OPTIMAL CONTROL OF COMMUNICATION AND PROPULSION IN NETWORKS OF SMART DRONES AND ROBOTS

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Abstract

Since the UAVs have been proposed to be deployed as relays in the future 5th generation networks, this project aims to develop cooperative communication schemes to enhance the robustness of the UAV networks. Decode-and-Forward protocol is used as the coding cooperation strategy in our models to obtain extra coding gain by the provided spatial diversity. For simplicity, the system model only consists of two stations and one mobile relay. The network performance is mainly evaluated by bit error rate, which can denote the quality of service.

The implement of DF coded cooperation in the relay networks has been extended in our later chapters, where we further explored the power allocation and detection schemes, as well as the optimal control of transmission under the constraint of energy.

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Abbreviations

AP: Access Point

AWGN: Addictive white Gaussian noise

BER: Bit Error Rate

BS: Base Station

CSI: Channel State Information

CRC: Cyclic Redundancy Check

DF: Decode-and-Forward

FER: Frame-Error Rate

SNR: Signal-to-Noise Ratio

UAV: Unmanned Aerial Vehicle

Chapter 1

Introduction

Terminals communicate with the access point (AP) or base station (BS) directly in wireless local area networks. Rather, in wireless ad hoc networks data is transfered from source to destination by deploying other mobiles as relays. Without requiring a fixed infrastructure, the nodes in mobile ad hoc networks (MANETS) communicate by establishing a temporary network based on past and current channel settings and mobile locations [1]. Relay-assisted communication provides a substantial benefit regarding path loss due to shorter links than a direct-transmission path. Multiple transmit channels suffering independent fading are preferred because of the spatial diversity they offer. Cooperative communication takes advantage of relay-assisted signalling and also achieve spatial diversity [2].

Unmanned aerial vehicles (UAVs) have been proposed to be hired as prospective relays in the future 5th generation mobile networks [3]. Compared with the traditional ground relays, cooperative UAV relays are likely to have a straight line-of-sight (LOS) with access points on grounds and have a better quality of service (QOS) due to its high flexibility property [4]. Moreover, UAV relays can be implemented rapidly and economically to extend wireless networks in some emergency situations, for instance, earthquake and some other natural disasters [2].

This project aims to explore efficient cooperation schemes for improving error performance in mobile ad hoc networks applied in UAV networks. To learn the error performance of cooperative communication in UAV networks, we perform simulations assuming specific problem formulations. Namely, there exist data-bearing nodes as relays moving in specific trajectories to forward messages from the source to destination and all the nodes have full knowledge of channels, code schemes, and each other actions. When investigating optional energy usage, ICLOCS (Imperial College London Optimal Control Software), interfaced through Matlab, is used to derive optimal power allocation to minimize the number of errors respecting energy budget, relay power and other constraints.

The report is structured as follows. Firstly, Chapter 2 reviews some previous work which are related to our model formulation. A general overview of some present works on UAV networks in several related fields is included. The general system model and problem definition are introduced in Chapter 3. In Chapter 4, the cooperative coding scheme is implemented to study spatial diversity in communication. Chapter 5 explores the optimal relay position in error performance for the use of cooperative communication in the UAV network. In Chapter 6, two power allocation schemes are developed to reduce the bit error rate in cooperative transmission. Simulations to find the trade-off between error performance and energy cost under our assumption are shown in Chapter 7. Subsequently, Chapter 8 gives pair power bounds of nodes meeting the minimum requirement of bit error rate. Finally, a brief conclusion of the project and potential works in future are included in Chapter 9.

Chapter 2

Literature Review

IN spite of the advantages provided by deploying UAVs as relay, there are still many challenges, such as establishing and maintaining effective communications among UAVs. [1] Thus, a lot of attempts have been made to study and evaluate the effects of UAV relays in wireless networks. Research into MANETs applied in UAV networks mainly focus on path planning under a constraint of communication and improvement of communication performance.

The three most common cooperative communication protocols are [5]:

- Amplify-and-Forward (AF), where relays simply amplify and retransmit messages to destination.
- Compress-and-Forward (CF), where relays compress data and transmit its estimate.
- Decode-and-Forward (DF), in which relays decode the received message and then re-encode before re-transmitting it.

We adopt DF mode in this project which has a characteristic that using different codes in the relay and source, called as Parallel Coding. In [6] energy efficient of parallel coding in local area communications has been investigated and compared with AF. Stefanov and Erkip [7] presented a parallel coding strategy operating on rate compatible punctured convolutional (RCPC) codes, which are adopted in this paper. They also obtained the diversity gains of cooperative coding by both analysis and simulation results, and gave suggestions on cooperative code-design criteria. A system model of cooperative multiple users relay networks was first proposed in [8], which analyzes the behavior of multi-user diversity under flat fading channels in relay cooperation networks .

Compared with previous works, [9] combines path planning and information transmission planning under principal constraints on vehicle motion and communication parameters, in which a linear programming optimization problem has been defined to determine a investigation assignment utilizing UAV relays. In [10], in order to maintain connectivity in wireless sensor network, a scheme is developed that combines relay networks and cooperative multiple-input and multiple-output (MIMO) strategies. Both of [9] and [10] work on typical research fields of mobile ad hoc network using UAV relays.

The work [11] implements a traditional cognitive radio system assisted by relays, and shows a trade-off between the data rate and the probability of accomplished communication. The result of this paper gives a useful insight into CR systems with relay-assisted transmission and has become a foundation of other works, such as [12]. In [12], the achievable data rate of a set-up in which the UAV relay extends the wireless network has been investigated. The optimal power allocation to maximize data rate under the power and interference constraints is derived. The effect of UAV altitude on data rates is highlighted in this article.

Chapter 3

General System Model

3.1 System Model

Consider a typical model of cooperative communication system consisting of three terminals with a single relay, shown in Fig 3.1. The source and sink (destination) nodes are stations, while the relay may change position. To send K bits from the source node to

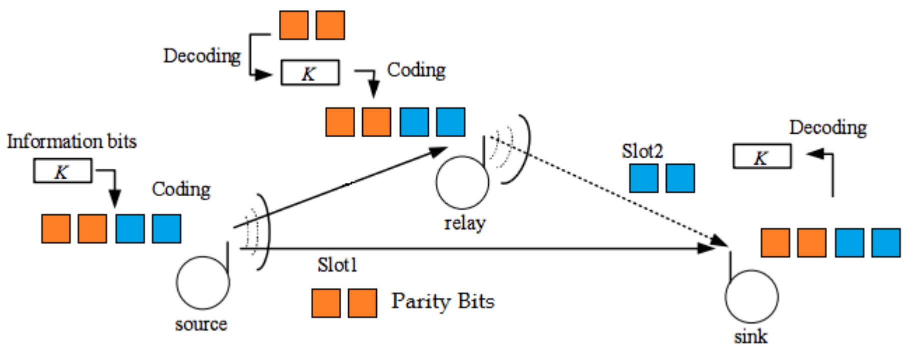


Figure 3.1: A Three-node Cooperative Communication Model using Decode-and-Forward strategy

sink node, the bits are encoded into $N = K/R$ bits with a coding rate R ($R = 1/4$), then divided into N_1 and N_2 bits streams for cooperation. For the purpose of realizing DF protocol, the relay node allocates its time slot into two consecutive segments. In the first segment, the N_1 coded bits are spread from transmitter at the source to both the sink and relay nodes. Then, the relay node recovers bits from the received message and also checks the correctness. Assuming perfect error-checking schemes, the relay can know exactly if the decoded data is correct. If the message has been perfectly decoded, the relay node will re-encode the data into N_2 bits and forward the bits to the sink in the next time segment. Otherwise, transmitter at source will re-transmit the N_2 bits directly. Lastly, the destination node combines the messages received from both the relay and source nodes before deciding.

In this work, BPSK (Binary Phase Shift Keying) is employed as our modulation strategy. Consider x as the modulated signal, i.e., $x \in \{-1, +1\}$. The signal y_{sr}, y_{sd} and y_{rd} received at the sink and relay nodes can be presented by

$$y_{sr} = \sqrt{P_s} h_{sr} x + n_{sr} \tag{3.1}$$

$$y_{sd} = \sqrt{P_s} h_{sd} x + n_{sd} \tag{3.2}$$

$$y_{rd} = \sqrt{P_r} h_{rd} x + n_{rd} \tag{3.3}$$

respectively, in which P_s and P_r denote source transmission power and relay transmission power respectively. Assuming that the three paths in the terminals are independent Rayleigh-fading channels, the corresponding channel coefficients h_{sd}, h_{sr} and h_{rd} are complex random Gaussian variables, with uniform variance and zero-mean, i.e $h_{sr} \sim N(0, \sigma_{sr}^2)$, $h_{sd} \sim N(0, \sigma_{sd}^2)$, $h_{rd} \sim N(0, \sigma_{rd}^2)$. n_{sr},n_{sd}, and n_{rd} represent additive white Gaussian noise (AWGN), with uniform variance N_0 and zero-mean, i.e., $n_{sr}, n_{sd}, n_{rd} \sim N(0, N_0)$.

3.2 RCPC codes

Channel codes have a significant effect on the quality of message in cooperative coding. Therefore, appropriate codes must be chosen carefully. In this model, we operate the coded cooperative communication system built on the rate-compatible punctured convolutional (RCPC) code [14]. Convolutional encoders usually act as binary filters which combine registers with modulo-2 operators, as shown in Fig 3.2. The bits in the shift registers will be outputted after the binary modulo operation.

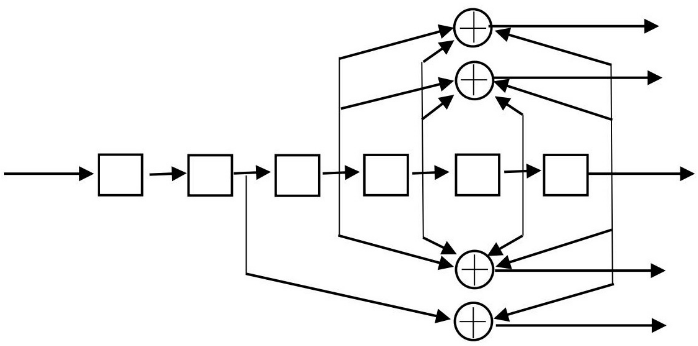


Figure 3.2: A RCPC Code Generator with Code Rate 1/4

For example, assume that rate $R_1 = 1/3$ code acts as the initial codewords. By "puncturing" one bit in three bits, a high-rate $R_2 = 2/3$ code is generated and its codewords are compatible with the original low-rate $R_1 = 1/3$ codewords.

Suppose that the inputed bits (1, 1, 0, 0, 1, 0, 0, 0,...) are encoded by convolutional code with generator matrix

$$G_1 = \begin{pmatrix} 1 & 0 & 1 & 1 & 0 & 1 & 1 \\ 1 & 1 & 1 & 1 & 0 & 0 & 1 \\ 1 & 1 & 0 & 0 & 1 & 0 & 1 \end{pmatrix} \tag{3.4}$$

Thus, the bits are encoded into $x_1 = (111, 100, 101, 000, 000, 110, 101, 001, ...)$, where the code rate $R_1 = 1/3$. By "puncturing" one bit, the generator matrix becomes

$$G_2 = \begin{pmatrix} 1 & 0 & 1 & 1 & 0 & 1 & 1 \\ 1 & 1 & 1 & 1 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 \end{pmatrix} \tag{3.5}$$

the coded information x is punctured to $x_2 = (11p, 1pp, 10p, 0pp, 00p, 1pp, 10p, 0pp, ...)$, in which p denotes erased bits. In this way, the codewords of a high-rate R_2 code are inserted in the original codewords of rate $R_1 = 1/3$.

To decode the RCPC codes, a Viterbi algorithm is performed using the rate $1/N$ code trellis, in which the metrics of each branch state are calculated and saved in memory. By comparing the preserved values, the receiver selects the finest path.

Chapter 4

Coded Cooperative Communications Simulation

Our first simulations are of exploration of user cooperation, which obtain diversity by the cooperative use of channels between several nodes. Firstly we establish the problem definition with related notations. Then, we study and analyze the performance of the proposed cooperative system model. Simulation results illustrate the robustness of the coded cooperative communication. In addition, proper code-design guidelines are provided with a description of a design of a particular code.

4.1 Problem Definition

The BS employs more than one antenna, and we have only one antenna at the transmitter for each mobile user. To simplify the system, we concentrates on the cooperation between two mobile terminals with a same destination. A channel encoder is employed to encode the original bits for each of the nodes, which are then multiplexed for cooperative communication. After that, the data is sent to a serial/parallel converter. BPSK is employed as the modulation scheme to map the symbols to the signal constellation before transmitting. The processes are shown in Fig 4.1.

The output of node T_i $(i = 1, 2)$ at discrete time slot t is given by $c^i(t)$. For antenna

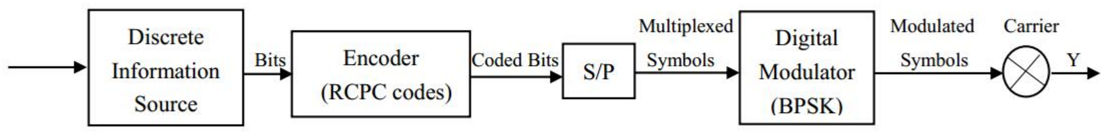


Figure 4.1: Block Diagram of Transmitter at the Source Node

j at the destination, the signal received from terminal i at time slot t is presented as

$$y_j(t) = \alpha^{i,d}(t)c^i(t) + n^{i,d}(t) \tag{4.1}$$

where the channel coefficient $\alpha^{i,d}$ denotes the fading level or the path loss from the node i to destination node. In this case, we assume the path gains are invariant and independent, such that as we mentioned before, they are specified by complex random Gaussian variables with uniform variance and zero mean. Similarly, the additive white Gaussian noise samples $n^{i,d}(t)$ between node i and destination are modeled as zero-mean complex random Gaussian variables as well.

We assume that the receivers have full knowledge of channel state information, and the channels are orthogonal for non-cooperation situations. A rate 1/4 convolutional code is used in our case, as shown in Fig 4.2. Node T_1 sends symbols to both node T_2 and

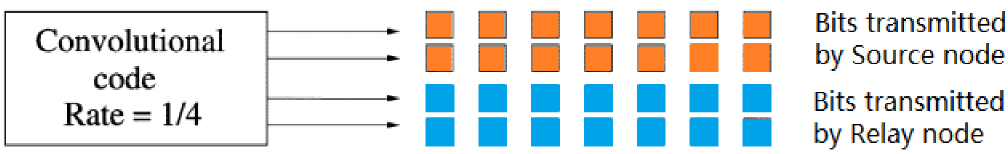


Figure 4.2: Coded Cooperation Using the Convolutional Code with Code Rate 1/4

the BS. If node T_2 decodes the symbols perfectly, known by a cyclic redundancy check (CRC), the relay will re-encode the decoded message to obtain the other part of coded bits which are not included in the data transmitted by T_1. Then, in next time segment node T_2 forwards the symbols to the BS. Otherwise, it will notify node T_1 if the correct message cannot be received at T_2, and then node T_1 transmits the other part of the signal by itself. Since we assume the BS estimates channel-states at every time slots, it does not matter whether the second half of message comes from node T_1 or T_2.

4.2 Performance Analysis

To prove that full diversity can be achieved by user cooperation, we analytically analyze the error performance in terms of frame-error probability (FEP) for two different situations. For the cooperative coding protocol, the frame error probability with a specific channel code is represented by P^{fr}. Then the FEP of T_1 is given by [13]

$$P^{fr} = (1 - P^{in})P^{BF} + P^{in}P^{QS} < P^{BF} + P^{in}P^{QS} \tag{4.2}$$

in which P^{in} means the FEP of the channel between user T_1 and T_2. P^{BF} and P^{QS} are error probabilities for block-fading channels when there exist cooperation and for the quasistatic channel from node T_1 to destination respectively. Consequently, for perfect inter-user channel, i.e $P^{in} = 0$, we have $P^{fr} = P^{BF}$, where the cooperation leads to a usual block-fading channel. For the block-fading Rayleigh channel, the upper bound on P^{fr} can be derived by the expression of pairwise error probability [14]:

$$\begin{aligned} P^c \leq & \sum_c \sum_{c \neq e} \frac{1}{(d_1^2(e,c)d_2^2(e,c))^{\frac{1}{2}}(E_{s_2}/4N_0)^{I_{d_2^2(e,c)}}(E_{s_1}/4N_0)^{I_{d_1^2(e,c)}}} + \\ & (\sum_c \sum_{c \neq e} \frac{1}{\Phi^2(e,c)E_{s_{in}}/4N_0}) \times (\sum_c \sum_{c \neq e} \frac{1}{\Psi^2(e,c)E_{s_1}/4N_0}) \end{aligned} \tag{4.3}$$

In which $I_x = 0$ if $x = 0$, else $I_x = 1$. $\Phi^2(e,c) = d_1^2(e,c)$ represents the Euclidean distance in the partial codewords transmitted in inter-user channel. And $\Psi^2(e,c) = d_1^2(e,c) + d_2^2(e,c)$ gives the Euclidean distance in whole codewords. The received average signal-to-noise ratios (SNR) at the BS from T_1 and T_2 are given by $E_{s_1}/4N_0$ and $E_{s_2}/4N_0$. Similarly, $E_{s_{in}}/4N_0$ denotes the received SNR at T_2. We investigate the achievable diversity in two extreme situations, which are given below.

$CaseA : The\ Inter-user\ channel\ in\ good\ quality$: As we mentioned before, if the inter-user channel performs good in error performance, i.e., the probability of error $P^{in} \approx 0$, which results in the usual block-fading channel $P^c \approx P^{BF}$. Thus, full diversity can be achieved. To simplify the analysis, we assume $E_{s_1} \approx E_{s_2} \approx E_{s_{in}} = E_s$, such that the upper bound on the frame-error probability can be given by [7]

$$P^c \leq (\frac{1}{E_s/4N_0})^2\{(\sum_c \sum_{c\neq e} \frac{1}{(d_1^2(e,c)d_2^2(e,c))^{\frac{1}{2}}})+(\sum_c \sum_{c\neq e} \frac{1}{\Phi^2(e,c)})\times\sum_c \sum_{c\neq e} \frac{1}{\Psi^2(e,c)})\} \tag{4.4}$$

At high SNRs, the above formulation can be replaced by the following approximation:

$$P^c \approx K(\frac{1}{E_s/4N_0})^2 \tag{4.5}$$

Where K is decided by the principal term. It proves that the full diversity can be obtained in this case, as implied by the SNR exponent.

$CaseB : The\ inter-user\ channel\ in\ bad\ quality$: Suppose the inter-user channel performs poorly, then the dominant term would be $P^{in}P^{QS}$ [7]. Since the channel quality is poor, we substitute $E_{s_{in}}/N_0$ by C_{in}. Hence, we have

$$P^c \leq (\sum_c \sum_{c\neq e} \frac{1}{C_{in}} \frac{1}{\Phi^2(e,c)})(\sum_c \sum_{c\neq e} \frac{1}{E_{s_1}/4N_0} \frac{1}{\Psi^2(e,c)}) \tag{4.6}$$

Thus, at high SNRs, we derive the approximation for P^c:

$$P^c \approx \frac{1}{C_{in}}(\frac{1}{E_{s_1}/4N_0})\frac{1}{min_{e,c}\{\Phi^2(c,e)\Psi^2(e,c)\}} \tag{4.7}$$

in which $min_{e,c}\{\Phi^2(e,c)\Psi^2(e,c)\}$ represents minimum code distance which decide the channel quality at high SNRs. As indicated in (4.7), the diversity, in this case, is mainly limited by the diversity of the non-cooperative channel between node T_1 and BS, but there still exists some coding gains due to the non-cooperative channel.

4.3 Simulation Results

In the simulation, both nodes T_1 and T_2 have channels with same quality to destination, and we study how the quality of the channel between user node T_1 and user node T_2 affects the performance of cooperative coding by implementing several assumptions with various inter-user qualities.

The total number of bits is 10^6, and we evaluate the channel performance by bit error rate (BER). We select the convolutional code with code rate 1/4 and generator polynomial (15, 17, 13, 15), and use binary phase shift keying (BPSK) modulator. By varying the average received SNR at the destination, we test different situations based on the quality of the users-to-destination channels. Meanwhile, we illustrate that a better quality inter-user channel improves the cooperative coding performance in BER by four different scenarios. Fig 4.3 shows that compared with single user transmission without

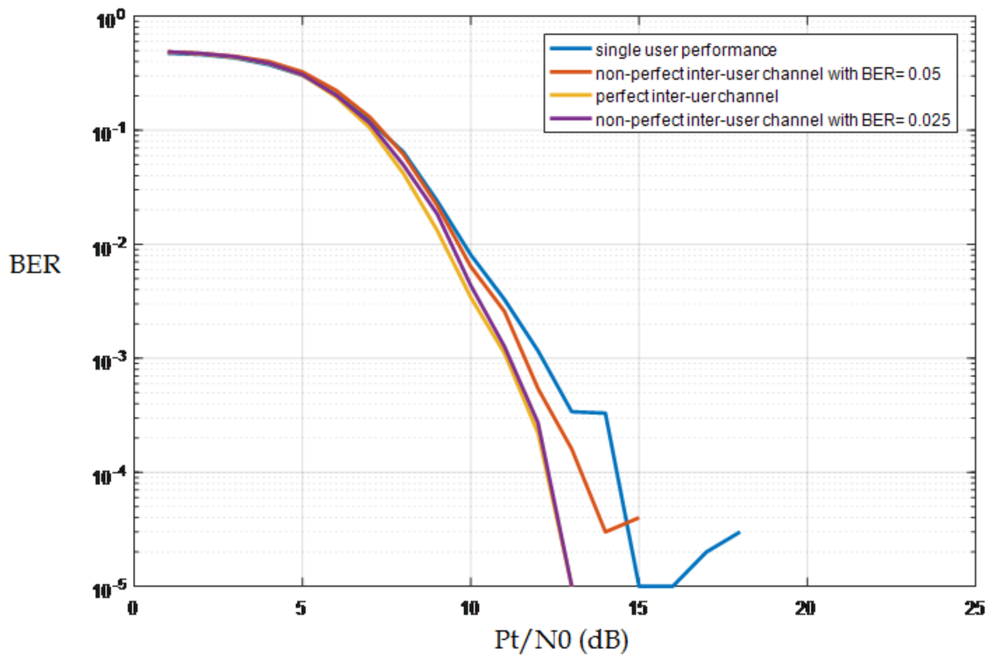


Figure 4.3: BER Performance of Direct Transmission and Cooperative Communication with Inter-user Channels in Different Qualities

cooperation, cooperative coding with perfect inter-user channel provides a clear benefit in term of BER, where the performance improvement in dB scale is about 0dB at SNR of 5 dB, 2.1 dB at SNR of 10dB, and 16dB at SNR of 13dB. It can be observed that cooperative communication achieves a higher diversity gain at a higher SNR. Fig 4.3 also indicates the BER performance for inter-user channels in different qualities, while the quality of inter-user channels is provided by BER. As we mentioned before, the poor quality of inter-user channel causes a limited system diversity, and we can observe there indeed still exist some coding gains from the direct communication.

4.4 Code-Design Criteria

It is clear that the cooperative communication leads to a block-fading channel with $f = 2$. Unlike a classic block-fading channel, it requires further constraints on the code-design due to some features involved by cooperation.

On the one hand, it is significant for the DF cooperation scheme that the relay can decode the message correctly. To realize that, the code for the inter-user channel must be an appropriate code with maximized coding gain for all pairs of codewords, which denoted by $d_1^2(c, e)$. On the other hand, when it fails to recover the information, the source node transmits all the bits to the destination directly by a same quasi-static channel. Thus, the coding gain is also supposed to be relatively large for all pairs of codeword, which is expressed by the squared distance between entire code words

$$\Psi^2(c, e) = d_1^2(c, e) + d_1^2(c, e) \tag{4.8}$$

In this work, the rate 1/4 code with the group of generator polynomials (15,17,13,15) has been used. From [15], we know that rate-1/2 code with the group of generator polynomials (15,17) acts finest in the inter-user channels. Meanwhile, to make sure it performs well without cooperation (quasi-static channel), we add extra parity bits with generator polynomials (13,15). Therefore, the overall rate-1/4 code serves our purpose.

Chapter 5

Cooperative Communication in UAVs simulation

5.1 Channel Model

In this simulation, all the paths including the source-to-relay link are assumed to be time-varying and frequency-flat (Rayleigh) fading channels with complex AWGN. The time-division multiple access schemes are adopted to achieve orthogonality of channels. Moreover, the receiver has full knowledge of CSI completing by feedback channels.

The path-loss is denoted as $g(d) \propto d^{-n}$, in which the path-loss exponent $n = 2 \sim 8$ in typical propagation scenarios, and is assumed 2 in our study. Hence, the received signal power at destination

$$P_r = g(d) P_t G_t G_r \tag{5.1}$$

where G_t and G_r are constants representing transmit and receive antenna gains respectively. Note that it represents average values, i.e the local mean power of area within several meters. In general, received signal strength is proportional to d^{-n}. We consider a free-space model, in which the received signal is given by

$$P_r = \frac{P_t G_t G_r \gamma^2}{(4\pi d)^2} \tag{5.2}$$

$$\eta_{tr} = \frac{G_t G_r \gamma^2}{(4\pi d)^2} \tag{5.3}$$

where d denotes the distance between the receiver and transmitter. Path-loss exponent is 2. The received SNR can be given by

$$\Gamma_{tr} = \frac{P_t \eta_{tr}}{N_0} \tag{5.4}$$

where N_0 is the AWGN power.

5.2 Problem Statement

The user T is traveling at an altitude of h meters so that it passes above station A and station B. Assume that it takes K time slots for node T moving from the top of station A to station B, where the Euclidean distance between two stations is D meters. This is depicted in Fig 5.1.

For each of the time slots, in the first segment, station A transmits M information bits with transmit power P_t while the node T and station B listen; During the second segment, the user relay T re-transmit the message to station B, adopting DF protocol with a rate-R convolutional code.

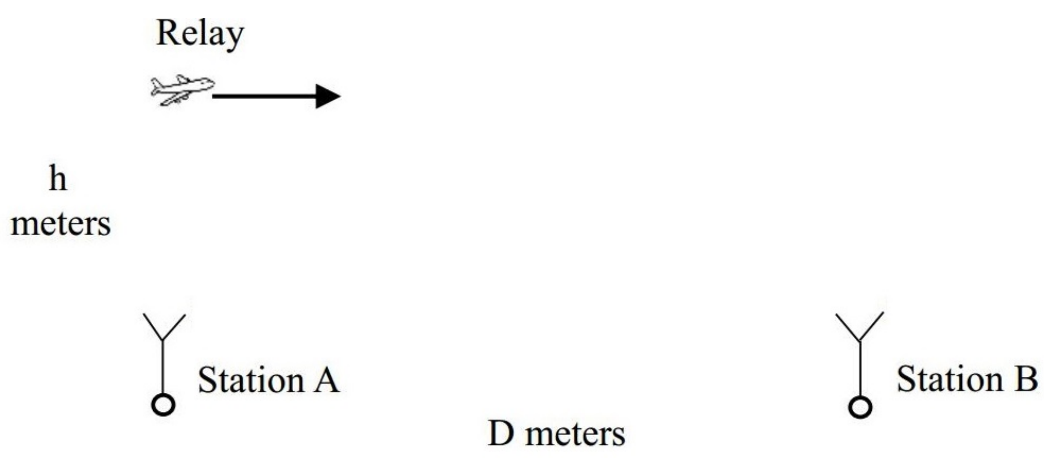


Figure 5.1: Experimental Set-up for Models in Chapter 5,6,and 7

Table 5.1: Parameters of simulation model in Chapter 5, 6 and 7

Parameters	**Values**
Number of Bits per Time Slot M	100000
Coding Strategy	RCPC Codes
Code Rate R	1/4
SNR	0-25 (dB)
Modulation Scheme	BPSK
Noise Channels	Rayleigh
Altitude h	1 meter
Distance between Stations D	100 meters
Path-loss Exponent n	2
Number of Time Slots	200
Transmit Power P_t	100 W

On the one hand, we simulate the entire transmission process, i.e. K time slots and evaluate the corresponding error performance for each time slots to find how the relay position affects the error performance of coded cooperative communication. On the other hand, by varying transmit power, we further study the influence of both channel quality and relatively transmit position together on communication quality. Note that the error performance is evaluated in terms of BER and all the transmitters always have the same transmit power P_t.

5.3 Problem Simulation

The related parameter values in simulation environment have been listed in Table 5.1. All the simulations generate the final results by averaging results from 100 trials.

5.3.1 Case A: The factor of relay position

With an appropriate fixed transmit power, the performance in BER for both coded cooperation and single user case is shown in Fig 5.2. The change of relay position does not have any effect on single user performance because the relay is not being used in this case.

For the cooperative communication case, we notice that the smallest value of BER is obtained before the halfway distance between station A and station B. As we use

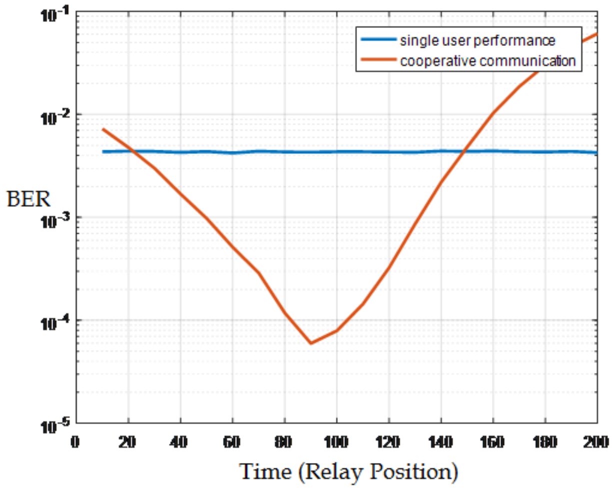


Figure 5.2: BER Performance of Single-User and Cooperative Communication Varying Relay Time (Relay Position)

different decoding schemes at relay node T and destination station B, the quality of the source-to-relay and relay-to-destination links affects the correctness of decoded bits in different degree. In other words, the link between the source and relay matters because of the weaker rate-1/2 code, i.e., the decoder at the relay recover the information by half of the rate-1/4 codewords. And this is also the main reason why the BER curve for the coded cooperative is non-symmetrical.

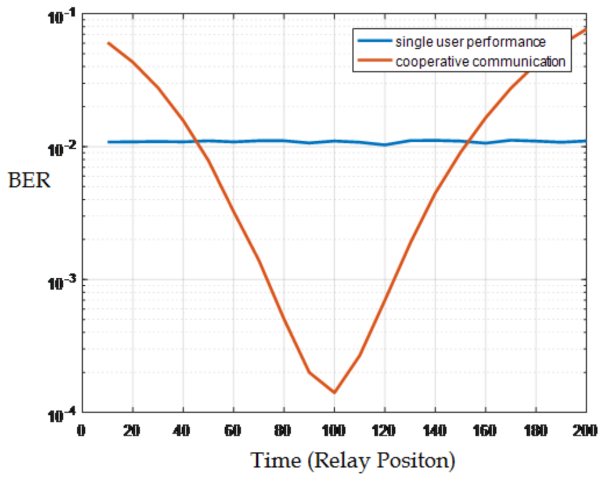


Figure 5.3: BER Performance of Single-User and Cooperative Communication Varying Time in Symmetric Case

To illustrate that, we have simulated another case, in which the destination also employs the rate-1/2 code, i.e., the original bits are recovered by codewords from relay T only. As a comparison, the single user case also employ a rate-1/2 code. In other words, at the destination, the message from the relay and the message from source have been processed separately, in which they both use rate-1/2 codes. The comparison of BER performance of them is shown in Fig 5.3. The cooperative curve is symmetric around the midpoint, which supports our conjecture.

5.3.2 Case B: The factor of transmit power

From the last simulation, we know that the coded cooperative communication presents a worse behavior than non-cooperation case when the relay is near the destination. Hence, as we only consider the impact of transmitting power, it is assumed that the relay node stays above the midpoint. The simulation result is shown below in Fig 5.4.

At the midpoint, coded cooperation improves error performance up to 20 dB. With a limited amount of bits, the values of BER go to zero after the transmit power-to-noise ratio increases over 11 dB and they normally perform as was predicted at low transmit power values. Fig 5.4 is a slice of the result in simulation in next section which describes the impact on BER in a more complete version.

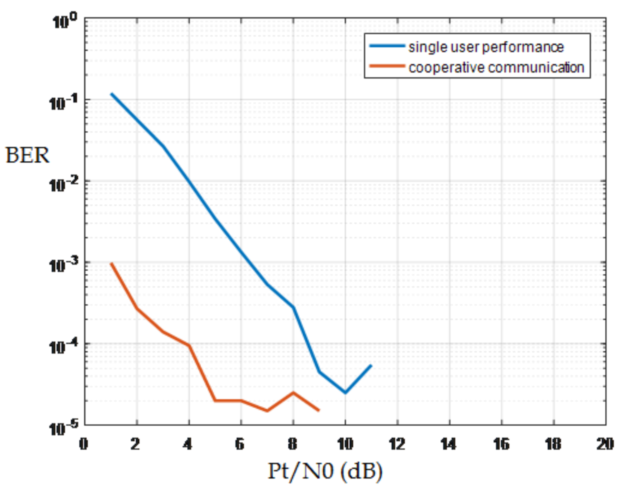


Figure 5.4: BER Performance of Single-User and Cooperative Communication Varying Transmit Power

5.3.3 Case C: Two factors

In order to observe the impact of this two factors visually, both of time and transmit power are considered as variables. A three-dimension figure is shown below, which indicates proper placement of the relay for employing DF cooperation in some degree.

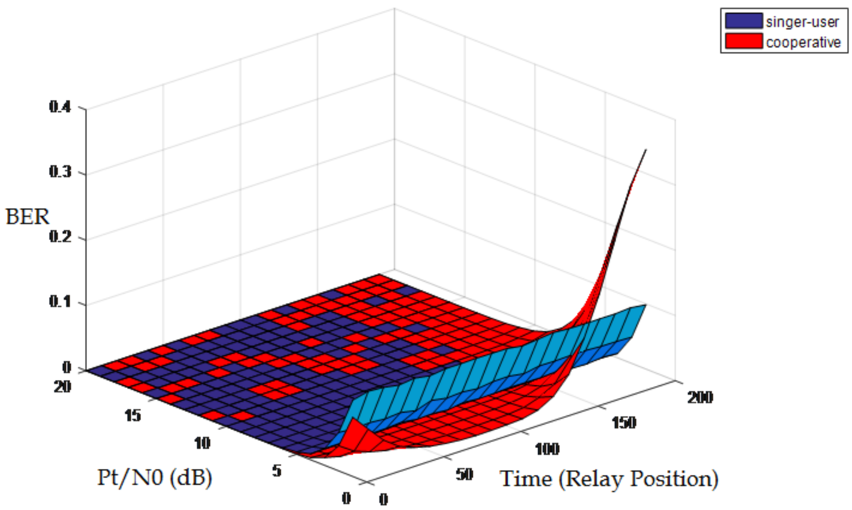


Figure 5.5: BER Performance of Single-User and Cooperative Communication Varying Relay Position and Transmit Power

The result is plotted in linear scale in Fig 5.5, so we can observe that the cooperative communication provides a great benefit on quality of service even when the transmit power-to-noise ratio is very low. Note that the number of bits is limited by the complexity of this simulation, so that the result data at very high SNR is unstable due to the effect of randomness in errors in our simulation.

Chapter 6

Power Allocation between Nodes

Simulations are now extended to the source and relay nodes having different transmit power to improve the received signal quality further. In this chapter, we are going to propose two power allocation strategies to increase the quality of service in a DF multi-user cooperative network satisfying the total transmit power $P = P_s + P_r$. A reasonable power allocation ratio has been calculated according to consideration of average received SNRs in the first strategy. Differently, the optimization in the second scheme is based on the operation of detection at the relay.

6.1 Power Transmit Ratio

As we know, the receiver at destination combines data from both relay and source, then process the data to recover the original message. However, these two channels (relay-to-destination and source-to-destination) may have different average channel state because of the difference in path-loss, which means there may exist a gap between the received SNRs from the relay node and the source node. In this section, the transmit power is reasonably allocated with respect to received SNR to obtain better transmission behavior [16].

As indicated in Equation (5.3) and Equation (5.4), the receive SNR is denoted by

$$\Gamma_{tr} = \frac{P_t \eta_{tr}}{N_0} \tag{6.1}$$

Let P be assumed to be the total transmit power of both nodes, and the powers allocated to relay and source nodes are given by $(1-\rho)P$ and ρP. Therefore, the received SNR from source and relay are presented by

$$\Gamma_{sd} = \frac{\rho P \eta_{sd}}{N_0} \tag{6.2}$$

$$\Gamma_{rd} = \frac{(1-\rho) P \eta_{rd}}{N_0} \tag{6.3}$$

respectively.

We aim to obtain an optimal transmit power ratio ρ^* to minimize BER. Nevertheless, it is almost impossible to find an exact expression for BER as a function of the value of power ratio , which means it may be hard to establish a closed-form formulation for the optimal power ratio. Thus, we propose a scheme consistent with Water-Filling theorem that achieves the transmit power ratio by forcing the received SNRs be uniform, i.e.

$$\Gamma_{sd} = \Gamma_{rd} \tag{6.4}$$

Thus, we obtain the transmit power ratio

$$\rho^o = \frac{1}{\eta_{sd}/\eta_{rd} + 1} \tag{6.5}$$

in which η_{sd}/η_{rd} is channel loss ratio of source-to-destination link to relay-to-destination link, determined by relay position in our model.

This simulation can be viewed as a developed version of simulations in Chapter 5, which substitutes the equal transmit powers ($\rho = 1/2$) in the former simulation by ρ^o.

6.2 Joint Optimization

As indicated before, the realization of Decode-and-Forward is essentially based on the correctness of decoding at the relay. In ideal assumption, the relay can know the correctness exactly and then decide to forward the data or not by attaching cyclic redundancy check

(CRC) codes. Inevitably, there exist limitations in CRC codes, and it is difficult to recognize all the erroneous patterns. Moreover, extra power and other hardware consumptions are required for supporting the error-checking mechanism.

Firstly, we suggest a detection way with erasure to avoid the propagation of errors instead of error-checking. Then, a joint optimization of power assignment strategy and the threshold ϵ in the erasing detection minimizing error probability will be formulated.

6.2.1 Detection with Erasure at Relay

Recall that the signal y_{sr} received by relay is given by

$$y_{sr} = \sqrt{P_s} h_{sr} x + n. \tag{6.6}$$

In which the P_s is transmitting power at source and h_{sr} denotes path coefficient between the relay node and the source node. Noise is presented by n and BPSK modulated signal $x \in \{1, -1\}$. Suppose that we have full knowledge about the channel, so whenever we received the signal y, it is divided by $\sqrt{P_s} h_{sr}$ (path gain).

$$y_{sr}^1 = \frac{y_{sr}}{\sqrt{P_s} h_{sr}} = x + \frac{n}{\sqrt{P_s} h_{sr}} \tag{6.7}$$

Then, in Rayleigh fading channels, we can convert this detection and decision problem to another case equipped with modified noise variance for AWGN. The noise is denoted as

$$N_0^1 = \frac{N_0}{P_s |h_{sr}|^2} \tag{6.8}$$

The probability density function of received signals at a relay is supposed to be Gaussian distribution. The erasure scheme at relay for BPSK modulated signals detection in AWGN is depicted in Fig 6.1.

As shown in Fig 6.1, an erasure region over $[-\epsilon, \epsilon]$ indicates "weak" signal area. In our proposed detection, whenever y_{sr}^1 in (6.7) falls into this region, the relay will not decode that such that then the source will send the parity part to the destination directly.

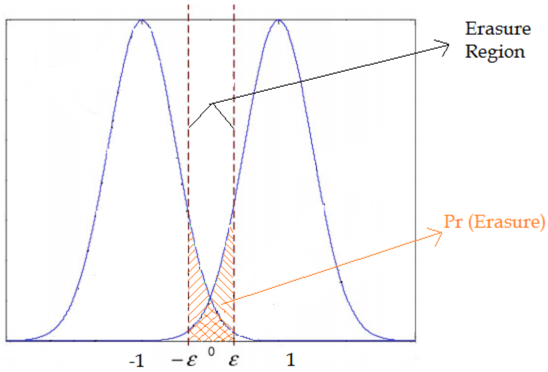


Figure 6.1: The erasure scheme at relay for BPSK modulated signals detection in AWGN

When the erasure operation happens, all the symbols at destination come from a source node.

6.2.2 Joint Optimization of Power Allocation and Erasing Detection Threshold

We must determine the erasure threshold ϵ optimizing BER performance. From the complementary error we can compute the error probability function $erfc(.)$ for Gaussian distribution [17], which is a function of threshold ϵ, we will derive the error probability function at destination below [16].

Probability of wrong decision at relay, i.e., probability, when the source transmits -1 and y_{sr}^1 falls within (ϵ, ∞) is given by

$$Pe, r(\epsilon) = \frac{1}{2} erfc\Big((\epsilon + 1)\sqrt{\frac{P_s|h_{sr}|^2}{N_0}}\Big). \tag{6.9}$$

Probability of correct decision at relay, i.e., probability when the source transmits -1 and y_{sr}^1 falls within $(-\infty, -\epsilon)$ is given by

$$Pc, r(\epsilon) = \frac{1}{2} erfc\Big((-\epsilon + 1)\sqrt{\frac{P_s|h_{sr}|^2}{N_0}}\Big). \tag{6.10}$$

Probability of erasure decision at relay, i.e, probability when the source terminal send bit

-1 but y_{sr} falls into the erasure region $[-\epsilon, \epsilon]$

$$P_{\mathcal{E}}, r(\epsilon) = 1 - Pe, r(\epsilon) - Pc, r(\epsilon) \tag{6.11}$$

At destination, the detected bits before decoding come from both the relay node and source node, so the probability of error is the average of error from source and error from relay, i.e,

$$Pe_{final} = \frac{1}{2}(Pe_{source} + Pe_{relay}) \tag{6.12}$$

where the probability of error from source is given by

$$Pe_{source} = \frac{1}{2}erfc\Big(\sqrt{\frac{P_r|h_{sd}|^2}{N_0}}\Big). \tag{6.13}$$

and the probability of error from relay is given by

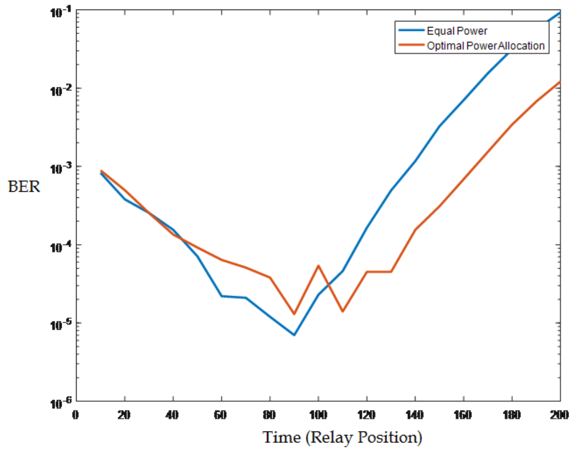
$$\begin{aligned} Pe_{relay} = & Prob(error|correct\ decision\ at\ relay)Pc, r(\epsilon) + \\ & Prob(error|wrong\ decision\ at\ relay)Pe, r(\epsilon) + \\ & Prob(error|erasure\ decision\ at\ relay)P_{\mathcal{E}}, r(\epsilon). \end{aligned} \tag{6.14}$$

in which each of the three terms means the corresponding error probability at the receiver in destination for each of the three different decisions made by the relay. The final error probability Pe_{final} (6.12) is therefore obtained as a function of erasure threshold. Notice that the expression is mainly derived for choosing optimal bound of erasure region, i.e, ϵ, but not used for calculating the value of bit error rate accurately.

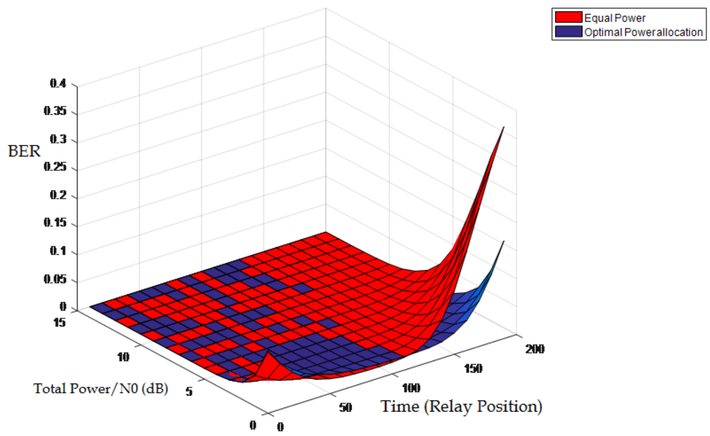
6.3 Problem Simulation

6.3.1 Case A: Power Allocation Ratio Scheme

As an extension of the simulations seen in Chapter 5, the equal transmit powers in the former simulation are replaced by powers based on allocation ratio in this case. Fig 6.2



(a) Optimal power ratio varying relay position



(b) Optimal power ratio varying total transmit power and relay position

Figure 6.2: Power Allocation Ratio Scheme

depicts the comparison of equal power allocation and power allocation with proper ratios with consideration of relay position as variable and two variables separately.

As we can observe from the Fig 6.2 (a), generally, this power allocation scheme outperforms equal power allocation especially after passing the midpoint. The improvement of BER values can be up to 10 dB nearing the end of time. Although the equal power allocation achieves the smallest value of BER, this power allocation scheme reduces the effect of the inter-user channel quality on signal quality effectively. In other words, when the quality of the channel between source and relay is not good, this power allocation strategy helps a lot.

6.3.2 Case B: Joint Optimization Scheme

Now, we know that the aforementioned threshold ϵ in erasing detection has an effect on the BER performance. According to the final error probability function (6.12), if the relay and source transmit powers can be tuned as well, a joint power allocation and erasing detection threshold optimization strategy can be developed to reduce errors. The cost function of optimization problem can be formulated as

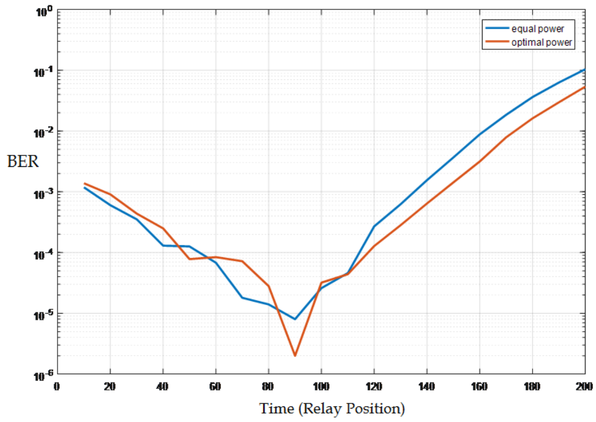
$$min\ Pe_{final}(\epsilon, P_r, P_t)$$

$$s.t \quad P_r + P_t = P \tag{6.15}$$

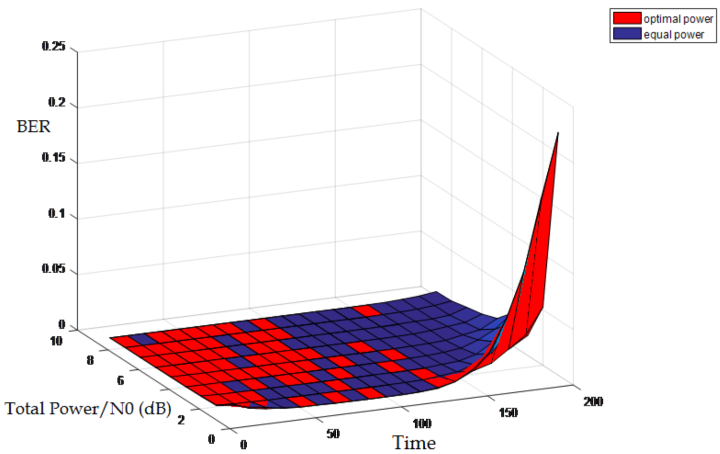
in which $Pe_{final}(\epsilon, P_r, P_t)$ is a derivation of (6.12) with an adaptable transmit power allocation.

Compared with simulations in Chapter 5, the detection with erasure strategy has been used instead of CRC codes, where the optimal values of both erasure threshold and transmit powers are adjustable by different wireless environment and channel qualities.

As Fig 6.3 shows, the erasure detection with optimal values of ϵ and P_t (or P_r) behaves well and stable. Similar with the former power allocation scheme, it improves the signal quality when the channel between the source and relay nodes is in poor quality. Besides, we obtains the lowest value of BER in simulations by using this strategy, which is the benefit of erasure detection. Compared with the first power allocation way, the detection with erasure makes sure that the error performance is relatively stable and not affected by the change of total transmit power values.



(a) Joint Optimization of Power Allocation and Erasing Detection Threshold Varying Relay Position



(b) Joint Optimization of Power Allocation and Erasing Detection Threshold Varying Total Transmit Power and Relay Position

Figure 6.3: Joint Optimization Scheme

Chapter 7

Power Bounds

7.1 Problem Statement

Recalling the case A in Chapter 5, the BER performance for coded cooperation with a fixed transmit power has been studied, depicted in Fig 5.2. Rather, we are going to explore the BER performance and transmit power from another version in this chapter.

In general, we will find the minimum power bounds at nodes which make sure the value of BER meets a given requirement. In the first experiment, with a fixed transmit power at the relay, the minimum values of transmits power required at the source node to satisfy the requirement of BER while varying the relay position will be found. In the second simulation, for fixed relay positions, to meet the BER requirement, the available regions of transmit power for node source and node relay will be further explored.

7.2 Problem Simulation

Since there does not exist an actual closed-form expression to evaluate BER, as a function of transmitting power, it is relatively difficult to force bit error rate is exactly a value. All the simulations take a long time in $Matlab$ due to the complexity; therefore only one variable is considered for each simulation.

7.2.1 Case A: Minimum Power at Source

Considering that the transmit power at relay is unitary, using normalized relay position, we force the value of BER to be equal to 10^{-5} over the changed relay positions by increasing the power at the source node adaptively. As depicted in Fig 7.1, the curve of power at the source to power at the relay ratio over different relay positions resembles the BER performance result in Fig 5.2, which is exactly what we expected for.

In addition, if we vary the transmit power at the relay not the source node, we may not be able to meet the requirement of an ideal BER performance. More specifically, when the relay is nearing the destination node, i.e, the value of relay position is nearing 1, we may be not able to obtain qualified signals even increase the transmit power at relay to a high level. This is mainly because that the poor quality of channel between the relay and source has an substantial effect on quality of service. To solve that, increasing transmit power at the source is an effective way.

Compared with invariant transmit power meeting the same BER requirement over the changed position, the adaptive transmit power scheme saves energy cost for about 20dB in our simulation.

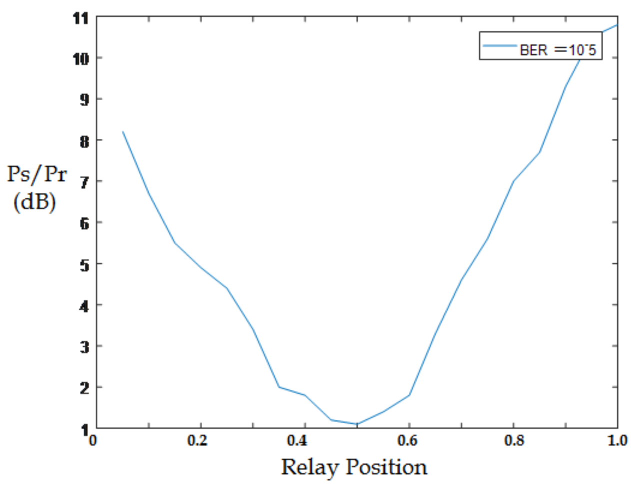
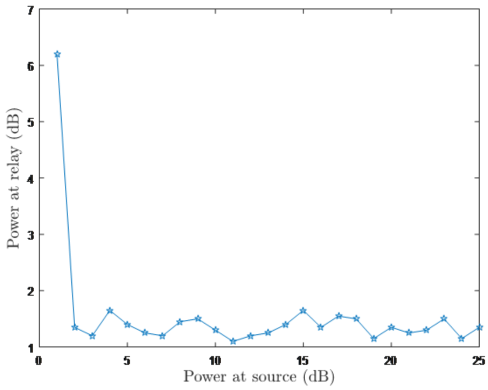


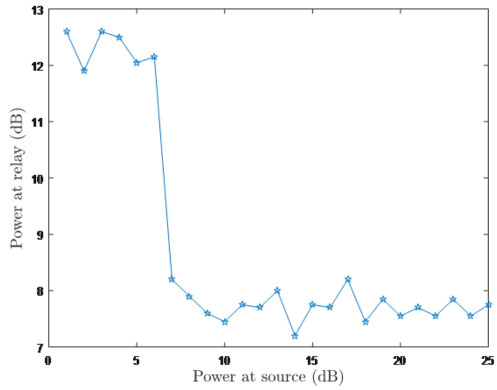
Figure 7.1: Adaptive Required Transmit Power at Source over Different Relay Positions

7.2.2 Case B: Pair Power Bound Region

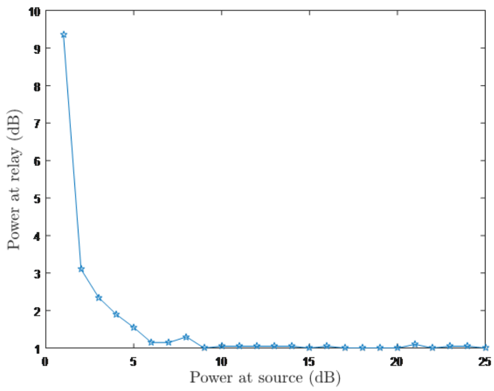
For a fixed relay position, to meet the error performance requirement, the available pair power region can be learned. For simplicity, only several relay positions are chosen to calculate the pair power bound region, as Fig 7.2 shows. For each point in the figures, the corresponding values of the power at source node and power at relay node make the BER value is equal to 10^{-5} as well as in the previous section. Thus, a general achievable pair power region can be plotted.



(a) Pair Power Region at Relay Position = 0.1



(b) Pair Power Region at Relay Position = 0.9



(c) Pair Power Region at Relay Position = 0.5

Figure 7.2: Pair Power Region for Various Relay Position

As we can observe from the group of images, the pair power region varies for different relay positions. With the increasing of relay position, the required transmit power at relay node becomes higher, which is mainly because the quality of channel between the relay and source becomes worse. However, the trend of required power at source with the change of relay position is totally different. As Fig 7.2 (c) shows, the required transmit power at source reaches a lower value when the relay is placed at the midpoint, compared with the other two situations. As far as I concerned, the reason for it is that the larger diversity gain at the midpoint "compensates" in the BER performance so that the required power can be lowered.

Notice that when the relay position is at 0.9, shown in Fig 7.2 (b), the required transmit power at relay falls to the convergent range until power at source increases to 7dB , which illustrates that the transmit power at source matters due to the poor inter-user channel quality, as what we mentioned in the previous section.

Chapter 8

Trade-off between Energy and Errors

In this chapter, the problem discussed make use of different models and notation than what has been previously presented. ICLOCS has been used with Ipopt solver, through Matlab interface, to solve the optimal control problems.

8.1 Energy Minimization

8.1.1 Notations and Model

There exists a mobile node T_1 and two base stations (the source and destination), and the node travels in a specific trajectory over K time slots as same as model before, where h denotes the length of each time slot assumed small enough. Similar with the assumption in [18], both mobile node and station nodes have sufficient storage capacity, equipped with initial data $S[0]$. Each transmitter has been assumed to have a maximum instantaneous transmit power P_{max}. By the end of the experiment, all the data must be sent to the destination point by using DF cooperative communication. Note that all the nodes are assumed to be in full-duplex mode.

8.1.2 Problem Formulations

Optimization occurs over the transmit powers and data rates to minimize energy. The optimization problem has been formulated as follows. To simplify the notation, the relay, source and destination are replaced by node 1, 2 and 3 separately in our formulation.

$$\arg\min_{p,r,s} \; J = \sum_{k=0}^{K} (p_1[k] + p_2[k])h \tag{8.1}$$

$s.t$

$$0 < p_i[k] < P_{max}, \qquad i \in \{1, 2\} \tag{8.2}$$

$$\{S_1[0],\ S_2[0],\ S_3[0]\ \} = \{D,\ 0,\ 0\ \} \tag{8.3}$$

$$\{S_1[K],\ S_2[K],\ S_3[K]\ \} = \{0,\ 0,\ D\ \} \tag{8.4}$$

$$\sum_{k=0}^{K} r_{13}[k]h = \frac{D}{2} \tag{8.5}$$

$$r_{12}[k] - Blog_2(1 + \frac{\eta_{12}[k]P_{12}[k]}{\sigma^2}) < 0 \tag{8.6}$$

$$r_{13}[k] - Blog_2(1 + \frac{\eta_{13}[k]P_{13}[k]}{\sigma^2}) < 0 \tag{8.7}$$

$$r_{23}[k] - Blog_2(1 + \frac{\eta_{23}([k]P_{23}[k]}{\sigma^2}) < 0 \tag{8.8}$$

$$r_{23}[k] + r_{13}[k] - \min\{\ \frac{1}{2}log_2(1 + P_s[k]h_{12}[k]),$$

$$\frac{1}{2}log_2(1 + P_r[k]h_{23}[k]) + \frac{1}{2}log_2(1 + P_s[k]h_{13}[k]\} < 0 \tag{8.9}$$

$$\dot{S_1}[k] = -r_{12}[k] - r_{13}[k] \tag{8.10}$$

$$\dot{S_2}[k] = r_{12}[k] - r_{23}[k] \tag{8.11}$$

$$\dot{S_3}[k] = r_{13}[k] + r_{23}[k] \tag{8.12}$$

$$r_{ij}[k] > 0, j \in \{1,\ 2,\ 3\}, i \in \{1,\ 2\} \tag{8.13}$$

$$S_i[k] < M, i \in \{1,\ 2,\ 3\} \tag{8.14}$$

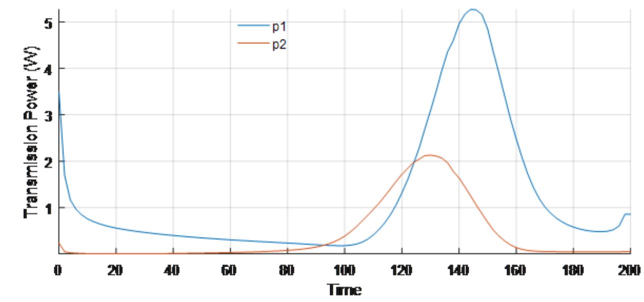
Table 8.1: Parameters of Simulation Model in Chapter 8

Parameters	**Values**
The Number of Time Slots: K	200
The Amount of Transmit Data D	10^9 Bits
Bandwidth: B	10^5 Hz
Maximum Power P_{max}	10 W
Noise Channels	Rayleigh
Relay Moving Velocity	10 m/s
Path-loss Exponent n	2
Distance between Stations	2000 m
Maximum Storage M	10^9 Bits

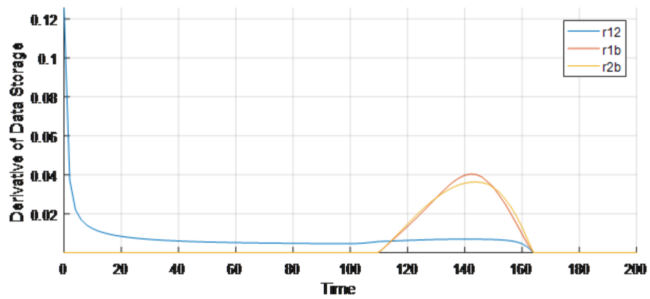
The cost function J represents the sum of energy cost at all transmitters over these K time slots. Constraint (8.3) and (8.4) define initial and final data storage of the nodes. Moreover, equation (8.5) indicates the degree of cooperation, i.e, 50% of the information is sent by relay. The Shannon capacity can be seen as an upper-bound of data rate for each path in (8.6) $\sim$ (8.8). Constraint (8.9) restricts the data rate with respect to DF cooperative communication. The storage update equations (8.10) $\sim$ (8.12) imply the direction of signal transmission. P_{max} and M are the maximum value of transmit power and storage buffer at nodes, as given in constraints (8.2) and (8.14).

8.1.3 Simulation Results

In this simulation, the NLP was terminated in 200 iterations. As shown in Fig 8.2, the source node keeps transmit data to the relay at a relatively low power level over the first half of intervals and the data rate in link source-to-relay keeps around a constant value. In this case, the total energy cost is 322.29 kJ, where 24% of the energy used by the relay user and the other 76% used by the source. The calculated energy cost will be used in next simulation as a constraint.



(a) Optimal Sequence of Transmit Power



(b) Optimal Sequence of Data Rate

Figure 8.1: Energy Minimization

8.2 Errors Minimization under Constraints of Energy

8.2.1 Problem Definition

The UAV model assumption in this case is identical with the one in the first section in this chapter but with different formulations. Differently, the number of total errors has been used as the cost function under the constraints of the energy. The optimization results varies with changed values of the energy cost constraints.

8.2.2 Problem Formulations

We consider the cost function as the number of total errors derived from the aforementioned error probability function in equation (6.12) with erasure threshold ϵ assumed to be zero. The formulation is thereby constructed as

$$\arg\min_{p,r,s} \; J = \sum_{k=0}^{K} (p_1[k] + p_2[k])h \tag{8.15}$$

$$s.t$$

$$0 < p_i[k] < P_{max}, \qquad i \in \{1, 2\} \tag{8.16}$$

$$\sum_{k=0}^{K} P_i[k]h - E_{max} < 0, \qquad i \in \{1, 2\} \tag{8.17}$$

$$\{S_1[0],\ S_2[0],\ S_3[0]\ \} = \{D,\ 0,\ 0\ \} \tag{8.18}$$

$$\{S_1[K],\ S_2[K],\ S_3[K]\ \} = \{0,\ 0,\ D\ \} \tag{8.19}$$

$$\sum_{k=0}^{K} r_{13}[k]h = \frac{D}{2} \tag{8.20}$$

$$r_{23}[k] + r_{13}[k] - \min\{\ \frac{1}{2}log_2(1 + P_s[k]h_{12}[k]),$$

$$\frac{1}{2}log_2(1 + P_r[k]h_{23}[k]) + \frac{1}{2}log_2(1 + P_s[k]h_{13}[k]\} < 0 \tag{8.21}$$

$$\dot{S}_1[k] = -r_{12}[k] - r_{13}[k] \tag{8.22}$$

$$\dot{S}_2[k] = r_{12}[k] - r_{23}[k] \tag{8.23}$$

$$\dot{S}_3[k] = r_{13}[k] + r_{23}[k] \tag{8.24}$$

$$r_{ij}[k] > 0, \quad j \in \{1,\ 2,\ 3\}, i \in \{\ 1,\ 2\} \tag{8.25}$$

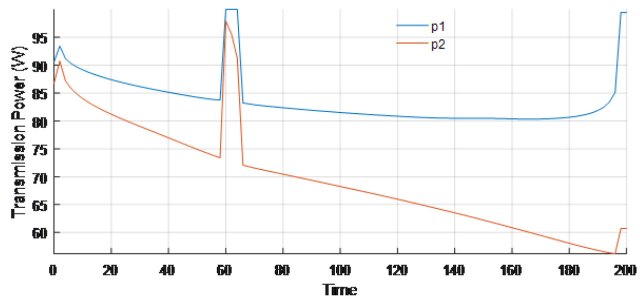
$$S_i[k] < M, \quad i \in \{1,\ 2,\ 3\} \tag{8.26}$$

Constraint (8.17) restricts the energy cost for each nodes, and the maximum energy E_{max} have an absolute effects on simulation results.

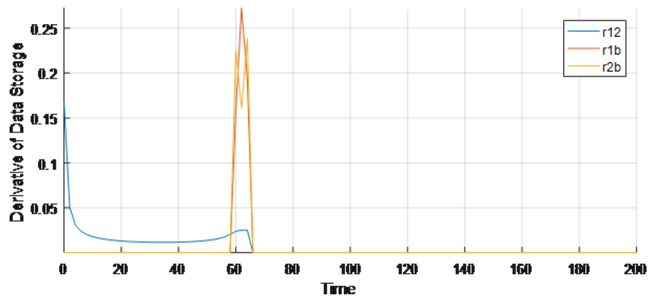
8.2.3 Simulation Results

The numbers of error under constraints with different values of energy cost have been listed in Table 8.2. Generally, there is a trade-off between the number of errors and energy cost in DF cooperative communication.

Given enough energy, the optimal power and data rate distributions are presented in Fig 8.3 (a)(b). As we can predicted, to minimize the errors, there will be a best location



(a) Optimal Sequence of Power



(b) Optimal Sequence of Data Rate

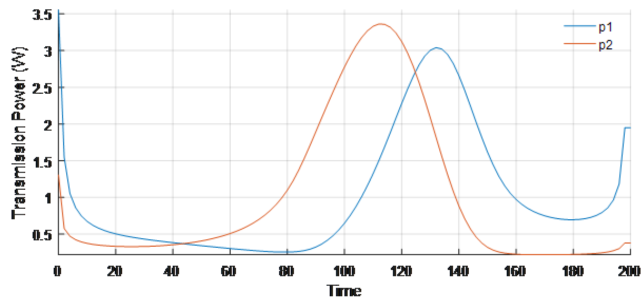
Figure 8.2: Error Minimization Given Enough Energy

for relay to forward the limited amount of data, which has been illustrated by the generated optimal solution in Fig 8.3. The minimum number of errors is 1.5734 with enough energy.

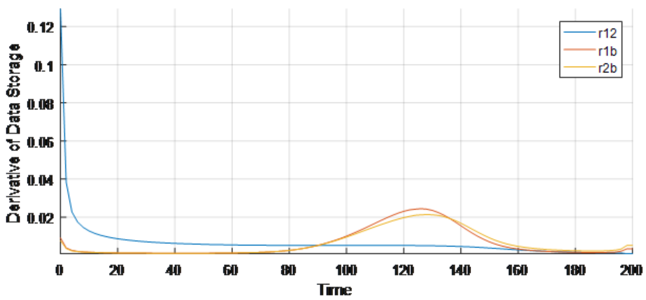
As a comparison, Fig 8.3 shows the optimal solution when the provided energy cost is about the minimum energy required in transmission, calculated from the last simulation. It is obvious that the optimal result figures resemble Fig 8.1 due to the very strict energy constraint.

Table 8.2: Number of Errors with Various Energy Cost Constraints

Number of Errors	1.5734	1.8267	3.9972	5.5787	12.7306	13.4264
Energy Cost (KJ)	Large Enough	800	600	500	400	323



(a) Optimal Sequence of Power



(b) Optimal Sequence of Data Rate

Figure 8.3: Error Minimization Given Least Energy

Chapter 9

Conclusion and Future Work

The initial goal of this project is to develop the cooperation protocols and algorithms between nodes in UAV swarms in order to improve the robustness of the UAV networks. To realize that, we utilize the spatial diversity in multi-user cooperation networks to obtain the extra coding gain.

In general, all the assumptions are built on a typical three-nodes network consisting of two stations and a mobile relay. Based on this model, we first analyze and illustrate the benefits of cooperative communication adopting DF protocol. Then, the appliance of the coding cooperation strategy in UAV relay networks has been studied, and obtain the proper relay position for cooperative communication. After that, we focus on the development of power allocation schemes to further reduce the BER, in which the proposed two power allocation strategies indeed improve the error performance illustrated in our simulations. Finally, a trade-off between the number of total errors and energy cost considering the assumption of cooperative transmission is specified with the data of optimal results in our simulations.

The next step following this piece of work will be the optimization in the degree of cooperation in UAV networks, which will achieve extra channel gains in another layer. Moreover, in this work, we investigate the transmit power bound for users meeting a fixed requirement of error performance, and the investigation for three nodes in our model can be extended to multi-user mobile networks.

Furthermore, all the trials in my work can be extended by using a more general assumption. In addition, path-planning strategies for cooperative communication in multi-user UAV networks are becoming a concentrated research area nowadays, since this field is initial in the future application of UAV relays.

Bibliography

[1] L. Gupta, R. Jain, and G. Vaszkun, "Survey of important issues in uav communication networks," *IEEE Communications Surveys & Tutorials*, vol. 18, no. 2, pp. 1123–1152, 2016.

[2] A. Merwaday and I. Guvenc, "Uav assisted heterogeneous networks for public safety communications," in *Wireless Communications and Networking Conference Workshops (WCNCW), 2015 IEEE.* IEEE, 2015, pp. 329–334.

[3] S. Chandrasekharan, K. Gomez, A. Al-Hourani, S. Kandeepan, T. Rasheed, L. Goratti, L. Reynaud, D. Grace, I. Bucaille, T. Wirth, and S. Allsopp, "Designing and implementing future aerial communication networks," *IEEE Communications Magazine*, vol. 54, no. 5, pp. 26–34, May 2016.

[4] L. Sboui, H. Ghazzai, Z. Rezki, and M. S. Alouini, "Achievable rates of uav-relayed cooperative cognitive radio mimo systems," *IEEE Access*, vol. 5, pp. 5190–5204, 2017.

[5] M. Baghani, S. Akhlaghi, and V. Golzadeh, "Average achievable rate of broadcast strategy in relay-assisted block fading channels," *IET Communications*, vol. 10, no. 3, pp. 346–355, 2016.

[6] M. T. Kakitani, G. Brante, R. D. Souza, and M. A. Imran, "Energy efficiency of amplify-and-forward, repetition coding and parallel coding in short range communications," in *Telecommunications and Signal Processing (TSP), 2012 35th International Conference on.* IEEE, 2012, pp. 212–216.

[7] A. Stefanov and E. Erkip, "Cooperative coding for wireless networks," *IEEE transactions on communications*, vol. 52, no. 9, pp. 1470–1476, 2004.

[8] S. Chen, W. Wang, and X. Zhang, "Performance analysis of multiuser diversity in cooperative multi-relay networks under rayleigh-fading channels," *IEEE Transactions on Wireless Communications*, vol. 8, no. 7, 2009.

[9] E. I. Gr, T. A. Johansen *et al.*, "Path-and data transmission planning for cooperating uavs in delay tolerant network," in *Globecom Workshops (GC Wkshps), 2012 IEEE*. IEEE, 2012, pp. 1568–1573.

[10] M. A. Marinho, E. P. De Freitas, J. P. C. L. da Costa, A. L. F. de Almeida, and R. T. de Sousa, "Using cooperative mimo techniques and uav relay networks to support connectivity in sparse wireless sensor networks," in *Computing, Management and Telecommunications (ComManTel), 2013 International Conference on*. IEEE, 2013, pp. 49–54.

[11] G. Zhao, J. Ma, Y. Li, T. Wu, Y. H. Kwon, A. Soong, and C. Yang, "Spatial spectrum holes for cognitive radio with directional transmission," in *Global Telecommunications Conference, 2008. IEEE GLOBECOM 2008. IEEE*. IEEE, 2008, pp. 1–5.

[12] L. Sboui, H. Ghazzai, Z. Rezki, and M.-S. Alouini, "Achievable rates of uav-relayed cooperative cognitive radio mimo systems," *IEEE Access*, vol. 5, pp. 5190–5204, 2017.

[13] A. Stefanov and E. Erkip, "Cooperative information transmission in wireless networks," in *Proceedings of the IEEE Asian-European Information Theory Workshop, Breisach, Germany, June 2002*, 2002.

[14] R. Knopp and P. A. Humblet, "On coding for block fading channels," *IEEE Transactions on Information Theory*, vol. 46, no. 1, pp. 189–205, 2000.

[15] P. Sweeney, "Error control codingfundamentals and applications, by shu lin and daniel j. costello jr., prentice-hall international, hemel hempstead, herts., uk, 1982. no. of pages: 720. price:£ 43.20," *International Journal of Satellite Communications and Networking*, vol. 2, no. 2, pp. 139–139, 1984.

[16] Y. Lee and H.-W. Shieh, "Detection with erasure in relay for decode-and-forward cooperative communications," *IEEE Transactions on Vehicular Technology*, vol. 62, no. 2, pp. 908–913, 2013.

[17] B. Sklar, *Digital communications.* Prentice Hall Upper Saddle River, 2001, vol. 2.

[18] O.J.Faqir, "An investigation into optimal control of communication energy in uav networks using interior point optimization techniques." Imperial College London, 2016.