability of finding a relay node is higher in the case of CFO for the OMR scheme, which is shown in Figure 4.12.

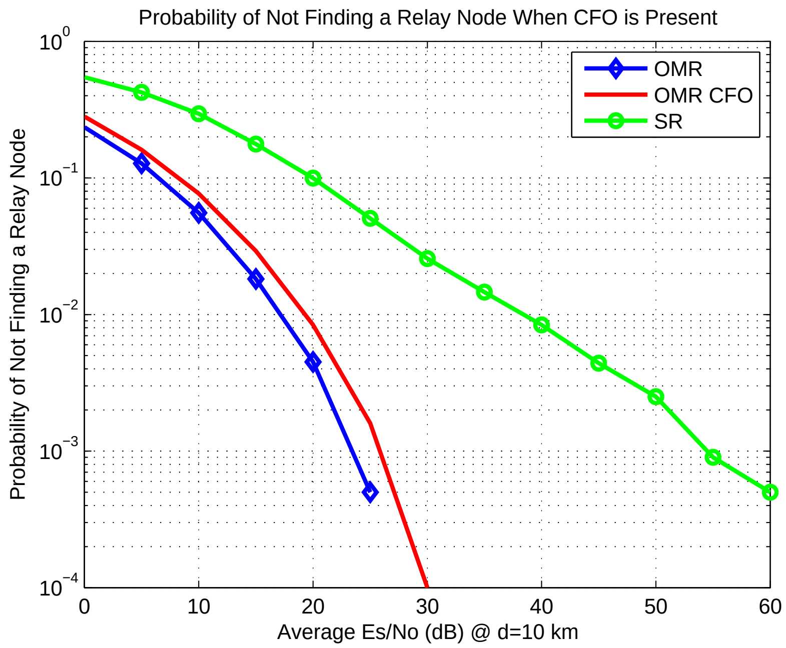

Figure 4.12: Probability of not finding a relay node in the presence of CFO

CHAPTER 5

CONCLUSION

In this thesis study, a cooperative relaying scheme namely opportunistic multiple relaying (OMR) and a special receiver structure to be used in destination nodes of the network employing OMR have been proposed. In OMR, different than most of the multiple node relaying schemes in the literature, the relay nodes are allowed to transmit in nonorthogonal channels without employing distributed space time coding (DSTC). Therefore, the communication system does not sacrifice from spectral efficiency which is quite low in the case when multiple nodes transmit in orthogonal channels. Additionally, employing DSTC is also hard to implement in practical communications systems due to its strict requirements for synchronization and high coordination between relays, which increases the control overhead for the system. The proposed scheme, OMR, is advantageous in comparison to previously introduced multiple relaying schemes in terms of spectral efficiency and control overhead for relay coordination.

The OMR scheme spans two time slots per communication attempt from the source to the destination. In the first time slot, the source node transmits its RFB and all other nodes in the network which are potential relays listen. Assuming an error detection mechanism is used by these potential relay nodes, the node, decoding the source's RFB successfully, retransmits to the destination in the next time slot with the other relay nodes.

In the thesis, the OMR scheme is compared to the Selection Relaying (SR) scheme, in which a single relay node is preselected by the source by considering the average channel qualities. In fact, this scheme corresponds to two hop routing which is currently utilized in most of the ad hoc networks. This scheme also spans two time slots for transmission. In the first time slot, the source node transmits its RFB to the selected relay node. Assuming an error detection mechanism is used by the relay, if the decoding is successful the relay transmits the RFB received from the source to the destination in the second slot. Since both schemes use two time slots, in terms of spectral efficiency two relaying schemes perform the same. However, OMR is simpler than SR since SR requires exchange of average link quality information between network nodes.

In the study, we first examined the receiver structure which is specifically proposed for the OMR scheme and compared both schemes for the cases when CFO is absent and present among network nodes. In addition to CFO, we have also considered many practical difficulties such as timing errors, imperfect frame synchronization and also propagation delays in this comparison and OMR is still proved to be superior to SR in terms error rate performance.

The energy consumed by the OMR scheme can be larger according to the number of selected relay nodes, however, it is also shown that comparing this additional energy requirement with the error rate improvement, the OMR scheme offers a favorable trade-off and as a result it is more efficient than SR if the energy consumed during transmission is considered.

In summary, the OMR scheme is shown to be suitable for the communications system model considered in this thesis. It can be concluded by observing the simulation results that the OMR scheme with the proposed receiver structure significantly outperforms SR which can be thought as two hop routing which is readily operated in today's communication systems.

As future work, network performance of the OMR scheme may be investigated and compared to the benchmark scheme SR. Throughput, communication delays and slot reuse may be selected as figures of merit for the comparisons that will be done for observing network performance.

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