Cooperative Communication with Systematic Raptor Codes in 3GPP

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Abstract

In this thesis, considering a one-relay cooperative system, we propose a new cooperative transmission scheme which implements the systematic Raptor code standardized in 3GPP. Within the framework of this scheme, we compare the bandwidth efficiency perfomance of different relaying protocols.

To improve the performance of this cooperative system, we use Reed-Solomon(RS) code as inner code which is concatenated with the systematic Raptor code. We first study the scenario when Channel State Information(CSI) is available at the receiver but not available at the transmitter. In this case, only fixed-rate RS code can be implemented. Then we study the scenario when CSI is available at both the transmitter and receiver, and develop an adaptive scheme applied to our model. Last, a straight forward channel estimation method is studied to make the estimation of CSI available at the transmitter. The performance of all the proposed models and protocols are obtained with Monte Carlo simulation.

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Contents

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List of Acronyms

3GPP	3rd Generation Partnership Project, 4
ACK	Acknowledgement, 27
AF	Amplify-and-Forward, 14
AR	Autoregressive, 52
BER	Bit Error Rate, 35
BPSK	Binary Phase Shift Keying, 31
CRC	Cyclic Redundancy Check, 30
CSI	Channel State Information, 5
DF	Decode-and-Forward, 15
DVB	Digital Video Broadcasting, 16
GF	Galois Field, 36
LDPC	Low-Density Parity-Check, 17
LT	Luby Transform, 17
MIMO	Multiple-Input-Multiple-Output, 12
RS	Reed-Solomon, 4
SNR	Signal-to-Noise Ratio, 10
STBC	Space-Time Block Code, 14

Chapter 1

Introduction

1.1 Motivation

Modern wireless communication is far more than just transmission of voice calls, short texts, and messages. More and more need for data of large size such as videos, images and music transmitted through wireless channels has emerged. With this desire, high-speed data transmission with satisfying reliability is what designers are seeking in the system design. The main problem that system designers encounter is the power degradation in the wireless channels caused by channel fading due to multipath propagation, which makes it difficult to recover the transmitted information data at the receiver side. Hence, the main focus of the transmitter and receiver design is to construct a robust and efficient scheme that could combat the side-effect of fading. Diversity in the signals received by the receiver is an effective way to mitigate the side effect. Multiple-Input and Multiple-Output(MIMO) transmissions apply multiple antennas at the transmitter and/or the receiver to achieve spatial diversity gain and the signals transmitted through different paths would experience different channels. Cooperative communication is an alternative way to achieve spatial diversity where antennas of different users serve as another user's virtual antennas [1]. Spatial separation of different users makes cooperative transmission practical and effective. It has been demonstrated that cooperative scheme can achieve significant diversity gain [2].

Perfect error-correcting code design is another technique to mitigate the fading influence to the data recovery. Robust coding scheme can effectively recover the erred symbols as well as the erased symbols through the channel. Combining the cooperative transmission and coding design for a system that is capable of minimizing the fading effect and thus achieving as large capacity as possible is of interest.

Implementing rateless error correcting codes in cooperative communication is of great advantage over the traditional fixed-rate codes. As for the fixed-rate codes, the Relay node in Decode-and-Forward(DF) cooperative system has to transmit exactly the same amount of data as the Source node to achieve the space and coding diversity. Using rateless codes such as Raptor codes [4] and Luby Transform(LT) codes [3] at the transmitters of both the Source node and the Relay node can make it possible that Destination is able to recover the source information as long as the number of the received symbols is slightly larger than that of the source symbols and the received symbols can be either from the Source or the Relay. With this advantage, cooperative transmission system with rateless coding is especially suitable for Digital Video Broadcasting(DVB) over distributed transmitters and users. The formal literatures on cooperative transmissions with rateless codes are based on non-systematic codes [5] [6] [7] [8] [9]. However, with the parity symbols appended to the original symbols, systematic codes have the great advantage that the decoding process is not needed if all the original symbols are received successfully. With error detecting codes such as Cyclic Redundancy Check(CRC), the received symbols can be easily determined error-free or not. Systematic codes are even more suitable for erasure channels since the received symbols are all error-free in the erasure channel scenario. These all make systematic codes ideal in high Signal-to-Noise Ratio(SNR) scenarios. On the other hand, since systematic Raptor codes are already accepted and standardized in 3rd Generation Partnership Project(3GPP), constructing a cooperative system with systematic Raptor codes would be more practical. For these reasons, it is very attractive to implement systematic Raptor codes in cooperative systems.

1.2 Contributions

In this thesis, we consider a three-node cooperative transmission system. Relay participating in the source-destination transmission is a Decode-and-

Forward(DF) relay. The transmission of a block of data is divided into two phases, the broadcasting phase and the cooperating phase. Relay participates in the second phase of transmission upon successfully decoding the original symbols. We implement a systematic Raptor code which is standardized in 3GPP as the error correcting code, since systematic Raptor codes have the advantage that with an error detection technique added, if it is found that all the source symbols are received without error, no decoding process is needed. To make the systematic Raptor codes, which are originally designed for the application layer, applicable to physical we use CRC to check for errors in a Raptor packet. Two cooperative protocols are compared in our model based on the degrees that the Source and Relay participate in the transmission [5] [10]. In the first protocol, only Relay transmits in the cooperating phase, while in the second protocol, both Source and Relay transmit in the cooperating phase. We find that the first protocol achieves better efficiency performance than the second one.

We also find that Reed-Solomon(RS) code in GF(8) is a perfect inner code considering the packet and symbols size. Hence, the Raptor codes and RS codes form a concatenated coding scheme. We first study the scenarios when the Channel State Information(CSI) is not available at the transmitter but available at the receiver. Models with different RS rates are provided. With RS code, the efficiency can be improved for both of the two cooperative protocols. We also propose a scheme that RS coding is only applied to Raptor parity symbols, and in this way no decoding is needed if all the Raptor source symbols are received without error. In the latter part of this thesis, we assume that perfect CSI is available at the trasmitter as well as well as the receiver and implement an adaptive transmission scheme to our model. We see that the efficiency performance is improved with the new adaptive model.

Furthermore, we apply an channel estimation technique to make the Source have the estimation of the current channel state. The channel state could be estimated from the transmission output of last block of data, and the estimation is transmitted from the receiver to the transmitter through an error free feedback channel, the bandwidth cost of which is neglectable. With simulation of system with the correlated Rayleigh fading channel, we show that the scheme with channel estimation and thus the adaptive RS rates has efficiency performance gain over the scheme with fixed-rate RS codes.

1.3 Thesis Outline

In Chapter 2, we talk about the background of the key parts of this thesis, including concept of fading, cooperative communications, rateless codes, Raptor codes, RS codes and adaptive transmissions. Formal work would be reviewed in the latter part in Chapter 2. In Chapter 3, the model of our system without CSI at the transmitter is introduced, and the advanced system with RS code is also presented in Chapter 3. The simulation results with and without RS code are given in Chapter 4. In Chapter 5, we propose an adaptive scheme with CSI available at both the transmitter and the receiver. We also present a straightforward channel estimation model in the latter part of Chapter 5. The simulation results of the model with CSI at both the transmitter and the receiver are provided in the same chapter. At last, conclusions and future works are discussed in Chapter 6.

Chapter 2

Background and Literature Review

2.1 Background

2.1.1 Fading

Signal propagation in the media suffers from different types of degradation. Thermal noise is caused by the electronic equipment applied at the receiver or amplifier. Inter-symbol interference comes from other signal being transmitted in the adjacent channels. The objects in the channel can reflect, refract and/or scatter the electromagnetic waves, which makes a transmitted signal arrive at the receiver through multi-path or long-distance path loss. Shadowing is another kind of path loss phenomena which is caused by the shadowing effect to the radio wave due to the obstacle in the propagation path.

Among these attenuation factors in the propagation media, the multi-path effect phenomena is defined as fading. Electromagnetic wave transmitted in the ionospheric layer or tropsopheric layer and also acoustic wave transmitted under water can all suffer from the reflection, refraction and/or scattering effects from these propagation media. Resulting from this, a specific signal transmitted at a specific time could arrive at the receiver through multi-path instead of one which is the scenario in free space transmission. Associated with each path are the attenuation factor and the signal delay. Transmission channels are also not fixed, due to the motion of the obstacles in the channel. Thus, the attenuation and delay for path n are also time-variant variance. The resultant expression of the received signal is then [11]:

$$x(t) = \sum_{n} \alpha_n(t) s[t - \tau_n(t)] \tag{2.1}$$

where s[t] is the transmitted signal, α_n is the attenuation factor for path n, and τ_n is the time delay for path n.

Assuming $s(t) = Re[s_l(t)e^{j2\pi f_c t}]$, then

$$x(t) = Re\{[\int_{-\infty}^{\infty} \alpha(\tau; t)e^{-j2\pi f_c \tau} s_l(t - \tau)d\tau]e^{j2\pi f_c t}\} \tag{2.2}$$

If we consider the scenario where the carrier is not modulated at frequency f_c, $s_l(t)$ would always be 1 for all t. If we make $\theta_n(t)$ to be $-2\pi f_c \tau_n(t)$, then the received signal can be expressed as

$$r_l(t) = \sum_n \alpha_n(t) e^{j\theta_n(t)} \tag{2.3}$$

From this, it is seen that the signals from different paths arrive at the receiver with time-variant attenuation factors and time-variant phase.

Due to the time-variance nature of multi-path signals, the received signal is consequently a random process. However, if the number of paths that signal transmit through is large enough, central limit theorem is applicable for characterizing the channel features. Thus, complex Gaussian random process could be a model for the signal at the receiver side. For modeling the fading effect in signal transmission channels and capturing the nature of channels, Rayleigh fading, Ricean fading and Nakagami-m fading are widely studied. Ricean fading model is applied when there is a line of sight propagation path between the transmitter and receiver which is the predominant signal transmission path. The envelope of the received signal through Ricean fading channel obeys Ricean distribution. Nakagami-m fading model is a flexible model with Nakagami-m distribution.

Rayleigh fading channel is applied when there's no line of sight propagation path between the transmitter and the receiver. It is actually a specific scenario of Nakagami-m fading when m=1. The envelope of the received signal obeys Rayleigh distribution:

$$P_R(r) = \frac{2r}{\Omega} e^{\frac{-r^2}{\Omega}} \quad (2.4)$$

where $\Omega = E(R^2)$.

The variance is usually assumed to be 1 to characterize Rayleigh channel. Fading could have either positive effect or negative effect to signal transmission. If the signal vectors add up constructively, then the received signal would be amplified by fading; on the other hand, if they add up destructively, the received signal would be weakened by fading, which makes the received Signal-to-noise ratio(SNR) decrease and thus signal recovery at the receiver difficult.

2.1.2 Cooperative Communication

Fading causes the received signal from multi-path to add up destructively and affects the signal transmission severely. When the power of the transmitted signal is fixed, received signal strength through fading channel is then considerably weakened. The transmitted signal may even suffer from bursts of errors. If additive noise at the receiver is fixed, SNR is thus decreased which makes signal detection and recovery unreliable. Signal transmission performance through Rayleigh fading channel is shown below:

$$r_l(t) = \alpha e^{j\phi} s_l(t) + z(t), 0 \leq t \leq T \quad (2.5)$$

where $z(t)$ is the complex-valued white Gaussian noise. Due to the severe impact that fading could contribute to the signal transmission, lots of research has been done to debate the negative effect to signal propagation efficiency and reliability. Power allocation, antenna design, error control coding and modulation techniques are some effective method that could debate fading impact.

Diversity technique is another method that is widely implemented in fading channels. The main idea is to send several copies of the same signal through different channels, such as different frequencies, different time slots or different propagation paths to make sure that there are different observations of the same signal at the transmitter. Thus, even signals from some paths are attenuated greatly, it is likely that there are still some signals from other paths are received with less path loss. Multiple-Input-Multiple-Output(MIMO) system applies multiple antennas at the transmitter and/or receiver to combat fading. With multiple antenna technique, either multiplexing gain or diversity gain can be obtained without extra bandwidth or power. If different sequences of information symbols are transmitted through the multiple antennas, the data rate could be enhanced and thus multiplexing gain is obtained. On the other hand, if the same sequence of information symbols is transmitted through the multiple antennas, the diversity gain would be obtained to combat fading effect. MIMO can improve both the throughput and the reliability of fading channels considerably without further resources needed. For this, it has already been accepted in some standard such as 802.11n and will be further implemented in the upcoming 3GPP Long Term

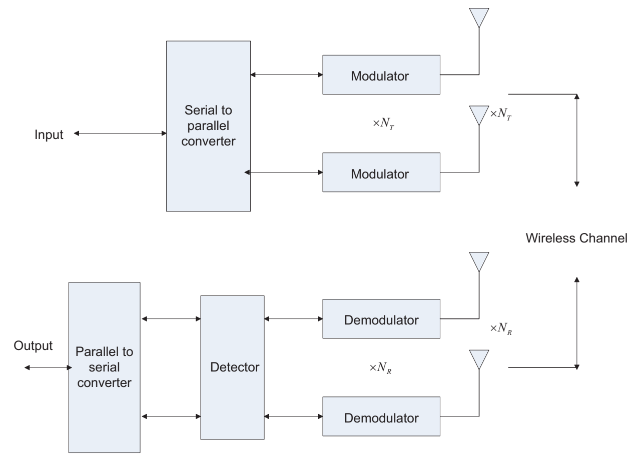

Figure 2.1: MIMO wireless transmission structure

Evolution(LTE) deployment.

Assuming the number of antennas at the transmitter is N_T and at the receiver is N_R, the MIMO signal transmission system is illustrated as in Figure 2.1. Single-Input-Single-Output is a special case when $N_T = N_R = 1$.

Multiplexing gain and diversity gain are a pair of trade-offs in a MIMO system. The diversity gain that could be obtained from $N_T \times N_R$ MIMO system varies from $N_T \times N_R$ to N_R. For consideration to debate fading effect, space diversity gain is what we mainly want to achieve with multiple antennas technique. If the separation spacing of the multiple antennas at the transmitter is large enough, the transmitted signal would transmit in different propagation paths and thus suffer separate levels of fading. The different versions of the same information symbols would be combined at the receiver to minimize the error rate of the signal recovery.

Space-Time Block Code(STBC) is a coding scheme implemented in MIMO system. It takes the advantage of the multiple antennas that several sequences of information symbols could be transmitted at the same time [12]. Alamouti code was first devised with $N_T = 2$ and $N_R = 1$. The generator matrix of Alamouti code is:

$$G = \begin{bmatrix} s_1 & s_2 \\ -{s_2}^* & {s_1}^* \end{bmatrix} \tag{2.6}$$

where s_1 and s_2 are two consequent symbols in the data stream; $-{s_2}^*$ is opposite to the conjugate of s_2 and ${s_1}^*$ is the conjugate of s_1. In Alamouti coding scheme, s_1 and s_2 are transmitted at the same time in two antennas. In the first time slot, s_1 and s_2 are transmitted from each antenna. In the second time slot, $-{s_2}^*$ and ${s_1}^*$ are transmitted. From the generator matrix, we can see that the spatial diversity of 2×1 Alamouti code is 2 and the spatial code rate is 1. Multiple antenna system acquires that the separation spacing of antennas is large which makes it physically difficult to be implemented on handsets due to the size limitation. The complexity of multiple antennas at the transmitter and the receiver is also considerable.

For these reasons, cooperative diversity has recently received much research interest. Cooperative communication is actually multiple-user MIMO system [13]. It makes use of antennas in separate nodes to set up a virtual MIMO system. For each transceiver, the complexity of antenna design would

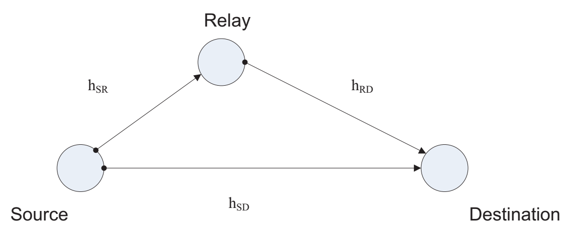

Figure 2.2: Three-node cooperative transmission system

be lower and also since all the nodes that take part in the cooperative communications are usually physically separated, the fading levels that signals from different propagation paths suffer would be more variable. A typical three-node cooperative system is illustrated as in Figure 2.2.

The Source node has information symbols to be transmitted to the Destination. The Relay is a transceiver operating at the same channel with Source. h_{SR}, h_{RD} and h_{SD} are the channel parameter from Source to Relay, from Relay to Destination and from Source to Destination, respectively. From this we can see that the Source and the Relay form a virtual MIMO system with antennas of the Relay also serving as antennas for the signal transmission from Source to Destination. STBC can also be implemented on the cooperative system [14], such as Alamouti code, which is called Distributed Space-Time Code (DSTC). Moreover, due to the physical separation nature of cooperative system, more sophisticated and efficient coding system is possible.

Amplify-and-Forward(AF) relay and Decode-and-Forward(DF) are the two types of relay teminals widely studied. An AF relay only transmits the

	Protocol I	Protocol II
Broadcasting phase	S-R, S-D	S-R, S-D
Cooperating phase	R-D	S-D, R-D

Table 2.1: Cooperating protocols

received signal or the amplified version of the received signal to the Destination and no decoding is performed. A DF relay demodulates and decodes the received signal and re-encodes and modulates the decoded symbols and then transmits to the Destination. Throughout this thesis, we consider DF relay in our cooperative system. Two cooperative protocols are mainlly studied based on the degrees that source and relay would participate in the transmission [10]. They are described in Table 2.1.

In both of the two protocols, the Source transmits to both the Relay and the Destination in the broadcasting phase. In the cooperating phase, only Relay transmits to the Destination if the system is operating in protocol I, while both Source and Relay transmit to the Destination if the system is operating in protocol II.

2.1.3 Rateless Code and Systematic Raptor Code Standardized in 3GPP

Rateless code, also called fountain code, can potentially generate limitless number of encoding symbols as needed [15]. On the other hand, there is no fixed coding rate for rateless code. The transmitter keeps generating encoding symbols on-the-fly until the receiver is able to decode the transmitted source symbols successfully. It is mainly used for signal transmission in erasure channels. If there are K source symbols encoded and transmitted, the receiver should be able to decode after K' symbols are received, where K' is slightly larger than K.

Traditional codes for erasure channels are mainly fixed-rate block codes. If a codeword cannot be decoded successfully with the selected code rate, the whole block of the received symbols will be discarded and retransmitted. To select a proper coding rate for the channel that the signal is to be transmitted through, the transmitter needs to have an estimation of the channel. For rateless code, this is not a must. The encoder at the transmitter keeps generating encoding symbols until the source symbols are decoded without error. Especially, rateless code has great advantage over fixed-rate code for application such as Digital Video Broadcasting(DVB). In DVB, when fixed-rate coding is applied, if one of the receivers does not receive one part of the information symbols correctly, the transmitter needs to retransmit this part of symbols and all the receivers will receive the retransmitted symbols even if they have already received the same ones. With rateless codes, the transmitter only needs to continue transmitting encoding symbols until all the receivers decode the source symbols without error, since the receiver is able to decode with any subset of K' symbols. Theoretically Raptor code can achieve a transmission rate that is very close to channel capacity on every channel [15].

Two widely known classes of fountain codes are LT codes and Raptor codes. LT codes were first published by Michael Luby in 2002 [3]. They are the first practical class of fountain codes. The encoder first generates a degree i using the degree distribution Ω_i which represents the probability that value i is selected. The generator polynomial of the degree distribution is $\Omega(x) = \sum_{i=0}^{k} \Omega_i x^i$. Then i distinct source symbols are selected randomly from the source symbols to do exclusive-or oepration and the output is the encoding symbol of the LT code. The transmitters keeps generating LT symbols until the receiver successfully decodes the source symbols. The selection of degree distribution $\Omega(x)$ is of great importance for the efficiency of LT codes. Assuming the number of source symbols is k and the transmitter has transmitted LT symbols when the receiver successfully decodes, the optimization goal of the degree algorithm is to make the coding overhead $(E[n]-k)/k$ as small as possible. On the other hand, the objective is to make sure that the source symbols could be decoded correctly after n encoding symbols are received [16]. Raptor codes are derived from LT codes. Outer codes are implemented that LT codes don't need to recover all the erased symbols but only a fixed fraction of them. By this means, the performance of the coding system is improved by decreasing the average coding overhead as well as the computational complexity. The outer code of Raptor code could also be a concatenation of two codes. One class of universal Raptor code uses high-rate Low-Density Parity-Check(LDPC) code as outer code. The K source symbols are first encoded with LDPC code. The output symbols of the LDPC encoder are called intermediate symbols. Then LT encoder is implemented to these intermediate symbols. The output symbols of the LT encoder are then the encoding symbols of the Raptor code. The decoding of the Raptor code is the concatenation of two Belief Propagation(BP) decoding.

In 3GPP, the systematic Raptor code is standardized. By encoding source symbols with systematic Raptor code, the original source symbols are transmitted as a part of the encoding symbols. The systematic Raptor encoding is made up of two steps [17]: in the first step, L intermediate symbols are generated from the K source symbols and the K source symbols triples $(d[i], a[i], b[i], 0 \leq i < K)$. Let $C'[0], C'[1], ..., C'[K-1]$ be the K source symbols and $C[0], C[1], ..., C[L-1]$ be the L intermediate symbols, the intermediate symbols should satisfy two conditions: 1. The K source symbols could be generated from the L intermediate symbols through the LT encoding. That it,

$$C'[i] = LTEnc[K, (C[0], C[1]..., C[L-1]), (d[i], a[i], b[i])] \tag{2.7}$$

for all i, $0 \leq i < K$. 2. Pre-coding relationships hold in the L intermediate symbols. The last $L-K$ symbols could be expressed in terms of the K source symbols, where S of the $L-K$ symbols are LDPC symbols and the rest $H = L-K-S$ symbols are Half symbols. To satisfy these two conditions, a Raptor decoding process could be applied to the K source symbols to obtain the intermediate symbols. Let A be the generator matrix which could be constructed with the pre-coding relationships and LT encoding generating matrix. Let D be the column vector which consists of $L - K$ zero symbols followed by the K source symbols $C'[0], C'[1], ..., C'[K-1]$. Then we can get:

$$A * C = D \tag{2.8}$$

where C is the column vector of L intermediate symbols.

The intermediate symbols can be calculated as:

$$C = A^{-1} * D \tag{2.9}$$

In the second step of Raptor encoding, LT encoder is implemented to the intermediate symbols to get repair symbols of Raptor code. The same triple generator mentioned above generates the triples $(d[i], a[i], b[i], i \geq K)$ for every repair symbol based on the encoding symbols ID. The number and set of intermediate symbols from which a repair symbol is generated can then be derived from the triples. Systematic Raptor repair symbols are then the outputs of the LT encoder with $C[0], C[1], ..., C[L-1]$ and $(d[i], a[i], b[i], i \geq K)$ as inputs, and the encoding symbols are the K source symbols with a number of repair symbols that are sufficient for successful decoding.

Let N be the number of received encoding symbols and $M = S + H + N$. To decode systematic Raptor code, it is a must that the same triple generator for generating $(d[i], a[i], b[i], 0 \leq i < N)$ and also the pre-coding relationships are available at the decoder. Then, an $M \times L$ matrix B could be constructed and the entry $A[i, j]$ of B takes value of 1 if the intermediate symbol which corresponds to index i is exclusive-ored to get the LDPC, Half or encoding symbols which correspond to index j. It also takes value of 1 when i and j correspond to the same LDPC or Half symbols. For the other cases, $A[i, j]$ is always 0. Let D be the column vector that consists of $S + H$ zeros and N received symbols, then we can get

$$A * C = D \tag{2.10}$$

Intermediate symbols vector C could be decoded if and only if A has full rank L. After C is decoded, the missing source symbols in the encoding symbols could be reconstructed by doing exclusive-or operations to the specific set of intermediate symbols and the set is determined by the triples $(d[i], a[i], b[i])$ calulated for the missing symbols.

2.1.4 Reed-Solomon Code

Reed-Solomon(RS) code is non-binary block code. One symbol in a RS codeword can consist of m bits of information data. RS coding is are based on finite Galois Fields(GF) and all the arithmetic operations of RS encoding and decoding must follow the arithmetic operations defined in a specific Galois field depending on the number of bits in one RS symbol [18]. Also, all the results of these arithmetic operations are members of the same Galois field. RS code is also systematic code, and a number of redundant symbols are appended to the k source information symbols to help to correct the erred or erased symbols in the codeword. If the length of a codeword after adding the parity symbols is n, then the minimum distance of the RS code is $d_{min} = n - k + 1$. RS code can correct up to $t = \lfloor \frac{n-k}{2} \rfloor$ erred symbols or $2{\times}t$ erasures in a codeword. The generator polynomial of a RS code is

$$g(x) = (x - a)(x - a^2)...(x - a^{2t}) \tag{2.11}$$

where a is the primitive element of the Galois field.

The codeword polynomial $c(x)$ is then expressed as

$$c(x) = g(x) * i(x) \tag{2.12}$$

where $i(x)$ is the information block, and a is the primitive element of the Galois field. The decoding procedure of RS code is the same as BCH code. The first step is to substitute the $2{\times}t$ roots of $g(x)$ to $r(x)$, and the $2{\times}t$ syndromes can be calculated. The second step is to determine the positions of the erred symbols in the codeword. There are many ways for this and Berlekamp-Massey and Euclid's algorithms are two commonly used algorithms [19]. Then by solving simultaneous equations the values of the erred symbols could be calculated. Based on the same encoder input and output block length, RS code can be designed to have the largest code minimum distance among all the linear codes. RS code can correct up to t erred symbol errors in one codeword no matters how many bits are corrupted in one symbol or where these corrupted bits are located. This makes RS code especially suited for channels that would cause burst errors.

2.1.5 Adaptive Transmission

If the channel state information is available at both the transmitter and the receiver, then adaptive transmission could be applied to ideally enhance the overall transmission efficiency. With an error-free feedback path from the receiver to the transmitter, the CSI could be obtained by the transmitter. With the CSI, the transmitter can adjust the power allocation, modulation method and also the channel coding rate to make sure the transmission scheme is optimized to achieve the maximum throughput in the specific channel condition.

For an adaptive transmission system, the channel state is quantized into $L+1$ finite distinct levels $V_0 < V_1 < ... < V_L$, where $V_0 = 0$ and $V_L = \infty$. The division of the channel states can be based on both channel parameters and the received SNR. If the channel state S belongs to the subset $[V_l, Vl + 1)$, for $l = 0, ..., L - 1$, then S is considered as state V_l and a code rate r_l and power p_l designed for this channel state would be applied to the transmitter. In [20], an adaptive coding technique is proposed based on a finite-state Markov channel.

2.2 Literature Review

Cooperative transmission was first proposed by J. Nicholas Laneman and Gregory W. Wornell in their ground-breaking work [1], where they examined an antenna-sharing scheme to achieve reliable transmission. The antenna-sharing scheme was compared with the single-hop transmission and also the multi-hop transmission and it was shown that this relaying scheme can achieve higher diversity gain than single-hop transmission and multi-hop transmission. In [21], Deqiang Chen and J. Nicholas Laneman showed that DF cooperative protocol with only one relay has full diversity order for extremely high signal to noise ratio. They also got the conclusion that when it comes to multiple-relay case, DF relaying scheme achieves about half of the diversity of AF relaying scheme. In [14], Zhimeng Zhong et al. proposed an AF cooperative scheme where in the second phase of transmission, the Source and Relay transmit to the Destination using Alamouti scheme. Sendonaris, A. et al. proposed a cooperating scheme using Code Division Multiple Access(CDMA) method when multiple users have data to transmit to the same receiver in their two-part thesis [27] [28], and they examined the performance of the proposed scheme from capacity perspective. Stefanov, A. et al. studied the cooperative system where the users may have multiple antennas [29] and they demonstrated that the error rates of all the users can be reduced by using space-time coding in the cooperative system. LT codes which are the first class of practical rateless codes were first proposed in [3] by M. Luby. Based on LT codes, Amin Shokrollahi in [4], introduced Raptor codes which have linear time encoding and decoding complexity. By combining LT codes with outer codes, which are LDPC codes most of the time, Raptor codes solve the error floor problem of LT codes. In [4], Shokrollahi proposed the general idea of the encoding and decoding method of systematic Raptor codes. Implementing rateless codes in the cooperative communication scheme was first proposed by J. Castura and Yongyi Mao [6], and in [26] J. Castura et al. studied the outage and throughput performance of rateless code in fading channels with delay constrants concluding that in fading channels rateless codes outperform fixed-rate codes in terms of both outage and throughput. Xi Liu and Teng Joon Lim extended Castura and Mao's work in [5], analyzing the relaying scheme with Raptor codes using three different protocols, Distributed Space-Time Codeing(DSTC), Time-Division(TD) and two-Hop(2H). Hongtao Zhang and Geng-Sheng Kuo in [2] studied a practical cooperative scheme implementing Raptor codes. They used DSTC protocol, and in the second phase, the Source and all the available relays transmit Orthogonal Frequency-Division Multiplexing(OFDM) modulated symbols to the Destination to achieve the diversity. Mehta, N.B. et al. examined a queued cooperative transmission shceme with rateless codes [9], they found that the combined system with rateless codes and queuing can significantly improve the throughtput performance while decreasing the transmission time. We see that all the previous research on implementing rateless codes in cooperative communication use non-systematic codes. In this thesis, we propose a cooperative scheme which implements the systematic Raptor code standardized in 3GPP. By using systematic codes in cooperative communication, the system can obtain the advantage that when all the source symbols are received without error, there is no need to decode.

Chapter 3

System Model: No Channel State Information at the Transmitter

3.1 Modes of Cooperation

The one-relay, three-node cooperative system is shown in Figure 2.2. Every node is equipped with only one antenna. The Source transmits the source data to the Destination and the Relay helps as needed. Actually, the Relay here could also be a Destination of the source data. In that case, the Relay receives the data from the Source and at the same time relays the data to other peer nodes to improve the overall channel use. In practical case, such as DVB application, there could be many relays in the same transmission system relaying the data received to other peer nodes. In this thesis, since we focus on the error control coding scheme and cooperative protocol, we consider one-relay case for simplicity. The relay we use in our cooperative system is a DF relay, which decodes the received symbols from the Source and re-encodes them before transmission. As it is known, the energy of the received signal is extremely small compared to the transmitted signal at the same node. If the Relay node works in full-duplex mode, which means the Relay transmits symbols to the Destination and receives symbols from the Source at the same time, the received symbols can hardly be recovered. For this reason, in our scheme, Relay works in half-duplex mode, which means in a give time slot, Relay either transmits or receives. As presented in Chapter 2, we study two cooperative protocols.

3.1.1 Cooperative Mode: Only Relay Transmits in the Cooperating Phase

The cooperative transmission of a block of data is divided into two phases, the broadcasting phase and the cooperating phase. In the broadcasting phase, the Source first broadcasts the source symbols, and both the Relay and the Destination listen. If either the Relay or the Destination is capable of decoding the source symbols, which means that it has received all the source symbols without error, it will send back an Acknowledgement(ACK) signal to the Source. Otherwise, if Source has not received any ACK signal, it will encode the source symbols into parity symbols of systematic Raptor code and broadcast to the Relay and the Destination until either of them sends back an ACK. Theoretically, the Raptor encoder can generate as many as symbols until the receiver successfully decodes the source symbols. However, the delay constraint is needed since in practical transmission, many applications require that the data should be transmitted with acceptable delay, such as video conference. Hence, in our model, if neither the Source or the Relay has sent the ACK after a pre-determined number of parity symbols have been transmitted by the Source, the outage case happens and the transmission of the current block fails. Otherwise, if the Destination successfully decodes the source symbols before the delay constraint is reached and sends the ACK_{DS} first, the Source will end the current block transmission and start to transmit the next block. If the Relay sends the ACK_{RS} first, Source will also stop transmitting and enter the waiting period and the cooperating phase begins. In the cooperating phase, the Relay re-encodes the source symbols into the parity symbols of Raptor codes and transmits the parity symbols to the Destination. The Destination will send an ACK_{DS} to the Source and ACK_{DR} to the Relay after it successfully decodes all the source symbols and the Source will start to transmit the next block of data. If Destination has not sent ACK_{DS} to the Source and ACK_{DR} to the Relay after a per-determined number of repair symbols have been transmitted by the Relay, the outage happens. All the ACK signals are transmitted through the error-free feedback channel. In practical, this feedback channel is feasible and the time cost and bandwidth cost for it is neglectable.

3.1.2 Cooperative Mode: Both Relay and Source Transmit in the Cooperating Phase

Now we consider the second cooperative protocol, where both the Source and the Relay transmit in the cooperating phase as in Figure 3.1. The broadcasting phase of this protocol is the same the the other protocol. The difference is in the cooperating phase. In the cooperating phase, the Source and the Relay transmit the same systematic Raptor repair symbols at the same time to the Destination. This is feasible through generating the same triples using the symbol IDs and the same triples generator. The Destination will receive an over-lapped version of the signals coming from both the Source and the Relay in the cooperating phase. The Destination sends the ACKs to the Source and the Relay when it has received enough error-free symbols for decoding, and the transmission is successful. The delay constraint also applies in this protocol. We can see that this protocol requires phase synchronization of the Source and the Relay.

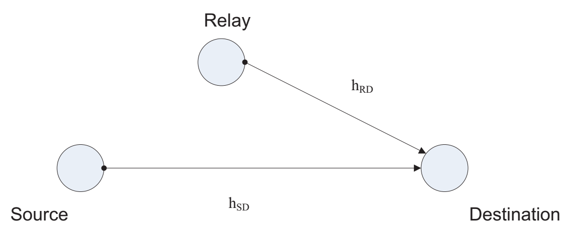

Figure 3.1: Second phase protocol II

3.2 System Model without RS code as Inner Code

In our model, the repair symbol triples $\{(d[0], a[0], b[0]), (d[1], a[1], b[1]), ..., d[n], a[n], b[n]\}$ generators are the same at the three nodes. Also, by recording the number of symbols transmitted from the Source and the Relay, the Relay and the Destination both have the knowledge of the encoding symbol IDs. With correct triples generator and the encoding symbol IDs, both the Relay and the Destination could decode source symbols from the systematic Raptor symbols correctly. Systematic Raptor code was originally implemented in the erasure channel and theoretically it can recover all the erased symbols. To make it work in a noisy channel, we have to make sure that all the received symbols that we use as the input of the decoder are error free. For this reason, we calculate CRC for each Raptor packet and append the CRC to the end of the Raptor symbols in each packet to detect any error in the received symbols. In our model, 32-bit CRC is selected for its strong error detection

F	G	T	K
100K bytes	6	84 bytes	1,220

Table 3.1: Recommended settings for systematic Raptor code in 3GPP

capability. We use the 32-bit CRC proposed in [23]. At the transmitter side, CRC is recalculated after a packet is received and compared with the CRC received in this packet. If there is CRC mismatch which means that there is error in this received packet, the whole packet would be discarded. For every received packet, both the Relay and the Destination do the CRC check, and they will either discard or keep the packet depending on whether there is error or not. In general, a Raptor symbol can be as short as one bit and as long as we like. In this thesis, we use the values suggested in the standard [17], which is 84 bytes. In 3GPP standard, there are recommended settings for the file size, packet size, symbol size and block size. We choose one of the settings as shown in Table 3.1.

On the basis of these parameters, the probability that a packet is lost in a noisy channel can be calculated. We assume that γ_r is the received SNR of a channel. For Binary Phase Shift Keying(BPSK) modulation, we know that the Bit Error Rate(BER) is

$$P_b(\gamma_r) = Q(\sqrt{2\times\gamma_r}) \tag{3.1}$$

Considering BPSK modulation, we define the channel SNR γ_c as

$$\gamma_c = E_c/No \tag{3.2}$$

where E_c is the transmit energy allocated to every BPSK symbol.

If α is the path loss exponent and d is the distance from the transmitter to the receiver, then

$$\gamma_r = \gamma_c \times \frac{h^2}{d^\alpha} \tag{3.3}$$

P_b is then expressed as a function of fading amplitude h as follows:

$$P_b(h) = Q(\sqrt{2\times(\gamma_c \times \frac{h^2}{d^\alpha})}) \tag{3.4}$$

and since we consider Rayleigh fading in this thesis, the Probability Density Function(pdf) of Relay fading is

$$P_{fading}(h) = 2h \times e^{-h^2} \tag{3.5}$$

A packet is made up of of T bytes and 32-bit CRC, so the packet loss rate is:

$$P_{packet}(h) = 1 - (1 - P_b(h))^{8T\times G+32} \tag{3.6}$$

where T is the symbol size in bytes, G is the number of symbols in one packet and the last 32 bits are CRC. As in Table 3.1, T is 84 bytes and G equals to 6. The packet loss rate under different received SNR can be then calculated and shown in Figure 3.2. As in Equation 3.6, the packet loss

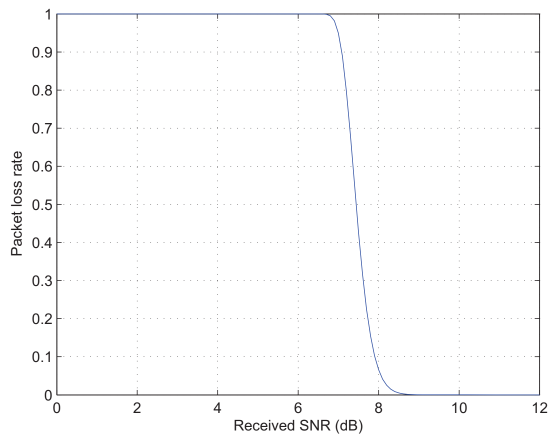

Figure 3.2: Packet loss rate of systematic Raptor code under different received SNR with recommended parameters

rate depends on the received SNR as well as the packet size. One way to reduce the packet loss rate is to make the packet size as small as possible. However, in practical case, each packet is sent together with its overhead. Meanwhile, we have CRC appended to the Raptor symbols in each packet. Smaller packet will make the bandwidth efficiency lower for the overhead and CRC cost. The overhead and packet loss rate are a pair of trade-offs. For this reason, in this thesis, we use the recommended parameters in [17] to ensure a proper set of parameters are selected considering the systematic Raptor code features and practical transmissions.

In [24],the decoding failure probability of systematic Raptor code with overhead ϵ is

$$P_f(\epsilon) = 0.85 \times 0.567^{\epsilon} \tag{3.7}$$

where $\epsilon = N - K$. N is the number of the received systematic Raptor symbols and K is the number of the source symbols. Since in practical transmission, the transmitter keeps transmitting Raptor symbols until the decoding at the receiver is successful, the overhead ϵ would be evaluated as the number of overhead symbols transmitted until the decoding succeeds. The probability density function of ϵ is expressed as

$$P_{overhead}(\epsilon) = \prod_{i=0}^{\epsilon-1} P_f(i) \times (1 - P_f(\epsilon)) \tag{3.8}$$

where $\epsilon > 0$.

Considering the equations of $P_{packet}(h)$ and $P_{overhead}(\epsilon)$, we can calculate the probability that L packets have been transmitted until the decoder decodes the K source symbols successfully.

$$P_L(L, h) = \sum_{i=K/G}^{L} \binom{L}{i} [P_{packet}(h)^{i-1} \times (1 - p(h))] \times (P_{overhead}(i{\times}G - K)) \tag{3.9}$$

The averaged bandwidth efficiency η can then be expressed as

$$\eta = \int_{h=0}^{\infty} P_{fading}(h) \sum\nolimits_{L=0}^{\infty} \frac{K}{L{\times}G} P_L(L, h) dh \tag{3.10}$$

The averaged bandwidth efficiency we talked above is for one-link scenario, which means no Relay participates in the transmission.

Since with rateless code the receiver can always decode the source symbols successfully as long as sufficient number of coding symbols are transmitted, we use bandwidth efficiency *eta* instead of BER to evaluate the performance of our models.

In [25], the realized rate R for a one-relay collaborative transmission scheme is upper bounded by the capacity of the cooperative system. Given channel realization (H_{sd}, H_c),

$$R \leq fC(H_{sd}, \gamma_c) + (1-f)C(H_c, \gamma_c) \tag{3.11}$$

where H_{sd} is the channel realization for transmission link $S-R$ in the first transmission phase, H_c is the channel realization of the combined transmission scheme in the second phase, f is the time fraction of the first phase and γ_c is the transmit SNR. It is obvious that when f is 0, it is the case that the Relay has all the knowledge of the source symbols and when f is 1, it is the case that the Relay is not able to decode the source symbols before the Destination. We notice that in cooperative protocol where only Relay transmits in the cooperating phase, H_c is actually the channel gain from the Relay to the Destination.

3.3 System Model with RS Code as Inner Code

Figure 3.2 shows the packet loss rate for the cooperative transmission model with systematic Raptor codes based on our parameters selection. As we see from this figure, the packet loss rate get extremly large when the received SNR is under 7 dB, and we need an inner code concatenated with systematic Raptor code to make the cooperative scheme have better bandwidth efficiency performance. An ideal inner code is RS code. RS code is a non-binary code which is a very good match for our model since the symbol size we select as recommended in 3GPP is measured by bytes, and we can use RS code based on GF(8). The RS code encodes every byte of source data into one RS symbol. Another advantage of RS code is that the overhead of the processor grows linearly as the size of the information data increases.

First we would want to apply RS encoding only to the systematic Raptor parity symbols. In this case, the source symbols are transmitted without RS encoding, and no decoding process is needed for sources symbols if there is no error in the received source symbols. However there is performance limit since in low SNR scenarios, the uncoded source symbols would be received with error with greater probability than the repair symbols.

The system model with RS code applied to both the source and repair symbols can achieve better bandwidth efficiency. Considering the trade-off between error-correcting capability and overhead of RS codes, we use RS(n,

172) codes which are RS(255, 172) codes shortened by $255 - n$ bytes. With this RS codes selection, we encode every two Rapter symbols of which the size is 168 bytes together with the 32- bit CRC into one RS codeword. Figure 3.3 illustrates the process of CRC and RS encoding. First, the 32-bit CRC is calculated for every two Raptor symbols and appended to the end of the two Raptor symbols. Then these $T \times 2 + 4$ bytes are encoded with RS(n, 172) code. After the RS encoding process finishes, there would be 3 RS codewords in one Raptor packet which will be transmitted through the wireless channel. The decoding process is just the opposite, where the three RS codewords in one Raptor packet are decoded with the RS decoder individually and CRC is re-calculated and compared with the received CRC. If there is error in this Raptor packet, the whole packet will be discarded. Finally, the error-free Raptor symbols would be input to the systematic Raptor decoder. If the source symbols are decoded successfully, the transmission for current file would be done and the receiver sends an ACK to the transmitter. Otherwise, the transmitter keeps generating and transmitting the next Raptor packet.

The general structure of this scheme is illustrated in Figure 3.4.

We assume that the RS code encodes k symbols into n symbols. Then the RS code can correct up to $t = \lfloor \frac{n-k}{2} \rfloor$ erroneous symbols. If the transmit power for every bit is constant, then the bit error rate(BER) can be expressed as

$$P_b = Q(\sqrt{2 \times \gamma_r}) \tag{3.12}$$

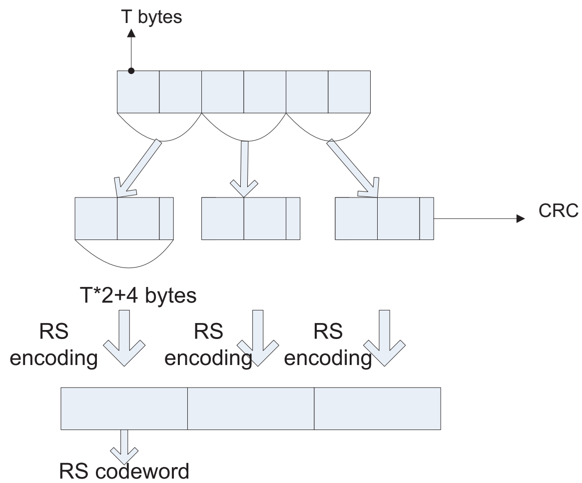

Figure 3.3: Illustration of the procedure of CRC and RS encoding

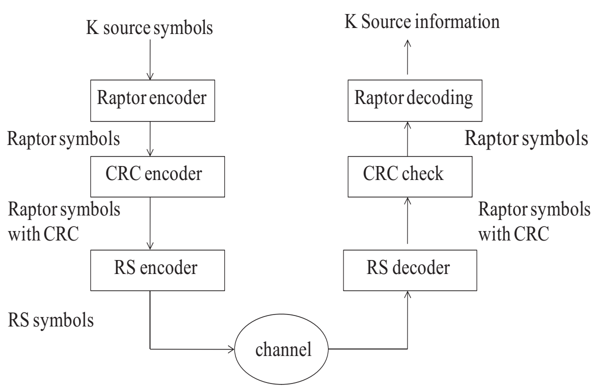

Figure 3.4: Configuration of the system combining Raptor code and RS code together

where γ_r is the received SNR. The probability that there is at least one error in an RS symbol of symbol size 8 bits is

$$P_s = 1 - (1 - P_b)^8 \tag{3.13}$$

The probability that the k symbols are not decoded successfully after RS decoding is

$$P_e = 1 - \sum_{i=0}^{t} [\binom{n}{i} P_s^i (1 - P_s)^{n-i}] \tag{3.14}$$

Since for our choice of parameters there are 3 RS codewords in one packet, the packet loss rate then becomes

$$P_L = 1 - (1 - P_e)^3 \tag{3.15}$$

The packet loss rate when n is 216, which is a RS(255, 172) code shortened by removing 39 bytes, under different received SNR is shown in Fig. 5. We can see that the system can operate well when the received SNR is as low as 5 dB with RS (216, 172) as inner code.

Chapter 4

Simulation Results for Model with No CSI at the Transmitter

4.1 Simulation Parameters

First, we assume that both of the transmitters at the Source and the Relay have the same transmit power. The CSI is not available at the transmitters but available at the receivers. We consider a flat slow Rayleigh fading channel, where the fading is constant over the transmission of a block of data and the fadings of different blocks of data are independent and identically distributed(i.i.d.). We use BPSK as the modulation method. Although our model is applicable to system with Source, Relay and Destination at arbitrate positions, for analysis simplicity, we assume that the Relay is located in the straight line from Source to Destination and the distance from Source to

Relay is always smaller than the distance from Source to Destination. If we assume the distance from Source to Destination is 1 and the distance from Source to Relay is d, then the distance from Relay to Destination would be 1-d. We assume that the long-distance path loss exponent is 2. Then the path loss from Source to Relay, from Source to Destination and from Relay to Destination is $1/d^2$, 1, and $1/(1-d)^2$, respectively.

4.2 Simulation Results

4.2.1 Simulation Results for System without RS Code

We assume Relay is in the middle of Source and Destination, which means $d = 0.5$. As in Table 3.1, the number of symbols in a block of source data is $K = 1220$. To decrease the number of decoding tries, in our simulation, the decoder will not start decoding until it has received 1250 error-free symbols. As discussed in Chapter 3, we need the delay constraint to make sure that the system is time-efficient. For the transmission from Source to Destination and Source to Relay, if the decoder has not received enough error-free symbols to decode until the Source has transmitted 1288 symbols, in which case the overhead of systematic Raptor code is around 5%, then this will be considered to be an outage case. Considering the possible transmission overhead, we assume in the transmission of the i-th block of data, the number of Raptor parity symbols, CRC checksum symbols and RS parity symbols are M_Raptor_i, M_CRC_i and M_RS_i, respectively. In the model that RS code

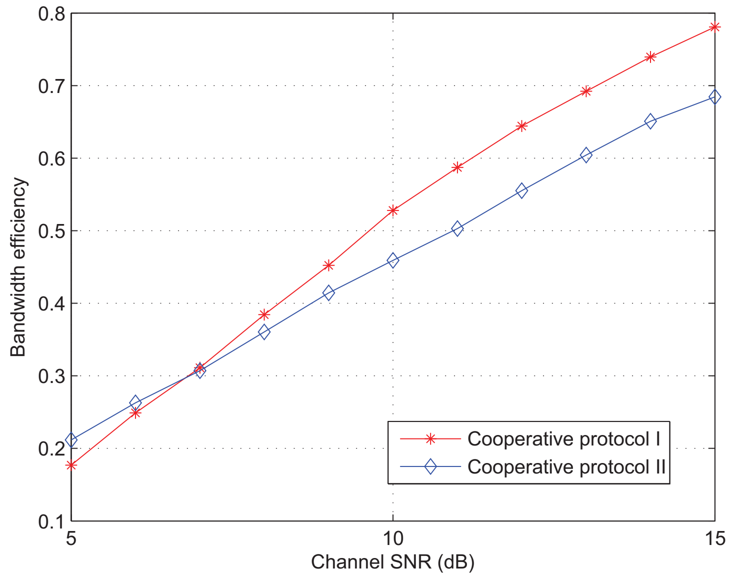

Figure 4.1: Bandwidth efficiency of cooperative system with systematic Raptor code when d is 0.5

is not used, $M\_RS_i = 0$. The number of symbols transmitted in every block can be then calculated as:

$$N_i = K + M\_Raptor_i + M\_CRC_i + M\_RS_i \tag{4.1}$$

If there are n blocks of data transmitted and n_{outage} of blocks are not transmitted successfully, the avaraged bandwidth efficiency of the transmission of these n blocks of data can be expressed as:

$$\eta = (n - n_{outage}) \times K / \sum_{i=0}^{n} N_i \tag{4.2}$$

We can see from Figure 4.1 that, in low SNR scenario, the bandwidth efficiency of the model with cooperative protocol I in which both the Source and the Relay transmit in the cooperating phase is higher than the model with cooperative protocol II in which only Relay transmits in the cooperating phase. Howerver, in high SNR scenario, the model with protocol I outperforms the model with protocol II. When the channel SNR is around 7 dB, the bandwidth efficiency of protocol I equals that of protocol II. We notice that at SNR=10 dB, protocol I achieves a bandwidth efficiency which is 18% greater than protocol II. As the channel SNR increases, protocol I shows more supperiority in aspect of bandwidth efficiency. At the same time, since protocol II requires phase synchronization of Source and Relay in the cooperating phase, protocol I is more suitable for practical transmission.

4.2.2 Simulation Resutls for System with RS Code

Figure 4.2 shows the simulation results for two models with protocol I, one with RS codes applied to all the systematic Raptor symbols and the other one with RS codes only applied to the Raptor parity symbols. From the simulation results, we can see that when channel SNR is under 12 dB, system with the three different RS rates, RS(174,172), RS(186,172) and RS(216,172) all have great bandwidth efficiency gain over the one without RS code. Models with RS applied to all symbols achieve better bandwidth efficiency performance than models with RS codes only applied to Raptor parity symbols, which is consistent with our expectation.

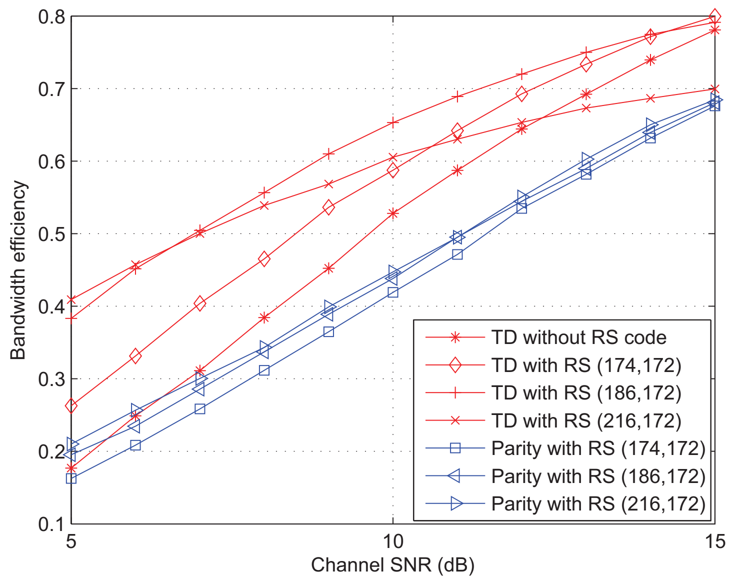

Figure 4.2: Bandwidth efficiency of cooperative system with RS codes as inner codes when d is 0.5

We can also see in 4.2 that, in low SNR scenarios, systems with lower-rate RS codes have better performance, but as the channel SNR increases, the performance gap becomes smaller. When SNR is high, systems with high-rate RS codes tend to have greater bandwidth efficiency. When channel SNR is greater than 6 dB, the system with RS(216, 172) has even worse bandwidth efficiency performance than the one with RS(186, 172). This result is reasonable since as the channel SNR gets higher, there are fewer errors in one received RS symbols. In this case, high rate RS code is strong enough to correct the errors, and sometimes even no RS code is needed. When a higher-rate RS code is strong enough, implementing a low-rate RS code will waste bandwidth on more RS parity symbols which are useless, and thus the bandwidth efficiency will be decreased.

Our simualtion results in Figure 4.3 show that with RS code as inner code, protocol I still achieves better bandwidth efficiency performance than protocol II.

4.3 Conclusion

Our simulation results show that, with systematic Raptor codes, cooperative communication system achieves good bandwidth efficiency. At the same time, the system with cooperative protocol I achieves better bandwidth efficiency performance than the system with cooperative protocol II. With RS codes as inner codes, the system can work well even in low channel SNR scenarios.

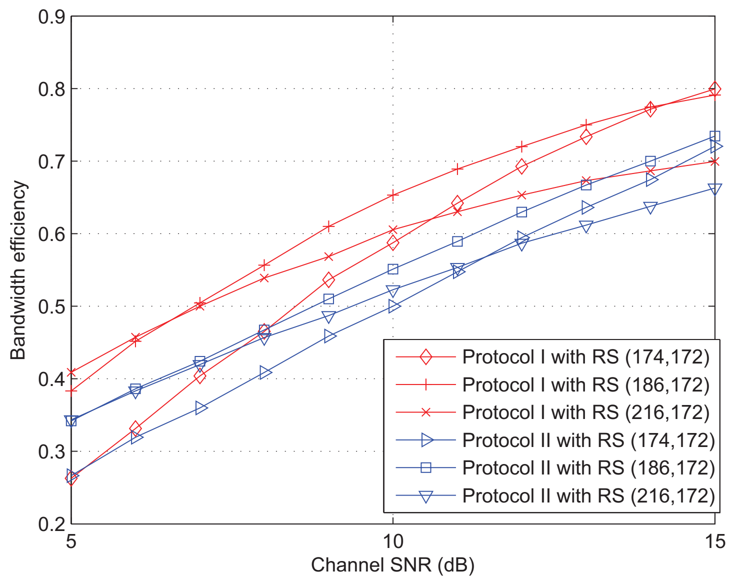

Figure 4.3: Bandwidth efficiency of cooperative system with systematic Raptor code and RS code when d is 0.5

We also see that, if we only apply RS codes to Raptor parity symbols, the bandwidth efficiency is not as good as the model with RS codes applied to all the Raptor symbols although it has the advantage that no decoding is needed when all source symbols are received in high SNR scenarios. Last, we show that as the channel SNR increases, systems with higher-rate RS codes have better bandwidth efficiency performance and as channel SNR decreases, systems with lower-rate RS codes have better bandwidth efficiency performance.

Chapter 5

System Model: Channel State Information Available at the Transmitter and Simulation Results

In this chapter, we assume that the CSI is available at the transmitters of Source and Relay as well as at the receivers. With this assumption, we will propose an adaptive transmission system based on the cooperative model presented in the previous chapters. The adaptive transmission protocol is demonstrated with bandwidth efficiency gain over the one without adaptive transmission through our Monte Carlo simulation. Then under the correlated Rayleigh fading scenario, we propose a channel estimation method which makes the transmitters have an estimation of the CSI.

5.1 Adaptive Transmission Models

5.1.1 Adaptive Transmission with CSI Available at the Transmitter

The cooperative transmission model presented in the previous chapter is based on the assumption that the transmitters do not have the CSI. With this assumption, the rate of RS code has to be selected before the transmission and will be fixed over the transmission of all blocks of data for all channel states. As in our simulation results in Chapter 4, high-rate RS codes can achieve better bandwidth efficiency when the channel SNR is high but cannot get as good performance as low-rate RS codes when the channel SNR is low. We want to find a way to optimize the bandwidth efficiency under different received SNR. Adaptive coding rate is a solution to this. If CSI is available at the transmitter, the transmitter can use a selected rate of RS code which can achieve the highest bandwidth efficiency under the specific channel state. First, we discuss the system model with the assumption that the perfect CSI is available at the transmitters of the Source and the Relay before the transmission of every block of data, which means that the transmitters know exactly the fading coefficient of Rayleigh fading. As in Chapter 4, we first assume that the fading is constant over the transmission of one block of data and the fadings of different blocks of data are i.i.d..

5.1.2 RS Coding Rate Selection Criteria

If the channel SNR in dB is γ_c and fading equals h, the received SNR γ_r could then be calculated as follows:

$$\gamma_r = \gamma_c + 20\times \lg h \tag{5.1}$$

Thus, for the three channels, Source-Destination, Source-Relay and Relay-Destination channels, the received SNR can be calculated as follows:

$$\gamma_{r\_SD} = \gamma_{c\_SD} + 20\times \lg h_{SD} \tag{5.2}$$

$$\gamma_{r\_SR} = \gamma_{c\_SR} + 20\times \lg h_{SR} \tag{5.3}$$

$$\gamma_{r\_RD} = \gamma_{c\_RD} + 20\times \lg h_{RD} \tag{5.4}$$

γ_{c_SD}, h_{SD}, γ_{c_SR}, h_{SR}, γ_{c_RD}, h_{RD}, are the channel SNR and fading of Source-Destination, Source-Relay and Relay-Destination channels, respectively. With the CSI available at the transmitters of both Source and Relay, the transmitters can get the knowledge of the expected received SNR. Then the Source and the Relay can choose the optimized rate of RS code which would be a trade-off between the packet loss rate and the codeword length.

Received SNR (γ_r)	RS code selected
$\gamma_r < 7dB$	No RS code is needed
$9dB \leq \gamma_r < 11dB$	RS(174, 172)
$8dB \leq \gamma_r < 9dB$	RS(178, 172)
$7dB \leq \gamma_r < 8dB$	RS(186, 172)
$\gamma_r < 7dB$	RS(216, 172)

Table 5.1: RS code selection under different received SNR

Since symbols received at Destination is what we really want, the Source always chooses the rate of RS code according to Source-Destination channel instead of Source-Relay channel. The Relay always chooses the rate of RS code according to Relay-Destination channel if the Relay participates in the transmission in the cooperating phase. The RS code that transmitters can choose should achieve an acceptable packet loss rate under different received SNR. If we require the packet loss rate P_L to be always smaller than 0.1, the shortest RS codes we can choose under different received SNR are as shown in Table 5.1.

5.1.3 System Model with Channel Estimation

In former section, we assumed that the perfect CSI is available at the transmitters before the data transmission. In fact, the CSI could be estimated to some extent from the transmission performance of previous block of data, when the channel is a slow fading channel. To perform the channel estimation, a low-rate feedback channel from the receiver to the transmitter will be needed, the cost of which is negligible. In the previous chapter, we assume that the perfect CSI is available before the transmission of a block of data and the adaptive coding rate is implemented based on this assumption. Since the packet loss rate of one block under different received SNR is known prior to the transmission with a specific RS coding rate, it is possible to estimate the received SNR and thus the CSI according to the packet loss rate. The Destination node would send to Source node an ACK signal when it has received enough error-free symbols as discussed in previous section, and thus the Source can have an estimation of the packet loss rate based on the number of packets already transmitted. The channel state can then be estimated from the previous block transmission. In this work, we estimate the channel state of the current block transmission based on the correlated fading channel model. Autoregressive(AR) model is used for generating such a correlated channel [22]. In this thesis, the AR model we use to obtain the correlated Rayleigh fading channels is a second-order AR model $X_t = 1.7625 \times X_{t-1} - 0.9503 \times X_{t-2}$.

5.2 Simulation Results

The simulation results for bandwidth efficiency of cooperative transmission with adaptive RS rates is shown in Figure 5.1. In this comparison, the distance from Source to Relay d is always 0.5 and the distance from Source to Destination is 1. The bandwidth efficiency for systems with fixed-rate RS codes is also provided for comparison.

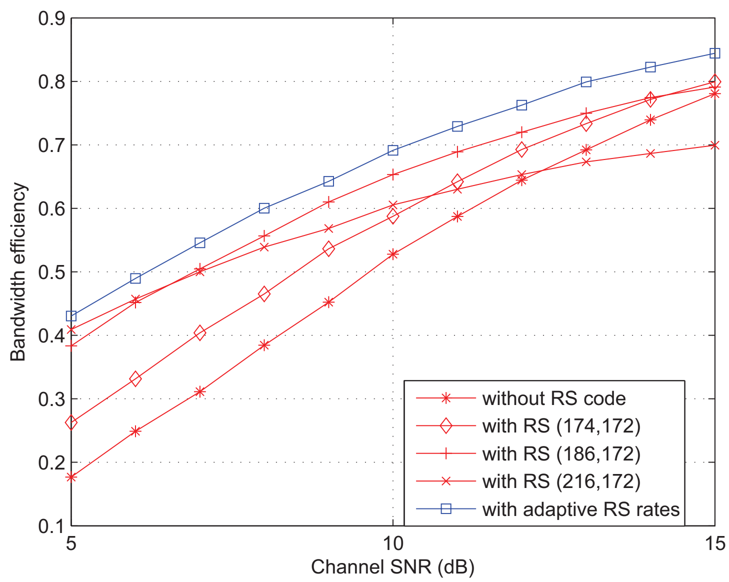

Figure 5.1: Comparison of bandwidth efficiency performance for models with fixed-rate RS codes and the one with adaptive rates when d is 0.5

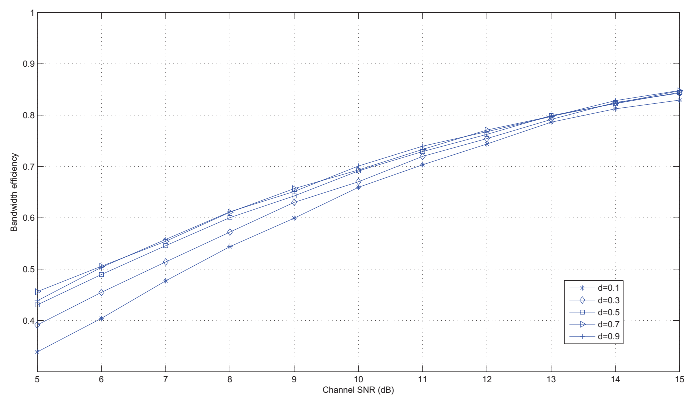

Figure 5.2: Comparison of bandwidth efficiency performance for adaptive transmission with different Source-Relay distance

From Figure 5.1, we can see that given the same Source-Relay distance d, the modol with adaptive RS rates, outperform the models with fixed-rate RS codes.

The bandwidth efficiency performance of the adaptive transmission model for different Source-Relay distance is provided in Figure 5.2. We can see from the simulation results in Figure 5.2 that, in high channel SNR scenarios, different distance from Relay to Source d does not affect the bandwidth efficiency performance. However, in low channel SNR scenarios, as the Relay moves from Destination to Source side, the bandwidth efficiency tends to become smaller. This is due to the feature of cooperative protocol I. When SNR is high, there is a great chance that the Destination and the Relay receive all the transmitted symbols simutaneously and the Destination would decode the source symbols successfully without Relay's help. Thus, in this

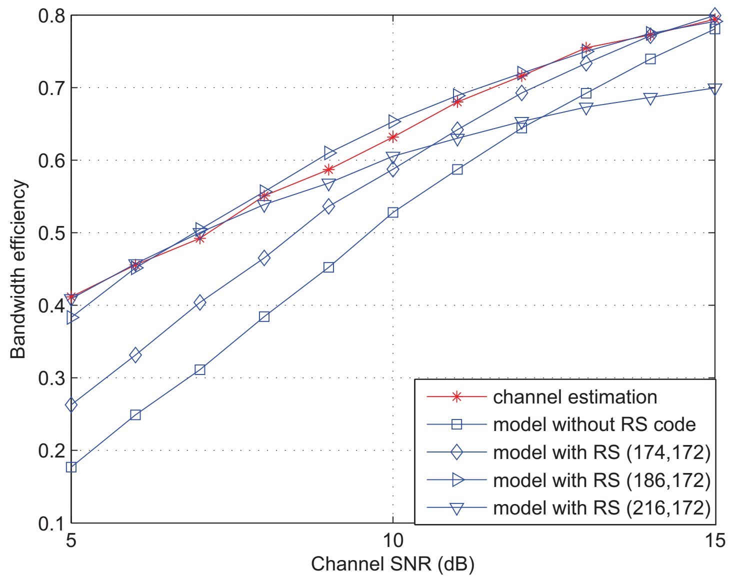

Figure 5.3: Comparison of bandwidth efficiency for adaptive model with channel estimation and models with fixed-RS rates

case, Source-Relay distance d does not affect the transmission. When the channel SNR is low, if Relay is located closer to Source, Relay would likely decode the source symbols successfully and transmit them to the Destination in the cooperating phase. However, Relay-Destination channel may be quite bad since the Relay is far from the Destination and thus smaller d would cause the effiency to be worse.

The performance of adaptive model with channel estimation is provided in Figure 5.3. We can see from the simulation result in Figure 5.3 that, even with our straightforward estimation method, the model with channel estimation and thus adaptive RS rates achieves better bandwidth efficiency performance than the models with fixed-rate RS codes.

Chapter 6

Concluding Remarks

6.1 Conclusion

In this thesis, we first implemented the systematic Raptor code standardized in 3GPP to cooperative transmission scheme. Using systematic Raptor code has the advantage that when all the source symbols are received without error, no decoding process is needed. Also, since the systematic Raptor codes are already standardized, it makes more sence for forward error control coding selection for pratical transmission.

In Chapter 3, we first presented our model and some design considerations for the model. We also studied two cooeprative protocols. In protocol I, only Relay transmits in the cooperating phase and in protocol II, both Source and Relay transmit in the cooperating phase. Then we proposed a new model with RS codes as inner codes for effiency improvement. Another model with

RS codes only applied to the Raptor parity symbols are also provided to maintain the advantage of systematic Raptor code when RS coding is used.

In Chapter 4, with our simulation results, we demonstrated that our model can achieve quite satisfying bandwidth efficiency. Also, models with RS inner codes can greatly improve the bandwidth efficiency performance. We also found that in our model, protocol I outperforms protocol II both with and without RS coding.

In Chapter 5, assuming perfect CSI is available at both the transmitters and the receivers, a new adaptive transmission model was proposed with adaptive RS rates, by using different RS codes that are optimized for different channel states. From the simulation results in the latter part of this chapter, it was showed that this adaptive transmission scheme has great performance improvement over the schemes with fixed-rate RS codes. We also discussed about a straightforward channel estimation scheme, and we can see can even with this straightforward method, this adaptive model still outperforms the ones with fixed-rate RS codes.

6.2 Future Work

Based on our current models and results, we think that there are some points that can be researched in the future to get more important results. Here are some of them which we think are most important:

1. Power allocation between the Source node and the Relay node can be

studied. The bandwidth efficiency performance can be furthermore improved with an ideal power allocation strategy.

2. We considered one-relay scenario, and more relay nodes can be considered to be applied to our model. Also, in our model, we assume Relay moves in the straight line from Source to Destination and actually other geography locations can also be applied to the model to examine the influence that the location of Relay has to the system performance.

3. We used a straightforward channel estimation method in our thesis, and it is very attractive if other efficient and accurate estimation techniques could be studied for the performance improvement.

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