

**ASYNCHRONOUS COOPERATIVE COMMUNICATION
SYSTEM USING OPPORTUNISTIC SELECTION
DIVERSITY TECHNIQUE**

Thesis submitted in the partial fulfilment of requirement for the award of the
Degree of
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IN
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Submitted by
Dhiraj Gupta
Roll. No. 80761007

Under guidance of
Dr. Amit Kumar Kohli
Assistant Professor, ECED
T.U. Patiala.



Electronics and Communication Engineering Department
THAPAR UNIVERSITY
PATIALA-147004, INDIA
JUNE-2009

DECLARATION

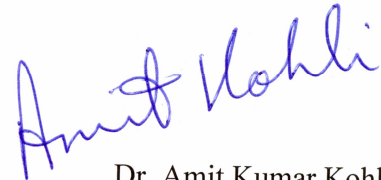
I hereby declare that the work, which is being presented in the thesis, entitled "ASYNCHRONOUS COOPERATIVE COMMUNICATION SYSTEM USING OPPORTUNISTIC SELECTION DIVERSITY TECHNIQUE" in partial fulfilment of the requirements for the award of degree of Master of Engineering in Electronics and Communication Engineering at Electronics and Communication Engineering Department of Thapar University, Patiala, is an authentic record of my own work carried out under the guidance of Dr. Amit Kumar Kohli.

I have not submitted the matter presented in the thesis for the award of any other degree of this or any other university.


Dhiraj Gupta

Roll No. 80761007

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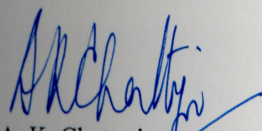
Dr. Amit Kumar Kohli

Assistant Professor

Electronics & Communication Engineering Department


Thapar University

Patiala-147004, (Punjab)


Dr. A. K. Chatterjee
Professor & Head
1.7.09.

Thapar University

Patiala-147004, (Punjab)


Dr. R. K. Sharma

Dean of Academic Affairs ECED,

Thapar University

Patiala-147004, (Punjab)

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Dhiraj Gupta
(80761007)

ABSTRACT

The revolutionary concept of space-time coding introduced in the last decade has demonstrated that the deployment of multiple antennas at the transmitter allows for simultaneous increase in throughput and reliability because of the additional degrees of freedom offered by the spatial dimension of the wireless channel.

A new form of realizing transmit diversity has been recently introduced under the name of user cooperation or cooperative diversity. The basic idea behind cooperative diversity rests on the observation that in a wireless environment, the signal transmitted by source node is overheard by other nodes, which can be defined as “partners/relays”. The source and its partners can jointly process and transmit their information, creating a “virtual antenna array”, and therefore emulating transmit diversity.

This report presents an asynchronous cooperative diversity method using opportunistic selection diversity technique. In this technique the cooperative diversity schemes are considered that do not require symbol-level timing synchronization or orthogonal channelization between the relays employed. Our scheme first selects the best relay from a set of M available relays, and then uses this “best” relay for cooperation between the source and destination. We develop and analyze a distributed method to select the best relay that requires no topology information and it is based on local measurements of the instantaneous channel conditions. The success (or failure) to select the best available path depends on the statistics of wireless channel, and a methodology to evaluate performance for any kind of wireless channel statistics, is provided.

Most of the ongoing research efforts in cooperative diversity assume coordination among the relays allows for accurate symbol level timing synchronization at the destination and orthogonal channel allocation, which can be quite costly in terms of signalling overhead in ad hoc networks, which are often defined by their lack of a fixed infrastructure and difficulty of centralized control.

Therefore, main focus will be on asynchronous cooperative diversity technique in the proposed work to circumvent this problem. The simplicity of the technique allows for immediate implementation in existing radio hardware, and its adoption could provide for improved flexibility, reliability, and efficiency in future 4G wireless systems.

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LIST OF ABBREVIATIONS

MIMO	Multiple input multiple output
RF	Radio frequency
CSI	Channel state information
SNR	Signal to noise ratio
RTS	Ready to send
CTS	Clear to send
MAC	Medium access control
MMSE	Minimum mean squared error
ISI	Inter symbol interference
CRC	Cyclic redundancy check
DFE	Decision feedback equalizer
CRP	Closest relays participate
ARP	All relays participate
ND	No delay
AD	Artificial delay
SRRC	Squared root raised cosine
FER	Frame error rate
CRP/ND	Closest relays participate with no delay
CRP/AD	Closest relays participate with artificial delay
ARP/ND	All relays participate with no delay
ARP/AD	All relays participate with artificial delay
FFF	Feed forward filter
FBF	Feedback filter
RC	Raised cosine

CHAPTER 1

INTRODUCTION

A quick glimpse of recent technological history reveals out that mobile communication systems create a new generation roughly every 10 years. First-generation analogue systems were introduced in the early 1980's, then second-generation (2G) digital systems came in the Early 1990's. Now third-generation (3G) systems are slowly unfolding all over the world while intensive conceptual and research work toward the definition of a future system has been already started.

2G systems, such as GSM and IS-95, were essentially designed for voice and low data rate applications. In an effort to address customer demands for high-speed data communication, telecommunication companies have been launching 3G systems where the business focus has shifted from voice services to multimedia communication applications over the Internet. Despite the increasing penetration rate of 3G systems in the wireless market, 3G networks are challenged primarily in meeting the requirements imposed by the ever-increasing demands of high-throughput multimedia and internet applications. Additionally, 3G systems consist primarily of wide area networks and thus fall short of supporting heterogeneous networks, including wireless local area networks (LANs) and wireless personal area networks (WPANs). Several wireless technologies co-exist in the current market customized for different service types, data rates, and users. The next generation systems also known as the fourth generation (4G) systems are envisioned to accommodate and integrate all existing and future technologies in a single standard. The key feature of the 4G systems would be "high usability" [1]; that is the user would be able to use the system at anytime, anywhere, and with any technology. Users carrying an integrated wireless terminal would have access to a variety of multimedia applications in a reliable environment at lower cost. To meet these demands, next generation wireless communication systems must support high capacity and variable bit rate information (adaptive) transmission with high bandwidth efficiency to conserve limited spectrum resources.

One major limitation of wireless systems is the fading channel that exists between users and the base station. When a user's channel realization is bad, it may be unable to communicate with the base station. Figure 1 illustrates this for the simple case of a sinusoidal signal propagating over two signal paths.

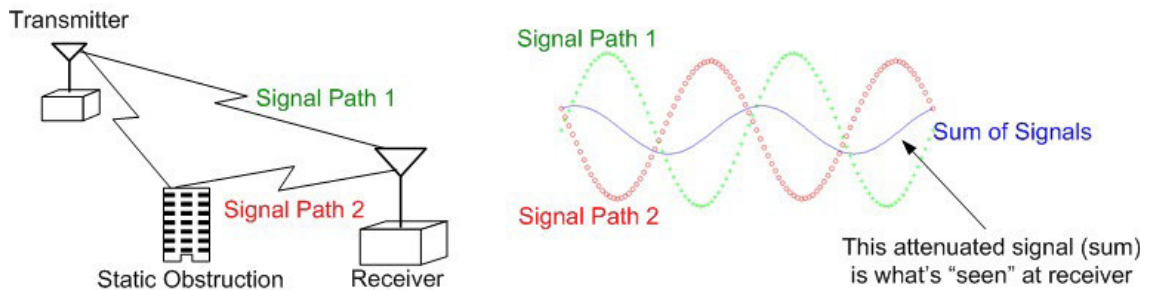


Fig.1: Multipath fading of a sinusoidal signal over two signal paths

“Diversity,” as it applies to wireless transmissions, combats multipath fading by providing the receiver with redundant signal information through uncorrelated (i.e. diverse) channels thereby allowing the receiver to average individual channel effects. To overcome this problem, many different forms of diversity have been studied including: spatial, temporal, and frequency diversity. Recently, there has been an increasing popularity in a specific form of spatial diversity, namely cooperative diversity.

1.1 DIVERSITY TECHNIQUES FOR FADING CHANNELS

Transmit diversity generally requires more than one antenna at the transmitter. However, many wireless devices are limited by size or hardware complexity to one antenna. There are various approaches to extract diversity from the wireless channel. The most common methods are briefly summarized as follows [2], [3], [4]:

1.1.1 Time Diversity

Time diversity means that the signal is spread in the time domain. If there is a short period of time in which signals interfere with each other, which distorts part of the signal, time diversity may help to reconstruct the signal in the receiver despite the errors. The methods for achieving time diversity are channel coding, interleaving, and retransmission protocols. In this form of diversity, the same signal is transmitted in different time slots separated by an interval longer than the coherence time of the channel. Channel coding in conjunction with interleaving is an efficient technique to provide time diversity. In fast fading environments where the mobility is high, time diversity becomes very efficient. However, for slow fading channel (e.g., low mobility environments, fixed-wireless applications), it offers little protection unless significant interleaving delays can be tolerated. Time diversity spreads the faulty bits over a longer period of time, and thus makes it easier to reconstruct the original data. If there are 4 successive erroneous bits in one byte, it is very difficult to recover the original data. However if these 4 false bits from the radio interface are evenly spread over 4 bytes by means of interleaving, then it is much easier to recover the data, for example, by means of error correcting coding. The longer the interleaving period, the better the protection provided by the time diversity. However, longer interleaving increases transmission delays and a balance must be found between the error resistance capabilities and the delay introduced.

1.1.2 Frequency Diversity

In this form of diversity, the same signal is sent over different frequency carriers, whose separation must be larger than the coherence bandwidth of the channel to ensure independence among diversity channels. Since multiple frequencies are needed, this is generally not a bandwidth-efficient solution. A natural way of frequency diversity, which is sometimes referred to as path diversity, arises for frequency-selective channels. When the multipath delay spread is a significant fraction of the symbol period, the received signal can be interpreted as a linear combination of the transmitted signal weighted by independent fading coefficients. Therefore, path diversity is obtained by resolving the multipath components at different delays using a RAKE correlator [2], which is the optimum receiver in the MMSE sense designed for this type of channels.

1.1.3 Space Diversity

In this form of diversity, which is also sometimes called as antenna diversity, the receiver and/or transmitter uses multiple antennas. This technique is especially attractive since it does not require extra bandwidth. To extract full diversity advantages, the spacing between antenna elements should be wide enough with respect to the carrier wavelength. The required antenna separation depends on the local scattering environment as well as on the carrier frequency. For a mobile station which is near the ground with many scatters around, the channel decorrelates over shorter distances, and typical antenna separation of half to one carrier wavelength is sufficient. For base stations on high towers, a larger antenna separation of several to tens of wavelengths may be required.

Recently, a new class of methods called cooperative communication has been proposed that enables single antenna mobiles in a multi-user environment to share their antennas and generate a virtual multiple-antenna transmitter that allows them to achieve transmit diversity.

Although transmit diversity is clearly advantageous on a cellular base station, it may not be practical for other scenarios. Specifically, due to size, cost, or hardware limitations, a wireless agent may not be able to support multiple transmit antennas. Examples include most handsets (size) or the nodes in a wireless sensor network (size, power). The mobile wireless channel suffers from fading; meaning that the signal attenuation can vary significantly over the course of a given transmission. Transmitting independent copies of the signal generates diversity and can effectively combat the deleterious effects of fading. In particular, spatial diversity is generated by transmitting signals from different locations, thus allowing independently faded versions of the signal at the receiver.

1.2 COOPERATIVE COMMUNICATION

Cooperative communication generates space diversity in a new and interesting way. The word cooperate derives from the Latin words co- and operate (to work), thus it connotes the idea of “working together”. Cooperation is the strategy of a group of entities working together to achieve a common or individual goal. The main idea behind cooperation is that each cooperating entity gains by means of the unified activity. Cooperation can be seen as the action of obtaining some advantage by giving, sharing or allowing something.

Cooperation is extensively applied by human beings and animals, and we would like here to map different cooperation strategies into wireless communication systems.

Space-time coding techniques are quite attractive for deployment in the cellular applications at base stations and have been already included in the 3rd generation wireless standards. Although transmit diversity is clearly advantageous on a cellular base station, it may not be practical for other scenarios. Specifically, due to size, cost, or hardware limitations, a wireless device may not be able to support multiple transmit antennas. Examples include mobile terminals and wireless sensor networks which are gaining popularity in the recent years. In order to overcome these limitations, yet still emulate transmit antenna diversity, a new form of realizing spatial diversity has been recently introduced under the name of user cooperation or cooperative diversity [5]-[9]. The basic idea behind cooperative diversity rests on the observation that in a wireless environment, the signal transmitted by the source node is overheard by other nodes, which can be defined as “partners” or “relays”. The source and its partners can jointly process and transmit their information, creating a virtual antenna array although each of them is equipped with only one antenna. Similar to physical antenna arrays, these virtual antenna arrays combat multipath fading in wireless channels by providing receivers with essentially redundant signals over independent channels that can be combined to average individual channel effects. The recent surge of interest in cooperative communication was subsequent to the works of Sendonaris [5], [6] and Laneman [7]-[9]. However, the basic ideas behind user cooperation can be traced back to Meulen’s early work on the relay channel [10]. A first rigorous information theoretical analysis of the relay channel has been introduced in [11] by Cover and Gamal for AWGN channels. Extending the work of [11] for fading channels, Sendonaris et al. [5]-[6] have investigated the achievable rate region for relay-assisted transmission and coined the term “user cooperation”.

Cooperative communication is one of the fastest growing areas of research, and it is likely to be a key enabling technology for efficient spectrum use in future. The key idea in user-cooperation is that of resource-sharing among multiple nodes in a network. The reason behind the exploration of user-cooperation is that willingness to share power and computation with neighboring nodes can lead to savings of overall network resources. Mesh networks provide an enormous application space for user-cooperation strategies to be implemented. In traditional communication networks, the physical layer is only responsible for communicating information from one node to another. In contrast, user-cooperation implies a paradigm shift, where the channel is not just one link but the

network itself. Cooperation is possible whenever the number of communicating terminals exceeds two. Therefore, a three-terminal network is a fundamental unit in user-cooperation.

1.2.1 A Brief History of Relaying

We summarize prominent contributions in the area of user-cooperation. Our list of contributions is by no means exhaustive, but we attempt to touch upon the many approaches to user-cooperation over the years. Communication from a single source to a single destination without the help of any other communicating terminal is called direct, single-user or point-to-point communication. User-cooperation is possible whenever there is at least one additional node willing to aid in communication. The simplest and oldest form of user-cooperation is perhaps multi-hopping, which is nothing but a chain of point-to-point links from the source to the destination. No matter what the channel, there is some attenuation of the signal with distance, which makes long-range point-to-point communication impractical. This problem is overcome by replacing a single long-range link with a chain of short-range links, where at each intermediate node there is a booster or repeater to enhance signal quality. Multi-hopping was conceived about the same time as smoke and drum signals, therefore we do not attempt to put a time stamp on it. In cooperative wireless communication, we are concerned with a wireless network, of the cellular or ad hoc variety, where the wireless agents, which we call users, may increase their effective quality of service (measured at the physical layer by bit error rates, block error rates, or outage probability) via cooperation. In a cooperative communication system, each wireless user is assumed to transmit data as well as act as a cooperative agent for another user (Fig. 1.2.1).

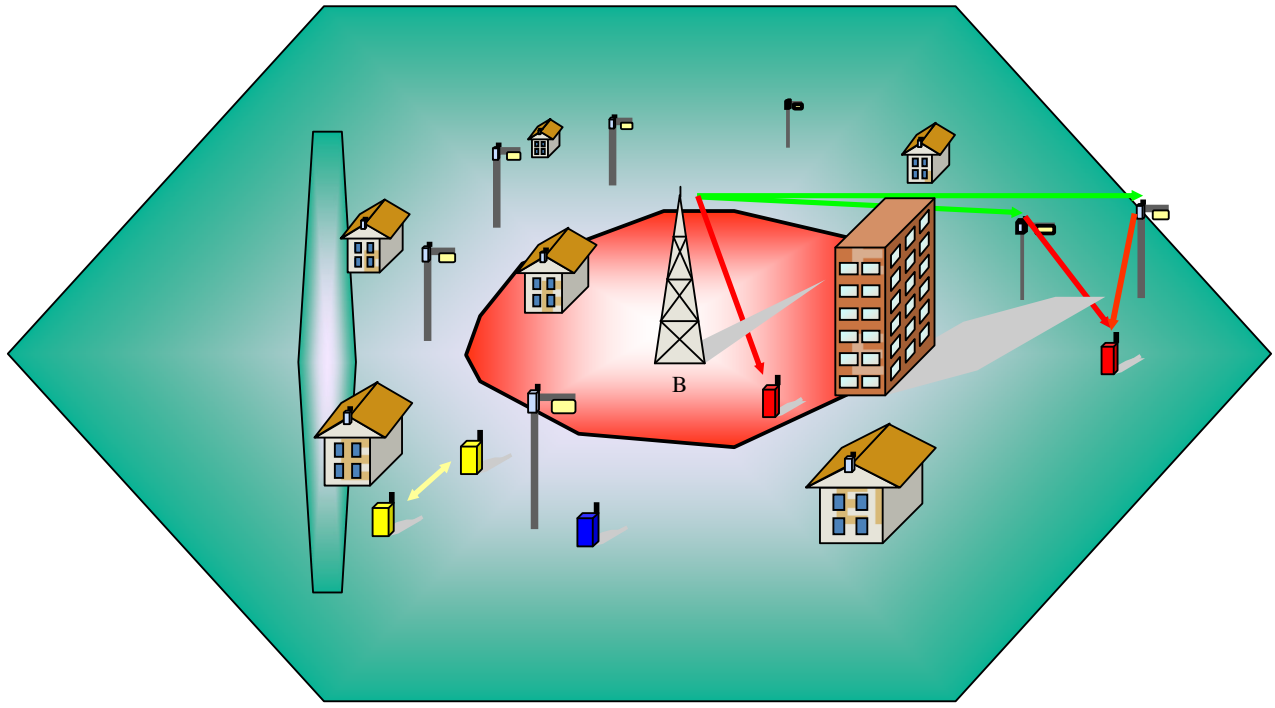


Fig.1.2.1: Relay assisted transmission.

Cooperation leads to interesting trade-offs in code rates and transmit power. In the case of power, one may argue on one hand that more power is needed because each user, when in cooperative mode, is transmitting for both users. On the other hand, the baseline transmits power for both users will be reduced because of diversity. In the face of this trade-off, one hopes for a net reduction of transmit power, given everything else being constant. Similar questions arise for the rate of the system. In cooperative communication each user transmits both his/her own bits as well as some information for his/her partner; one might think this causes loss of rate in the system. However, the spectral efficiency of each user improves because due to cooperation diversity the channel code rates can be increased. Again a tradeoff is observed. The key question, whether cooperation is worth the incurred cost, has been answered positively by several studies, and is demonstrated by plots toward the end of this article. One may also describe cooperation as a zero sum game in terms of power and bandwidth of the mobiles in the network. The premise of cooperation is that certain (admittedly unconventional) allocation strategies for the power and bandwidth of mobiles lead to significant gains in system performance. In the cooperative allocation of resources, each mobile transmits for multiple mobiles.

1.3 SYSTEM MODEL

In our model we use asynchronous cooperative diversity method using opportunistic selection diversity technique. In this technique the cooperative diversity schemes are considered that do not require symbol-level timing synchronization or orthogonal channelization between the relays employed. Our scheme first selects the best relay from a set of M available relays, and then uses this “best” relay for cooperation between the source and destination.

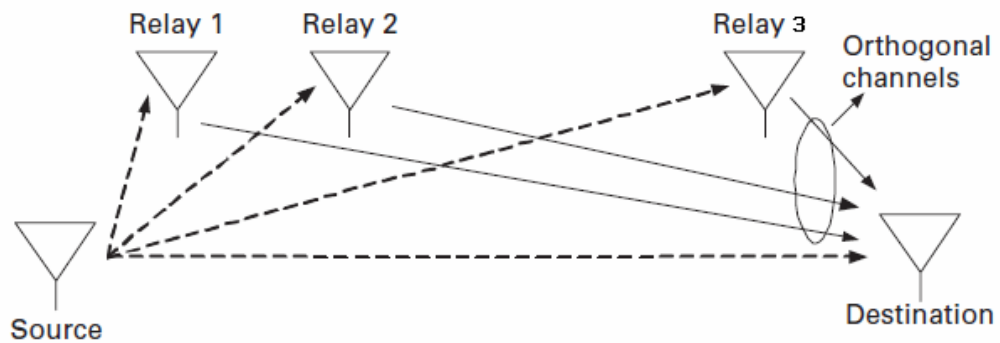


Fig 1.3: Classic relay channel with three relays and one source and one destination.

we propose and analyze a practical scheme that forms a virtual antenna array among single antenna terminals, distributed in space. The setup includes a set of cooperating relays which are willing to forward received information toward the destination and the proposed method is about a distributed algorithm that selects the most appropriate relay to forward information toward the receiver. The decision is based on the end-to-end instantaneous wireless channel conditions and the algorithm is distributed among the cooperating wireless terminals. The channel estimates a_{si} , a_{id} at each relay, describe the quality of the wireless path between source-relay-destination, for each relay. Since the two hops are both important for end-to-end performance, each relay should quantify its appropriateness as an active relay, using a function that involves the link quality of both hops.

PROBLEM STATEMENT

This report presents the following work

- 1). Firstly, we select the best relay from a set of M available relays, and then uses this best relay for cooperation between the source and destination.
- 2). Then, we transmit the data by using asynchronous cooperative diversity that do not require symbol-level timing synchronization between the relays employed.

ORGANIZATION OF REPORT

This report is organized in five chapters

Chapter I summarize the basic problem statement of the research work and give the overview cooperative diversity technique.

In Chapter II, we discuss the simple cooperative diversity based network path selection by selecting the best relay out of number of relays available for the cooperation.

In Chapter III, we discuss asynchronous cooperative diversity method.

In chapter IV, we transmit the data asynchronously as discussed in chapter III by using the best relay selection technique discussed in chapter II

In chapter V, the simulation results are obtained for the asynchronous cooperative diversity method using opportunistic selection technique.

Finally we conclude our work by comparing various simulation results by merging the asynchronous data transfer with the best path selection by using the opportunistic relay selection method.

CHAPTER 2

SIMPLE COOPERATIVE DIVERSITY BASED NETWORK PATH SELECTION

Our scheme first selects the best relay from a set of M available relays and then uses this “best” relay for cooperation between the source and the destination. We develop and analyze a distributed method to select the best relay that requires no topology information and is based on local measurements of the instantaneous channel conditions. This method also requires no explicit communication among the relays. The success (or failure) to select the best available path depends on the statistics of the wireless channel, and a methodology to evaluate performance for any kind of wireless channel statistics, is provided. The communication scheme exploits the wireless channel at its best, via distributed cooperating relays, we naturally called it opportunistic relaying.

2.1 MAIN CONTRIBUTION IN PATH SELECTION

A new protocol for selection of the “best” relay between the source and destination is suggested and analyzed. This protocol has the following features.

- 1) The protocol is distributed and each relay only makes local channel measurements.
- 2) Relay selection is based on instantaneous channel conditions in slow fading wireless environments. No prior knowledge of topology or estimation of it is required.
- 3) The amount of overhead involved in selecting the best relay is minimal. It is shown that there is a flexible tradeoff between the time incurred in the protocol and the resulting error probability.

2.2 DESCRIPTION OF OPPORTUNISTIC RELAYING

According to opportunistic relaying, a single relay among a set of M relay nodes is selected, depending on which relay provides for the “best” end-to-end path between source and destination (Figs. 2.2.1 and 2.2.2).

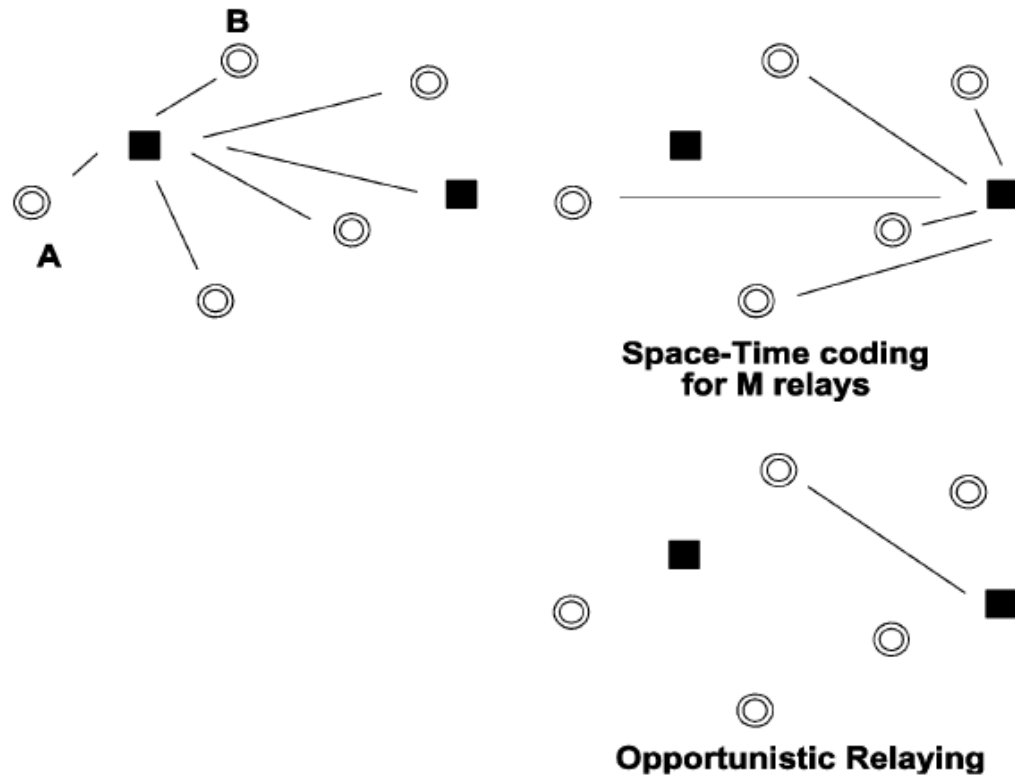


Fig.2.2.1: Transmission is overheard by neighboring nodes. Distributed space– time coding is needed so that all overhearing nodes could simultaneously transmit.

In this work, we analyze “opportunistic relaying” where the relay with the strongest transmitter-relay-receiver path is selected among several candidates in a distributed fashion using instantaneous channel measurements.

The wireless channel a_{si} between source and each relay, as well as the channel a_{id} between relay i and destination affect performance. These parameters model the propagation environment between any communicating terminals and change over time, with a rate that macroscopically can be modelled as the Doppler shift, inversely proportional to the channel coherence time. Opportunistic selection of the “best” available relay involves the discovery of the most appropriate relay, in a distributed and “quick” fashion, well before the channel changes again. The relay nodes monitor the instantaneous channel conditions toward source and destination, and decide in a distributed fashion which one has the strongest path for information relaying, well before

the channel changes again. In that way, topology information at the relays (specifically location coordinates of source and destination at each relay) is not needed. The selection process reacts to the physics of wireless propagation, which are in general dependent on several parameters including mobility and distance. By having the network select the relay with the strongest end-to-end path, macroscopic features like “distance” are also taken into account. Moreover, the proposed technique is advantageous over techniques that select the best relay a priori, based on distance toward source or destination, since distance-dependent relay selection neglects well-understood phenomena in wireless propagation such as shadowing or fading: communicating transmitter-receiver pairs with similar distances might have enormous differences in terms of received SNRs. More specifically, the relays overhear a single transmission of a ready-to-send (RTS) packet and a clear-to-send (CTS) packet from the destination. From these packets, the relays assess how appropriate each of them is for information relaying. The transmission of RTS from the source allows for the estimation of the instantaneous wireless channel $a_{s,i}$ between source and relay i at each relay (Fig. 2.2.2).

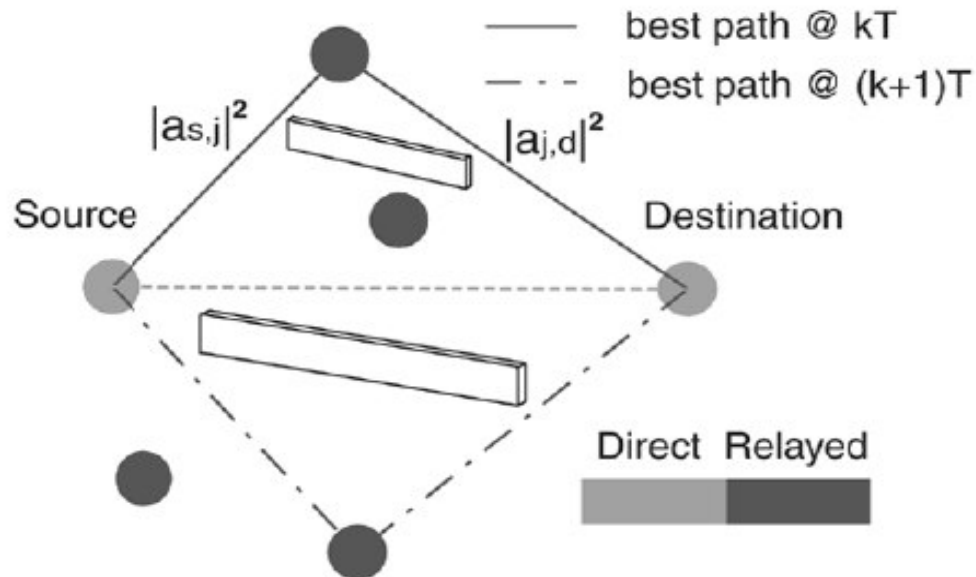


Fig.2.2.2: Source transmits to destination and neighboring nodes overhear the communication. “Best” relay among M candidates is selected to relay information, via a distributed mechanism and based on instantaneous end-to-end channel conditions.

Similarly, the transmission of CTS from the destination allows for the estimation of the instantaneous wireless channel a_{id} between relay and destination at each relay according to the reciprocity theorem. Since communication among all relays should be minimized for reduced overall overhead, a method based on time was selected: as soon as each relay receives the CTS packet, it starts a timer from a parameter h_i based on the instantaneous channel measurements a_{si} , a_{id} . The timer of the relay with the best end-to-end channel conditions will expire first. That relay transmits a short duration flag packet, signaling its presence. All relays, while waiting for their timer to reduce to zero (i.e., to expire), are in listening mode. As soon as they hear another relay to flag its presence or forward information (the best relay), they back off. For the case where all relays can listen source and destination, but they are “hidden” from each other (i.e., they cannot listen each other), the best relay notifies the destination with a short duration flag packet and the destination notifies all relays with a short broadcast message. The channel estimates a_{si} , a_{sd} at each relay, describe the quality of the wireless path between source-relay-destination, for each relay. Since the two hops are both important for end-to-end performance, each relay should quantify its appropriateness as an active relay, using a function that involves the link quality of both hops. Two functions are used in this work: under Policy I, the minimum of the two is selected, while under Policy II, the harmonic mean of the two is used

- Under Policy I

$$h_i = \min \{ |a_{si}|^2, |a_{id}|^2 \} \quad (2.2.1)$$

- Under Policy II

$$h_i = \frac{2}{\frac{1}{|a_{si}|^2} + \frac{1}{|a_{id}|^2}} = \frac{2 |a_{si}|^2 |a_{id}|^2}{|a_{si}|^2 + |a_{id}|^2} \quad (2.2.2)$$

The relay that maximizes function h_i is the one with the “best” end-to-end path between initial source and final destination. After receiving the CTS packet, each relay will start its own timer with an initial value T_i inversely proportional to the end-to-end channel quality h_i according to the following equation:

$$T_i = \frac{\lambda}{h_i} \quad (2.2.3)$$

$$T_i = \frac{\lambda}{h_i} \quad (2.2.4)$$

Here, λ is a constant. The units of λ depend on the units of h_i . Since h_i is a scalar, λ has the units of time. For the discussion in this work, λ have simply values of microseconds.

$$f(a,b) = \frac{ab}{a+b+1} \quad (2.2.5)$$

$$h_b = \max\{h_i\} \quad (2.2.6)$$

$$T_b = \min\{T_i\}, \quad i \in [1 \dots M] \quad (2.2.7)$$

Therefore, the “best” relay has its timer reduced to zero first. This is the relay b that participates in forwarding information from the source. The rest of the relays will overhear the “flag” packet from the best relay (or the destination, in the case of hidden relays) and back off. After the best relay has been selected, then it can be used to forward information toward the destination. Whether that “best” relay will transmit simultaneously with the source or not is completely irrelevant to the relay selection process.

2.2.2 Note on Time Synchronization

In principle, the RTS/CTS transmissions between source and destination, existent in many medium access control (MAC) protocols, is only needed so that all intermediate relays can assess their connectivity paths toward source and destination. The reception of the CTS packet triggers at each relay the initiation of the timing process, within an uncertainty interval that depends on different propagation times. Therefore, an explicit time synchronization protocol among the relays is not required. Explicit time synchronization would be needed between source and destination only if there was no direct link between them. In that case, the destination could not respond with CTS to RTS packet from the source, and, therefore, source and destination would need to schedule their RTS/CTS exchange by other means. In such cases, “crude” time synchronization would be useful.

2.2.3 A Note on CSI

CSI at the relays, in the form of link strengths (not signal phases), is used at the network layer for “best” relay selection. CSI is not required at the physical layer and is not exploited either at the source or the relays. The wireless terminals in this work do not exploit CSI for beam forming and do not adapt their transmission rate to the wireless channel conditions, either because they are operating in the minimum possible rate or because their hardware do not allow multiple rates.

2.3 PROBABILISTIC ANALYSIS OF OPPORTUNISTIC RELAYING

The probability of having two or more relay timers expire “at the same time” is zero. However, the probability of having two or more relay timers expire within the same time interval is nonzero and can be analytically evaluated, given knowledge of the wireless channel statistics. The only case where opportunistic relay selection fails is when one relay can not detect that another relay is more appropriate for information forwarding. Note that we have already assumed that all relays can listen initial source and destination, otherwise they do not participate in the scheme.

We will assume two extreme cases:

- 1) All relays can listen to each other and
- 2) All relays are hidden from each other (but they can listen source and destination). In that case, the flag packet sent by the best relay is received from the destination which responds with a short broadcast packet to all relays. Alternatively, other schemes based on “busy tone” (secondary frequency) control channels could be used, requiring no broadcast packet from the destination and partly alleviating the “hidden” relays problem.

2.4 SIMPLIFYING COOPERATIVE DIVERSITY THROUGH OPPORTUNISTIC RELAYING

We now consider the impact of opportunistic relaying on the cooperative diversity scenario. The main result of this section is that opportunistic relaying can be used to simplify a number of cooperative diversity protocols involving multiple relays. In particular, we focus on the cooperative diversity protocol in [14], which requires the relays to use a space–time code while simultaneously transmitting toward the destination. We show that this protocol can be simplified considerably by simply selecting the best relay in the second stage. Perhaps surprisingly, this simplified protocol achieves the same diversity-multiplexing tradeoff achieved in [9]. Furthermore, it does not matter whether the relay implements an amplify and forward or a decode and forward protocol in terms of the diversity-multiplexing tradeoff. We also note that opportunistic relaying can be used to simplify the non-orthogonal relaying protocols proposed in [12].

2.4.1 Channel Model

We consider an i.i.d. slow Rayleigh fading channel model following [7]. A half duplex constraint is imposed across each relay node, i.e., it cannot transmit and listen simultaneously. We assume that the nodes (transmitter and relays) do not exploit the knowledge of the channel at the physical layer. Note that in the process of discovering the best relay described in the previous section, the nodes do learn about their channel gains to the destination. However, we assume that this knowledge of channel gain is limited to the network layer protocol. The knowledge of channel gain is not exploited at the physical layer in order to adjust the code rate based on instantaneous channel measurements. In practice, the hardware at the physical layer could be quite constrained

to allow for this flexibility to change the rate on the fly. It could also be that the transmitter is operating at the minimum transmission rate allowed by the radio hardware. Throughout this section, we assume that the channel knowledge is not exploited at the physical layer at either the transmitter or the relays. If the discrete time received signal at the destination and the relay node are denoted by $Y[n]$ and $Y_1[n]$ respectively,

$$Y[n] = a_{sd} X[n] + Z[n], \quad n=1, 2, \dots, \frac{T}{2}$$

(source transmits destination receives) (2.4.1)

$$Y[n] = a_{rd} X_1[n] + Z[n], \quad n = \frac{T}{2}, \frac{T}{2} + 1, \dots, T$$

(best relay transmits destination receives) (2.4.2)

$$Y_1[n] = a_{sr} X[n] + Z_1[n] \quad n = 1, 2, \dots, \frac{T}{2}$$

(source transmits best relay receives) (2.4.3)

Here a_{sd} , a_{rd} , a_{sr} respective channel gains from the source to destination, best relay to destination, and source to the best relay, respectively. The channel gains between any two pair of nodes are i.i.d. $N(0,1)$. The noise $Z[n]$ and $Z_1[n]$ at the destination and relay are both assumed to be i.i.d. circularly symmetric complex Gaussian $N(0, \sigma^2)$. $X[n]$ and $X_1[n]$ are the transmitted symbols at the transmitter and relay, respectively. T denotes the duration of time-slots reserved for each message and we assume that the source and the relay each transmit orthogonally on half of the time-slots. We impose a power constraint at both the source and the relay:

$$E[|X[n]|^2] \leq P \tag{2.4.4}$$

and

$$E[|X_1[n]|^2] \leq P \tag{2.4.5}$$

For simplicity, we assume that both the source and the relay to have the same power constraint.

We will define

$$\rho \triangleq \frac{P}{\sigma^2} \tag{2.4.6}$$

to be the effective SNR. This setting can be easily generalized when the power at the source and relays is different.

2.4.2 Digital Relaying—Decode and Forward Protocol

We will first study the case where the intermediate relays have the ability to decode the received signal, re-encode, and transmit it to the destination. We will study the protocol proposed in [14] and show that it can be considerably simplified through opportunistic relaying. The decode and forward algorithm considered in [9] is briefly summarized as follows. In the first half time-slots, the source transmits and all the relays and receiver nodes listen to this transmission. Thereafter, all the relays that are successful in decoding the message, re-encode the message using a distributed space-time protocol, and collaboratively transmit it to the destination. The destination decodes the message at the end of the second time-slot. Note that the source does not transmit in the second half time-slots. The main result for the decode and forward protocol is given in the following theorem.

Theorem 1 ([14]): The achievable diversity-multiplexing tradeoff for the decode and forward strategy with M intermediate relay nodes is given by

$$d(r) = (M+1)(1-2r) \text{ for } r \in (0,0.5) \tag{2.4.7}$$

The following theorem shows that opportunistic relaying achieves the same diversity multiplexing tradeoff if the best relay selected according to Policy 1.

Under opportunistic relaying, the decode and forward protocol with M intermediate relays achieves the same diversity-multiplexing tradeoff stated in Theorem1.

2.4.3 Analog Relaying Basic Amplify and Forward

We will now consider the case where the intermediate relays are not able to decode the message, but can only scale their received transmission (due to the power constraint) and send it to the destination. The basic amplify and forward protocol was studied in [6] for the case of a single relay. The source broadcasts the message for first half time-slots. In the second half time-slots, the relay simply amplifies the signals it received in the first half timeslots. Thus, the destination receives two copies of each symbol. One directly from the source and the other via the relay. At the end of the transmission, the destination then combines the two copies of each symbol through a matched filter. Assuming i.i.d. Gaussian codebook, the mutual information between the source and the destination can be shown to be

$$I(X, Y) = \frac{1}{2} \log(1 + \rho a_{sd}^2 + f(\rho a_{sr}^2, \rho a_{rd}^2)) \quad (2.4.8)$$

$$f(a, b) = \frac{ab}{a+b+1} \quad (2.4.9)$$

The amplify and forward strategy does not generalize in the same manner as the decode and forward strategy for the case of multiple relays. We do not gain by having all the relay nodes amplify in the second half of the time-slot. This is because at the destination, we do not receive a coherent summation of the channel gains from the different receivers. If γ_j is the scaling constant of receiver, then the received signal will be given by

$$y[n] = \left(\sum_{j=1}^M \gamma_j a_{rd}^j \right) x[n] + z[n] \quad (2.4.10)$$

Since this is simply a linear summation of Gaussian random variables, we do not see the diversity gain from the relays. A possible alternative is to have the M relays amplify in a round-robin fashion. Each relay transmits only one out of every M symbols in a round robin fashion. This strategy has been proposed in [9], but the achievable diversity-

multiplexing tradeoff is not analyzed. Opportunistic relaying on the other hand provides another possible solution to analog relaying. Only the best relay (according to Policy 1) is selected for transmission. The following theorem shows that opportunistic relaying achieves the same diversity- multiplexing tradeoff as that achieved by the (more complicated) decode and forward scheme.

Opportunistic relaying provides an alternative solution to space time codes for cooperative diversity by using a clever relaying protocol. There is no loss in diversity-multiplexing tradeoff¹¹ if a simple analog relaying based scheme is used in conjunction with opportunistic relaying. Even if the intermediate relays are digital, a very simple decode and forward scheme that does eliminates the need for space-time codes can be implemented. The relay listens and decodes the message in the first half of the time-slots and repeats the source transmission in the second half of the time-slots when the source is not transmitting. The receiver simply does a maximal ratio combining of the source and relay transmissions and attempts to decode the message. The combination of this simple physical layer scheme and the smart choice of the relay is essentially optimum.

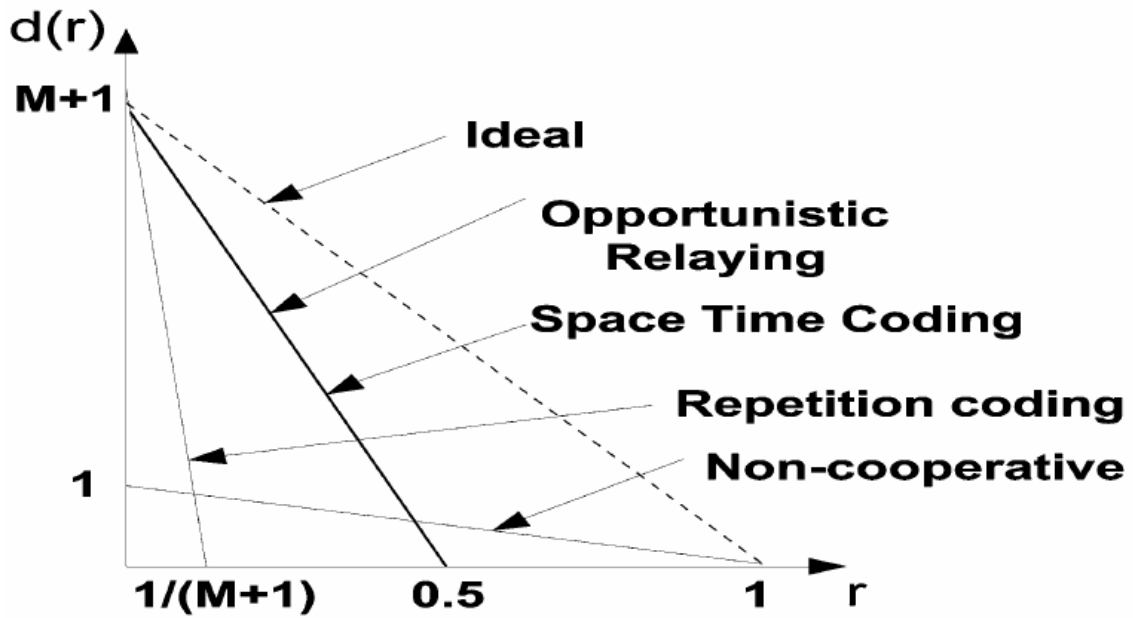


Fig.2.4.3: Diversity-multiplexing of opportunistic relaying is exactly the same with that of more complex space-time coded protocols.

The diversity-multiplexing tradeoff is plotted in Fig. 2.3.3. Even though a single terminal with the “best” end-to-end channel conditions relays the information, the diversity order in the high SNR regime is on the order of the number $M+1$ of all participating terminals. Moreover, the tradeoff is exactly the same with that when space-time coding across M relays is used.

ASYNCHRONOUS COOPERATIVE DIVERSITY

A strong demand for personal communications systems and devices, the wireless communications market has undergone tremendous growth in the past few decades. As an alternative to cellular networks, ad hoc wireless networks have attracted considerable attention in recent years. An ad hoc wireless network is a collection of wireless mobile nodes that self-configure to form a network without the aid of any established infrastructure [13]. Thus, unlike cellular systems, in which the coordination of mobiles in a given area is done via the base-stations, ad hoc networks utilize other mobiles as relays to transfer information from a source to its destination. The lack of required infrastructure in an ad hoc wireless network is highly appealing in both military and commercial applications [13]. The impairments caused by multipath fading and the time varying nature of the wireless channel must be considered in designing an ad hoc wireless network. The broadcast nature of the radio channel introduces characteristics in ad hoc wireless networks that can be exploited in the form of cooperative diversity [16], a strategy whereby cooperating nodes between the source and its destination forward the received data generated by the source to the destination after some processing at each relay terminal as shown in Fig. 3.1. In [14], [9], the authors developed and analyzed several energy-efficient cooperative diversity protocols that combat fading in wireless networks. In their work, different nodes in the wireless network share their antennas and resources to create a virtual array. For the decode-and-forward scheme proposed in this work, the relay nodes first fully decode the transmission from the source terminal.

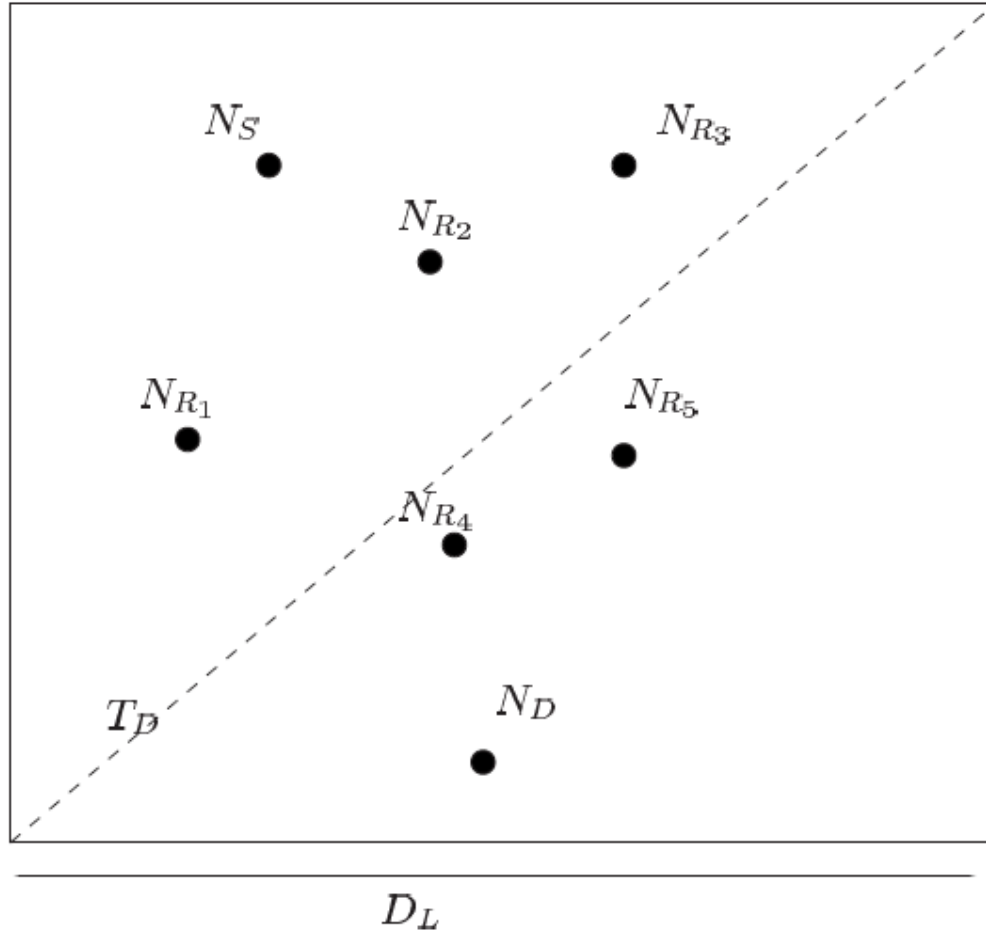


Fig.3.1: Ad-hoc wireless network. Node N_S wishes to communicate with node N_D with the help of relay nodes $N_{R1}, N_{R2}, \dots, N_{R5}$ in a region of size $D_L \times D_L$ with maximum signal propagation delay T_D .

Next, they will either forward that information to the destination in the assigned slot, or they can cooperatively utilize a space-time code to allow the destination terminal to take advantage of distributed spatial diversity to average out the fading. In [15], [16], [17], to achieve a better trade-off between energy and spectral efficiency while using similar orthogonal channel allocation schemes as in [14], various coding schemes were proposed across the source and the relay nodes, which achieve not only cooperative diversity gain but also coding gain. The aforementioned cooperative schemes assume orthogonal

channel allocation and synchronization of the signals of the cooperating terminals at the receiver, both of which require significant overhead in an ad hoc wireless network.

In [18], they essentially employ adaptive decode and forward or amplify and forward schemes (i.e. non-regenerative relaying schemes [19], [20]) on each relay node as in [21], so that relay nodes can choose to transmit or remain silent depending on the received signal-to-noise-ratio (SNR). The main difference between the solution described here and that of [18] is that the scheme of [18] is limited in efficiency by the need to intentionally increase the data symbol period T_s to avoid the inter-symbol interference (ISI) caused by the asynchronous transmission of signals to the destination. In contrast, here we design a novel receiver to avoid such a penalty. Additionally, we also demonstrate that artificially introducing delays at the relay can significantly improve system performance.

As seen from the above, the existing cooperative diversity schemes [14], [9], [15], [16], [17], [22] are more suitable for cellular architectures because orthogonal channel allocation and/or synchronization of relay nodes are assumed, which will be difficult in ad-hoc wireless networks due to their infrastructure-less nature. Therefore, finding schemes which relax this coordination is important for achieving cooperative diversity in practice. In this paper, this problem will be attacked with approaches that capture the essence of ad hoc networks from a physical layer design perspective. In particular, a distributed delay diversity approach is proposed to achieve the diversity gains promised by distributed space-time codes. Unlike the extension of other approaches [26] to the synchronization problem in distributed space-time coding, the proposed system also admits a robust and easily trainable receiver when synchronization is not present in the system.

For a cellular network, a transmit diversity scheme was proposed in [24] that had multiple antennas at the base-station transmit various delayed versions of a common signal to create an effectively frequency-selective fading channel at a single antenna at the mobile receiver. When there are multiple antennas at one base station, transmitting various delayed versions of the same signal on the transmit antennas can be easily implemented. However, in the case of an ad hoc network with multiple relays, the recovered signals at each relay node are not necessarily identical due to the demodulation/decoding errors resulting from the presence of fading and thermal noise on the link from the source to the relay. To address this, a cyclic redundancy check (CRC) code [25] can be used so that each relay will know if it received a correct packet. If the

received packet is error-free, the relay node will then forward the information packet to the destination, after possibly introducing an additional intentional artificial delay. If not, this packet of data will be dropped by the relay. Assuming that the CRC code enables the relay nodes to correctly detect all packet errors, the destination node will see an equivalent multi-path fading channel in the form of the artificially introduced relay delays.

There are two main contributions:

- (1) Two related protocols that implement distributed delay diversity;
- (2) The development of a novel fractional spaced decision feedback equalizer (DFE) that combines the inputs from two independent channels, one that is frequency selective (from the relays), and a second that is frequency non-selective (directly from the source), and minimizes the mean squared error (MMSE) at the decision point in the receiver.

3.1 SYSTEM MODEL

Consider an network as shown in Fig.3.1.1, where the source node NS transmits messages to the destination node N_D with the help of a set of K nearby relays

$R = \{ N_{R_1}, N_{R_2}, \dots, N_{R_k} \}$. Relays are indexed according to their distance from the source, with N_{R_1} being closest to the source and N_{R_k} being the furthest. Each node has a single half duplex radio and a single antenna. Data is formatted into packets and each packet is protected by CRC error detecting which we assume is always able to detect packet error.

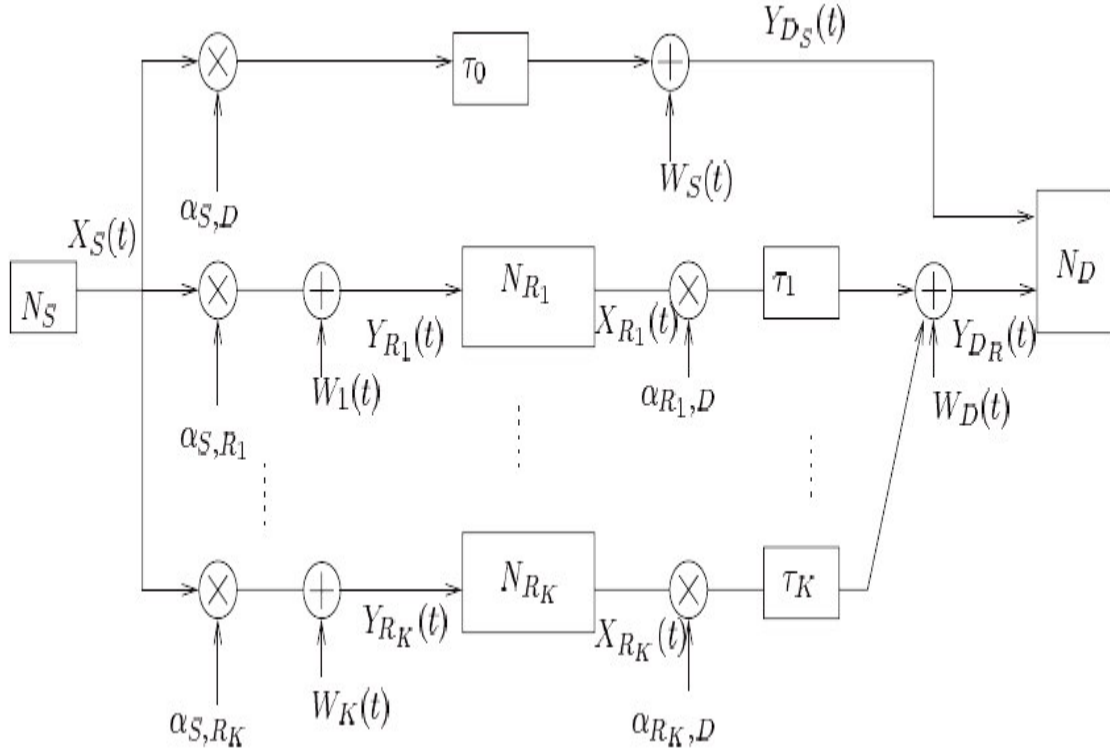


Fig. 3.1.1: System model of an ad hoc wireless network under the assumption that all K relays are in the decoding set.

In this chapter, we mainly focus on a two-hop scenario whose mathematical model is shown in Fig.3.1.1, though the results can be generalized for the multi-hop case. In the two-hop case, signalling of the packet occurs over two orthogonal time slots, and it is assumed that the inter-node distances are fixed for the duration of both time slots. During the first slot, termed the broadcast period, the source broadcasts to both N_D and a set $P \subseteq R$ of the relays. The relays in P are the participating relays. Each relay $N_{R_k} \in P$ receives a signal $Y_{R_k}(t)$ from the source and, after demodulation, checks for errors using the CRC code. The set $D \subseteq P$ of participating relays that receive the packet without errors is called the decoding set, and the number of decoding relays $|D| = M$. The value of M is random and depends on the channel quality between source and each relay. During the second time slot, termed the relay period, all nodes in D transmit

signals $X_{R_k}(t)$ to N_D , which combines the transmissions from the relay(s) and a stored copy of the source transmission using the joint DFE receiver. In Fig. 3.1.1, it is assumed that all K relays are in D , but in general some relays could detect errors and not participate in the relay period. Narrow-band transmission is assumed here, where the channel between any pair of nodes is frequency non-selective. In addition, quasi-static fading is assumed, where the path gains remain fixed during the transmission of a whole packet, but are independent from node to node and packet to packet. Time delays are introduced on each path from the source to the destination. This time delay incorporates the processing time at the relay nodes and the propagation delay of the whole route. More specifically τ_o is the delay from N_S to N_D , and τ_k is the cumulative delay for the transmission from N_S to N_{R_K} , processing at N_{R_K} and for transmission from N_{R_K} to N_D . The noise processes $W_S(t)$, $W_D(t)$ and $W_k(t)$, $k = 1, \dots, K$ are independent complex white Gaussian noise with two-sided power spectral density N_0 . The complex channel gain $\alpha_{i,j}$ captures the effects of both path loss and the quasi-static fading from node N_i to node N_j , where $i \in \{S, R_1, \dots, R_K\}$, and $j \in \{R_1, \dots, R_K, D\}$. Statistically, $\alpha_{i,j}$ will be modelled as zero mean, mutually independent complex jointly Gaussian random variables with variances $\sigma_{i,j}^2$. The fading variances can be assigned using wireless path loss models based on the network geometry. Here, it is assumed that $\sigma_{i,j}^2 \propto \frac{1}{d_{i,j}^\mu}$, where $d_{i,j}$ is the distance from node N_i to N_j , and μ is a constant whose value, as estimated from field experiments, lies in the range $2 \leq \mu \leq 5$ [5]. It is assumed that $\alpha_{i,j}$ is estimated accurately at the receiver, but is not available to the transmitter. It is assumed that each relay node transmits with identical power unless otherwise stated. Under the modelling assumed above, the signals in Fig.3.1.1 are:

$$Y_{R_k}(t) = \alpha_{S,R_k} X_S(t) + W_k(t), \quad k = 1, \dots, K \quad (3.1.1)$$

$$Y_{D_S}(t) = \alpha_{S,D} X_S(t) + W_S(t) \quad (3.1.2)$$

$$Y_{D_R}(t) = \sum_{j=1}^K \alpha_{R_j, D} X_{R_j}(t - \tau_j) + W_D(t) \quad (3.1.3)$$

where $Y_{D_R}(t)$ and $Y_{D_R}(t)$ have no common support in the time domain, and $W_S(t)$ and $W_D(t)$ are independent and identically distributed white Gaussian random processes. The transmitted signal from the source is

$$X_S(t) = \sum_{k=-\infty}^{\infty} I_k h_{T_X}(t - kT), \quad (3.1.4)$$

where $h_{T_X}(t)$ is the impulse response of the transmit pulse shaping filter, T is the symbol period, and I_k is the k th complex data symbol with

$$\begin{aligned} I_k &= a_k + jb_k, \frac{1}{2} E[|I_k|^2] \\ &= \sigma_i^2 = 1, \end{aligned} \quad (3.1.5)$$

and $\{I_k\}$ is a sequence of uncorrelated symbols that is independent of $\{W_j(t)\}$. It is assumed that $h_{T_X}(t)$ has a squared root raised cosine (SRRC) impulse response with a filter roll-off factor $\beta \in [0, 1]$. Denote each front-end receiver filter response as $h_{R_x}(t)$, which is matched to the SRRC transmitter filter, i.e.,

$$h_{R_x}(t) = h_{T_X}^*(-t).$$

It is assumed that all nodes transmit with equal power $P = \sigma_i^2$.

Because outage probability is a more suitable metric than average error probability for quasi-static fading, the measure of performance is the outage probability of the frame error rate (FER), which is defined as follows. Given one realization of the connection between the source node and the destination node (i.e., one realization of the random locations of $K + 2$ nodes in a given area, realizations of channel fading gains $\alpha_{i,j}$ and the set D), the frame error event at N_D is caused by the additive noise and ISI in the

equivalent multi-path channel. An outage is declared when the FER at N_D is above a predetermined threshold (e.g., 0.1). The outage probability will be obtained by then calculating the likelihood of such an event over the realizations of the random connection between node N_S and N_D .

3.2 PROTOCOL DESCRIPTION

Two protocols are proposed, which differ in the composition of P :

3.2.1 Closest Relays Participate (CRP)

In this protocol, the participating set is $P = \{N_{R1}, N_{R2}\}$, i.e. only the two relays that are closest to the source participate. While this protocol serves to illustrate key concepts associated with the proposed system, its actual implementation would require the determination of which two nodes are closest to the source, which imposes additional overhead on the system. However, as the number of possible relay nodes per-hop in this protocol is upper bounded, if a system can meet the demand of such overhead in selecting the closest two relay nodes, CRP is a viable option which costs less overall energy across network than the ARP protocol described below. The motivation for employing the two nodes closest to the source in the CRP protocol is to maximize the likelihood that the relay destination link is able to achieve diversity two. The CRP protocol is largely included to demonstrate key aspects of the idea, whereas the protocol described next is shown to be more effective in simulation.

3.2.2 All Relays Participate (ARP)

In this protocol, all relays in the network participate, and so $P = R$. The advantage of this protocol is that there is very little centralized control required, since any node that decodes a packet heard during the broadcast period simply transmits during the relay period. On the other hand, this protocol might cause many nodes involved in forwarding source information, which results in more energy consumption across network than the CRP protocol. One way to handle this is to normalize the transmission power by dividing the relay transmission power by M . However, this number is not known a priori and must

be estimated. Each relay can either transmit its signal immediately after processing or after an artificial delay, which gives rise to two versions of the protocol:

No Delay (ND): Each relay in D transmits the signal immediately after receiving and processing the packet (we assume the processing time is the same for all relays). As shown in the numerical results, the performance under this protocol can be limited if the overall path delays of the relay nodes are similar, and, hence, the anticipated delay diversity is not always achieved.

Artificial Delay (AD): Each relay in D waits for a random amount of time. The delay timer is selected from a pool of possible artificial delays (e.g. $\{T, 2T, \dots\}$). Before a node transmits during the relay period, it delays the signal by its currently assigned artificial delay. Numerical results will demonstrate that by choosing the pool carefully and assigning different artificial delays to nodes in close geographical proximity, significant performance gains are observed, because the desired delay diversity is almost always achieved. Altogether, there are four options for the protocol, which are denoted CRP/ND, CRP/AD, ARP/ND, and ARP/AD. The pool of possible artificial delays used by variant AD is a key system design issue. For pools containing only short delays, receiver implementation will be simpler because the effective ISI channel will be shorter, but there will be a higher chance of encountering node geometries that incur diversity loss. Conversely, for longer delays, receiver implementation is more difficult, but there is a less chance of such diversity loss.

Consider an ad hoc wireless network employing the ARP protocol, where each node carries with it a current artificial delay from the pool that it will employ whenever it is asked to serve as a relay. Now, whenever a source transmits a packet, it attaches at the end of that packet a few bits indicating the artificial delay from the pool it would employ if it were playing the role of relay. Per above, all participating relays hear the transmission and attempt decoding. If a node is successful, which is more likely if the node is near the source, and it realizes the source is employing the same artificial delay as itself, the node switches randomly to a different artificial delay from the pool. Although this does not impact performance for the current packet transmission, since the source will not transmit during the relay period, future transmissions where the geographically-close current source and current relay might both be asked to serve as relays, will be improved. In effect, this protocol encourages the desired condition that nodes in close proximity are assigned different artificial delays from the pool and will work to maintain such even under node mobility.

3.3 JOINT DFE RECEIVER

The proposed system requires a receiver that can jointly process the output of a frequency-selective channel and the output of an independent frequency non-selective channel. For the application considered here, these channels correspond to that from the relays and that from the source, respectively. A straightforward approach would be to first employ a standard equalizer to process the signal from the frequency-selective channel; then, a number of straightforward combining schemes could be used to combine the output of such with the signal from the orthogonal channel. However, it will be shown here that such schemes are inferior to an equalizer specifically designed to jointly process the output of the two channels under the MMSE criterion.

The signal $Y_{D_S}(t)$, and hence $y_{s,k}$, is collected by the receiver while the source is transmitting, and the signal $Y_{D_R}(t)$, and hence $y_{D,k+\psi}$, is collected by the receiver while the relays are transmitting, and then both are processed jointly after the signal from the source is delayed to coincide with the relayed signal.

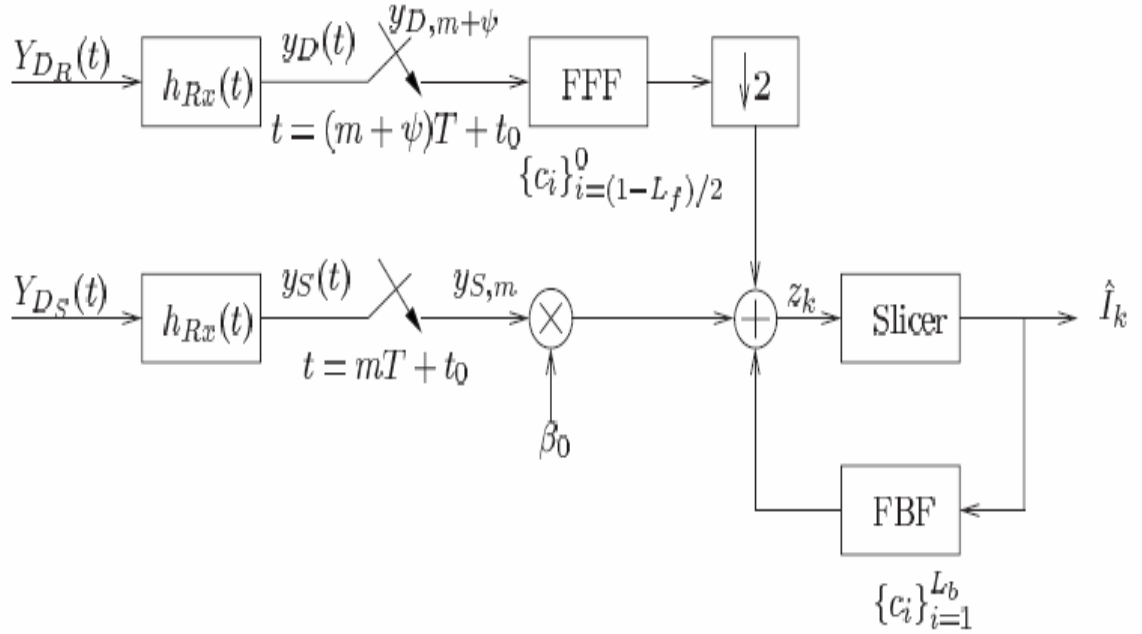


Fig.3.3.1: Functional description of the joint DFE receiver.

Hence, the joint DFE receiver structure is motivated, and the coefficients of the DFE feed forward filter (FFF), DFE feedback filter (FBF), and channel combining are chosen jointly based on an MMSE criterion. Note that this receiver structure will be more broadly applicable, as it can be employed in any application where multiple orthogonal channels, some of which are frequency selective, need to be jointly processed. For example, its extension to the case that some node-to-node channels are inherently frequency-selective is straightforward.

The FFF is an anti-causal filter with L_f $T/2$ -spaced taps and coefficients $\{c_{(1-L_f)/2}, \dots, c_{-1}, c_{-1/2}, c_0\}$. The FBF is a causal filter with L_b T -spaced taps and coefficients $\{c_1, c_2, \dots, c_{L_b}\}$. The length L_b of the FBF is assumed to be equal to the length of the channel, i.e., $L_b = L$ [16]. In practice, L_f is chosen one to five times the channel pre-cursor length, which is determined by the position of the peak amplitude response of $h_D(t + t_0)$ [19]. For the signal $Y_{DS}(t)$ received while the source node is

transmitting, whose support does not overlap that of $Y_{D_R}(t)$, the equivalent discrete-time channel model at the output of the T-spaced sampler is

$$\begin{aligned} y_{S,k} &= y_S(kT + t_0) \\ &= \alpha_{S,D} I_k + v_{S,k}, \end{aligned} \quad (3.3.1)$$

where $y_S(t)$ is the output of the receiver filter during the time the source is transmitting and $\{v_{S,k}\}$ is a sequence of independent complex Gaussian random variables with zero mean and variance $E[|v_{S,k}|^2] = 2N_0$ which are independent of $\{v_{D,k+\psi}\}$. The coefficients of the FFF and FBF, as well as β_0 which is used to scale and derotate for the direct path $y_{S,k}$, can be obtained by assuming correct past decisions and minimizing the mean squared error (MSE)

$$MSE = E[|I_k - u_k^T c|^2]$$

Where the x^T denotes non-conjugate transpose of a vector x . The data vector u_k is defined as

$$u_k \triangleq [y_{D,k+(L_f-1)/2}, \dots, y_{D,k+1}, y_{D,k+1/2}, y_{D,k}, y_{S,k}, I_{k-1}, I_{k-2}, \dots, I_{k-L_b}]^T, \quad (3.3.2)$$

and the vector of filter coefficients c is denoted as

$$c \triangleq [c_{(1-L_f)/2}, \dots, c_{-1}, c_{-1/2}, c_0, \beta_0, c_1, c_2, \dots, c_{L_b}]^T \quad (3.3.3)$$

By applying the orthogonality principle [29], i.e., $E[(I_k - z_k) u_k^*] = 0$, where $z_k = u_k^T c$, the filter coefficients are determined as:

$$c_{(1-L_f)/2:0} = (1 - \beta_0 \alpha_{S,D}) \Omega^{-1} p \quad (3.3.4)$$

$$\beta_0 = \alpha_{S,D}^* \frac{1 - \tilde{U}_0}{2N_0 / \sigma_c^2 + |\alpha_{S,D}|^2 (1 - \tilde{U}_0)}, \quad (3.3.5)$$

and

$$c_j = - \sum_{i=(1-L_f)/2:0} h_{D,j-1} c_i, j=1,2,\dots,L_b, \quad (3.3.6)$$

where $(1-L_f)/2:0 = (1-L_f)/2, \dots, -1, -1/2$,

\mathbf{p} is a column vector of dimension L_f with $p_i = h_{D,-i}^*, i = (1-L_f)/2:0$, and the scalar $\tilde{U}_0 = \mathbf{p}^\dagger \mathbf{\Omega}^{-1} \mathbf{p}$, where \mathbf{p}^\dagger is the conjugate transpose of \mathbf{p} . The matrix $\mathbf{\Omega}$ is determined by the autocorrelation of the data vector \mathbf{u}_k , $\mathbf{\Omega} = \mathbf{\Gamma} - \mathbf{\Lambda}^* \mathbf{\Lambda}^T$, where the elements of matrices $\mathbf{\Gamma}$ and $\mathbf{\Lambda}$ are

$$\Gamma_{i,j} = \frac{1}{2} E[y_{D,k-i} y_{D,k-j}^*] = \sum_{n \in \mathcal{Z}} h_{D,n-i}^* h_{D,n-j} + \phi_{vD}((i-j)T) \quad (3.3.7)$$

for $i, j \in \{\frac{1-L_f}{2}, \dots, -1, -1/2, 0\}$,

$$\text{and } \Lambda_{i,j}^T = h_{D,i-j} \quad (3.3.8)$$

for $i \in \{1, 2, \dots, L_b\}$, and $j \in \{(1-L_f)/2:0\}$.

ASYNCHRONOUS COOPERATIVE DIVERSITY METHOD USING OPPORTUNISTIC SELECTION TECHNIQUE

In asynchronous cooperative diversity method using opportunistic selection technique, we first select the best relay from a set of M available relays and then use this “best” relay for cooperation between the source and destination. We analyze a distributed method to select the best relay that requires no topological information and is based on local measurements of the instantaneous channel conditions. This method also requires no explicit communication among the relays. After selection of best path by using the opportunistic relay, we transfer the data by using asynchronous cooperation diversity method.

The data path selection by using the opportunistic relay removes the complexity of most of the proposed solutions, which require distributed space–time coding algorithms. The best relay selection algorithm lends itself naturally into cooperative diversity protocols, which improve reliability in wireless communication systems using distributed virtual antennas. The protocol is distributed, and each relay only makes local channel measurements. Relay selection is based on instantaneous channel conditions in the slow fading wireless environments. No prior knowledge of topology or estimation of it is required. Opportunistic relaying provides an alternative solution with a very simple physical layer to the conventional cooperative diversity protocols that rely on the space–time codes.

4.1 CHANNEL MODEL FOR COOPERATION WHEN SOURCE AND RELAY EXCHANGE ROLES:

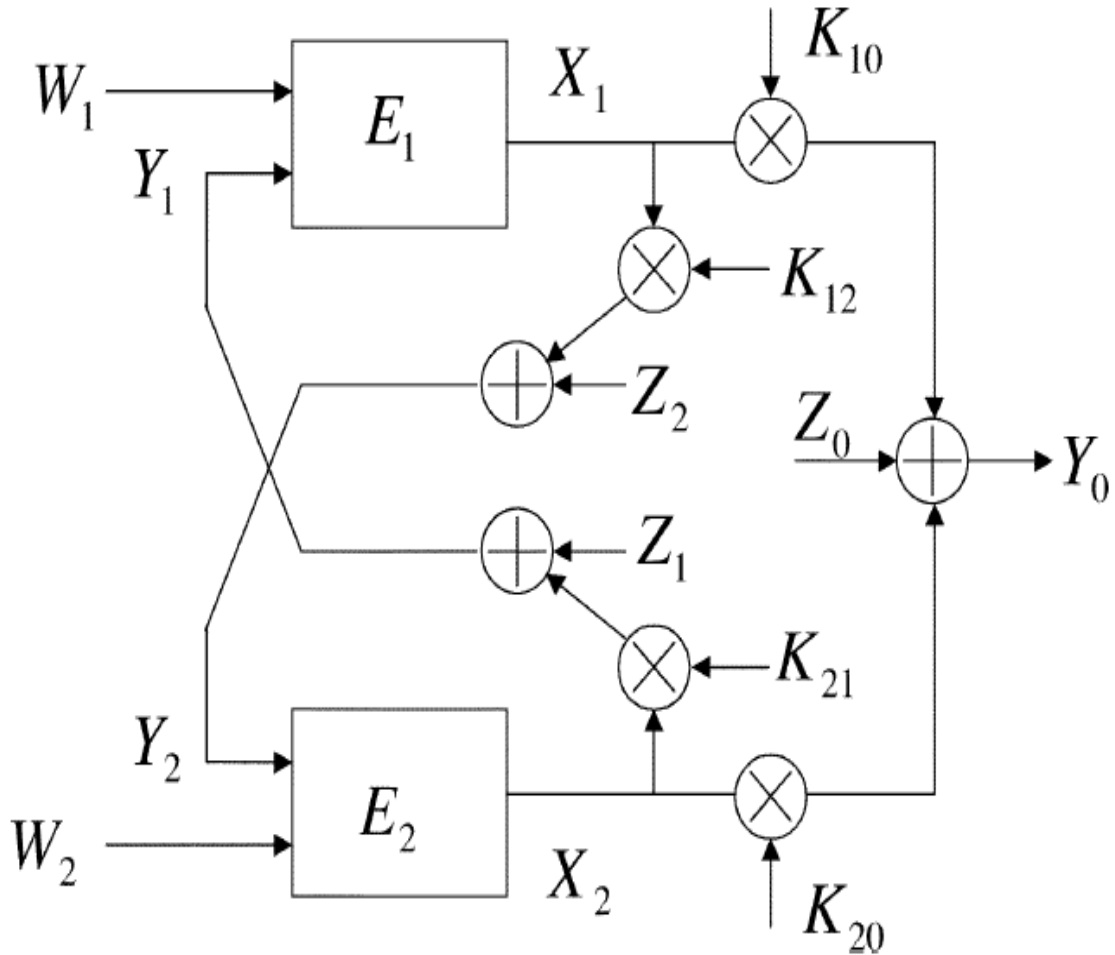


Fig.4.1: Channel model for cooperation when source and relay exchange roles.

Here, we consider the channel model of Figure 4.1. There are two sources and a single destination. Both transmitters can overhear each other, and are willing to cooperate by forwarding information from the other. Transmitters are capable of full-duplex communication. The mathematical model for this channel is given by the following equations

$$Y_0 = K_{10}X_1 + K_{20}X_2 + Z_0 \quad (4.1.1)$$

$$Y_1 = K_{21}X_2 + Z_1 \quad (4.1.2)$$

$$Y_2 = K_{12}X_1 + Z_2, \quad (4.1.3)$$

with $Z_0 \sim N(0, E_0)$, $Z_1 \sim N(0, E_1)$ and $Z_2 \sim N(0, E_2)$. In general, we assume that $E_1 = E_2$. The system is causal and transmission is done for B blocks of length n , therefore the signal of Source 1 at time j , $j = 1, \dots, n$, can be expressed as $X_1(W_1, Y_1(j-1), Y_1(j-2), \dots, Y_1(1))$, where W_1 is the message that Source 1 wants to transmit to the destination in that block. Similarly, for Source 2 we have $X_2(W_2, Y_2(j-1), Y_2(j-2), \dots, Y_2(1))$. We assume that Source 1 divides its information W_1 into two parts: W_{10} , which is sent directly to the destination, and W_{12} , which is sent to Source 2 and then forwarded by Source 2 to the destination. Source 1 structures its transmit signal so that it is able to send the above information as well as some additional cooperative information to the destination. This is done as follows

$$X_1 = X_{10} + X_{12} + U_1 \quad (4.1.4)$$

where the power is divided as

$$P_1 = P_{10} + P_{12} + P_{U1} \quad (4.1.5)$$

Here, U_1 refers to the part of the signal that carries cooperative information. Thus, X_{10} uses power P_{10} to send W_{10} at rate R_{10} directly to the destination, X_{12} uses power P_{12} to send W_{12} to Source 2 at rate R_{12} , and U_1 uses power P_{U1} to send cooperative information to the destination. Forwarding is based on the principle of decode and forward, therefore the transmission rate of W_{12} , i.e. R_{12} , and the power allocated to W_{12} , i.e. P_{12} , should be such that W_{12} can be perfectly decoded by Source 2. Source 2 similarly structures its transmit signal X_2 and divides its total power P_2 .

4.2.1 System Model

In the above proposed model the relay nodes monitor the *instantaneous* channel conditions towards source and destination, and decide in a distributed fashion which one has the *strongest* path for information relaying, well before the channel changes again. In that way, topology information at the relays (specifically location coordinates of source and destination at each relay) is not needed. The selection process *reacts* to the physics of wireless propagation, which are in general dependent on several parameters including mobility and distance. By having the network select the relay with the strongest end-to-end path, *macroscopic* features like "distance" are also taken into account. the proposed technique is advantageous over techniques that select the best relay *a priori*, based on distance toward source or destination, since distance dependent relay selection neglects well-understood phenomena in wireless propagation such as *shadowing* or *fading*: communicating transmitter-receiver pairs with similar distances might have enormous differences in terms of received SNRs. the relays overhear a single transmission of a Ready-to-Send (RTS) packet and a Clear-to-Send (CTS) packet from the destination. From these packets, the relays assess how appropriate each of them is for information relaying. The transmission of RTS from the source allows for the estimation of the instantaneous wireless channel a_{si} between source and relay i , at each relay i (fig. 4.2). Similarly, the transmission of CTS from the destination, allows for the estimation of the instantaneous wireless channel a_{id} between relay i and destination, at each relay i , according to the reciprocity theorem [66]. Note that the source does not need to listen to the CTS packet³ from the destination. As soon as each relay receives the CTS packet, it starts a

timer from a parameter h_i based on the instantaneous channel measurements a_{si} , a_{id} . The timer of the relay with the best end-to-end channel conditions will expire first. That relay transmits a short duration *flag* packet, signalling its presence. All relays, while waiting for their timer to reduce to zero (i.e. to expire) are in listening mode. As soon as they hear another relay to flag its presence or forward information (the best relay), they back off. For the case where all relays can listen to source and destination, but they are "hidden" from each other (i.e. they can not listen to each other), the best relay notifies the destination with a short duration *flag* packet and the destination notifies all relays with a

short broadcast message. The channel coefficients a_{si} , a_{id} at each relay, describe the quality of the wireless path between source-relay-destination, for each relay i .

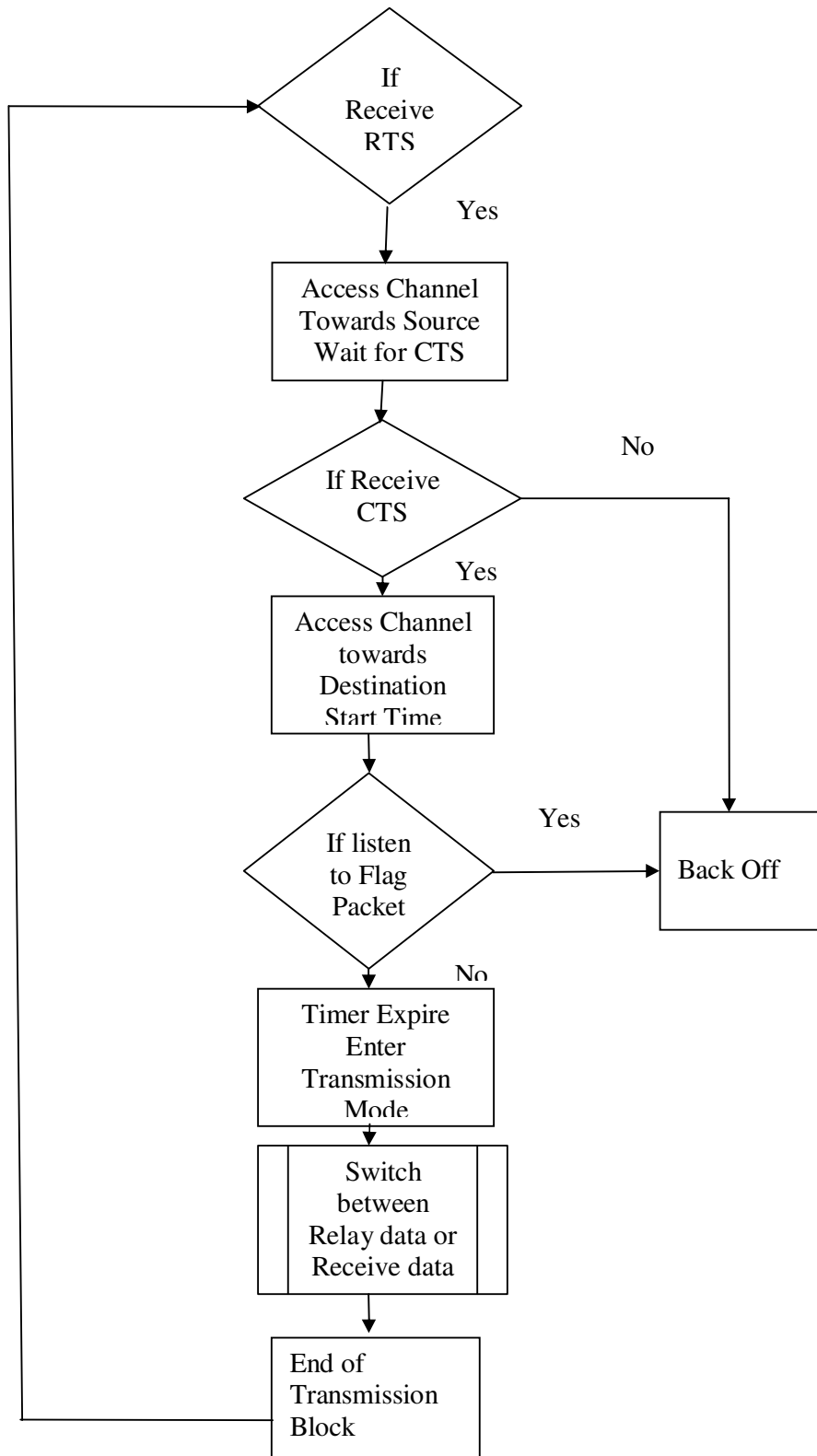


Fig.4.2.1: Flowchart of the algorithm as performed at each relay.

4.3 PROTOCOL DESCRIPTION

4.3.1 All Relay Participation

In this protocol, all relays in the network participate. The advantage of this protocol is that there is very little centralized control required, since any node that decodes a packet heard during the broadcast period simply transmits during the relay period. On the other hand, this protocol might cause many nodes involved in forwarding source information, which results in more energy consumption across network than the CRP protocol. In order to optimize the selection technique we use the opportunistic selection technique which is explained in the chapter second.

4.3.2 Opportunistic Relay Selection

Two functions are used in this work: under Policy I, the minimum of the two is selected, while under Policy II, the harmonic mean of the two is used

- Under Policy I

$$h_i = \min \{ a_{si}^{-2}, a_{id}^{-2} \} \quad (4.3.1)$$

- Under Policy II

$$h_i = \frac{2}{\frac{1}{a_{si}^{-2}} + \frac{1}{a_{id}^{-2}}} = \frac{2 a_{si}^{-2} a_{id}^{-2}}{a_{si}^{-2} + a_{id}^{-2}} \quad (4.3.2)$$

The relay i that maximizes function h_i is the one with the "best" end-to-end path between initial source and final destination. After the best relay has been selected, then it can be used to forward information towards the destination. Whether that "best" relay will transmit simultaneously with the source or not, is completely irrelevant to the relay selection process.

We consider an i.i.d. slow Rayleigh fading channel model following [7]. A half duplex constraint is imposed across each relay node, i.e., it cannot transmit and listen

simultaneously. We assume that the nodes (transmitter and relays) do not exploit the knowledge of the channel at the physical layer. Note that in the process of discovering the best relay described in the previous section, the nodes do learn about their channel gains to the destination. However, we assume that this knowledge of channel gain is limited to the network layer protocol. The knowledge of channel gain is not exploited at the physical layer in order to adjust the code rate based on instantaneous channel measurements. In practice, the hardware at the physical layer could be quite constrained to allow for this flexibility to change the rate on the fly. It could also be that the transmitter is operating at the minimum transmission rate allowed by the radio hardware. Throughout this section, we assume that the channel knowledge is not exploited at the physical layer at either the transmitter or the relays. If the discrete time received signal at the destination and the relay node are denoted by $Y[n]$ and $Y_1[n]$ respectively,

$$Y[n] = a_{sd} X[n] + Z[n], \quad n=1, 2, \dots, \frac{T}{2}$$

(source transmits destination receives) (4.3.3)

$$Y[n] = a_{rd} X_1[n] + Z[n], \quad n = \frac{T}{2}, \frac{T}{2} + 1, \dots, T$$

(best relay transmits destination receives) (4.3.4)

$$Y_1[n] = a_{sr} X[n] + Z_1[n] \quad n = 1, 2, \dots, \frac{T}{2}$$

(source transmits best relay receives) (4.3.5)

Here a_{sd} , a_{rd} , a_{sr} respective channel gains from the source to destination, best relay to destination, and source to the best relay, respectively. The channel gains between any two pair of nodes are i.i.d. $N(0,1)$. The noise $Z[n]$ and $Z_1[n]$ at the destination and relay are both assumed to be i.i.d. circularly symmetric complex Gaussian $N(0, \sigma^2)$. $X[n]$ and $X_1[n]$ are the transmitted symbols at the transmitter and relay, respectively. T denotes the duration of time-slots reserved for each message and we assume that the source and the relay each transmit orthogonally on half of the time-slots. We impose a power constraint at both the source and the relay:

$$E[|X[n]|^2] \leq P \tag{4.3.6}$$

and

$$E[|X_1[n]|^2] \leq P \quad (4.3.7)$$

For simplicity, we assume that both the source and the relay to have the same power constraint.

We will define

$$\rho \triangleq \frac{P}{\sigma^2} \quad (4.3.8)$$

to be the effective SNR. This setting can be easily generalized when the power at the source and relays is different.

In the two-hop case, signalling of the packet occurs over two orthogonal time slots, and it is assumed that the inter-node distances are fixed for the duration of both time slots. During the first slot, termed the broadcast period, the source broadcasts to both N_D and a set $P \subseteq R$ of the relays. The relays in P are the participating relays. Each relay $N_{R_k} \in P$ receives a signal $Y_{R_k}(t)$ from the source and, after demodulation, checks for errors using the CRC code. The set $D \subseteq P$ of participating relays that receive the packet without errors is called the decoding set, and the number of decoding relays $|D| = M$. The value of M is random and depends on the channel quality between source and each relay. During the second time slot, termed the relay period, all nodes in D transmit signals $X_{R_k}(t)$ to N_D , which combines the transmissions from the relay(s) and a stored copy of the source transmission using the joint DFE receiver.

More specifically τ_o is the delay from N_S to N_D , and τ_k is the cumulative delay for the transmission from N_S to N_{R_k} , processing at N_{R_k} and for transmission from N_{R_k} to N_D . The noise processes $W_S(t)$, $W_D(t)$ and $W_k(t)$, $k = 1, \dots, K$ are independent complex

white Gaussian noise with two-sided power spectral density N_0 . The complex channel gain $\alpha_{i,j}$ captures the effects of both path loss and the quasi-static fading from node N_i to node N_j , where $i \in \{S, R_1, \dots, R_K\}$, and $j \in \{R_1, \dots, R_K, D\}$. Statistically, $\alpha_{i,j}$ will be modelled as zero mean, mutually independent complex jointly Gaussian random variables with variances $\sigma_{i,j}^2$. The fading variances can be assigned using wireless path loss models based on the network geometry. Here, it is assumed that $\sigma_{i,j}^2 \propto \frac{1}{d_{i,j}^\mu}$, where $d_{i,j}$ is the distance from node N_i to N_j , and μ is a constant whose value, as estimated from field experiments, lies in the range $2 \leq \mu \leq 5$ [5]. It is assumed that $\alpha_{i,j}$ is estimated accurately at the receiver, but is not available to the transmitter. It is assumed that each relay node transmits with identical power unless otherwise stated. Under the modelling assumed above, the signals in Fig.3.1.1 are:

$$Y_{R_k}(t) = \alpha_{S,R_k} X_S(t) + W_k(t), \quad k = 1, \dots, K \quad (4.3.9)$$

$$Y_{D_S}(t) = \alpha_{S,D} X_S(t) + W_S(t) \quad (4.3.10)$$

$$Y_{D_R}(t) = \sum_{j=1}^K \alpha_{R_j,D} X_{R_j}(t - \tau_j) + W_D(t) \quad (4.3.11)$$

where $Y_{D_S}(t)$ and $Y_{D_R}(t)$ have no common support in the time domain, and $W_S(t)$ and $W_D(t)$ are independent and identically distributed white Gaussian random processes. The transmitted signal from the source is

$$X_S(t) = \sum_{k=-\infty}^{\infty} I_k h_{T_X}(t - kT), \quad (4.3.12)$$

where $h_{T_X}(t)$ is the impulse response of the transmit pulse shaping filter, T is the symbol period, and I_k is the k^{th} complex data symbol with

$$\begin{aligned}
I_k &= a_k + jb_k, \frac{1}{2} E [|I_k|^2] \\
&= \sigma_i^2 = 1,
\end{aligned} \tag{4.3.13}$$

and $\{I_k\}$ is a sequence of uncorrelated symbols that is independent of $\{W_j(t)\}$. It is assumed that $h_{Tx}(t)$ has a squared root raised cosine (SRRC) impulse response with a filter roll-off factor $\beta \in [0, 1]$. Denote each front-end receiver filter response as $h_{Rx}(t)$, which is matched to the SRRC transmitter filter, i.e.,

$$h_{Rx}(t) = h_{Tx}^*(-t).$$

It is assumed that all nodes transmit with equal power $P = \sigma_i^2$.

4.4 RECEIVER AND OPTIMIZATION

Let

$$h_{c,R}(t) = \sum_{i \in D} \alpha_{i,D} \delta(t - \tau_i) \tag{4.4.1}$$

be the complex base band impulse response of the equivalent multipath channel between the collection of transmitting relays and the destination node. Denote the raised cosine (RC) pulse by

$$h_{RC}(t) = h_{Tx}(t) \otimes h_{Tx}^*(-t) \tag{4.4.2}$$

where \otimes is the convolution operation.

Thus the equivalent complex base band impulse response at the destination for the transmissions from the relays is

$$h_D(t) = \sum_{i \in D} \alpha_{i,D} h_{RC}(t - \tau_i) \quad (4.4.3)$$

it will be assumed that the receiver is able to accurately estimate this channel. The complex noise at the output of the receiver filter is

$$v_D(t) = W_D(t) \otimes h_{Rx}(t), \quad (4.4.4)$$

which has autocorrelation function

$$\begin{aligned} \phi_{v_D}(\tau) &= \frac{1}{2} E[v_D(t) v_D^*(t + \tau)] \\ &= N_0 h_{RC}(\tau) \end{aligned} \quad (4.4.5)$$

for the SRRC receiver. The receiver structure is depicted in Fig.3.3.1. Note the difference from the standard DFE, since the signal $Y_{D_S}(t)$ received while the source is transmitting must also be jointly processed. This structure, along with the joint optimization of such, is one of the contributions of this work. The continuous time signal at the output of $h_{Rx}(t)$ at N_D during the time the relays are transmitting is

$$\begin{aligned} y_D(t) &= h_{Rx}(t) \otimes Y_{D_R}(t) \\ &= \sum_{n=-\infty}^{\infty} I_n h_D(t - nT) + v_D(t). \end{aligned} \quad (4.4.6)$$

The fractional spaced (i.e., T/2 spaced) equalizer is considered due to its robust performance [27]. The input-output relation for the discrete time equivalent channel from the multiple relays to the input of the feed forward filter at the destination is

$$\begin{aligned} y_{D,k+\psi} &\triangleq y_D[(k+\psi)T + t_0] \\ &= \sum_{n=0}^L I_{k-n} h_{D,k+\psi} + v_{D,k+\psi}, \end{aligned} \quad (4.4.7)$$

where

$$\begin{aligned} h_{D,n+\psi} &= h_D((n+\psi)T+t_0), \quad v_{D,k+\psi} \\ &= v_D(kT+\psi T+t_0) \end{aligned} \quad (4.4.8)$$

with k and n integer (int.), and $\psi \in \{0, \frac{1}{2}\}$. By properly selecting the initial sampling time t_0 , the channel impulse response $h_D(t+t_0)$ is approximated as nonzero over the time interval $[0, LT]$, where L is an integer. The FFF is an anti-causal filter with L_f $T/2$ -spaced taps and coefficients $\{c_{(1-L_f)/2}, \dots, c_{-1}, c_{-1/2}, c_0\}$. The FBF is a causal filter with L_b T -spaced taps and coefficients $\{c_1, c_2, \dots, c_{L_b}\}$. The length L_b of the FBF is assumed to be equal to the length of the channel, i.e., $L_b = L$ [28]. In practice, L_f is chosen one to five times the channel pre-cursor length, which is determined by the position of the peak amplitude response of $h_D(t+t_0)$ [28]. For the signal $Y_{D_S}(t)$ received while the source node is transmitting, whose support does not overlap that of $Y_{D_R}(t)$, the equivalent discrete-time channel model at the output of the T -spaced sampler is

$$\begin{aligned} y_{S,k} &= y_S(kT+t_0) \\ &= \alpha_{S,D} I_k + v_{S,k}, \end{aligned} \quad (4.4.9)$$

where $y_S(t)$ is the output of the receiver filter during the time the source is transmitting and $\{v_{S,k}\}$ is a sequence of independent complex Gaussian random variables with zero mean and variance $E[|v_{S,k}|^2] = 2N_0$ which are independent of $\{v_{D,k+\psi}\}$.

The coefficients of the FFF and FBF, as well as β_0 which is used to scale and derotate for the direct path $y_{S,k}$, can be obtained by assuming correct past decisions and minimizing the mean squared error (MSE)

$$MSE = E[|I_k - u_k^T c|^2]$$

Where the x^T denotes non-conjugate transpose of a vector x . The data vector u_k is defined as

$$\mathbf{u}_k \triangleq [y_{D,k+(L_f-1)/2}, \dots, y_{D,k+1}, y_{D,k+1/2}, y_{D,k}, y_{S,k}, I_{k-1}, I_{k-2}, \dots, I_{k-L_b}]^T, \quad (4.4.10)$$

and the vector of filter coefficients \mathbf{c} is denoted as

$$\mathbf{c} \triangleq [c_{(1-L_f)/2}, \dots, c_{-1}, c_{-1/2}, c_0, \beta_0, c_1, c_2, \dots, c_{L_b}]^T \quad (4.4.11)$$

By applying the orthogonality principle [29], i.e., $E[(\mathbf{I}_k - \mathbf{z}_k) \mathbf{u}_k^*] = 0$, where $\mathbf{z}_k = \mathbf{u}_k^T \mathbf{c}$, the filter coefficients are determined as:

$$c_{(1-L_f)/2:0} = (1 - \beta_0 \alpha_{S,D}) \Omega^{-1} \mathbf{p} \quad (4.4.12)$$

$$\beta_0 = \alpha_{S,D}^* \frac{1 - \tilde{U}_0}{2N_0 / \sigma_c^2 + |\alpha_{S,D}|^2 (1 - \tilde{U}_0)}, \quad (4.4.13)$$

and

$$c_j = - \sum_{i=(1-L_f)/2:0} h_{D,j-1} c_i, \quad j = 1, 2, \dots, L_b, \quad (4.4.14)$$

where $(1-L_f)/2:0 = (1-L_f)/2, \dots, -1, -1/2$,

\mathbf{p} is a column vector of dimension L_f with $p_i = h_{D,-i}^*, i = (1-L_f)/2:0$, and the scalar

$\tilde{U}_0 = \mathbf{p}^\dagger \Omega^{-1} \mathbf{p}$, where \mathbf{p}^\dagger is the conjugate transpose of \mathbf{p} . The matrix Ω is determined by the autocorrelation of the data vector

$$\mathbf{u}_k, \quad \Omega = \Gamma - \Lambda^* \Lambda^T,$$

where the elements of matrices Γ and Λ are

$$\Gamma_{i,j} = \frac{1}{2} E[y_{D,k-i} y_{D,k-j}^*] = \sum_{n \in \mathcal{Z}} h_{D,n-i}^* h_{D,n-j} + \phi_{VD}((i-j)T) \quad (4.4.15)$$

for $i, j \in \{\frac{1-L_f}{2}, \dots, -1, -1/2, 0\}$,

$$\text{and } \Lambda_{i,j}^T = h_{D,i-j} \quad (4.4.16)$$

for $i \in \{1, 2, \dots, L_b\}$, and $j \in \{(1-L_f)/2:0\}$.

4.5 PERFORMANCE ANALYSIS

4.5.1 Mean Squared Error

To aid in the performance analysis, suppose temporarily that only the combined relay signal $Y_{DR}(t)$ is used to estimate the source packet $\{I_k\}$, i.e., $Y_{DS}(t)$ is disregarded. The coefficient vector \tilde{c} of the FFF and FBF has been obtained in [32], [27] using the MMSE criterion, which is denoted as

$$\tilde{c} \triangleq [\tilde{c}_{(1-L_f)/2}, \dots, \tilde{c}_{-1}, \tilde{c}_{-1/2}, \tilde{c}_0, \tilde{c}_1, \tilde{c}_2, \dots, \tilde{c}_{L_b}]^T$$

with entries $\tilde{c}_{(1-L_f)/2:0} = \Omega^{-1} p$, and

$$\tilde{c}_j = - \sum_{i=(1-L_f)/2:0} h_{D,j-1} \cdot c_i, \quad j = 1, 2, \dots, L_b,$$

Given \tilde{c} , the minimum mean squared error for the standard DFE can be shown to be

$$(M\tilde{S}E)_0 = \sigma_c^2 (1 - \tilde{U}_0) \quad [33], \text{ where } \sigma_c^2 = 2\sigma_f^2 = 2s.$$

However, when $Y_{DS}(t)$ and $Y_{DR}(t)$ are employed to jointly estimate I_k , the minimum mean squared error can be shown to be

$$(MSE)_0 = (M\tilde{S}E)_0 \frac{2N_0}{2N_0 + |\alpha_{S,D}|^2 (M\tilde{S}E)_0}. \quad (4.5.1)$$

The input to the slicer z_k can be expressed in a generic way, i.e.,

$$z_k = u_k^T c = I_k U_0 + \sum_{n \neq 0} I_{k-n} U_n + \tilde{v}_k$$

where \tilde{v}_k is Gaussian noise term which is independent of the ISI, and $\{U_n\}$ are ISI coefficients. The signal-to-interference-and-noise-ratio (SINR) at the input of the slicer is thus defined as [33]

$$SINR = \frac{|U_0|^2 \sigma_c^2}{\sigma_c^2 \sum_{n \neq 0} |U_n|^2 + E |\tilde{v}_k|^2} \quad (4.5.2)$$

Combining Eq. (4.5.1) and Eq. (4.5.2), we obtain

$$SINR = \frac{\sigma_c^2 - (MSE)_0}{(MSE)_0} = SIN\tilde{R} + \frac{\sigma_c^2 |\alpha_{s,D}|^2}{2N_0}, \quad (4.5.3)$$

where the first equation is due to the lack of correlation in the data sequence, as well as the relationship of $(MSE)_0 = \sigma_c^2(1-U_0)$ [33], and $SIN\tilde{R} = \frac{\sigma_c^2 - (MSE)_0}{(MSE)_0}$ is the SNR of the

DFE-MMSE without utilizing the direct path knowledge $\{y_{S,k}\}$. Given the direct path

signal as in (3.3.1), $\frac{\sigma_c^2 |\alpha_{s,D}|^2}{2N_0}$ is the signal-to-noise ratio in $y_{S,k}$. Therefore, the joint

DFE-MMSE estimation of the data sequence as proposed here achieves the sum of the SNR from the two channels at the input to the slicer. One channel is from the relays in D , and the other one is from the source NS directly. Clearly, as the number of relays increases, the performance improvement expected by also processing the signal from the source, which only contributes a single degree of diversity, decreases due to the diminishing marginal returns for an additional degree of diversity as the diversity order increases.

4.5.2 Diversity Gain

As a case study, this section considers a scenario where the number of participating relays is two. This is always the case for the CRP protocol, but could also occur in the ARP protocol when $K = 2$. This analysis will demonstrate that the artificial delays introduced in protocol variant AD are needed to achieve a diversity gain equal to the number of transmitting nodes, which in this scenario is three. Note the outage probability considered

in this paper is defined as the probability that the frame error probability conditioned on the channel fading parameters is below a prescribed threshold [33]. This is equivalent to the probability that the SINR at the input of the slicer of DFE-MMSE is below a resulting threshold γ_T , i.e. $P_{out} \triangleq \Pr[SINR < \gamma_T]$.

From Eq. (4.5.3), we can see that \tilde{SINR} is essentially the SNR of an unbiased DFE-MMSE [23] for the channel between relays and destination. On the other hand, the fractional spaced equalizer realizes both the matched filter and the symbol rate feed-forward equalizer [34, pp. 388] whose mean squared error satisfies [35]:

$$\log\left[\frac{\sigma_c^2}{(MSE)_0}\right] = \frac{1}{2\pi} \int_{-\pi}^{\pi} \log(1 + \rho |S_{hh}(\theta)|^2) d\theta, \quad (4.5.4)$$

$$\text{where } \rho = \frac{\sigma_c^2}{2N_0} \text{ and } |S_{hh}(\theta)|^2 = \frac{1}{T} \sum_m |F(\theta + 2\pi m) / 2\pi T|^2$$

is the folded power spectrum of an equivalent composite channel impulse response including both the transmit filter $h_{Tx}(t)$ and channel filter $h_{c,R}(t)$. Let $H_{RC}(f)$ and $H_{c,R}(f)$ denote the frequency response of $h_{RC}(t)$ and $h_{c,R}(t)$, respectively. Then we have $F(f) = H_{RC}(f) H_{c,R}(f)$ since the receiver's front end filter has a squared-root-raised cosine impulse response. For the purpose of simplicity in derivation and without loss of generality, assume the roll-off factor is $\beta = 0$. It is straightforward to show that

$$|S_{hh}(\theta)|^2 = \frac{1}{T} \sum_m |F(\theta / 2\pi T)|^2 = T \left| \sum_{i \in D_R(s)} \alpha_{i,D} e^{-j\tau_i \theta / T} \right|^2,$$

for $\theta \in [-\pi, \pi]$.

Denote

$$C_1 = \frac{1}{2\pi} \int_{-\pi}^{\pi} \log(1 + \rho |S_{hh}(\theta)|^2) d\theta$$

and

$$C_2 = \log(1 + |\alpha_{s,D}|^2)$$

It can be shown that $P_{out} \in [P_{out,L}, P_{out,U}]$ where $P_{out,U} = \Pr[C_1 + C_2 < 2\log(1 + \gamma_T/2)]$

and $P_{out,L} = \Pr[C_1 + C_2 < \log(1 + \gamma_T)]$.

Actually, $(C_1 + C_2)/2$ is the instantaneous mutual information of a relay channel with relay nodes using an identical codebook independent of what is sent by the source node [36]. It has been shown in [37] that when two relay nodes both have successfully decoded the source message and the relative delay satisfies $|\delta_T| B_w > 2$

where $\delta_T = \tau_1 - \tau_2$ and $B_w = 1/T$ is the bandwidth of the base band signal when $\beta = 0$, a relay channel having mutual information $(C_1 + C_2)/2$ achieves diversity of order 3,

$$\text{i.e. } \frac{-\log \Pr[(C_1 + C_2)/2 < R]}{\log \rho} \rightarrow 3, \text{ as } \rho \rightarrow \infty \quad (4.5.5)$$

where R is a fixed code rate. Thus, under a given SNR threshold γ_T and as SNR increases, the decoding set almost surely consists of two relay nodes, and it can be concluded that the diversity order defined by

$$d_0 \triangleq \lim_{\rho \rightarrow \infty} -\log P_{out} / \log \rho$$

is three based on the bounds of P_{out} as provided above, as well as Eq. (4.5.5).

Therefore, in order to achieve the same diversity order as the synchronous space-time coded approach, the cumulative delay of the disparate paths needs to satisfy the condition of $|\delta_T| B_w > 2$. This implies that there are certain node geometries under which systems employing relays that do not introduce artificial delay (ND) will experience a loss in diversity, hence motivating the use of the Artificial Delay (AD) variant.

SIMULATION RESULTS

The performance of the proposed schemes will be compared with that of [9] in which an orthogonal space-time block code [31] is employed under the assumption that the relay symbol boundaries are synchronized at the destination. This comparison allows the determination of how much performance can be retained by the proposed protocols while relaxing the symbol synchronization requirements.

In Fig. 5.1, the outage probability of the CRP protocol is compared with that of [9] employing the space-time orthogonal block codes when both of the two nearest nodes are available to forward the correctly received packets. Also considered for comparison is the single hop transmission without any relaying as indicated by the dotted-star line in Fig. 5.1, which is allowed to increase its transmit power proportionally if M is larger than zero in the relaying schemes, i.e., the transmit SNR is $(1+M)/N_0$, to make a fair comparison. In order to see the impact of relative delays on the performance, D is increased from 1 to 3 with the maximum delay T scaled proportionally from $1.5T$ to $4.5T$ while fixing $K + 2 = 100$. Since the received SNR at N_j from N_i is

$$E \left[\frac{|\alpha_{i,j}|^2}{N_0} \right] = 1 / (N_0 d_{i,j}^\mu),$$

the transmit power will be scaled from 1 to D_L^μ to make the average received SNR be

$$\left(\frac{D_L}{d_{i,j}} \right)^\mu / N_0.$$

Therefore, the x-label of Fig. 4 is the average scaled transmit SNR, D_L^μ / N_0 .

From Fig. 5.1, it can be seen that the CRP protocol using the DFE-MMSE at N_D can achieve a diversity gain over the single-hop scheme, as expected. However, for the CRP/AD protocol, the result demonstrates that the performance is only slightly (< 1 dB) worse than a synchronous system. Therefore, it is concluded that even if symbol

synchronization is impossible due to the infrastructureless nature of an ad hoc wireless network, comparable performance can be obtained by employing the decision feedback equalizer at N_D and setting the delays as a new resource for the involved relay nodes to compete. Increasing the maximum delay T from $1.5T$ to $4.5T$ does not affect the gain much under variant ND, which is expected since in the CRP protocol only nearest two nodes are selected leading to irresolvability of two paths when no extra delay is inserted as in variant AD. Also notice even under variant AD, there is also not much performance improvement when the intentional delay is increased from $1T$ to $3T$.

Fig. 5.3 demonstrates the performance of the ARP/ND protocol. In Fig. 5.3 and the following two figures, the path loss exponent is set to zero so that the diversity achieved can be observed more easily. Such a setting would perfectly match a system with some form of closed loop relay power control. However, if such is not performed (or it is not accurate), the same diversity will be achieved in each of the schemes but the performance will be worse. Energy normalization across the whole network is considered in Fig. 5.3 to show the performance contributed purely by the cooperative diversity gain. With the path loss coefficient $\mu = 1.5$, if M nodes are involved in relaying, the total signal power collected from all these paths plus the one from the source directly is $(M + 1)$. Then multiply N_0 by a factor of $(M + 1)/3$ if $M \geq 2$ such that the transmit SNR for each node in D is $\frac{3}{(M + 1)N_0}$, where the coefficient 3 is for the purpose of comparing with the case of $K = 2$, in which the maximum number of transmit nodes is 3. (one is NS, another 2 are relay nodes). In terms of both simulation results and the matched filter bound, it can be observed that as $K + 2$ is increased from 10 to 100 in a given area, not much improvement is made on the system performance. This is due to the increasing density of relay nodes in this area, which leads to different clusters of nodes. The delays from N_S to the relay nodes in each cluster and then to N_D are similar. The number of clusters will determine the asymptotic diversity gain in a given area when equalizer is employed at N_D .

Fig. 5.4 demonstrates that for the ARP/AD protocol, randomly introducing the artificial delays to the signals transmitted by the active relay nodes can change the asymptotic tendency observed in Fig. 5.3 even in the relatively low transmit SNR region, which implies the improvement in diversity gain even if the density of nodes is increased. Note that this protocol requires no coordination of the relays whatsoever, and that the performance will be improved. Hence, it is very suitable for implementation to achieve

the gains promised by cooperative diversity. Of course, eventually there are diminishing returns when more relay nodes are added, since the fixed number of resolvable paths for a given delay pool are all exploited with very high probability for any large number of nodes.

The separate combination scheme refers to an approach in which the coefficient β in Fig. 3.3.1 is first replaced by the MMSE coefficient for a direct link, i.e. $\widehat{\beta}_0 = \alpha_{s,D}^* / (|\alpha_{s,D}|^2 + 2N_0 / \sigma_c^2)$ and the FFF and FBF coefficients are determined assuming $\alpha_{s,D} = 0$ in Eq. (4.4.12) and Eq. (4.4.14). To normalize the linear combination, a scaling factor 1/2 is introduced to both $\widehat{\beta}_0$ and FFF and FBF coefficients. The pre-combination scheme refers to an approach in which a matched filter is put at the front end of receivers for each link and then the two outputs are added together before performing a fractional spaced DFE-MMSE equalization. The FFF and FBF coefficients in this case can be calculated similarly as in Section 3.3.1. Our simulation results exhibit significant amount of gains over both of these two approaches.

Assumptions

A network of $K+2$ uniformly distributed nodes in a square area with one side length D_L as in Fig. 1 is considered. The maximum propagation delay T_D in this area along the diagonal line is set as a rational number of symbol periods T , e.g., $T_D = 3T$. If the bit rate is $2/T = 2(\text{Mbps})$, this translates to an area of one side length $D_L = 636.5(\text{m})$. The signal to noise ratio (SNR) defined as the ratio of the transmitted signal power to the receiver noise power at each transmitter side is $\sigma_1^2 / N_0 = 1/N_0$ due to the normalized signal power. Each packet consists of $L_P=200$ uncoded QPSK symbols, where

$I_k = a_k + jb_k, a_k, b_k \in \{1, -1\}$. The SRRC transmit filter $h_{Tx}(t)$ is truncated to $[-4T, 4T]$ with a roll-off factor $\beta = 0.35$. The length L_b of the FBF is assumed to be equal to the length of the channel, and L_f is chose to be equal to twice the channel pre-cursor length.

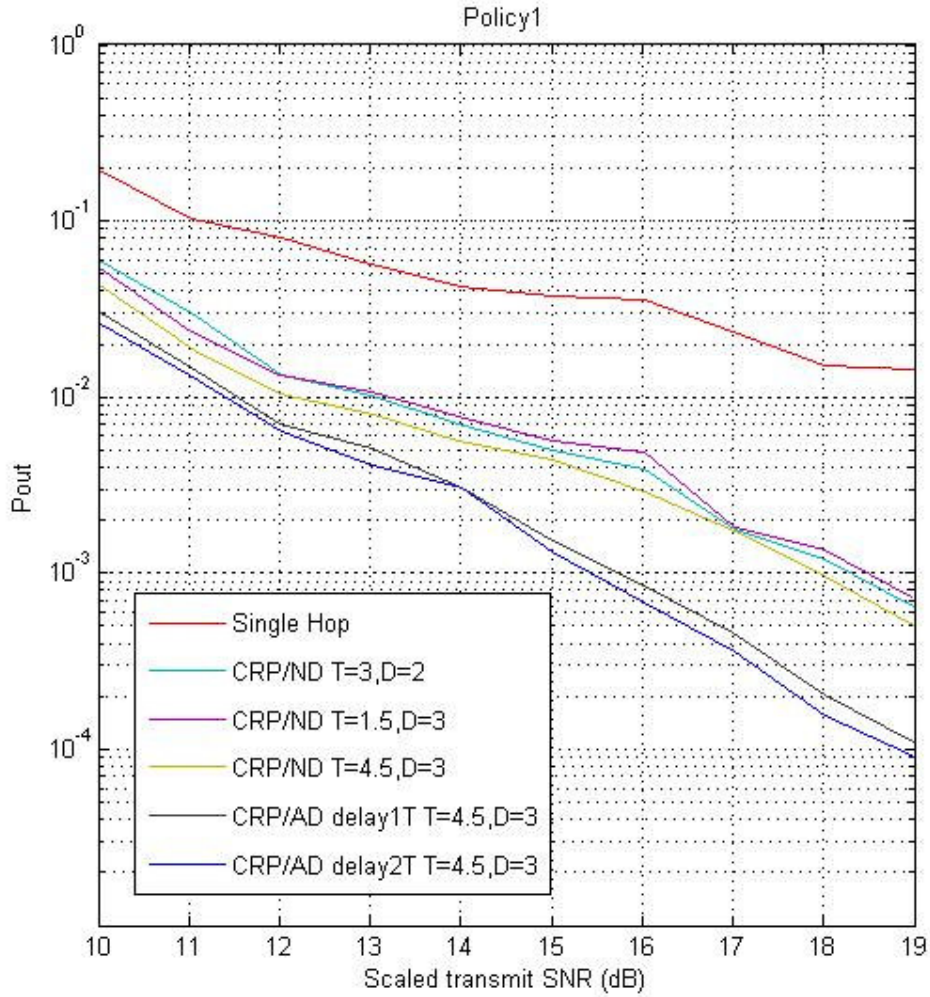


Fig. 5.1: Outage probability comparison of Protocol CRP The path loss coefficient $\mu=1$. The number of nodes in an area is $K + 2 = 100$. D is the length of one side of the square region considered. T is the maximum propagation delay in the region in terms of the number of symbol periods.

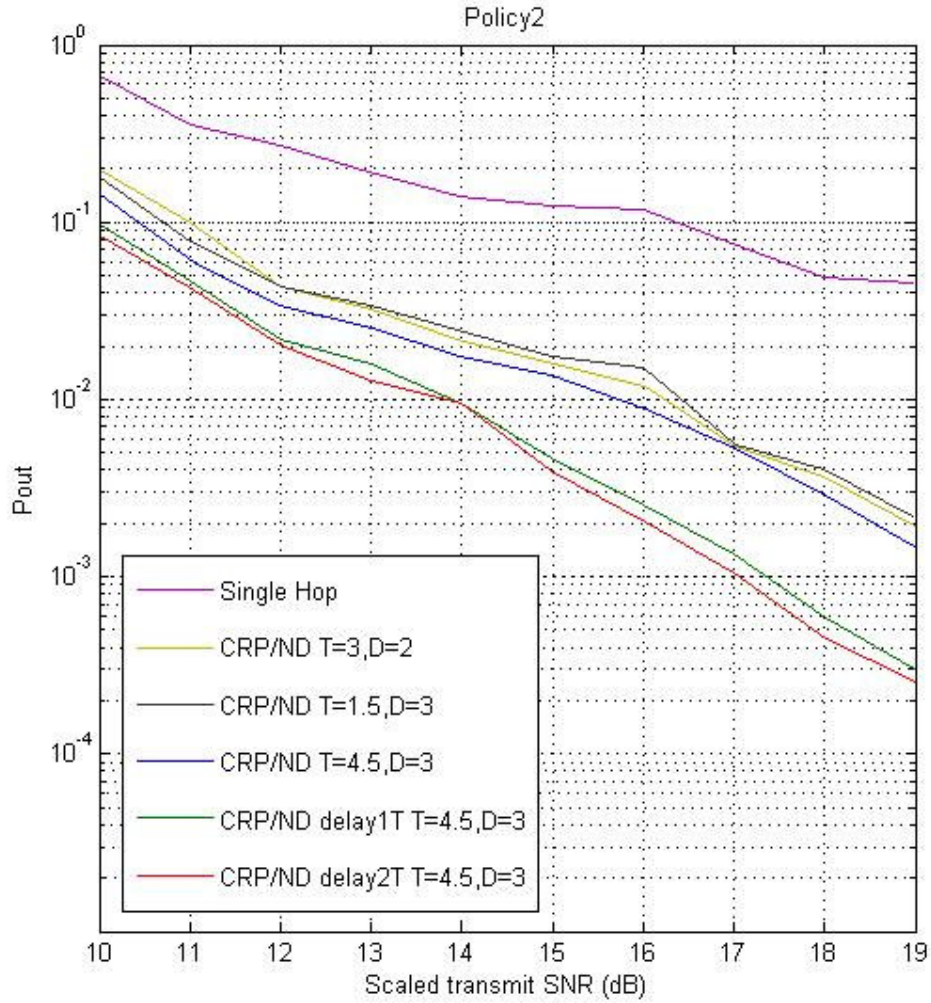


Fig. 5.2: Outage probability comparison of Protocol CRP. The path loss coefficient $\mu=1$. The number of nodes in an area is $K + 2 = 100$. D is the length of one side of the square region considered. T is the maximum propagation delay in the region in terms of the number of symbol periods.

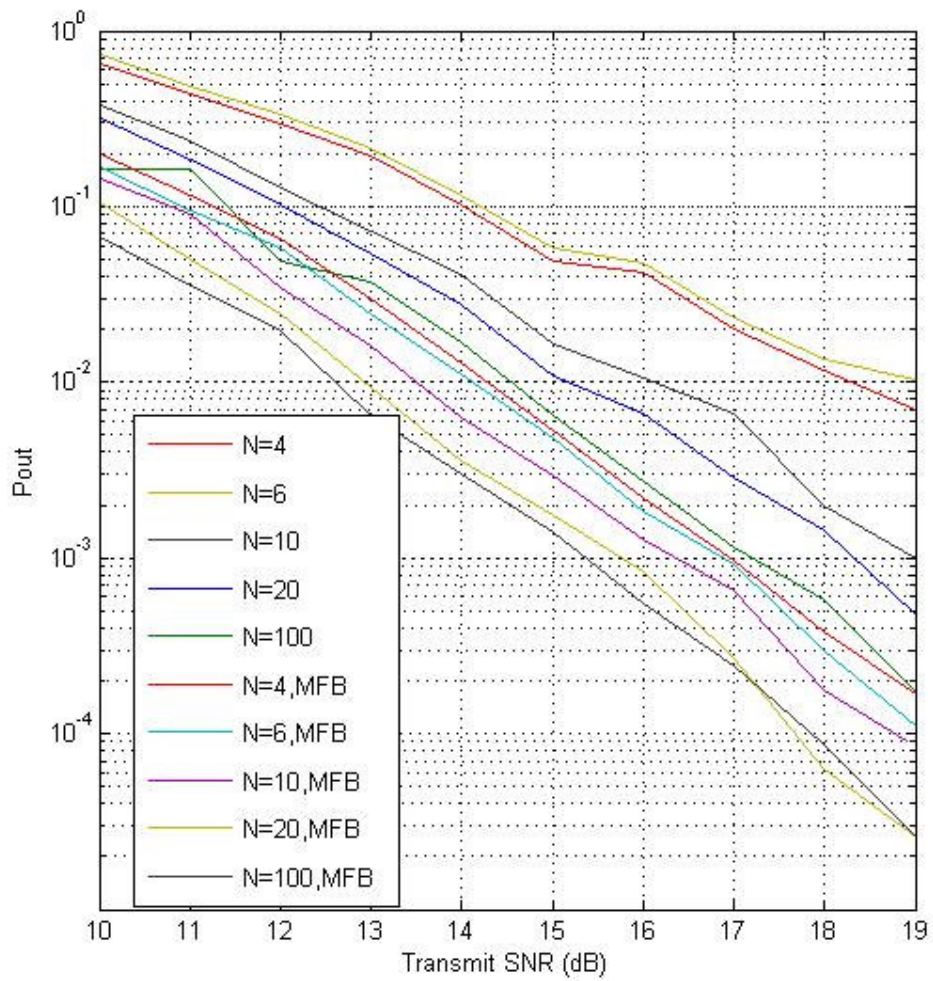


Fig. 5.3: The outage probability of Protocol ARP/ND with normalization of the received noise power. In the simulations, the parameters are set as $\mu = 1.5$, $D = 3$, $T = 4.5T$.

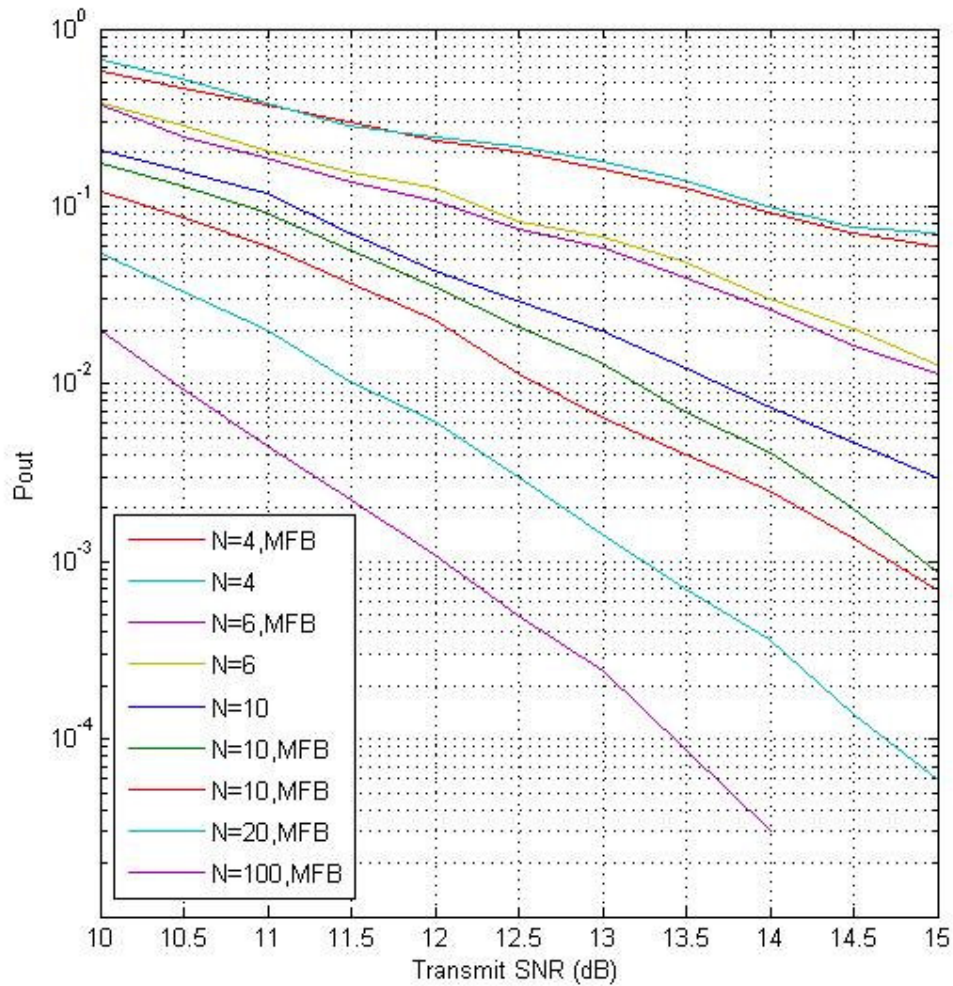


Fig.5.4: The outage probability of Protocol ARP/AD with normalization of the received noise power. In simulations, the parameters are set as $\mu = 1.5$, $D = 3$, $T=4.5T$. The pool of delays is $\{T, 2T, \dots, 6T\}$ from which delays are randomly allocated to the packets transmitted by the active relays. MFB in the figure stands for matched filter bound.

CONCLUSIONS AND FUTURE WORK

In this work, we have studied the latest techniques of virtual antenna systems by using the cooperation between the various ad-hoc devices. In asynchronous cooperative diversity method using opportunistic selection technique, we first select the best relay from a set of M available relays and then use this “best” relay for cooperation between the source and destination. We analyze a distributed method to select the best relay that requires no topological information and is based on local measurements of the instantaneous channel conditions. This method also requires no explicit communication among the relays. After selection of best path by using the opportunistic relay, we transfer the data by using asynchronous cooperation diversity method.

The data path selection by using the opportunistic relay removes the complexity of most of the proposed solutions, which require distributed space–time coding algorithms. The best relay selection algorithm lends itself naturally into cooperative diversity protocols, which improve reliability in wireless communication systems using distributed virtual antennas. The protocol is distributed, and each relay only makes local channel measurements. Relay selection is based on instantaneous channel conditions in the slow fading wireless environments. No prior knowledge of topology or estimation of it is required. Opportunistic relaying provides an alternative solution with a very simple physical layer to the conventional cooperative diversity protocols that rely on the space–time codes.

The proposed technique makes use of opportunistic relay diversity along with the asynchronous data transfer cooperation diversity to enhance the data rate efficiency, which utilizes minimum mean squared error receiver for combining desperate inputs in the multiple relay channel. This asynchronous diversity scheme do not require symbol level timing synchronization, which can be quite costly in terms of signalling overhead in the mobile ad-hoc networks, which are often defined by their lack of a fixed infrastructure and the difficulty of centralized control. Due to the simplicity, the presented asynchronous diversity technique facilitates the implementation of high data rate advanced wireless communication systems including OFDM, space-time architectures and BLAST

The physical layer approach of employing the DFE-MMSE at the destination was taken as a means to realize such diversity gains, and a novel joint DFE-MMSE equalizer was derived. Based on the proposed outage probability criterion, simulation results demonstrate the performance improvements of the protocols over the single hop scheme, as well as performance comparable to protocols requiring strict symbol synchronization [9]. The result is a promising scheme for realizing the gains of cooperative diversity in networks, without significant signalling overhead or centralized control. We restrict our attention to two hop relay networks where the destinations jointly process the direct link and the relay link information. Our intention is to explore the two-hop case to demonstrate how diversity gain can still be maintained even without symbol level synchronization in wireless networks using our proposed protocols, as well as the novel DFE-MMSE receiver. There are several important issues not addressed in this work but can be continued in future work, we give a brief discussion of them below.

The first one is the extension of our work to the multi-hop case. If the outage probability at the destination is too high to be acceptable under a given transmission power constraint, relaying with multiple hops should be deployed. The idea will be similar as the two-hop case. One possible hopping strategy could be that each level of relay nodes retrieves the source information by jointly processing the signals from the two closest previous levels of relay nodes using a joint DFE-MMSE receiver that is similar to the one developed in this paper, or, of course, an analogous joint DFE-MMSE receiver could be derived to process signals from more levels of relaying. The decoding set at each level is subject to both the SINR at the input of the slicer under the ARP protocol and locations of these nodes. Incorporating location information is to avoid flooding the whole network in selecting relay nodes [30].

The second is the relationship between the diversity gain and density and geometry of intermediate nodes in a network. Under the ARP protocol, any node which succeeds in decoding the source packets forwards that information towards the destination. In a dense ad-hoc network, the same level of relay nodes could be very close to each other, which makes their transmissions unresolvable even after introducing some random delays from a fixed delay pool as under protocol variant AD. Therefore, achievable diversity gain should be a function of node density and their relative locations, as well as the size of the random delay pool.

REFERENCES

- [1] S. Y. Hui and K. H. Yeung, "Challenges in the Migration to 4G Mobile Systems," *IEEE Communication Magazine*, vol. 41, pp. 54 - 59, December 2003
- [2] T. S. Rappaport, "Wireless Communications: Principles and Practice", Prentice Hall PTR, 2000.
- [3] W. C. Jakes, "Microwave Mobile Communications", New York: Wiley, 1974.
- [4] D. Tse and P. Viswanath, "Fundamentals of Wireless Communication", Cambridge University Press, 2005.
- [5] A. Sendonaris, E. Erkip, and B. Aazhang, "User Cooperation Diversity – Part I: System Description," *IEEE Trans. Communication.*, vol. 51, pp. 1927-1938, Nov. 2003.
- [6] A. Sendonaris, E. Erkip, and B. Aazhang, "User Cooperation Diversity – Part II: Implementation, Aspects and Performance Analysis," *IEEE Trans. Communication*, vol. 51, pp 1939-1948, Nov. 2003
- [7] J. N. Laneman, D. N. C. Tse, and G. W. Wornell, "Cooperative Diversity in Wireless Networks: Efficient Protocols and Outage Behavior," *IEEE Trans. Inf. Theory*, vol. 50, no. 12, pp. 3062-3080, Dec. 2004.
- [8] J. N. Laneman, G. W. Wornell, and D. N. C. Tse, "An Efficient Protocol for Realizing Cooperative Diversity in Wireless Networks," in *Proceedings of the IEEE International Symposium on Information Theory (ISIT)*, Washington, DC, June 2001.
- [9] J. N. Laneman and G. W. Wornell, "Distributed Space-Time Coded Protocols for Exploiting Cooperative Diversity in Wireless Networks," *IEEE Trans. Inf. Theory*, vol. 49, no. 10, pp. 2415-2525, Oct. 2003.
- [10] E. V. D. Meulen, "Three-terminal communication channels," *Advances in Applied Probability*, vol. 3, pp. 120-154, 1971.
- [11] T. M. Cover and A. A. El Gamal. "Capacity theorems for the relay channel," *IEEE Trans. Inf. Theory*, vol. 25, pp. 572-584, Sept. 1979.
- [12] K. Azarian, H. E. Gamal, and P. Schniter, "On the achievable diversity- vs-multiplexing tradeoff in cooperative channels," *IEEE Trans. Inf. Theory*, vol. 51, pp. 4152–4172, Dec. 2005.
- [13] A. Goldsmith and S. Wicker, "Design challenges for energy-constrained ad hoc wireless networks," *IEEE Personal Communication*, vol. 9, pp. 8–22, Aug. 2002.

- [14] J. N. Laneman and G.W.Wornell, "Energy-efficient antenna-sharing and relaying for wireless networks," in Proc. *IEEE Wireless Communications and Networking Conference WCNC*, Chicago, IL, Sept. 2000.
- [15] A. Stefanov and E. Erkip, "Cooperative coding for wireless networks," in Proc. *IEEE Conference on Mobile and Wireless Communications Networks*, Stockholm, Sweden, Sept. 2002.
- [16] T. Hunter and A. Nosratinia, "Coded cooperation under slow fading, fast fading, and power control," in Proc. Asilomar Conference on Signals, Systems, and Computers, Nov. 2002.
- [17] A. Stefanov and E. Erkip, "Cooperative space-time coding for wireless networks," in Proc. *IEEE Information Theory Workshop*, La Sorbonne, Paris, France, April 2003.
- [18] A. Scaglione and Y. W. Hong, "Opportunistic large arrays: cooperative transmission in wireless multihop ad hoc networks to reach far distances," *IEEE Trans. Signal Proc.*, vol. 51, pp. 2082–2092, Aug. 2003.
- [19] M. Hasna and M.-S. Alouini, "End-to-end performance of transmission systems with relays over Rayleigh-fading channels," *IEEE Trans. Wireless Comm.*, vol. 2, no. 6, pp. 1126–1131, Nov. 2003.
- [20] M. Hasna and M.-S. Alouini, "Harmonic mean and end-to-end performance of transmission systems with relays," *IEEE Trans. Communication*, vol. 52, no. 1, pp. 130–135, Jan. 2004.
- [21] D. T. J. Laneman and G. Wornell, "Cooperative diversity in wireless networks: efficient protocols and outage behavior," *IEEE Trans. Inform. Theory*, vol. 50, pp. 3062–3080, Dec. 2004.
- [22] J. Boyer, D. Falconer, and H. Yaniko meroglu, "Multihop diversity in wireless relaying channels," *IEEE Trans. Communication*, vol. 52, pp. 1820–1830, Oct 2004.
- [23] D. Goeckel and Y. Hao, "Macroscopic space-time coding: motivation, performance criteria, and a class of orthogonal designs," in Proc. *Conference on Information Sciences and Systems (CISS)*, March 2003.
- [24] N. Seshadri and J. H. Winters, "Two signaling schemes for improving the error performance of frequency-division-duplex (FDD) transmission systems using transmitter antenna diversity," in Proc. 43rd *IEEE Vehicular Technology Conference*, 1993, pp.508–511.
- [25] S. Lin and D. J. Costello, "Error Control Coding: Fundamentals and Applications", Prentice-Hall, 1983.

- [26] M. A. Khojastepour, A. Sabharwal, and B. Aazhang, "On the capacity of cheap relay networks," in *Proc. Conference on Information Sciences and Systems (CISS)*, March 2003.
- [27] J. E. Smee and N. C. Beaulieu, "Error-rate evaluation of linear equalization and decision feedback equalization with error propagation," *IEEE Trans. Communication.*, vol. 46, pp. 656–665, May 1998.
- [28] I. J. Fevrier, S. Gelfand, and M. Fitz, "Reduced complexity decision feedback equalization for multipath channels with large delay spreads," *IEEE Trans. Communication.*, vol. 47, pp. 927–937, June 1999.
- [29] J. G. Proakis, *Digital Communications*, 3rd ed. New York: McGraw-Hill, 1995.
- [30] B. Sirkeci-Mergen and A. Scaglione, "A continuum approach to dense wireless networks with cooperation," in *IEEE Infocom*, Miami, U.S., March 13-17, 2005.
- [31] S. M. Alamouti, "A simple transmit diversity technique for wireless communications," *IEEE J. Select. Areas Commun.*, vol. 16, pp. 1451–1457, Oct. 1998.
- [32] J. E. Smee and N. C. Beaulieu, "On the equivalence of the simultaneous and separate MMSE optimizations of a DFE FFF and FBF," *IEEE Trans. Commun.*, vol. 45, pp. 156–158, 1997.
- [33] P. Balaban and J. Salz, "Optimum diversity combining and equalization in digital transmission with applications to cellular mobile radio – part I & II," *IEEE Trans. Commun.*, vol. 40, pp. 885–907, May 1992.
- [34] J. R. Barry, E. A. Lee, and D. G. Messerschmitt, *Digital Communications*. Kluwer Academic, 2004.
- [35] J. M. Cioffi, G. P. Dudevoir, M. V. Eyuboglu, and G. D. Forney, "MMSE decision-feedback equalizers and coding II: coding results," *IEEE Trans. Commun.*, vol. 43, pp. 2595–2603, Oct. 1995.
- [36] S. Wei, "Diversity-multiplexing tradeoff of asynchronous space-time coded cooperative diversity," *Proc. Allerton Conf. Commun., Control, Computing*, Oct. 2004.
- [37] S. Wei, "Diversity-multiplexing tradeoff of asynchronous cooperative diversity in wireless networks," *IEEE Trans. Inform. Theory*, Feb. 2006, 1st revision submitted.