Performance Analysis of User Cooperation in Wireless Peer-to-Peer Networks

by

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This is to certify that I have examined this copy of a master's thesis by

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and have found that it is complete and satisfactory in all respects,
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To my parents

ABSTRACT

Peer-to-peer (P2P) architectures for file sharing among ad hoc, possibly dynamic, collections of hosts are generating an increasing fraction of the traffic on today's Internet and are reshaping the way new network applications are designed. The idea is to have hosts participate in an overlay network, enabling signaling, routing, and searching among participating hosts. Once a host locates the document(s) of interest, direct connections are established to mediate their transfer. The key principle is to allow, and in fact encourage, participating hosts to play dual roles as servers and clients - thus hosts are considered peers.

Recently, wireless peer-to-peer networking has gained attention in the research community, where the peers are distributed over the geography and are capable of cooperation in a wireless fashion. The wireless scenario introduces specific design challenges; the wireless channel is time-varying and hostile, and the system resources, in terms of available transmission power and bandwidth, are scarce. In this study, building on the recent body of work on cooperative networks, we aim to develop an information theoretic framework to assess the performances of various peer-to-peer protocols that may be considered in the wireless regime. Various design criteria will be studied: maximization of the system capacity, minimization of the average download time, fairness among peers in energy utilization, optimal rate allocation to the layers when scalable video transmission is considered.

ÖZETÇE

Günümüzde görevdeş ağlar bir taraftan İnternet trafiğinin önemli bir kısmını teşkil ederken diğer taraftan da yeni ağ uygulamalarının tasarımını etkiliyor. Görevdeş ağlardaki ana fikir kullanıcıların bilgi arayabilecekleri ve bilgi alışverişinde bulunabilecekleri bir ağa dahil edilmeleridir. Bir kullanıcı bir dosyayı paylaşıma açtığında dosya transferini olanaklı kılacak bağlantılar oluşturulur. En önemli amaç ağa iştirak eden kullanıcıları alıcı olmanın yanı sıra sunucu da olabilecekleri şekilde dosya paylaşmaya teşvik etmektir.

Son zamanlarda telsiz görevdeş ağlar araştırma dünyasının bir hayli ilgisini çekti. Görevdeş ağın telsiz ortamda olması ise ekstra tasarım zorlukları getirmektedir; telsiz kanal zamanla değişkendir ve sistem kaynakları -bant genişliği ve güç açısından- oldukça kısıtlıdır. Bu çalışmada, kullanıcı işbirlikli ağlar üzerine yakın zamanda yapılan çalışmaları baz alarak çeşitli protokollerin performanslarını karşılaştıracağımız bilgi kuramsal bir analiz yapıyoruz. Üzerinde çalıştığımız çeşitli tasarım kriterlerini şu şekilde sıralayabiliriz; sistem sığasının enbüyültülmesi, ortalama dosya indirme zamanının enküçültülmesi, kullanıcılar arasında enerji tüketimi açısından en adil olunması ve ölçeklenebilir video iletiminde gönderim hızının katmanlara en iyi şekilde tahsis edilmesi.

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

NOMENCLATURE

P2P	Peer to Peer
AWGN	Additive White Gaussian Noise
AF	Amplify and Forward
DF	Decode and Forward
DPC	Dirty Paper Coding
H.264	A video coding standard
BL	Base Layer
EL	Enhancement Layer
CIF	Common Intermediate Format
fps	frames per second
GOP	Group of Pictures

Chapter 1

INTRODUCTION

The rapid development of world wide web applications along with the dramatic growth in cellular networks over the past decades brought with it the continually growing need for easy and cheap data sharing over mobile networks. Peer to peer networking came as a solution for data sharing in distributed environments in early 1990's but owes its popularity to Napster [1], which in 1999 enabled millions of people to share especially their mp3 and multimedia files. These networks simply consist of dynamic nodes connected via internet, which collaborate to provide resources to each other and are thus both content providers and content requesters.

1.1 Peer-to-peer Networking

The main goal of peer-to-peer networking is to share system resources in terms of power, cpu, storage, bandwidth, etc. in a dynamic, distributed and heterogeneous network as effective, secure and fair as possible. To achieve the goal many researches have been done and many architectures have been developed recently. These architectures range from completely centralized to completely decentralized. The pioneering networks including Napster, also known as first generation networks, are based on a client - server architecture as shown in Fig. 1.1. For Napster each client has to index all its shared files and then send this index information to the central server when connected to the network. If a client wants to download a file, it is able to search all connected clients' files by sending search queries to the server. The server then searches this file in demand in its list and returns another list of search results. These results provide the client with the meta-data of the files and speed of the clients owning them. The client chooses one of the files in the search results and begins downloading it directly from the client sharing it. This client-server architecture is considered as a peer-to-peer protocol, since the files are not stored in the servers and fully transferred among clients. However, this architecture has certain drawbacks. First, it suffers from single point failures, that is, if the Napster server is turned off, e.g. for legal issues, the network is totally gone. Second, the need of central servers increases expenses. These drawbacks motivated people to develop decentralized architecturres and second generation networks were born.

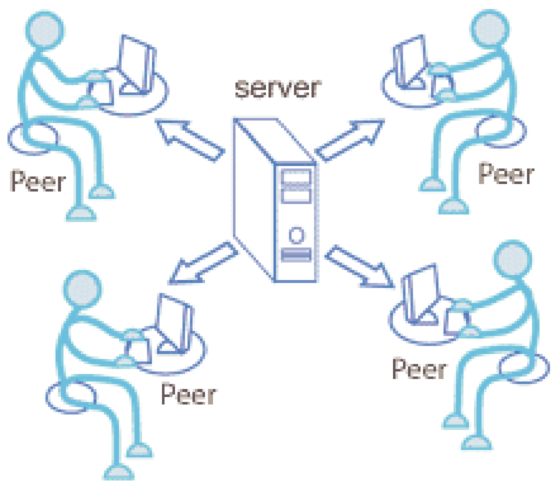


Figure 1.1: Centralized Network Model: Clients are connected to central servers (Figure taken from [2]).

Gnutella [3] is a peer-to-peer networking protocol, which uses a distributed architecture in which clients are directly connected to other clients without need to any central servers as shown in Fig. 1.2. When a client runs Gnutella it is connected to a certain number of clients that are also connected to a certain number of clients. If a client starts searching a file, it sends the search query to the clients it is connected to, each of which forwards the query to its own clients that are connected to it. This forwarding process continues until predetermined time to live (TTL) value drops to 0. The search query replies go to the requestor client along the path they came. Like Napster, client chooses one of the matches and starts downloading the file directly from the matched client. Since the network does not rely on central servers, any link failure affects a few number of clients. However, forwarding of the search queries dramatically increases network traffic and thus renders the protocol slow and inefficient.

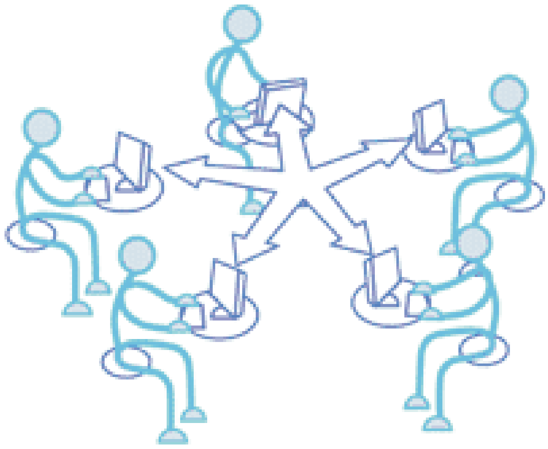


Figure 1.2: Decentralized Network Model: Each client is connected to a certain number of clients (Figure taken from [2]).

The drawbacks of client-server and decentralized architectures lead to the development of third generation hybrid methods. These hybrid methods follow hierarchical designs (Fig. 1.3). The clients are divided in two groups; supernodes, which have fast connections to the network and ordinary nodes, which have slower connections to the network. Each ordinary node is connected to a supernode, which is connected to other supernodes, and every process regarding the ordinary node is performed by its supernode. This hierarchy reduces the search traffic. Kazaa [4] is an example hybrid architecture.

1.2 Wireless Peer-to-Peer Networking and User Cooperation

The popularity of peer-to-peer networks, the prevalence of mobile devices, and advances in mobile technologies such as wireless LANs and 3G networks, facilitated the migration of peer-to-peer applications into wireless environment and fueled numerous

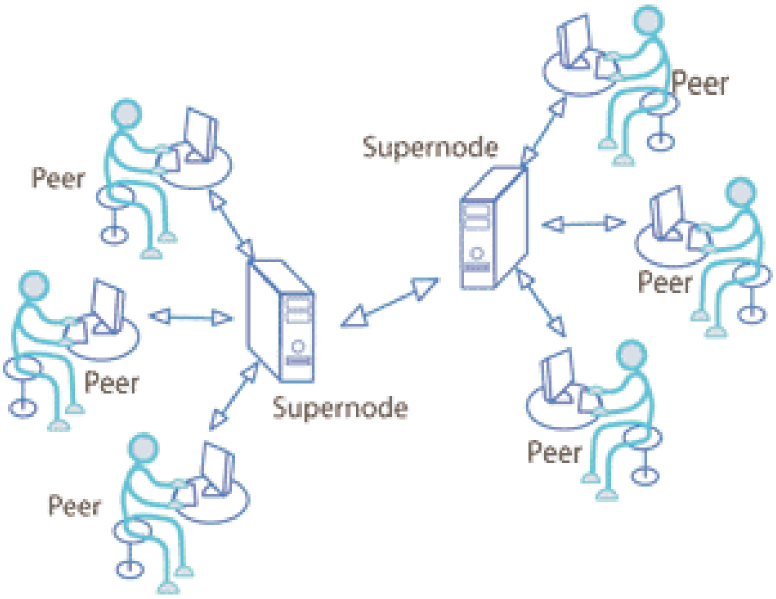


Figure 1.3: Hybrid Network Model: Ordinary nodes are connected to supernodes and supernodes are connected to each other. (Figure taken from [2]).

researches, both academic and commercial [5], [6].

One of the main challenges of peer-to-peer-networking is to provide network services in a decentralized and unstable environment. For the wireless environment, the conditions are even more severe. Wireless channels suffer from propagation losses, fading, shadowing and interference. The links are no more stable and bandwidth is very precious. These facts necessitate the development of schemes that mitigate problems of wireless peer-to-peer networks. *User cooperation* constitutes an effective means in this sense by achieving multiplexing gain -by parallel downloading- or diversity gain -by user cooperation diversity. Parallel downloading is a technique, in which users download different parts of the same file from multiple sources instead of downloading the entire file from a single source. User cooperation diversity, on the other hand, is a technique where single antenna users share their information to form a virtual antenna array and achieve benefits of transmitter diversity. These two user cooperation methods can be used separately or together. We examine the user cooperation concept and the methods detailed in chapter 2.

1.3 Prior Work on User Cooperation

The fundamental ideas behind user cooperation stem back to Meulen's work on the relay channel [7]. Since then cooperative wireless communications concept has been attracting more and more attention in research community due to the substantial benefits it is offering in terms of system robustness and increased performance. User cooperation can be employed in mobile applications including -but not limited to- wireless sensor, multi-hop wireless, cellular and peer-to-peer networks to provide robustness, time and resource savings by improving link quality, channel capacity and power efficiency.

User cooperation concept is information theoretically investigated for ad hoc and cellular networks in several recent researches. Sendonaris et. al. [8], [9] considered a network with a single receiver and two cooperating transmitters each having information of their own to send. By their work they show that user cooperation increases the capacity of the system and leads to a more robust system by decreasing the susceptibility of the achievable rates to channel variations. Laneman et. al. [10] focused on the case of two cooperating terminals communicating to either the same or separate destination terminals. They demonstrate that by using distributed antennas, the benefits of spatial diversity can be achieved without any need for physical arrays. By this way, the system performances are increased for the same power consumption level or less power is consumed to achieve the same performances. Hunter et. al. [11], [12] propose coded cooperation, where the users transmit additional parity for its partner's data instead of repeating it. Based on the new concepts introduced in these researches, several work has been proposed [13]-[15]. Jindal et. al. [16] analyzed an interference channel with two independent transmitters and two independent receivers where each transmitter wants to communicate to a different receiver. In this work, they find that cooperation at the transmitter side significantly increases system performances in terms of increased capacity, but cooperation at the receiver side does not bring noteworthy performance improvements without transmitter cooperation. This is the only work, to our best knowledge, that considers both transmitter and receiver cooperation.

1.4 Contributions of the Thesis to the Field of Study

This thesis differentiates itself from the previous work on cooperative communications in a number of ways. First, we investigate the peer-to-peer networks information theoretically. Second, we extend the joint transmitter and receiver cooperation concept investigated by Jindal et. al. to peer-to-peer networks. In wireless peer-to-peer networks, in contrast to cellular networks, since the requested file may be served by more than one user, transmitting users are not all sending independent information. Likewise, receiving users are not receiving special independent information because one file may be in demand by several users. Therefore relaying receivers do not use their received signals to solely help transmitters, which is the case in the above mentioned scenarios, but they also process their receptions for their own use.

The thesis mainly provides solutions to the optimal rate allocation problems in a cooperative wireless peer-to-peer network. These problems can be enumerated as follows:

1. Which of the user cooperation methods, user cooperation diversity or parallel downloading, is advantageous when the goal is to minimize the downloading time of the file in demand?

2. If the peers are randomly distributed in a geographical region, which method is advantageous on the average, when the average is across the download time and taken over sufficient number of geographical distributions?

3. If the transmitter peers are sending a scalable video how should the cooperation methods be used together in order to maximize the bit rate and thus the quality of the video?

1.5 Outline of the Thesis

We begin by introducing the reader to user cooperation concept in chapter 2. We explain two user cooperation methods, user cooperation diversity and parallel downloading, and a hybrid cooperation method. We then describe broadcast, multiple access and relay channels. Later we give a general overview of the wireless channel and Gaussian channel capacity subjects, and introduce our system model in chapter 3. We first describe the wireless channel and its impairments and then mention to the famous channel capacity concept. Then we describe the wireless peer-to-peer system model that we work on throughout the thesis. The problems and results based on our two-transmitter two-receiver wireless peer-to-peer network that we define in chapter 3 are discussed in chapters 4, 5 and 6. In chapter 4, the effects of user cooperation on the performance of our system is examined through capacity optimization. In chapter 5, average system performances are considered and compared. We deal with scalable video transmission problem in Chapter 6. Chapter 7 summarizes the conclusions of the ideas developed in this thesis and discusses future work.

Chapter 2

USER COOPERATION

A wireless communication network consisting of numerous interconnected nodes, introduces new ingredients to the system such as interference, cooperation and multi-user channels. In this chapter we examine how these ingredients are involved in a cooperative network. We consider three multi-user channel types; broadcast, multiple access and relay channels. A *broadcast channel* consists of a single terminal transmitting to many receiving terminals. The transmitting terminal sends either the same or independent messages to the receivers and we will consider the former case for our system. In contrast to the broadcast channel, the channel where multiple terminals wish to communicate to a single terminal is called *multiple access channel*. The introduction of several signals to the same destination results in *interference*. Interference can be mitigated by constructing orthogonal channels for each different signal or using orthogonal coding strategies such as dirty paper coding which we mention in section 3.4. The last multi-user channel that we consider is the relay channel. In a *relay channel* [17] there is a transmitter, a receiver and also relays to improve the communication between the receiver and transmitter. In classical relay systems, relays neither request any information for their own use nor send their own information; rather they are intermediate nodes solely helping the receiver. A cooperative wireless network is a combination of numerous broadcast, multiple access and relay channels. The only difference is that relay nodes are not necessarily dummy nodes only forwarding others' information like in the classical relay channel, but they can also request information for their own use. We can conclude that in a cooperative wireless network each node can be a receiver, transmitter and relay at the same time.

2.1 Cooperation Methods

This section provides answers to how user cooperation is used and which multi-user channels are involved in a cooperative wireless network. We describe two fundamental cooperation methods, user cooperation diversity and parallel downloading, in detail.

2.1.1 Parallel Downloading Method

Instead of downloading the entire file from a single source, downloading different parts of the same file from several sources in parallel is called parallel downloading [18] or swarming [19]. Parallel downloading concept was first mentioned in 1999 by Byers et. al. [20] as a way to speed up the downloads by parallel accessing to multiple mirror sites. The main idea of parallel downloading is to divide the file in a number of chunks and give the client the facility to simultaneously download different chunks from different sources. After the chunk is downloaded by the client, it is immediately served to the access of other clients. BitTorrent [21], [22] divides files into typically 256KB sized pieces. Peers first download pieces that are the least available among the peers. This is the idea that allowed BitTorrent to replicate files in a short amount of time, increase the availability of sources and by this way provide high download rates to the clients.

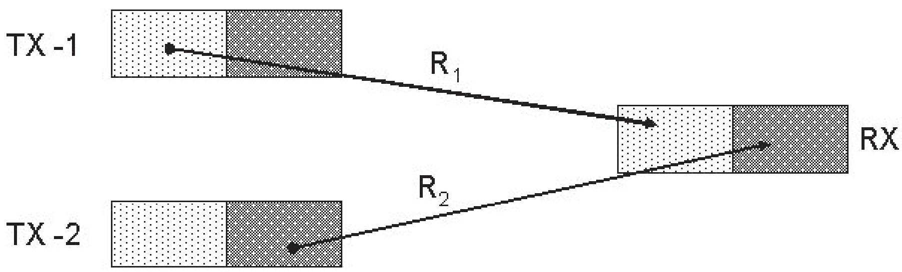


Figure 2.1: Parallel Downloading Method: Total rate flow to the receiver is $R_1 + R_2$ bits/s

Parallel downloading method is simply illustrated in Fig. 2.1. Receiver gets the first portion of the file from Transmitter-1 with rate R_1 bits/s and the second portion from Transmitter-2 with rate R_2 bits/s. Thus the total rate flow to the receiver is $R_1 + R_2$ bits/s. Dividing the information into several parts and transmitting each part from different paths may increase the total rate flow to the receiver through multiplexing gain.

2.1.2 User Cooperation Diversity Method

Transmitter diversity is a fading mitigation scheme in which the same information is transmitted over different fading paths. Since different paths probably do not experience deep fades at the same time, combination of the signals at the receiver reduces the effect of fading. The so-called user cooperation diversity is a spatial transmitter diversity technique in which single antenna users share their antennas to form a virtual antenna array achieving benefits of multiple antenna systems. User cooperation diversity concept was first introduced by Sendonaris et al [8], [9] as a method to achieve diversity gain through distributed transmissions.

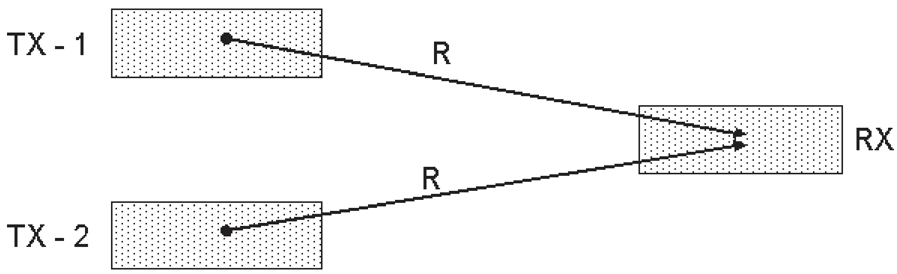


Figure 2.2: User Cooperation Diversity Method: Total rate flow to the receiver is R bits/s

Fig. 2.2 is the illustration of user cooperation diversity method. Both transmitters simultaneously send the same part of the file with rate R bits/s, thus the total rate flow to the receiver is R bits/s. Increased power allocated to the same information may increase the total rate flow to the receiver through diversity gain.

2.1.3 Hybrid Method

User cooperation diversity and parallel downloading methods can be used in conjunction. For example, there may be both common and distinct files in demand. The common files can be sent by user cooperation diversity method, whereas parallel downloading can be utilized for the transmission of the distinct files. This hybrid method can also be used for the transmission of a scalable video. All the transmitters may send the base layer to benefit from diversity and the enhancement layers may each be sent by different transmitters in a parallel fashion. We will deal with this scalable video transmission problem in Chapter 6.

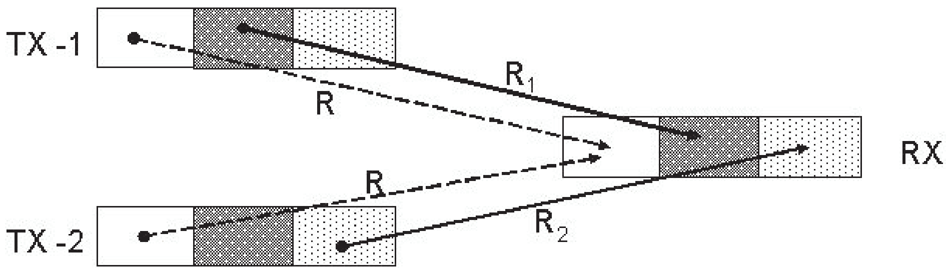


Figure 2.3: Hybrid Method: Total rate flow to the receiver is $R + R_1 + R_2$ bits/s

The illustration of the method is shown in Fig. 2.3. The first portion of the file is transmitted by both of the transmitters with rate R bits/s. The second and third portions are transmitted by Transmitter-1 with rate R_1 and Transmitter-2 with rate R_2, respectively. This results in a total rate flow of $R+R_1+R_2$ bits/s to the receiver. This method may be advantageous if there are receivers demanding both common and distinct files.

2.2 Relay Transmission Protocols

Relaying constitutes the basis for the cooperation in wireless peer-to-peer networks. There are several relay transmission protocols that relays use to forward the information received from the source to the other relays or destination, two of which we describe here and use in our work; decode-and-forward and amplify-and-forward transmission.

2.2.1 Decode-and-Forward Transmission

Relays using decode-and-forward transmission scheme fully decode, re-encode and retransmit their received signals. If decode-and-forward transmission scheme is used, the error in the received signal is corrected in each hop of the signal from one relay to the other and by this way error propagation is prevented. However, decoding of the signal in each relay increases delay, computational load on the relays and relay design complexity.

2.2.2 Amplify-and-Forward Transmission

For amplify-and-forward transmission method, the relay first scales its received signal by an amplification factor and then transmits this scaled version of the signal to the destination. The relay chooses an amplification factor such that it remains within its power constraint. Since decoding of the received signal is not required, implementing amplify-and-forward transmission scheme in the relay design is simpler compared to decode-and-forward scheme. However for multi-hop communications, forwarding the received signal without decoding it in each hop may cause error propagation as the number of hops increases. Additionally, amplify-and-forward method can work even if the channel is at outage but also is not appropriate for wireless networks, because wireless channels are unreliable and susceptible to a lot of interference [23].

Chapter 3

FUNDAMENTALS AND SYSTEM MODEL

Before examining user cooperation in detail, this chapter provides the reader with a summary of the basic features of wireless channel modeling and channel capacity concepts and then introduces the system model we work in the thesis.

3.1 Wireless Channel Modeling

Transmission through the air interface places inevitable limitations on the reliable communication over wireless channels. The wireless channel is susceptible to time-varying channel impairments among which are interference, path loss, shadowing and fading. These effects are often modeled based on the empirical measurements.

The transmitted signal strength attenuates as it travels from the transmitter to receiver. The ratio of the linear transmitted power to the linear received power is defined as linear *path loss*:

$$PL = \frac{P_t}{P_r} \tag{3.1}$$

where P_t is the transmitted and P_r the received signal powers.

We use a log-distance path loss model with path loss exponent γ [23].

$$\overline{PL} \text{ dB} = K \text{ dB} - 10\gamma log_{10}(\frac{d}{d_0}) \tag{3.2}$$

$$K \text{ dB} = 20log_{10}\frac{\lambda}{4\pi d_0} \tag{3.3}$$

$$d_0 = \frac{4h_t h_r}{\lambda} \tag{3.4}$$

Here, $\overline{PL}$ dB is the average path loss in dB, h_t is the transmitter and h_r the receiver antenna heights, λ is the wavelength and d is the distance between the transmitter and receiver. We set path loss exponent γ to 4 and h_t, h_r to 2m each.

As the transmitted signal propagates, it experiences absorption, reflection, scattering and diffraction due to the obstacles on its path, which results in an attenuation of the signal power. This attenuation caused by the obstacles between the transmitter and receiver is called *shadowing* and frequently modeled as a log-normal distribution with the path loss as its mean. In other words path loss is a random variable with log-normal distribution around the average path loss formulated in Eq. (3.2).

For the combined path loss and shadowing model, the ratio of the the received power to the transmitted power is [23]:

$$\frac{P_r}{P_t}\text{ dB} = K\text{ dB} - 10\gamma log_{10}(\frac{d}{d_0}) - \Psi_{dB} \tag{3.5}$$

where Ψ_{dB} is zero mean Gaussian distributed random variable with variance $\sigma^2_{\Psi_{dB}}$.

Due to the scattering of the transmitted signal in the transmission path, multiple copies of the signal arrive at the receiver. However these signals arrive in slightly different times resulting in a self-interference called *multipath fading* and may severely reduce the received signal power. We use the Rayleigh distribution to model the amplitude of the faded received signal [23]. If X and Y are two zero mean Gaussian distributed random variables with equal variances σ^2, the random variable $Z = \sqrt{X^2 + Y^2}$ is Rayleigh and Z^2 is exponentially distributed. The received signal envelope is Rayleigh distributed and received signal power is exponentially distributed with mean $2\sigma^2$. In other words $\overline{P_r} = 2\sigma^2$, where $\overline{P_r}$ is the average received signal power determined by Eq. (3.5).

The square root of the ratio of the received power to the transmitted power is called *fading coefficient*, which capture the combined effects of path-loss, shadowing and multipath Rayleigh fading and denoted by h:

$$h^2 = \frac{P_r}{P_t} \tag{3.6}$$

3.2 Gaussian Channel Capacity

The channel capacity issue was first studied by Shannon in the late 1940s in his work named "A mathematical theory of communication" [24]. Shannon defined channel capacity to be the upper bound on the amount of information that can be transmitted with arbitrarily small probability of error. In order to calculate this maximum achievable transmission rate, he also introduced a measure of the amount of information in a message and called this measure as mutual information. He formulated channel capacity as the maximum of the mutual information between the input and output of the channel, where the maximization is over all input distributions:

$$C = \max_{E[X^2] \leq P} I(X;Y) \tag{3.7}$$

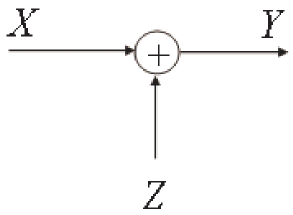


Figure 3.1: Gaussian Channel

Consider an additive white Gaussian noise channel, where the output Y is the sum of the input X and the Gaussian noise Z as shown in Fig. 3.1:

$$Y = X + Z \tag{3.8}$$

The capacity of such a channel is given by Shannon's famous formula:

$$C = log(1 + \frac{P}{N}) \text{ bits per transmission} \tag{3.9}$$

and this capacity is achieved by the input distribution of $CN(0, P)$. Here P is the transmitted -also received- power level, N is the Gaussian noise variance and $CN(0, P)$ denotes the zero-mean complex Gaussian distribution with variance P.

For the band-limited channel with additive white Gaussian noise, the capacity is given by Shannon-Hartley theorem:

$$C = Blog(1 + \frac{P}{N_0 B}) \text{ bits per second} \tag{3.10}$$

where B is the bandwidth of the channel in Hz and N_0 is the noise spectral density in Watts per Hz.

For the wireless fading channel model described in section 3.1 the additive white Gaussian channel output is $Y = hX + Z$ and the capacities are:

$$C = log(1 + \frac{h^2 P}{N}) \text{ bits per transmission,} \tag{3.11}$$

and

$$C = Blog(1 + \frac{h^2 P}{N_0 B}) \text{ bits per second} \tag{3.12}$$

for the AWGN and band-limited AWGN channels, respectively.

In the presence of noise, as long as $R < C$ error-free transmission can be accomplished.

3.3 System Model

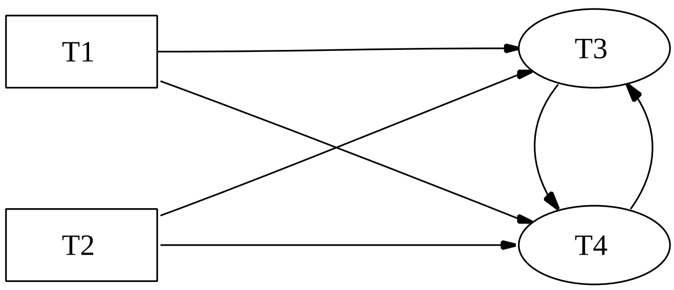


Figure 3.2: System model.

Consider a four-user peer-to-peer system as shown in Figure 3.2. T1 and T2 are the transmitting peers having the same K bit sized file. T3 and T4 are the receiving peers both demanding this file. The aim is to send this file to the receiving peers in the shortest time. On the one hand, transmitting peers cooperate to broadcast same or different portions of the file, that is they utilize parallel downloading or user cooperation diversity methods, and on the other hand receiving peers cooperate by exchanging the file portions that they received before, using either decode-and-forward or amplify-and-forward schemes. We assume channel state information is available to all of the peers. This simple system model is an example of decentralized peer-to-peer networks mentioned in chapter 1, however a real network with a lot of users may motivate one to use hybrid designs. The channel can be formulated in matrix form as:

$$\begin{bmatrix} y_3 \\ y_4 \end{bmatrix} = \begin{bmatrix} h_{13} & h_{23} & 0 & h_{43} \\ h_{14} & h_{24} & h_{34} & 0 \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \\ x_3 \\ x_4 \end{bmatrix} + \begin{bmatrix} n_3 \\ n_4 \end{bmatrix} \tag{3.13}$$

where y_3 and y_4 are the received signals at T3 and T4; x_1, x_2, x_3 and x_4 are the transmitted signals from T1, T2, T3 and T4; n_3 and n_4 are additive white Gaussian noise terms of receivers T3 and T4 with distributions $CN(0, N_3)$ and $CN(0, N_4)$, respectively. $\{h_{ij}\}$ are the fading coefficients between terminals i and j. Each terminal has a transmit power constraint of P_i. For the ease of exposition of the ideas, we assume users can receive and transmit simultaneously, channel state information is available to all of the receivers and transmitters, and inter-transmitter, inter-receiver, transmitter-receiver channels are all orthogonal.

3.4 Interference and Dirty Paper Coding

We said that we assume inter-receiver, inter-transmitter and transmitter-receiver channels are orthogonal to each other thus preventing any interference. Since there is only one channel pair at the transmitter side and one pair at the receiver side, there is not any interference on the inter-transmitter and inter-receiver channels. However interference may occur on the transmitter-receiver channels. For example if T1 sends portion-1, T2 sends portion-2 and T3 wants to receive only portion-1, then portion-2 will be interference for T1-T3 channel. For the cancelation of such transmitter-receiver channel interferences we use a technique called *dirty paper coding*.

Dirty paper coding [25] is a coding technique that makes it feasible to cancel the effects of interference known a priori to the transmitter. This feature renders this technique suitable for simultaneously transmitting independent signals to several receivers.

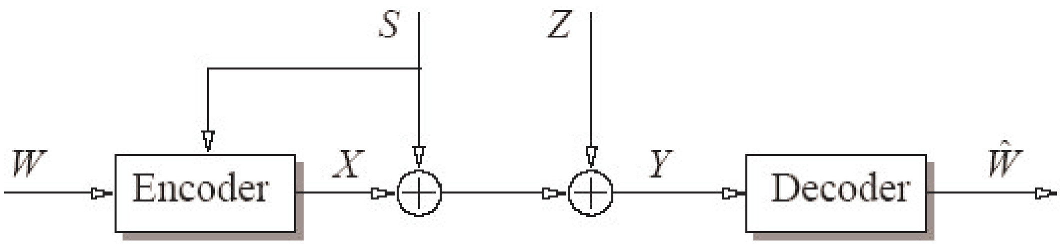


Figure 3.3: Generalized DPC channel (Figure taken from http://www.personal.psu.edu/aun121/MIMO/non_linear.pdf).

Consider the AWGN channel shown in Fig. 3.3 with output $Y = X + S + Z$, where X is the input with power constraint P, S is the interference with $N(0, Q)$ and Z is the Gaussian distributed noise with $N(0, N)$. For this channel the Shannon capacity is given by $C = \frac{1}{2}log(1+\frac{P}{N+Q})$. However if the interference S is known to the transmitter, the transmitter may encode the message in a way that interference will be canceled when decoded at the receiver. Thus DPC capacity becomes independent of the interference: $C_{DPC} = \frac{1}{2}log(1 + \frac{P}{N})$. Several methods has been developed to achieve this capacity [26].

For our system model the transmitters both have the same file portions and cooperate to decide which portions to send. Therefore each one knows in advance which portion is going to be transmitted by the other. Additionally one transmitter's transmission is interference to the other if the receiver does not decode both transmissions. For these reasons dirty paper coding is applicable to our system and cancels transmitter-receiver channel interferences.

Dirty paper coding can be applied in multiple input - multiple output multiuser channels to cancel interference or increase the gain achieved through diversity [27], and digital watermarking of images [28]. Although capacity approaching algorithms are developed [29], this coding technique has certain drawbacks. First, it requires channel state information of all receivers available at the transmitter. Second, the algorithms are computationally complex and are not easy to implement.

3.5 Channel Capacity Formulations

In this section we show how we derive the capacity constraint equations. We consider the simple network in Figure 3.4.

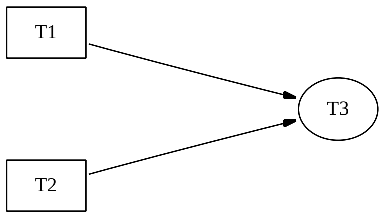


Figure 3.4: Multiple Access Channel.

When transmitters decide to use parallel downloading method, that is they cooperate to send different portions of the file, multiple access channel capacity constraint gets involved in the calculations. The achievable rates for the given simple network are constrained as follows [30]:

$$R_1 < C\left(\frac{h_{13}^2 P_1}{N_3}\right) \tag{3.14}$$

$$R_2 < C\left(\frac{h_{23}^2 P_2}{N_3}\right) \tag{3.15}$$

$$R_1 + R_2 < C\left(\frac{h_{13}^2 P_1 + h_{23}^2 P_2}{N_3}\right) \tag{3.16}$$

where $C(x) = \log_2(1 + x)$ is the AWGN channel capacity and R_1 and R_2 are the transmission rates of T1 and T2, respectively.

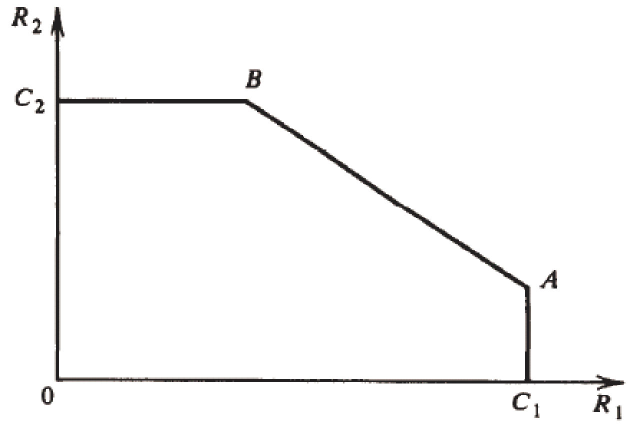


Figure 3.5: Achievable rate region for the multiple access channel. Here $C_1 = C\left(\frac{h_{13}^2 P_1}{N_3}\right)$ and $C_2 = C\left(\frac{h_{23}^2 P_2}{N_3}\right)$

The capacity region or achievable rate region (closure set of all (R_1, R_2) rate pairs) is shown in Fig. 3.5. The $(C_1, 0)$ point corresponds to the maximum rate from transmitter 1 when transmitter 2 sends nothing. The point A corresponds to the maximum achievable rate from transmitter 2 when transmitter 1 sends at its capacity.

Instead of sending different portions, if transmitters cooperate to simultaneously send the same portions of the file, that is they use user cooperation diversity method, the maximum achievable rate $R = R_1 = R_2$ is calculated by:

$$R < C\left(\frac{\left(h_{13}\sqrt{P_1} + h_{23}\sqrt{P_2}\right)^2}{N_3}\right) \tag{3.17}$$

3.6 Numerical Analysis

In the thesis we mainly deal with rate allocation optimization problems. According to the goal, we either maximize the rates or minimize the delays. To solve the optimization problems numerically, we use the *fmincon* function in MATLAB's optimization toolbox, which finds the minimum value of the given constrained nonlinear multi-variable function.

Chapter 4

DELAY MINIMIZATION THROUGH CHANNEL CAPACITY OPTIMIZATION

In this chapter we discuss, through capacity optimization, the effects of user cooperation on the performance of the two-transmitter two-receiver wireless peer-to-peer network that we introduced in section 3.3. At the transmitter side, we utilize either parallel downloading, where transmitters send independent file portions, or user cooperation diversity, where transmitters simultaneously send same portions of the file. At the receiver side, we first analyze no cooperation case and then consider two cooperation strategies; decode-and-forward (DF) and amplify-and-forward (AF). We compare the performances of these transmitter and receiver cooperation schemes based on the time elapsed for the worst receiver to receive the whole file.

4.1 Cooperation at the Transmitter Side

4.1.1 Parallel downloading

When parallel downloading method is used, transmitters cooperate to send different portions of the file. T1 transmits αK bits, and T2 transmits the remaining $(1-\alpha)K$ bits of the file, where α is a constant between 0 and 1. Remember the file is divided into several smaller sized chunks (e.g. 256KB for BitTorrent) and with parallel downloading some of the chunks are transmitted by T1 and the remaining by T2, and by dirty paper coding the sum rate is achieved. However, the optimal αK and $(1-\alpha)K$ solutions are not necessarily multiples of the chunk size. Therefore the optimal rate solutions calculated according to this α value, constitutes an upper bound.

4.1.2 User cooperation diversity

When user cooperation diversity method is used, instead of sending different portions both transmitters simultaneously send the same portions. Therefore both T1 and T2 is responsible of transmitting the whole K bit-sized file.

We now define our peer-to-peer routing protocols. We examine two type of protocols, which we name as "first type" or "Type-I" and "second type" or "Type-II protocols." We start with defining the first type protocols in 4.2 and will give the differences between these two types in detail at the beginning of section 4.3 where we define the second type protocols.

4.2 First Type Protocols

4.2.1 Cooperation at the Receiver Side

Protocols for No Cooperation Case

Without any cooperation at the receiver side, receiving peers receive directly from the transmitting peers and thus $x_3 = x_4 = 0$. T1 and T2 adjust their transmission rates such that their transmitted signals can be perfectly decoded by both of the receivers. These adjustments are therefore made according to the channels that become the bottleneck, i.e. have the lowest quality. Hence we have the following constraints on the transmission rates of T1 and T2 for parallel downloading:

$$R_1 < \min\left\{C\left(\frac{|h_{13}|^2 P_1}{N_3}\right), C\left(\frac{|h_{14}|^2 P_1}{N_4}\right)\right\} \tag{4.1}$$

$$R_2 < \min\left\{C\left(\frac{|h_{23}|^2 P_2}{N_3}\right), C\left(\frac{|h_{24}|^2 P_2}{N_4}\right)\right\} \tag{4.2}$$

$$R_1 + R_2 < \min\left\{C\left(\frac{|h_{13}|^2 P_1 + |h_{23}|^2 P_2}{N_3}\right), C\left(\frac{|h_{14}|^2 P_1 + |h_{24}|^2 P_2}{N_4}\right)\right\} \tag{4.3}$$

where (4) signifies the multiple-access channel capacity constraint for independent transmissions.

Times elapsed for T1 and T2 to send all their assigned portions are $\alpha K/R_1$ and $(1-\alpha)K/R_2$ seconds, respectively. Since our aim is to make the file available to both of the receiving peers in the shortest time, we can formulate the time optimization problem as:

$$\min_{\alpha,R_1,R_2}\{t\} = \min_{\alpha,R_1,R_2}\left\{\max\left(\frac{\alpha K}{R_1}, \frac{(1-\alpha)K}{R_2}\right)\right\} \tag{4.4}$$

subject to the constraints on α, R_1, R_2 and $R_1 + R_2$.

For user cooperation diversity method the constraint on the cooperative transmission rate is:

$$R < \min\left\{C\left(\frac{(\sqrt{|h_{13}|^2P_1}+\sqrt{|h_{23}|^2P_2})^2}{N_3}\right), C\left(\frac{(\sqrt{|h_{14}|^2P_1}+\sqrt{|h_{24}|^2P_2})^2}{N_4}\right)\right\} \tag{4.5}$$

and the time optimization problem is:

$$\min_{R}\{t\} = \min_{R}\left\{\frac{K}{R}\right\} \tag{4.6}$$

subject to the constraint on R.

These optimization problem statements for no cooperation case are also valid for the receiver cooperation methods we will mention next.

In order to include the randomness of the fading amplitudes into the problem, we take the expected values of the minimized delay times, where expectations are over the fading amplitudes.

Protocols using Decode and Forward Transmission

As mentioned in 2.2.1, relays using decode and forward scheme fully decode, re-encode and retransmit their received signals.

With parallel downloading method, each transmitter should adjust its transmission rate such that its signal can be decoded by at least one of the receivers. This can be in two ways: First, one of the receivers fully decodes both of the transmitters' signals and relays it such that the other receiver can decode both signals by coherently combining the directly sent signal with the relayed signal. Second, each of the receivers decode one of the transmitters' signal and relays it to the other peer. The first scenario is expected to be advantageous over the second when one receiver has good channels with the transmitters and the other not.

For the first scenario, in the first block T1 and T2 transmits and T3 decodes these transmissions. In the next blocks, T1 and T2 continues transmitting and T3 decoding, but T3 also relays its received signal from the previous block. Therefore T4 receives two copies of T1's signal; one directly from T1 in the first block and the other relayed by T3 in the next block. It coherently combines these two copies and thus benefits from transmitter diversity. The same argument applies for T2's signal. The achievable rates are then constrained as follows:

$$R_1 < \min\left\{C\left(\frac{|h_{13}|^2P_1}{N_3}\right), C\left(\frac{(\sqrt{|h_{14}|^2P_1}+\sqrt{|h_{34}|^2P_{31}})^2}{N_4}\right)\right\} \tag{4.7}$$

$$R_2 < \min\left\{C\left(\frac{|h_{23}|^2P_2}{N_3}\right), C\left(\frac{(\sqrt{|h_{24}|^2P_2}+\sqrt{|h_{34}|^2P_{32}})^2}{N_4}\right)\right\} \tag{4.8}$$

$$R_1 + R_2 < \min\{C\left(\frac{(|h_{13}|^2P_1+|h_{23}|^2P_2}{N_3}\right), \\ C\left(\frac{(\sqrt{|h_{14}|^2P_1}+\sqrt{|h_{34}|^2P_{31}})^2+(\sqrt{|h_{24}|^2P_2}+\sqrt{|h_{34}|^2P_{32}})^2}{N_4}\right)\} \tag{4.9}$$

The first terms in (4.7) and (4.8) signifies the maximum rates decodable at T3 and the second terms at T4, respectively. (4.9) stands for the multiple access channel capacity for transmitters sending independent messages. P_{31} and P_{32} are the power values that T3 allocates for relaying T1 transmitted and T2 transmitted signals, respectively and $P_{31} + P_{32} = P_3$.

If instead T4 has better channels with the transmitters than T3 has, it will be advantageous if T4 receives and relays T3 the T1 and T2 transmitted signals and T3 coherently combines this relayed signal from T4 with the direct signals from T1 and T2. The capacity equations will be similar to equations (4.7)-(4.9).

For the second configuration, assume T1-T3 channel has the highest quality, i.e. the highest SNR among the transmitter-receiver channels. T1 adjusts its transmission rate such that receiver T3 can fully decode the information it receives from T1. Likewise, T2 adjusts its transmission rate such that perfect decoding is feasible at receiver T4. In the first block, T1 and T2 broadcast their assigned portions. In the next blocks, T1 and T2 continues their transmissions, T3 relays T1's transmission from the previous block to T4 and T4 relays T2's previous transmission to T3. The same protocol will apply if T2-T4 channel is the best.

Thus the achievable rates for this system should satisfy the following constraints:

$$R_1 < \min\left\{C\left(\frac{|h_{13}|^2P_1}{N_3}\right), C\left(\frac{(\sqrt{|h_{14}|^2P_1}+\sqrt{|h_{34}|^2P_3})^2}{N_4}\right)\right\} \tag{4.10}$$

$$R_2 < \min\left\{C\left(\frac{|h_{24}|^2P_2}{N_4}\right), C\left(\frac{(\sqrt{|h_{23}|^2P_2}+\sqrt{|h_{43}|^2P_4})^2}{N_3}\right)\right\} \tag{4.11}$$

$$R_1 + R_2 < \min\{C\left(\frac{(\sqrt{|h_{23}|^2P_2}+\sqrt{|h_{43}|^2P_4})^2+|h_{13}|^2P_1}{N_3}\right), C\left(\frac{(\sqrt{|h_{14}|^2P_1}+\sqrt{|h_{34}|^2P_3})^2+|h_{24}|^2P_2}{N_4}\right)\} \tag{4.12}$$

The terms in (4.10) signifies the maximum decodable transmission rate of T1 at T3 and T4, respectively. Likewise, the terms in (4.11) signifies the maximum decodable transmission of T2 at T4 and T3, respectively. Again (4.12) comes from the multiple access channel capacity constraint.

If T1-T4 or T2-T3 channels have the highest quality, then it will be advantageous if T4 receives and relays T3 the T1 transmitted signal and T3 receives and relays T4 the T2 transmitted signal. The capacity calculations are similar to equations (4.10)-(4.12).

In user cooperation diversity method, the receiver with the highest capacity, say T3, decodes what it receives cooperatively from T1 and T2 in the first block. In the next block, T1 and T2 continues transmitting and T3 relays its received signal from the previous block. Therefore T4 receives three copies of the same information. The achievable rates are constrained as follows:

$$R < min\left\{C\left(\frac{(\sqrt{|h_{13}|^2P_1}+\sqrt{|h_{23}|^2P_2})^2}{N_3}\right), C\left(\frac{(\sqrt{|h_{14}|^2P_1}+\sqrt{|h_{24}|^2P_2}+\sqrt{|h_{34}|^2P_3})^2}{N_4}\right)\right\} \tag{4.13}$$

If instead the receiver with the highest capacity is not T3 but T4, then T4 will relay T1 and T2 transmitted signals to T3. The achievable rate constraint is similar to equation (4.13).

Protocols using Amplify and Forward Transmission

As mentioned in 2.2.2, relays using amplify and forward scheme simply amplify their received signal and relay it. The relay chooses an amplification factor such that it remains within its power constraint.

Let y_3 be T3's observation of T1's and T2's transmitted signals in the first block.

$$y_3 = h_{13}x_1 + h_{23}x_2 + n_3 \tag{4.14}$$

T3 amplifies its observation with an amplification factor of β_3 and transmits:

$$x_3 = \beta_3 y_3 \tag{4.15}$$

To remain within its power constraint, T3 determines its amplification factor according to:

$$\beta_3 \leq \sqrt{\frac{P_3}{|h_{13}|^2 P_1 + |h_{23}|^2 P_2 + N_3}} \tag{4.16}$$

In the next block, T4 receives T3-relayed signal and coherently combines it with its observation of T1 and T2 transmitted signals from the first block:

$$\begin{aligned} y_4 &= h_{14}x_1 + h_{24}x_2 + h_{34}x_3 + n_4 && (4.17)\\ &= (h_{14} + \beta_3 h_{34} h_{13})x_1 + (h_{24} + \beta_3 h_{34} h_{23})x_2 + \beta_3 h_{34} n_3 + n_4 && (4.18) \end{aligned}$$

For parallel downloading method, the sum rate decodable at T3 is then bounded by:

$$R_1 + R_2 < C\left(\frac{|h_{14} + \beta_3 h_{34} h_{13}|^2 P_1 + |h_{24} + \beta_3 h_{34} h_{23}|^2 P_2}{\beta_3^2 |h_{34}|^2 N_3 + N_4}\right) \tag{4.19}$$

Considering the same arguments for T4 yields the following sum rate bound:

$$R_1 + R_2 < C\left(\frac{|h_{13} + \beta_4 h_{43} h_{14}|^2 P_1 + |h_{23} + \beta_4 h_{43} h_{24}|^2 P_2}{\beta_4^2 |h_{43}|^2 N_4 + N_3}\right) \tag{4.20}$$

with

$$\beta_4 \leq \sqrt{\frac{P_4}{|h_{14}|^2 P_1 + |h_{24}|^2 P_2 + N_4}} \tag{4.21}$$

Therefore $R_1 + R_2$ should be less than the minimum of these capacities.

With user cooperation diversity method the constraint on the cooperative transmission rate of the transmitters is:

$$R < \min\{C\left(\frac{(\sqrt{|h_{14} + \beta_3 h_{34} h_{13}|^2 P_1} + \sqrt{|h_{24} + \beta_3 h_{34} h_{23}|^2 P_2})^2}{\beta_3^2 |h_{34}|^2 N_3 + N_4}\right)$$
$$C\left(\frac{(\sqrt{|h_{13} + \beta_4 h_{43} h_{14}|^2 P_1} + \sqrt{|h_{23} + \beta_4 h_{43} h_{24}|^2 P_2})^2}{\beta_4^2 |h_{43}|^2 N_4 + N_3}\right)\} \tag{4.22}$$

For both DF and AF schemes the receivers are one block behind the transmitters, but for a large number of blocks, the reduction in the reception rates is negligible.

4.2.2 Numerical Analysis of the System

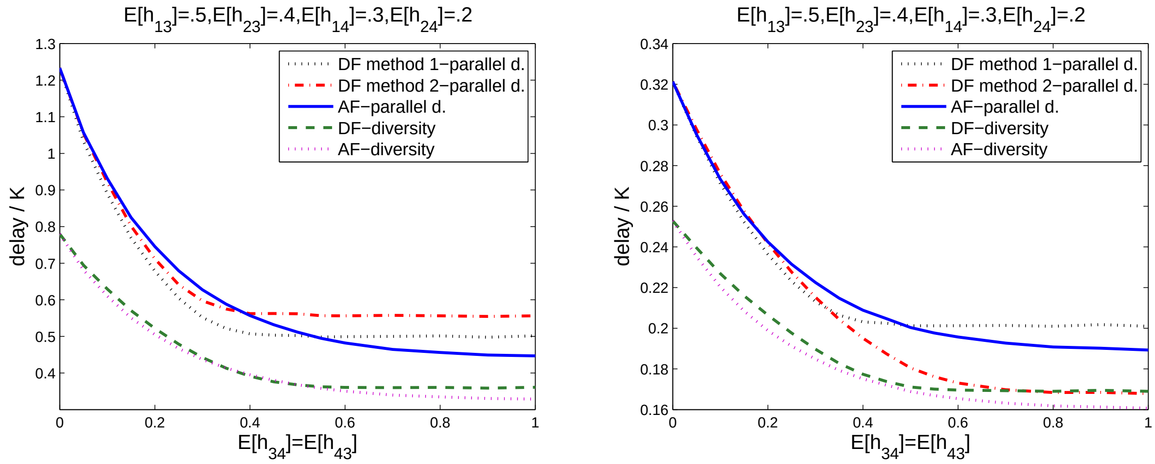
We compare the performance of receiver cooperation methods (DF and AF) and transmitter cooperation methods (parallel downloading and user cooperation diversity [31]). We chose noise power values of $N = N_1 = N_2 = 0.5$ for the analysis. Let power $P = P_1 = P_2 = P_3 = P_4$. We set P value to either 2 (signifying low SNR) or 20 (signifying high SNR). For parallel downloading method, we observed that there are many solutions to the same optimization problem each yielding the same minimal value. In this situation we preferred the solution that distributes the load to the transmitters in the most fair way.

Figures 4.1, 4.2 and 4.3 illustrate maximum of the receiver delays over file size K as a function of the expected values of the inter-receiver channel fading coefficients for three different transmitter-receiver channel quality scenarios. Theses scenarios are:

1) T3 has much more better channel qualities with the transmitters than T4 has; $E[h_{13}] = .5$, $E[h_{23}] = .4$, $E[h_{14}] = .3$, $E[h_{24}] = .2$,

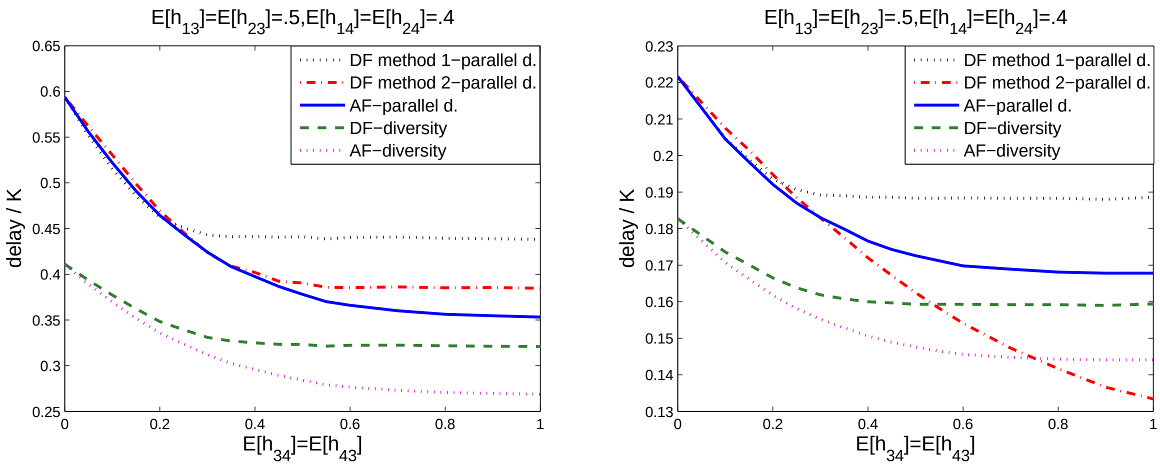
2) T3 has slightly better transmitter-receiver channels than T4 has; $E[h_{13}] = E[h_{23}] = .5$, $E[h_{14}] = E[h_{24}] = .4$,

3) T3 and T4 have same channel qualities with the transmitters on the average; $E[h_{13}] = E[h_{23}] = E[h_{14}] = E[h_{24}] = .5$.



(a) P=2 (b) P=20

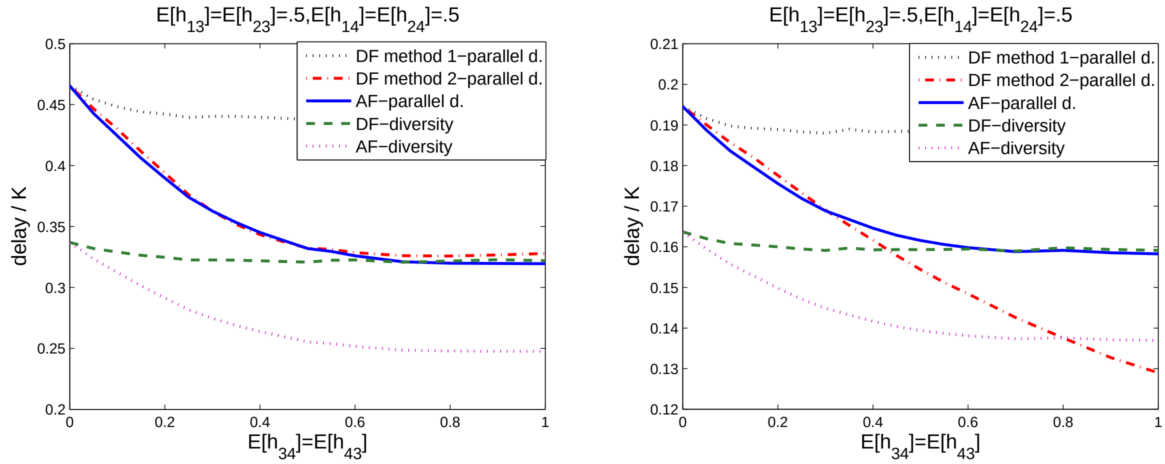
Figure 4.1: Delay for $P = 2$, $E[h_{13}] = .5$, $E[h_{23}] = .4$, $E[h_{14}] = .3$, $E[h_{24}] = .2$ values.



(a) P=2 (b) P=20

Figure 4.2: Delay for $P = 2$, $E[h_{13}] = E[h_{23}] = .5$, $E[h_{14}] = E[h_{24}] = .4$ values.

We observe from Fig. 4.1 that when one of the receivers have much more better channel qualities with the transmitters than the other has, the first decode-and-



(a) P=2 (b) P=20

Figure 4.3: Delay for $P = 2$,$E[h_{13}] = E[h_{23}] = E[h_{14}] = E[h_{24}] = .5$ values.

forward method for parallel downloading is better for low SNR, because for this case the bad receiver (T4) does not resolve the messages of T1 and T2 before it receives the good receiver's (T3) observations. Fig. 4.2(a) shows however, that when the receivers have similar channels with the transmitters, the second method is advantageous except for low inter-receiver fading coefficients. Fig. 4.3(a) illustrates the results when all the expected transmitter-receiver channel qualities are equal. For this case, first method of DF scheme for parallel downloading and DF scheme for diversity becomes almost equivalent to no cooperation scenarios, because at the optimal transmission rate calculated for the case of equal transmitter-receiver channel qualities, the receiver which uses the relayed observations of the other to resolve the message, is in fact capable of decoding it itself without the other's aid.

For low SNR values ($P = 2$ case) and low inter-receiver channel qualities DF scheme performs slightly better than AF scheme. As the amount of receiver cooperation increases, delay of DF scheme becomes constant, however delay of AF continues on decreasing until large inter-receiver fading coefficient values. For high SNR values ($P = 20$ case) however, as the receiver cooperation increases delay with AF method becomes constant but with DF method delay continues decreasing.

We observe from figures 4.1(a), 4.2(a) and 4.3(a) that for the low SNR case user cooperation diversity method is better. Figures 4.1(b), 4.2(b) and 4.3(b) are the analysis results for the higher SNR case and show that as the inter-receiver channel quality increases, parallel downloading method starts to perform better for DF scheme. Jindal et. al. has only considered amplify-and-forward method for receiver cooperation strategy. In their model since each transmitter sends independent information to a different receiver, if the first receiver decodes the message intended for the second receiver and then forwards it to the second receiver, there will be no gain for the first receiver. However, for our scenario decode-and-forward method can be advantageous because both receivers demand the same file and thus can benefit from both transmitters' transmissions.

4.3 Second Type Protocols

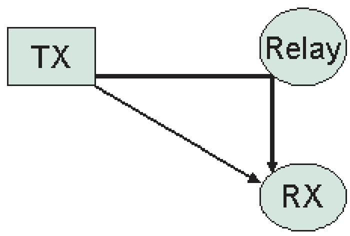
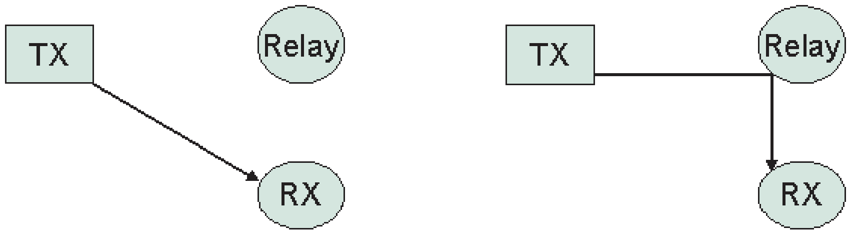


Figure 4.4: Receiver combines the direct transmission with the relayed transmission and resolves the message

Because message resolving is performed by combining the directly received signal(s) with the relayed signal(s) as shown in Fig. (4.4), the protocols we examined in the previous section requires high coordination among nodes, large buffer sizes and strict synchronization of the data packets. In addition, these problems are even more severe as the number of nodes increases and system becomes more complex. For this reason we also examine protocols in which messages are resolved from only the direct channels as shown in Fig. (4.5).



(a) Direct Transmission (b) Relayed Transmission

Figure 4.5: Signal resolving is performed via either the direct channel in one hop (a) or if better the transmitter-relay-receiver channels in two hops (b)

4.3.1 Protocols for Parallel Downloading Method

For parallel downloading, we define nine protocols -one for no receiver cooperation case- and write rate constraint and optimization problem equations for each protocol like we did in section 4.2. Again we assume dirty paper coding at the transmitters which prevents interference of one transmitter's signal to the other.

Protocol for no receiver cooperation case: If there is no cooperation between receivers T3 and T4, they separately decode T1 and T2's transmissions. So the transmission rates of T1 and T2, R_1 and R_2, are determined according to the worst receiver channel conditions.

$$R_1 < \min\left\{C\left(\frac{(|h_{13}|^2 P_1}{N_3}\right), C\left(\frac{(|h_{14}|^2 P_1}{N_4}\right)\right\} \tag{4.23}$$

$$R_2 < \min\left\{C\left(\frac{(|h_{23}|^2 P_2}{N_3}\right), C\left(\frac{(|h_{24}|^2 P_2}{N_4}\right)\right\} \tag{4.24}$$

$$R_1 + R_2 < \min\left\{C\left(\frac{(|h_{13}|^2 P_1 + |h_{23}|^2 P_2}{N_3}\right), C\left(\frac{(|h_{14}|^2 P_1 + |h_{24}|^2 P_2}{N_4}\right)\right\} \tag{4.25}$$

$$t = max\left\{\frac{\alpha K}{R_1}, \frac{(1-\alpha)K}{R_2}\right\} \tag{4.26}$$

Here t is the delay time and α is a constant taking values in the range from 0 to 1. The minimizations are to adjust the rates according to the worst channels and Eq. 4.25 comes from the multiple access channel constraint.

Protocol 1 : T1's transmission is decoded by T3 and relayed to T4. T2's transmission is decoded by T4 and relayed to T3.

$$R_1 < C\left(\frac{(|h_{13}|^2 P_1}{N_3}\right) \tag{4.27}$$

$$R_2 < C\left(\frac{(|h_{24}|^2 P_2}{N_4}\right) \tag{4.28}$$

$$R_3 < \min\left\{C\left(\frac{(|h_{34}|^2 P_3}{N_4}\right), R_1\right\} \tag{4.29}$$

$$R_4 < \min\left\{C\left(\frac{(|h_{43}|^2 P_4}{N_3}\right), R_2\right\} \tag{4.30}$$

$$t = \max\left\{\frac{\alpha K}{\min\{R_1, R_3\}}, \frac{(1-\alpha)K}{\min\{R_2, R_4\}}\right\} \tag{4.31}$$

Here R_3 and R_4 are the transmission rates of users T3 and T4. R_3 is constrained by not only T3-T4 channel's physical conditions but also T1's transmission rate R_1, because T3 can not forward faster than its reception rate.

Protocol 2: T1's transmission is decoded by T4 and relayed to T3. T2's transmission is decoded by T3 and relayed to T4. The derivations are similar to Protocol 1 (T3 and T4 reversed).

Protocol 3: Both T1's and T2's transmissions are decoded by T3 and relayed to T4. Constraint on R_1 is as in Eq. (4.27).

$$R_2 < C\left(\frac{(|h_{23}|^2 P_2}{N_3}\right) \tag{4.32}$$

$$R_1 + R_2 < C\left(\frac{(|h_{13}|^2 P_1 + |h_{23}|^2 P_2}{N_3}\right) \tag{4.33}$$

T3's receiving rate is the sum of R_1 and R_2, so its transmission rate R_3 can not exceed $R_1 + R_2$.

$$R_3 < \min\left\{C\left(\frac{(|h_{34}|^2 P_3}{N_4}\right), R_1 + R_2\right\} \tag{4.34}$$

$$t = \max\left\{\frac{\alpha K}{R_1}, \frac{(1-\alpha)K}{R_2}, \frac{1}{R_3}\right\} \tag{4.35}$$

Protocol 4: Both T1's and T2's transmissions are decoded by T4 and relayed to T3. The derivations are similar to Protocol 3 (T4 and T3 reversed).

Protocol 5: T1's transmission is decoded by both T3 and T4. T2's transmission is decoded by T3 and relayed to T4. Constraints on R_1, R_2 and $R_1 + R_2$ are given by equations (4.23), (4.28) and (4.33), respectively. Constraint on T3's transmission rate and the optimization problem is as follows:

$$R_3 < \min\left\{C\left(\frac{(|h_{34}|^2 P_3}{N_4}\right), R_2\right\} \tag{4.36}$$

$$t = \max\left\{\frac{\alpha K}{R_1}, \frac{(1-\alpha)K}{min(R_2, R_3)}\right\} \tag{4.37}$$

Protocol 6: T1's transmission is decoded by T4 and relayed to T3. T2's transmission is decoded by both T3 and T4.

Protocol 7: T1's transmission is decoded by both T3 and T4. T2's transmission is decoded by T4 and relayed to T3.

Protocol 8: T1's transmission is decoded by T3 and relayed to T4. T2's transmission is decoded by both T3 and T4.

The derivations for protocols 6,7 and 8 are similar to those for Protocol 5.

4.3.2 Protocols for User Cooperation Diversity Method

For user cooperation diversity method, we define three protocols -one for no receiver cooperation case- and find the minimum delay result in a similar way as we find it for the parallel downloading method.

Protocol for no receiver cooperation case: T1 and T2 simultaneously transmit the same information with rate R and these transmissions are decoded by both T3 and T4.

$$R < \min\left\{C\left(\frac{(|h_{13}|\sqrt{P_1} + |h_{23}|\sqrt{P_2})^2}{N_3}\right), C\left(\frac{(|h_{14}|\sqrt{P_1} + |h_{24}|\sqrt{P_2})^2}{N_4}\right)\right\} \tag{4.38}$$

$$t = \frac{K}{R} \tag{4.39}$$

Protocol 1: Only T3 decodes the joint transmissions of T1 and T2, and relays it to

T4.

$$R < C\left(\frac{(|h_{13}|\sqrt{P_1} + |h_{23}|\sqrt{P_2})^2}{N_3}\right) \tag{4.40}$$

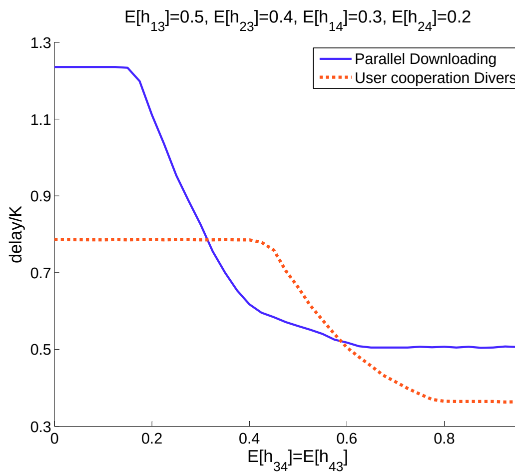
$$R_3 < \min\left\{C\left(\frac{(|h_{34}|^2 P_3}{N_4}\right), R\right\} \tag{4.41}$$

$$t = \max\left\{\frac{K}{min(R_1, R_3)}\right\} \tag{4.42}$$

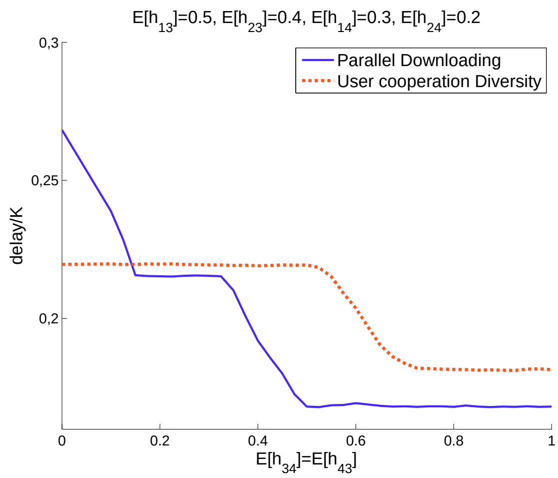
Protocol 2: Only T4 decodes the joint transmissions of T1 and T2, and relays it to T3. The derivations are similar to the first protocol.

4.3.3 Numerical Analysis of the System

We use the same noise and transmitter power values as in the previous section (N is 0.5, P is 2 or 20) and perform the same analyses. Figures 4.6, 4.7 and 4.8 show the maximum receiver delay over file size K as a function of the inter-receiver channel fading coefficient means for three different transmitter-receiver channel quality scenarios.

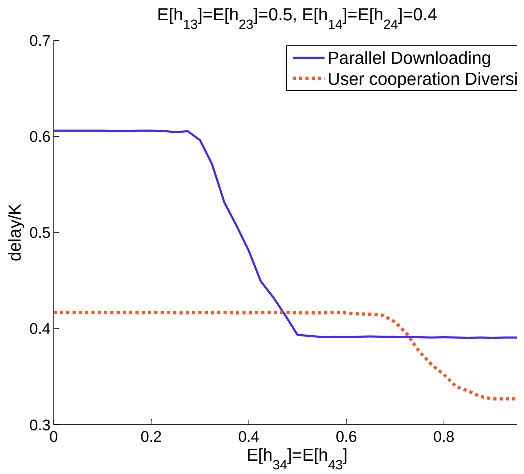


(a) P=2

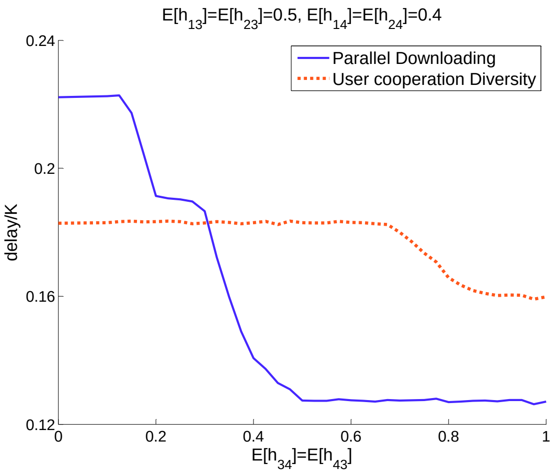


(b) P=20

Figure 4.6: Delay for $P = 2$, $E[h_{13}] = .5$, $E[h_{23}] = .4$, $E[h_{14}] = .3$, $E[h_{24}] = .2$ values.

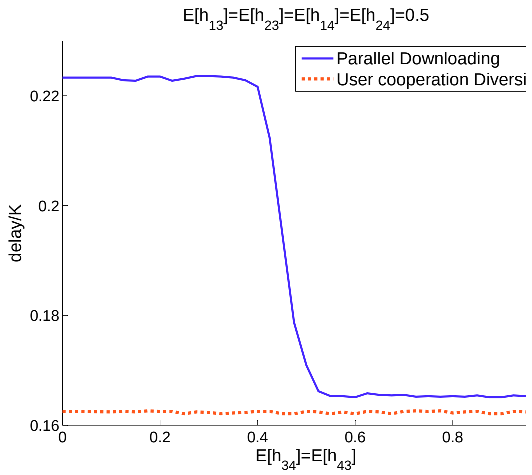


(a) P=2

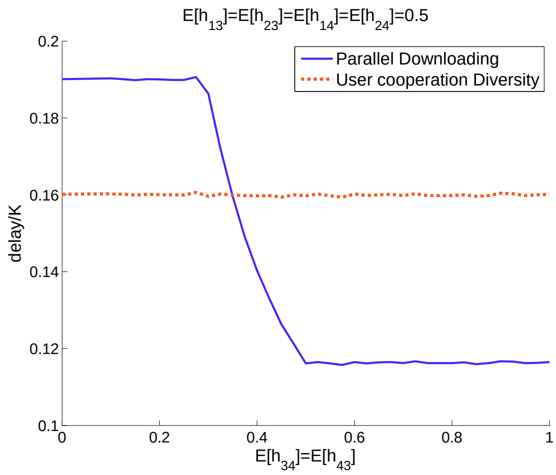


(b) P=20

Figure 4.7: Delay for $P = 2$, $E[h_{13}] = E[h_{23}] = .5$, $E[h_{14}] = E[h_{24}] = .4$ values.



(a) P=2



(b) P=20

Figure 4.8: Delay for $P = 2$,$E[h_{13}] = E[h_{23}] = E[h_{14}] = E[h_{24}] = .5$ values.

From all these figures we observe that for low SNR (P=2), user cooperation diversity is better than parallel downloading method (except for some values in the middle) and for high SNR (P=20), parallel downloading is worse than user cooperation diversity method for low inter-receiver channel quality values but starts to outperform as this quality and so cooperation increases.

The delay values at $x = 0$ point gives no receiver cooperation state results. That is why the flat lines beginning at $x = 0$ means that for the corresponding inter-receiver channel conditions, receiver cooperation is needless. We see that for low SNR these lines are longer for parallel downloading method.

As a last result, first type protocols perform better than second type protocols except for high SNR cases of second and third channel scenarios.

Chapter 5

AVERAGE DELAY

In chapter 4, numerical analyses were performed by using fixed fading coefficient mean values; that is specific channel conditions were considered. We investigated three different transmitter-receiver channel quality scenarios and for each scenario varied the inter-receiver channel from no-cooperation to full-cooperation states. We preferred this method in order to clearly identify which schemes outperform in which circumstances. Our results and comments were for specific channel conditions, however there are infinitely many channel condition states, and performance comparisons based on the average results may be more meaningful for real system analyzes.

In this chapter, delay times for parallel downloading and user cooperative diversity methods are compared in an averaged manner. We randomly distribute the four nodes on a circular area and based on the wireless channel model described in section 3.1 compute the fading coefficient means. Later, we numerically analyze the system with these mean values for different fading states and take the average. This gives the result for one random distribution. We repeat this procedure for a sufficient number of geographical distributions and refresh the average value in each step to obtain the final average delay value.

5.1 Average delay for the First Type Protocols

For the system described in section 4.2 we considered a total of six protocols for parallel downloading method; one for no-cooperation, one for amplify-and-forward, four for decode-and-forward schemes and four protocols for user cooperation diversity method; one for no-cooperation, one for amplify-and-forward, two for decode-and-forward schemes. We numerically analyze the system to calculate the delay values for each protocol. For parallel downloading method, we choose the minimum of the six results as the minimum delay value for parallel downloading. Likewise the minimum result of the four user cooperation diversity method protocols is chosen to be the minimum delay value for user cooperation diversity.

5.2 Average delay for the Second Type Protocols

For the system described in section 4.3, we defined nine protocols for parallel downloading method -one for no receiver cooperation case- for parallel downloading method and three protocols for user cooperation diversity method -one for no receiver cooperation case. We find the minimum delay values in a similar way as we find it for Type-I protocols.

5.3 Numerical Analysis Results

We numerically analyze the system to obtain average delay values for parallel downloading and user cooperation diversity methods and compare these values. We distributed the nodes to the geography 1000 times and for each distribution we considered 50 independent fading steps. We first take an average across the fading states for each distribution and then take the average across the results of each distribution to obtain the final delay result.

We chose the parameters as follows:
$B = 1$ MHz, (transmitter bandwidth)
$P = 1$ W, (maximum transmission power)
$N_0 = 10^{-10}$ W/Hz, (noise power spectral density)
$R = 15$ m, (radius of the circle)
$K = 1$ MB, (file size)
$f_c = 2$ GHz, (carrier frequency)
$v = 3$ km/h, (node velocity)

f_c and v are used for Rayleigh fading calculations.

Table 5.1 and Table 5.2 summarizes the results for Type-I and Type-II protocols, respectively. First and second columns give the average delay results in seconds with and without receiver cooperation, respectively. The third column gives the percentage of the distributions the method in question is better than the other.

Table 5.1: Delay results for average delay optimization of Type-I protocols

	Without receiver cooperation	With receiver cooperation	Which method is advantageous?
Parallel down.	73s	26.04s	0%
User cooperative div.	18.1s	34s	100%

Table 5.2: Delay results for average delay optimization of Type-II protocols

	Without receiver cooperation	With receiver cooperation	Which method is advantageous?
Parallel down.	37.94s	24s	23%
User cooperative div.	11.17s	16.04s	77%

Results show that user cooperation diversity method is better than parallel downloading method on the average. Remember in chapter 4 we found that user cooperation diversity method performs better for low SNR values. The two results suggest that for real configurations nodes will probably be connected via low SNR channels. We check this suggestion by decreasing N_0 value to 10^{-11} and the results for second type protocols are shown in Table 5.3. It is seen that despite user cooperation diversity method has less average delay values, for the 62% of the random distributions parallel downloading method outperforms proving the suggestions. This was 23% for the high N_0 case. In other words, for 62 % of the distributions parallel downloading method is better, that is it gives lower delay results. However for the remaining 38% distributions, when the channel conditions are very bad, parallel downloading gives extremely high delay values compared to diversity method that when we include these values to the average they increase the average delay and as a result the average delay value became higher than the average delay value of diversity method. We found that if we further decrease N_0 (to $5 \cdot 10^{-12}$) parallel downloading method also outperforms on the average.

Table 5.3: Delay results for average delay optimization of Type-II protocols with decreased noise (increased SNR)

	Without receiver cooperation	With receiver cooperation	Which method is advantageous?
Parallel down.	9.07s	5.69s	62%
User cooperative div.	2.87s	3.97s	38%

If the results for cases with and without receiver cooperation are compared, we see that the effect of receiver cooperation is more dramatic for parallel downloading method.

Second type protocols performed better than first type protocols on the average opposed to results in Chapter 4 in which we found first types are better than second types for the four of the six configurations.

Chapter 6

OPTIMAL RATE ALLOCATION FOR SCALABLE VIDEO TRANSMISSION

The fast and unprecedented growth in multimedia applications over bandwidth limited and error-prone networks, stimulated research for developing robust and ubiquitous techniques for video transmission [32]. Scalable video coding has been a popular technique that offers simple and highly flexible solutions for video transmission over heterogeneous networks having varying bandwidths and signal to noise ratios, and this renders the method useful for mobile video transmission [33], [34], [35], [36]. This technique enables the encoder to code and transmit the compressed bitstream in multiple quality layers that can be combined by the decoders. Different combinations of the layers result in several output video with different resolutions, frame rates and SNRs.

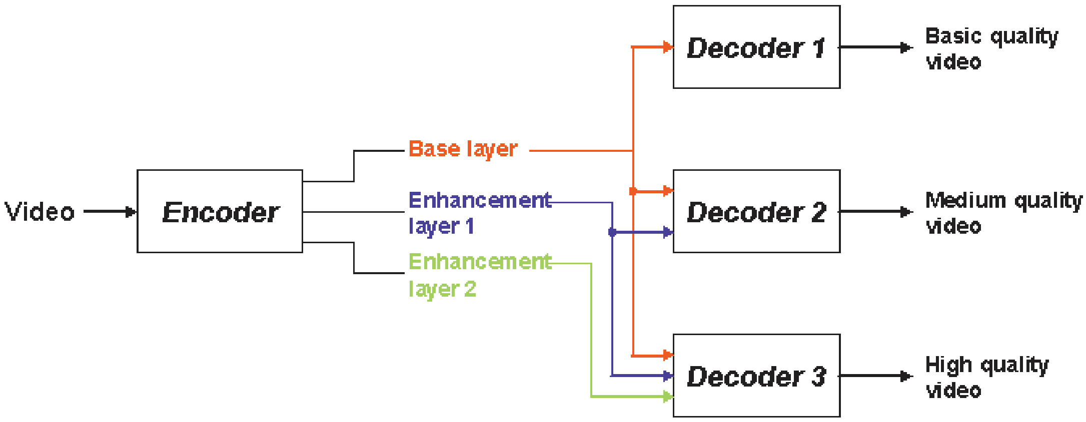


Figure 6.1: Scalable video coding

In this chapter, we deal with the transmission of a scalable video. sizes are sufficient. The scalable video consists of a base layer and/or one or two enhancement layers. For achieving an acceptable quality video receivers should at least receive the base layer. This time we do no use the cooperation methods separately rather we use them in combination. For the exposition of main ideas let us start with an example scenario. Assume the base layer is streamed simultaneously by both transmitters and the enhancement layers are transmitted one by the first transmitter and the other by the second transmitter. Therefore, in the transmission of the base layer and enhancement layers, user cooperative diversity and parallel downloading methods are used respectively.

6.1 Protocols for Scalable Video Transmission

We define 10 protocols and analyze them by providing the channel equations with the assumption that T3 is the advantageous receiver, that is its channel conditions with the transmitters are more favorable than T4's. For the reverse case the variables are reversed.

The variables used in the derivations and their definitions are as follows:

P_i : Power constraint of user i

R_{BL} : Transmission rate of base layer

R_{EL1} : Transmission rate of enhancement layer 1

R_{EL2} : Transmission rate of enhancement layer 2

R_3 : T3's transmission rate

R_4 : T4's transmission rate

R_{T3} : Total rate flow in T3 (T3's total receiving rate)

R_{T4} : Total rate flow in T4 (T4's total receiving rate)

P_{1BL} : Power allocated by T1 for the transmission of base layer)

P_{1EL} : Power allocated by T1 for the transmission of enhancement layer(s)

P_{1BL} : Power allocated by T1 for the transmission of base layer)

P_{2EL} : Power allocated by T2 for the transmission of enhancement layer(s)

Note that:

$$P_{1BL} + P_{1EL} \leq P_1 \tag{6.1}$$

$$P_{2BL} + P_{2EL} \leq P_2 \tag{6.2}$$

We examine the protocols in two main groups. For protocols 1-5 base layer is decoded by both receivers and for protocols 6-10 base layer is decoded by T3 only and relayed to T4. In other words T4 receives the base layer in one single hop (directly) for 1-5 and in two hops for 6-10. So we will also call these protocols as single-hop and two-hop protocols. Two-hop protocols are advantageous when one receiver has favorable, the other unfavorable channels with the transmitters and the inter-receiver channel is sufficiently good.

For the single-hop protocols both transmitters send the base layer and both receivers should receive and decode it by its own. Therefore the base layer transmission rate should be adjusted according to the minimum of the receivers' base layer reception rates:

$$R_{BL} < \min\left\{C\left(\frac{(h_{13}\sqrt{P_{1BL}} + h_{23}\sqrt{P_{2BL}})^2}{N_3}\right), C\left(\frac{(h_{14}\sqrt{P_{1BL}} + h_{24}\sqrt{P_{2BL}})^2}{N_4}\right)\right\} \tag{6.3}$$

The first and second elements in the minimum operator of Eq. 6.3 are the base layer reception rates of T3 and T4, respectively.

Protocol 1: Enhancement layer 1 is decoded by T3 and relayed to T4, enhancement layer 2 is decoded by T4 and relayed to T3. Since T3 receives and relays enhancement layer 1, R_{EL1} should be adjusted according to the worst of the T1-T3 and T3-T4 channels (Eq. 6.4). T3's relaying rate is constrained by T3-T4 channel capacity (Eq. 6.5). Equations 6.6 and 6.7 follow from the same arguments. Equations 6.8 and 6.9 are the multiple access channel capacity constraints.

$$R_{EL1} < \min\left\{C\left(\frac{h_{13}^2 P_{1EL}}{N_3}\right), R_3\right\} \tag{6.4}$$

$$R_3 < \left\{C\left(\frac{h_{34}^2 P_3}{N_4}\right)\right\} \tag{6.5}$$

$$R_{EL2} < \min\left\{C\left(\frac{h_{24}^2 P_{2EL}}{N_4}\right), R_4\right\} \tag{6.6}$$

$$R_4 < \left\{ C\left(\frac{h_{43}^2 P_4}{N_3}\right)\right\} \quad (6.7)$$

$$R_{BL} + R_{EL1} < C\left(\frac{(h_{13}\sqrt{P_{1BL}} + h_{23}\sqrt{P_{2BL}})^2 + h_{13}^2 P_{1EL}}{N_3}\right) \quad (6.8)$$

$$R_{BL} + R_{EL2} < C\left(\frac{(h_{14}\sqrt{P_{1BL}} + h_{24}\sqrt{P_{2BL}})^2 + h_{24}^2 P_{2EL}}{N_4}\right) \quad (6.9)$$

The total rate flow to the receivers are:

$$R_{T3} = R_{T4} = R_{BL} + R_{EL1} + R_{EL2} \quad (6.10)$$

Protocol 2: Enhancement layer 1 is decoded by T3 but not relayed to T4, enhancement layer 2 is decoded by T4 and relayed to T3.

Equations 6.6, 6.7, 6.8 and 6.9 are valid for this protocol. In addition:

$$R_{EL1} < C\left(\frac{h_{13}^2 P_{1EL}}{N_3}\right) \quad (6.11)$$

$$R_3 = 0 \quad (6.12)$$

The reception rates are:

$$R_{T3} = R_{BL} + R_{EL1} + R_{EL2} \quad (6.13)$$

$$R_{T4} = R_{BL} \quad (6.14)$$

Protocol 3: Enhancement layer 1 and 2 are decoded by T3 but not relayed to T4. Equations 6.11 and 6.12 are valid.

$$R_{EL2} < C\left(\frac{h_{23}^2 P_{2EL}}{N_3}\right) \quad (6.15)$$

$$R_4 = 0 \quad (6.16)$$

$$R_{BL} + R_{EL1} + R_{EL2} < C\left(\frac{(h_{13}\sqrt{P_{1BL}} + h_{23}\sqrt{P_{2BL}})^2 + h_{13}^2 P_{1EL} + h_{23}^2 P_{2EL}}{N_3}\right) \quad (6.17)$$

Equation 6.17 is the multiple access channel capacity constraint. The reception rates are the same as Protocol 2.

Protocol 4: Enhancement layer 1 and 2 are decoded by T3 and only enhancement layer 1 is relayed to T4.

Equations 6.4, 6.5, 6.15, 6.16 and 6.17 are valid.

The reception rates are:

$$R_{T3} = R_{BL} + R_{EL1} + R_{EL2} \tag{6.18}$$

$$R_{T4} = R_{BL} + R_{EL1} \tag{6.19}$$

Protocol 5: Enhancement layer 1 and 2 are decoded by T3 and relayed to T4. Equations 6.5, 6.11, 6.15, 6.16 and 6.17 are valid. In addition:

$$R_{EL1} + R_{EL2} < R_3 \tag{6.20}$$

The reception rates are the same as Protocol 1.

For two-hop protocols, with the assumption that T3 has more favorable channel conditions with the transmitters than T4 has, T3 decodes the base layer and relays it to T4. Therefore base later transmission rate should be adjusted according to the minimum of T3's base layer reception rate from the transmitters and T4's reception rate from T3:

$$R_{BL} < \min\left\{C\left(\frac{(h_{13}\sqrt{P_{1BL}} + h_{23}\sqrt{P_{2BL}})^2}{N_3}\right), R_3\right\} \tag{6.21}$$

$$R_3 < \left\{C\left(\frac{h_{34}^2 P_3}{N_4}\right)\right\} \tag{6.22}$$

Protocol 6: Enhancement layer 1 and 2 are decoded by T3 but not relayed to T4. Equations 6.11, 6.15, 6.16 and 6.17 are valid.

The reception rates are the same as Protocol 2.

Protocol 7: Enhancement layer 1 and 2 are decoded by T3 and relayed to T4. Equations 6.11, 6.15, 6.16 and 6.17 are valid. In addition:

$$R_{BL} + R_{EL1} + R_{EL2} < R_3 \tag{6.23}$$

The reception rates are the same as Protocol 1.

Protocol 8: Enhancement layer 1 and 2 are decoded by T3 and only enhancement layer 1 is relayed to T4.

Equations 6.11, 6.15, 6.16 and 6.17 are valid. In addition:

$$R_{BL} + R_{EL1} < R_3 \tag{6.24}$$

The reception rates are the same as Protocol 4.

Protocol 9: Enhancement layer 1 is decoded by T4 and relayed to T3. There is no second enhancement layer.
Equation 6.7 is valid. In addition:

$$R_{EL1} < \min\left\{C\left(\frac{h_{14}^2 P_{1EL}}{N_4}\right), R_4\right\} \tag{6.25}$$

if enhancement layer is sent by T1, or

$$R_{EL1} < \min\left\{C\left(\frac{h_{24}^2 P_{2EL}}{N_4}\right), R_4\right\} \tag{6.26}$$

if enhancement layer is sent by T2. The reception rates are:

$$R_{T3} = R_{T4} = R_{BL} + R_{EL1} \tag{6.27}$$

Protocol 10: Enhancement layer 1 is decoded by T3 but not relayed to T4, enhancement layer 2 is decoded by T4 and relayed to T3.
Equation 6.6, 6.7, 6.8 and 6.11 are valid.
The reception rates are the same as Protocol 2.

Note that for all protocols by setting R_{EL2} to 0, two layer scalability is achieved. In other words, if the optimization gives $R_{EL2} = 0$, this means that optimal results are obtained when two layer scalability is used.

Optimization Problem:

We optimize the system either to maximize the sum of total rate flows in the receivers (Eq. 6.28) or to maximize the worse (minimum) of the rate flows in the receivers (Eq. 6.29). In mathematical form the goal is either of the following:

$$\max_{\text{Rate \& Power Constraints}} \{R_{T3} + R_{T4}\} \tag{6.28}$$

$$\max_{\text{Rate \& Power Constraints}} \{min(R_{T3}, R_{T4})\} \tag{6.29}$$

Assume T3 is the advantageous receiver. If we aim to maximize T4's reception rate (second goal), all the transmitter power will be allocated according to the layer(s) that T4 will receive so that little or no power remains for the enhancement layers to be sent to T3, that it T3 is sacrificed for T4. If channel conditions of T4 are much more worse than those of T3, this goal is very ineffective. On the other hand if we try to maximize the sum rate (first goal), since the same amount of power results in much more increase in R_{T3} than in R_{T4}, little power will be allocated to the layers that both T3 and T4 receives and the remaining huge power will be allocated to the enhancement layers for T3. This time T4 will achieve extremely low rates. In conclusion, the results achieved with the first goal are expected to be more favorable for the advantageous receiver than those achieved with the second goal. However, for the disadvantageous receiver the situation is reversed; second goal is more favorable for it. Of course by designing more effective goals moderate results can be achieved.

6.2 Numerical Analyses and Results

We set transmission powers P_1 to P_4 to 0.1W, channel bandwidth B to 2.45MHz, noise power spectral density N_0 to 10^{-10}W/Hz (Note $N_3 = N_4 = N_0 \cdot B$). We assume the transmitter-receiver channel fading coefficients are: $h_{13} = 0.045$, $h_{23} = 0.04$ and $h_{24} = 0.03$. We varied T1-T4 channel fading coefficient h_{14} from 0 to 0.09. We set the inter-receiver channel fading coefficients to be first relatively worse ($h_{34} = h_{43} = 0.015$) and then relatively better ($h_{34} = h_{43} = 0.05$) compared to the transmitter-receiver channel fading coefficients (All the fading coefficient values are chosen to be in the range of typical values obtained by the channel model of chapter 5). We numerically analyze the system for each setting to maximize the minimum of the receiver reception rates (second goal) when only parallel downloading method is used (one transmitter sends BL and the other EL1), only user cooperation diversity method is used (only BL is sent) and they are used in conjunction (hybrid method). Full diversity method signifies single layer coding and we also considered no receiver cooperation case (protocol 3 of hybrid method). We then plotted the resulting minimum of the reception rate values versus h_{14}. We find the optimal values by choosing the highest valued result among the ten results corresponding to the ten protocols we defined.

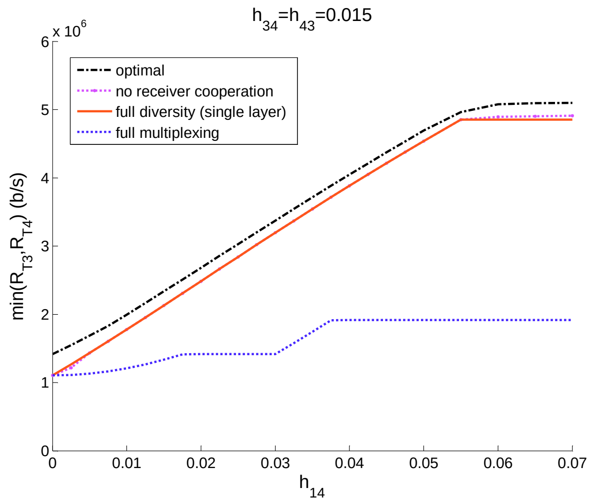


Figure 6.2: $\min(R_{T3}, R_{T4})$ vs T1-T4 channel fading coefficient h_{14} plotted when inter-receiver channel fading coefficients are $h_{34} = h_{43} = 0.015$, that is high cooperation is not possible.

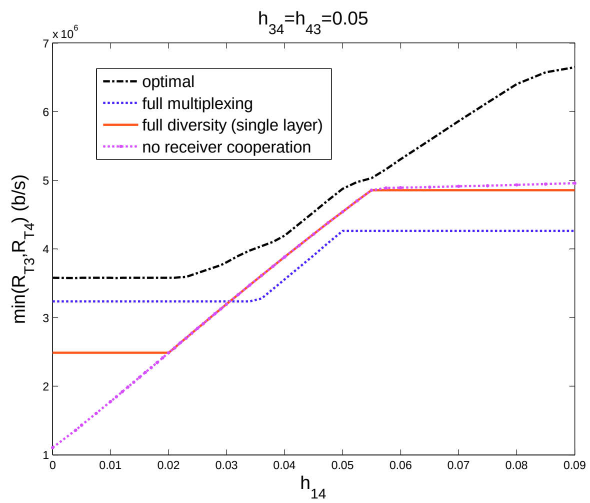


Figure 6.3: $\min(R_{T3}, R_{T4})$ vs T1-T4 channel fading coefficient h_{14} plotted when inter-receiver channel fading coefficients are $h_{34} = h_{43} = 0.05$, that is high cooperation is possible.

Fig. 6.2 shows results for low receiver cooperation case. We observe that slightly better results are achieved when parallel downloading and user cooperation methods are used in conjunction instead each is used alone. When receiver cooperation is higher (Fig. 6.3), this gain is also much more higher. Figures 6.2 and 6.3 also show the effects of receiver cooperation and scalable video coding on the maximum rates. As expected, when inter-receiver channel quality and thus cooperation is high, the difference between the optimal values and the values achieved when receivers do not cooperate is high. But as T1-T4 channel quality and thus h_{14} increases, the difference decreases till a high h_{14} value. After this value the non-optimal curves saturate but optimal solution continues increasing because T1-T4 channel can support more and more transmission rate as h_{14} increases. Additionally, if we compare the optimal curve with the single layer (full diversity) curve, we observe that utilizing scalable video coding increases the rates substantially especially for moderate h_{14} values (values in the range of the other transmitter-receiver fading coefficients).

For video coding we employ the video coding standard known as H.264 [37]. We code the standard video sequence *mobile* in CIF format with 30 fps. We choose the GOP size and intra period to be 16. We apply a 1% of packet loss rate, choose a FEC coding rate of 1/2 and physical layer packet size of 256 bytes. We compare the results with and without scalable coding at $h_{14} = 0.02$ value (a probable value if the h_{13}, h_{23} and h_{24} values are considered). Results are presented in table 6.1. We see that if the receiver cooperation is high, there is about a 1.5 dB of PSNR difference between the scalable and non-scalable (single layer) coded videos.

		Scalable	Single Layer
low cooperation case	bit rate (kpbs)	2674	2345
	PSNR (dB)	33.91	33.62
high cooperation case	bit rate (kpbs)	3573	2345
	PSNR (dB)	35.17	33.62

Table 6.1: PSNR results achieved with and without scalable video coding for low and high receiver cooperation cases. Actual rates are half since 1/2 FEC code is applied.

We also consider in which circumstances the single hop (protocols 1-5) or two-hop (protocols 6-10) protocols give the optimal result. When the inter-receiver channel quality is low ($h_{34} = h_{43} = 0.015$), one-hop protocols give the optimal result. However, when the inter-receiver channel quality is high ($h_{34} = h_{43} = 0.05$), two-hop protocols give the optimal result until moderate h_{14} values (0.035). This is an expected result because when receivers can cooperate well, the receiver having bad channels with the transmitters can cope with this situation by taking the information it demands from the other receiver, which has good channels with the transmitters. However when receiver cooperation is insufficient, it will be more advantageous if receivers get the base layer on their own.

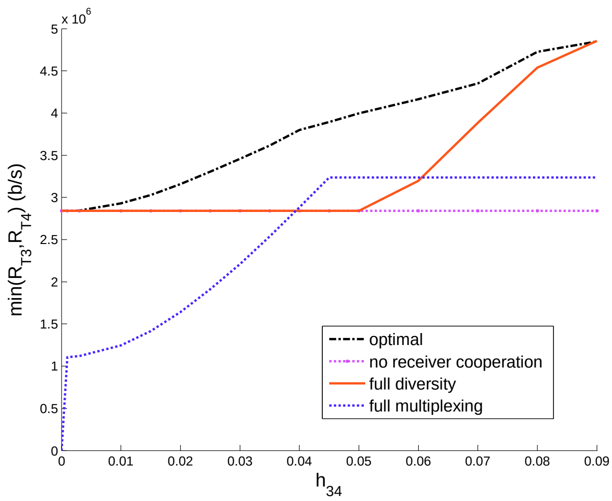


Figure 6.4: $\min(R_{T3}, R_{T4})$ vs inter-receiver channel fading coefficient h_{34}.

We examine the effect of inter-receiver cooperation on the system performance. We assume the transmitter-receiver channel fading coefficients are: $h_{13} = 0.045$, $h_{14} = 0.025$, $h_{23} = 0.04$ and $h_{24} = 0.03$. This time we varied he inter-receiver channel fading coefficients $h_{34} = h_{43}$ from 0 to 0.05. We optimize the rates to maximize the minimum of the reception rates of the receivers. Figure 6.4 shows the results. Gain achieved by the hybrid method is prominent especially for moderate h_{13} values.

Chapter 7

CONCLUSIONS

In this last chapter, we summarize the contributions of the thesis and present several issues for future work.

7.1 Contributions

User cooperation is an effective method that can dramatically increase system performance especially in terms of data rates and system robustness. Prior research on user cooperation consider cooperative models in which each receiver demands independent information from other receivers. Therefore a receiver processing another receiver's information does not benefit from this processed information (except may be for interference cancelation purposes). However for peer-to-peer systems receivers may be demanding the same information, and this situation changes the problem and brings new motivations. In this thesis, we investigated the effect of user cooperation on a general two transmitter - two receiver wireless peer-to-peer network, in which receivers demand the same file and transmitters have this file in demand, by comparing the performances of several transmission protocols. To allocate the optimal power to the channels transmitters should know channel state information of all transmitter-receiver and receiver-receiver channels. Receivers should also be aware of the channel condition between each other to decide at how much rate they cooperate. We considered two main cooperation techniques at the transmitter side: first parallel downloading, in which transmitters cooperate to transmit different portions of the information to benefit from multiplexing gain, and second user cooperation diversity, in which transmitters simultaneously broadcast the same portion of the information to benefit from diversity gain. At the receiver side, we investigated results for decode-and-forward and amplify-and-forward transmission schemes, and also we consider the case when there is no cooperation between the receivers. Throughout the thesis we compared the performances of these receiver and transmitter cooperation methods.

We presented a delay minimization problem for file downloading in a system with fixed channel fading coefficients and examined the benefits of user cooperation through capacity optimization. We first observed that user cooperation diversity method performs better than parallel downloading method. However with sufficiently high SNR and inter-receiver channel quality, parallel downloading method can outperform user cooperation diversity method when decode and forward transmission scheme is used.

We then considered average results to be more realistic where averages are across download times and taken over random distributions (corresponding to random fading coefficients and random channel conditions).We found that on the average user cooperation diversity method is better than parallel downloading method. We had also found in the pervious delay minimization problem that user cooperation diversity method performs better for low SNR. These two results suggest that for real configurations nodes will probably be connected via low SNR channels.

We also discussed how user cooperation methods, parallel downloading and user cooperation diversity, can be used in conjunction for the transmission of a scalable video. For this problem, we observed that better results are achieved when parallel downloading and user cooperation methods are used in conjunction (hybrid method) instead each is used alone, especially when receiver cooperation is high. Additionally, when we compared the hybrid method with the single layer coding, we observed that utilizing scalable video coding increases the rates substantially. We categorized the protocols in mainly two groups; one-hop and two-hop protocols. When the inter-receiver channel quality is low, one-hop protocols give the optimal result. However, when the inter-receiver channel quality is high, two-hop protocols start giving the optimal results. This was an expected result because when receivers can cooperate well, the receiver having bad channels with the transmitters can cope with this situation by taking the information it demands from the other receiver, which has good channels with the transmitters. However when receiver cooperation is insufficient, it will be more advantageous if receivers get the base layer on their own.

7.2 Future Work

Although our model is quite simple, it is only the beginning of a research investigating the benefits of user cooperation in wireless peer-to-peer networks. A hybrid network consisting of receivers demanding both the same and independent information, requires the development of new protocols combining the results of prior researches with the deductions of this work. Generalized results can be deduced for M-transmitter N-receiver generalized networks. A more realistic but more complex network also contains intermediate idle users that may relay the information from transmitters to receivers and thus includes multi-hop routing concept to the problem.

We also did not consider channel coding in detail in this thesis. This could be added in the future work. Optimizations with respect to FEC rate determining, PSNR maximization and packet size setting can also be included.

For the rate allocation for scalable video coding problem more effective optimization goals can be determined because if one of the receivers is very advantageous over the other, trying to maximize the disadvantageous receiver's reception rate will result in allocating more power for the base layers so that little or no power remains for enhancement layer(s) for the advantageous receiver. This goal can unnecessarily sacrifice the advantageous receiver. To prevent this, a high and a low threshold rate can be determined. The low threshold rate is found by searching for the minimum acceptable rate corresponding to minimum acceptable quality video. After supplying the disadvantageous receiver with this rate the remaining transmitter power is used for the advantageous receiver as enhancement layers. If the advantageous receiver's reception rate reaches the high threshold rate, the rate which supplies the user with a very satisfactory video quality, the last remaining transmitter power is used to increase the disadvantageous receiver's reception rate.

Again for the scalable video transmission problem fading can be incorporated to the problem and the proposed method can be adapted to real-time video streaming. This time the base layer rate is adjusted according to the worst scenario among the geographical distributions and fading states.

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