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Fountain Codes over Wireless Mobile Relay Channels

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Abstract—Cooperative communications, where parallel relays forward information to a destination node, can effectively improve the latency in mobile ad-hoc networks. In practice, the performance of data transmission often compromises with the variation of channel coefficient and the mobility of network nodes. The conventional fixed rate cooperative relaying cannot make the outage probability reach zero without having precise channel state information (CSI) at the transmitter. In this paper we study the performance of using fountain codes in a mobile relay network. Specifically, we develop both feedback and non-feedback fountain coded cooperative communication protocols and analyze the performance of these protocols in terms of transmission efficiency over different wireless channels. It is observed that the number of total relay nodes plays a significant role on the performance improvement and the transmission efficiency varies with channel models. Simulation results justify that the proposed feedback based protocol always outperforms its non-feedback counterpart in a variety of metrics.

I. INTRODUCTION

Cooperative communication is an effective way to improve throughput, link reliability, power consumption, and coverage in wireless networks [1][2]. In literature a comprehensive study has been done to develop cooperative relaying protocols and resource management techniques to exploit its potential benefits [1][3][4][5]. In the conventional cooperative relaying, fixed-rate code is employed for transmission, in which energy of orthogonal transmissions from different nodes is combined by the receiver. The problem with such fixed-rate coding is that the outage probability never reaches zero without having precise channel state information (CSI) available at the transmitter.

In comparison to fixed-rate codes, rateless codes or fountain codes [6] do not have a predetermined rate for transmission and have gained a lot of research interest since its introduction [7]. In fountain encoding, the source unconsciously of channel state information (CSI) can generate as many encoding symbols as needed, depending on the instantaneous quality of the channel. At the receiving side, the receiver keeps accumulating incoming information until it is capable to decode source information successfully.

The first rateless coding framework over wireless relay channels was introduced by Castura et al. [8]. As it decodes source information successfully, this relay assists the source as a secondary antenna. In this framework, the relay node synchronizes itself with the source before starting transmission.

The source and relay then transmit to the destination using space time Alamouti code. Xi et al [9] studied several single relay cooperative schemes and derived their achievable rate in flat Rayleigh faded channel. Yang et al [10] studied the performance of fountain code in low power regimes. Molisch et al [11] studied fountain codes from the perspective of mutual information accumulation in multiple parallel relay assisted networks over block fading Rayleigh channel. It is shown that information accumulation rather than energy accumulation costs lower energy expenditure and lower transmission time. The amount of accumulated information in a specific time depends on the specific channel and noise level. Therefore, the transmission time varies according to the channel characteristics. This is the motivation for studying the performance of fountain codes in relay networks under different channel models.

All the aforementioned works have not taken into account nodes mobility that can affect the performance of the system in mobile ad hoc networks. In this paper, we investigate how fountain codes can help in information relaying in mobile relay networks. We propose fountain code based feedback and non-feedback protocols and study their performance in a mobile network over different fading channel.

In the feedback based protocol, the source node and relay nodes continue their transmissions to the destination until they receive the acknowledgment of a successful reception from the destination. In the non-feedback based protocol, the source autonomously generates a large number of duplicated symbols to make sure that all relay nodes can successfully decode the source information. After transmitting these symbols, source node ceases its transmission and relay nodes forward the received source information to the destination through different orthogonal channels.

The remainder of the paper is organized as follows. We first introduce the system model in section II. We then present our fountain coded cooperative communication protocols in Section III and decoding of Raptor code over wireless relay channel in Section IV. Section V presents the simulation results, followed by Section VI to conclude our paper.

II. SYSTEM MODEL

We consider a system model consisting of a source node s , a destination node d and R available relay nodes where

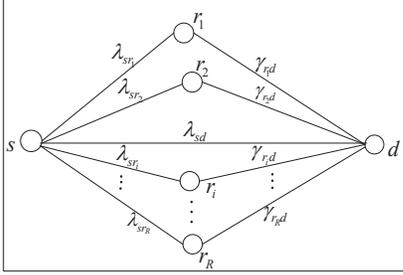


Fig. 1. System setup with source s , destination d , and R parallel relays. λ_{sr_i} denotes the channel gain from source to the i -th relay, $\gamma_{r_i d}$ denotes the channel gain from i -th relay to the destination and, λ_{sd} denotes the channel gain between source and destination.

relay nodes r_1, r_2, \dots, r_R assist s in passing its information to d . Without loss of generality, we assume that the index of the relay nodes indicates the quality of the received signal at the relays, i.e., r_1 and r_R denote the best relay and the worst relay respectively. We assume that the relay nodes and the destination node are mobile and their mobility is restricted within a small area.

We assume that all nodes are operated in half-duplex mode, i.e., they can either transmit and receive at a time and perfect channel state information (CSI) is only available at all the receivers. To transmit a k bit message to a destination node d , the source node s generates a large number of code streams using raptor code. The code stream is then modulated and sequentially transmitted to the destination. Relay nodes monitor source transmission and as soon as they decode the source information successfully they start to transmit the received information to the destination. The destination d keeps accumulating the mutual information from source and relays until it is capable to decode information successfully. Upon successful decoding, the destination acknowledges the relays and the source or the relays only depending different protocols with one bit through the feedback channel.

Most work on cooperative communications assume the allocation of orthogonal channels [12], [13], [14] to different terminals, i.e., inter-user orthogonality. On the other hand, our system is based on orthogonal channel allocation where the source transmits to the destination and relays in one channel and the relays transmit to the destination in other different orthogonal channels. Moreover, we assume that all the nodes use their own fountain coding routine to encode the data.

III. FOUNTAIN CODED COOPERATIVE PROTOCOLS

To improve the performance of mobile relay networks, we propose two fountain coded cooperative communication protocols, where source node and relay nodes use their own fountain routines to encode information and then transmit to the destination through different orthogonal channels. We assume that the decoder knows the encoding degree distribution of the received encoded symbols by an extra robust CDMA channel with long sequence length.

A. Feedback based protocol

In the first step of this protocol, a source encodes the information with a fountain code before transmission. Relay nodes listen to this transmission and forward the source information to the destination using their own fountain codes as soon as they have decoded the information. Both source and relays continue their transmissions until they receive an acknowledgment from the destination indicating that the reception has been successful. The protocol works as follows:

1. The source starts to transmit its encoded data targeting the destination and relays.
2. Both relays and destination node accumulate information from source transmission.
3. Since the source to relay link is superior to source to destination link, relays decode the information faster than the destination.
4. After successfully decoding the source information, relay nodes join the source to transmit to the destination. Each relay uses its own fountain encoding routine to encode information and then transmit to the destination through pre-allocated orthogonal channel.
5. The destination collects information from both source and relays and attempts to decode information once the accumulated mutual information is slightly greater than the source information. If the decoding is successful then it sends an acknowledgement to the source. Otherwise it collects more information. This procedure continues until the successful reception.

B. Non-feedback based protocol

In this protocol, source autonomously generates a large number of encoded symbols, hoping that the destination can successfully receive the information and feedback is not needed. The protocol works as follows:

1. Source observes the channel condition to the relays and generates a sufficient number of encoded packets so that even the worst relay can decode the source information successfully.
2. Source node transmits information on its allocated orthogonal channel targeting to the relays and destination node.
3. Relays and the destination d consistently receives signals from source transmission and accumulate the mutual information.
4. As soon as a relay node has sufficient information to decide on a codeword, it switches from reception mode to transmission mode. It encodes information using its own fountain encoding routine and transmit on the pre-allocated orthogonal channel.
5. We assume the destination d can only accumulate partial information from source transmission, which is not enough for successful decoding. It will rely on the relay nodes to collect the remaining information.
6. The destination d collects mutual information from relays and starts decoding when the accumulated mutual information is slightly greater than the source information. After successfully decoding of source information the destination sends a feedback to relays.

C. Transmission efficiency

In the following we evaluate the performance of these two protocols by considering the total amount of time required to recover the source information. Theoretically in rate less coded system, the probability of outage is always driven to zero as long as there is no constraint on decoding delay. Therefore, the primary metric of performance we use in our work is transmission efficiency rather than outage probability which is a common measure to evaluate the performance of cooperative communications.

Let n denote the number of time units required for the destination to discover k -bit source message. We assume one bit be transmitted in one time unit by a transmitter. The transmission efficiency is given by $R = k/n$. Since the data rates of source-relay link are greater than the source-destination rate, relay nodes can decode the source information faster than the destination. The source information is decoded at relay r_j once the accumulated information satisfies

$$\sum_{j=1}^{n_j^1} CH_{sr_j}[i] \geq k, \quad (1)$$

where n_j^1 is the required time for r_j to decode source information and $CH_{sr_j}[i]$ is the data rate between s and relay r_j at time instant i . The data rate of a wireless link ab can be given by

$$CH_{ab}[i] = \log_2(1 + \gamma_{ab}), \quad (2)$$

where $\gamma_{ab} = G_{ab}|H_{ab}|^2 \frac{E_s}{N_0}$ and G_{ab} and h_{ab} denote the path loss and channel coefficient of ab link respectively. In both protocols, as soon as the relay decodes source information it encodes the received information using fountain code and transmit on the pre-assigned orthogonal channel. In feedback protocol, the source node continues its transmission until the receiver successfully decodes the source information. Therefore, in this protocol the destination may reliably decode the source information when the accumulated information satisfies

$$\sum_{i=1}^n CH_{sd}[i] + \sum_{j=1}^R \sum_{i=n_j^1}^n CH_{r_jd}[i] \geq nR. \quad (3)$$

Let $\overline{C_m H_{ab}} = \frac{1}{m} \sum_{i=1}^m CH_{ab}[i]$ be the average rate for m period of time over the channel ab . Therefore Equation-3 yields

$$n \cdot \overline{C_n H_{sd}} + \sum_{j=1}^R (n - n_j^1) \overline{C_{n-n_j^1} H_{r_jd}} \geq nR. \quad (4)$$

The maximum transmission efficiency R is defined as

$$\overline{C_n H_{sd}} + \sum_{j=1}^R \left(1 - \frac{n_j^1}{n}\right) \overline{C_{n-n_j^1} H_{r_jd}} = R. \quad (5)$$

In rateless coded system the receiver attempts decoding as soon as the accumulated information is equal or slightly greater than the source information. Therefore, the maximum transmission efficiency R is achieved when source information is discovered at the first attempt of decoding. For simplicity we assume that the average time required to decode source information is the

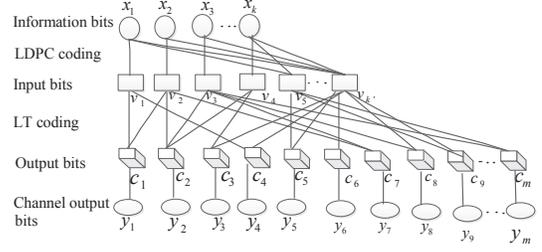


Fig. 2. Factor graph of Raptor codes. Input bits: LDPC codewords; Output bits: LT codewords

same for all relays. Let the decoding time in relay nodes be n^1 . So the transmission efficiency is

$$\overline{C_n H_{sd}} + (1 - f) \sum_{j=1}^R \overline{C_{n-n^1} H_{r_jd}} = R. \quad (6)$$

where $f = \frac{n^1}{n}$. Substituting $n^1 = \frac{k}{\overline{C_{n^1} H_{sr}}}$ in Equation-6 the decoding time n is

$$n = \frac{k \left(\overline{C_{n^1} H_{sr}} + \sum_{j=1}^R \overline{C_{n-n^1} H_{r_jd}} \right)}{\overline{C_{n^1} H_{sr}} \left(\overline{C_n H_{sd}} + \sum_{j=1}^R \overline{C_{n-n^1} H_{r_jd}} \right)}. \quad (7)$$

In non-feedback protocol the source node ceases its transmission after relay nodes successfully decode source information. The transmission efficiency of this protocol is

$$f \cdot \overline{C_{n^1} H_{sd}} + (1 - f) \sum_{j=1}^R \overline{C_{n-n^1} H_{r_jd}} = R. \quad (8)$$

and minimum required time to make the decoding successful is

$$n = \frac{k \left(\overline{C_{n^1} H_{sr}} + \sum_{j=1}^R \overline{C_{n-n^1} H_{r_jd}} - \overline{C_{n^1} H_{sd}} \right)}{\overline{C_{n^1} H_{sr}} \left(\sum_{j=1}^R \overline{C_{n-n^1} H_{r_jd}} \right)}. \quad (9)$$

IV. RAPTOR ENCODING AND DECODING

In our proposed relaying schemes, the source and relays employ a special class of fountain codes, namely Raptor codes. Raptor codes are universally capacity achieving over the binary erasure channel (BEC) [6] and nearly capacity-achieving over other channel models such as binary symmetric channels (BSC), AWGN and fading channels [8], [18], [19]. The LDPC code encodes k bit message $\{x = x_1, x_2, \dots, x_k\}$ into k' bit message $\{v = v_1, v_2, \dots, v_{k'}\}$ and the LT encoder then encodes the vector $\{v = v_1, v_2, \dots, v_{k'}\}$ to an infinite binary sequence $\{c_1, c_2, \dots, c_m\}$. We use a Raptor code construction with $k = 9,500$, $k' = 10,000$ where the outer LDPC code has 4-regular left-degree distribution and Poisson right-degree distribution. The LT code of our Raptor code has a degree

distribution in BEC channel as Equation-10, and a degree distribution in AWGN and other noisy channels as Equation-11.

$$\Omega_{BEC}(x) = 0.008x + 0.49x^2 + 0.166x^3 + 0.073x^4 + 0.083^5 + 0.056x^8 + 0.037x^9 + 0.056x^{13} + 0.025x^{65} + 0.003x^{66}. \quad (10)$$

$$\Omega(x) = 0.006x + 0.492x^2 + 0.03396x^3 + 0.2403^4 + 0.006^5 + 0.096x^8 + 0.049x^{14} + 0.018x^{30} + 0.0356x^{33} + 0.033x^{200}. \quad (11)$$

As mentioned before, the degree of the encoded information is transmitted to the destination by an extra robust CDMA channel with long sequence length. To use identical random-number generator both in encoder and decoder as used in [9], it needs strict synchronization that increases the complexity in multiple relay networks. The receiver collects information progressively until the received accumulated information is slightly greater than the source information k . The first decoding attempt is accomplished at time $t_1 = \frac{k}{C}$ where C is the achievable end-to-end data rate of the relay network. If the decoded information is erroneous, another decoding attempt is made after a new batch of symbols has been received. The number of received symbol at l^{th} decoding attempt is

$$m_l = t_1 C + (l - 1)t_{inc} C, \quad (12)$$

where t_{inc} is the time difference between two decoding attempts.

The decoding of Raptor codes could be accomplished using Belief Propagation (BP) algorithm and Gaussian Elimination (GE) algorithm over BEC channel. The decoding graph of raptor is a factor graph that is truncated to length m as shown in Fig.2 where $\{y = y_1, y_2, \dots, y_m\}$ corresponds to transmitted codeword $\{c_1, c_2, \dots, c_m\}$. The receiver attempts decoding at a prescribed set of times $\{t_1, t_2, \dots\}$ where $t_1 < t_2 < \dots$. In GE decoding method, at the l^{th} decoding attempt, the receiver performs GE on m_l output symbols. Each received output symbols represents a linear equation of unknown values $\{x = x_1, x_2, \dots, x_k\}$. Thus x can be decoded if the system $[G_{ldpc} G_{m_l}]x = y$ is solved where $[G_{ldpc}]$ and G_{m_l} are the generator matrix of LDPC code and LT code respectively.

In noisy channel, the decoding of raptor code is accomplished using the standard BP algorithm on factor graph G_m . At the l^{th} decoding attempt, it performs BP decoding on factor graph G_{m_l} by iteratively passing the LLR (log-likelihood ratio) messages from input bits to output bits, and then from output bits back to input bits. Let $\mu_{c_o, v_i}^{j,l}$ and $\nu_{v_i, c_o}^{j,l}$ denote the message passed from the output bit c_o to the input bit v_i and input bit v_i to the output bit c_o respectively at the j^{th} iteration of l^{th} decoding attempt. In every iteration, the following message update rules are applied in parallel to all input and output nodes in the factor graph

$$\tanh \frac{\mu_{c_o, v_i}^{(j,l)}}{2} = \tanh \frac{(Z_{c_o})}{2} \prod_{i' \neq i} \tanh \frac{\nu_{v_i, c_o}^{j,l}}{2}, \quad (13)$$

$$\nu_{v_i, c_o}^{(j+1,l)} = \sum_{o' \neq o} \mu_{c_{o'}, v_i}^{(j,l)}, \quad (14)$$

where Z_{c_o} is log-likelihood ratios (LLR) of the output bit c_o that is calculated based on the channel observation and knowledge of the CSI at the receiver. We use binary phase shift keying (BPSK) as modulation scheme and assume that the transmitted codeword $c_o \in 0, 1$ is equal probability. Therefore the channel log likelihood ratio corresponding to the output node c_o in the AWGN channel can be expressed as

$$Z_{c_o} = \log \frac{pr(y_o | c_o = 0)}{pr(y_o | c_o = 1)} = \frac{2}{\sigma^2} y_o, \quad (15)$$

where $\sigma^2 = \frac{E_b}{N_o}$ and y_o is the noisy observation of the channel. In Rayleigh fading channel the channel intrinsic log likelihood information while channel state information is available at the receiver is given by

$$Z_{c_o} = \log \frac{pr(y_o | c_o = 0)}{pr(y_o | c_o = 1)} = \frac{2}{\sigma^2} y_o \cdot a, \quad (16)$$

where a is the normalized Rayleigh fading factor with $E[a^2] = 1$ and density function $f(a) = 2a \exp(-a^2)$. Similarly in Rician fading channel $Z_{c_o} = \frac{2}{\sigma^2} y_o \cdot a$ with $f(a) = 2a(1 + \zeta) \exp(a^2(1 + \zeta) - \zeta) I_0(2a\sqrt{\zeta(1 + \zeta)})$ where I_0 and ζ denote the modified Bessel function of order zero and Rice factor respectively. The Rice factor $\zeta = \frac{\vartheta^2}{2\omega^2}$ is the relation between the power of the LOS component ϑ , and the power of the Rayleigh component ω . In the end of l^{th} decoding attempt, if the decoder is confident that the transmitted message is decoded, it sends an ACK through a noiseless feedback channel to terminate the transmission of the current code word. Otherwise it collects another set of output symbols and initiates next decoding attempt to decode again.

V. SIMULATION RESULT

In this section, we conduct simulations to investigate the performance of fountain coded cooperative protocols in a mobile relay network. Our simulation model consists of a source destination pair with R relay nodes where relay nodes are randomly placed in the area $-1 < x < 1, -0.5 < y < 0.5$ (see Fig. 3). The source is placed at (-1,0) and the destination is at (1,0). The mobility of the nodes are adjusted in such a way so that they do not exit the simulation area. We

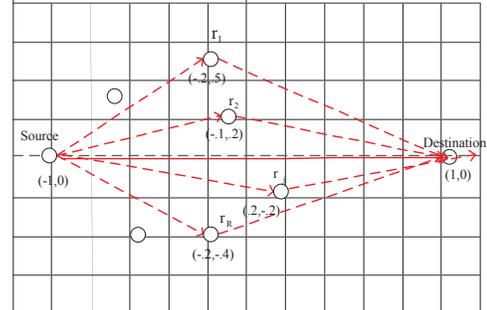


Fig. 3. Simulation model

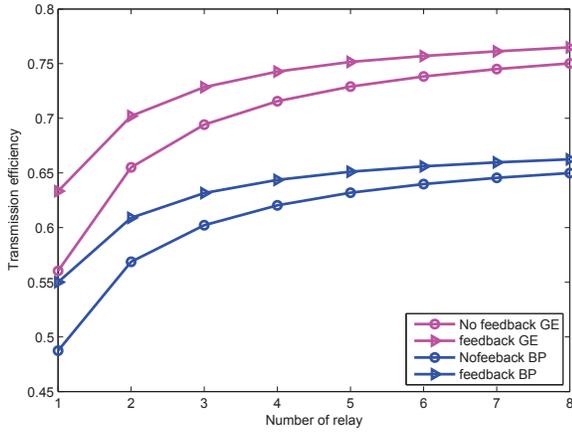


Fig. 4. Transmission efficiency vs number of relay in BEC

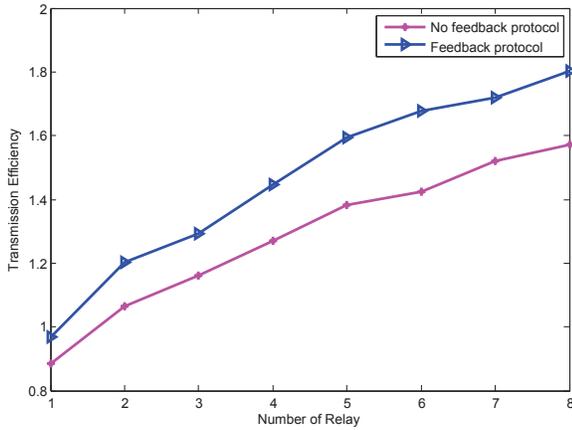


Fig. 5. Transmission efficiency vs number of relay in AWGN channel

employ Brownian motion model [17] to change the position of the nodes. The position update equation: $\text{New_Position} = \text{old_Position} + \text{Random_Movement}$ is used for updating the position of the nodes. The performance study focuses on the cooperative communication protocols in different channel models.

Fig.4 demonstrate the transmission efficiency from different number of relay nodes in BEC channel. The erasure probability of source destination link is considered as 0.5. To determine the erasure probability of each link, the distance between source and destination is considered as a reference. It is observed in Fig.4 that the feedback based protocol outperforms the non-feedback based protocol. The reason is that in the feedback based protocol relays and source continue their transmission until the destination sends back an acknowledgment whereas in the non-feedback protocol, the source has no information on the reception of the destination. The transmission efficiency is always improved with a higher number of participating relay nodes with the cost of signaling overhead and higher power consumption.

Moreover, the adopted decoding method also significantly affects the performance of the protocols. As shown in Fig.4, the decoding based on Gaussian Elimination method performs better than the BP decoding method.

Fig.5 presents transmission efficiency from different num-

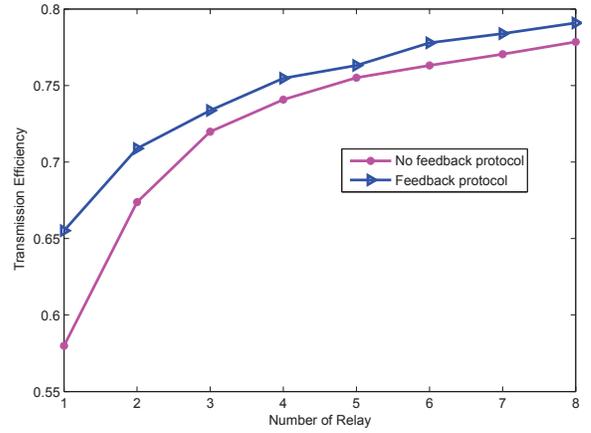


Fig. 6. Transmission efficiency vs number of relay in Rayleigh channel

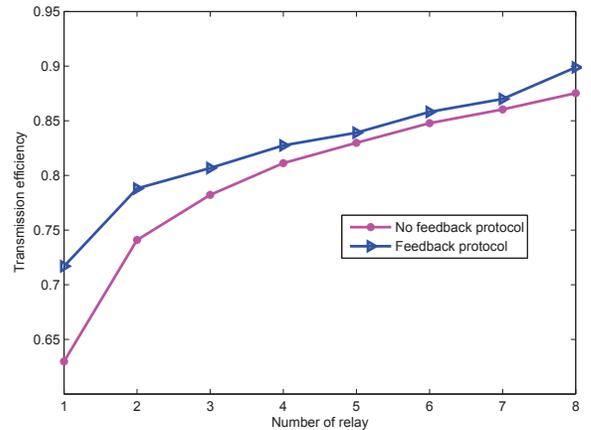


Fig. 7. Transmission efficiency vs number of relay in Rician channel

ber of relay in AWGN channel. In noisy channel the path gains of each link is determined by distance law $10d^{-4}$. The bit error rate 10^{-4} is considered as the threshold of successful decoding. Here also, the feedback protocol shows better performance than the non-feedback protocol in terms of transmission efficiency.

The performance of fountain code in Rayleigh and Rician fading channel is presented in Fig.6 and Fig.7. In Rician channel the rice factor $\zeta = 1$ is considered. It is shown that the feedback protocol outperforms its non feedback counterpart in terms of transmission efficiency in both of these channels.

VI. CONCLUSION

This paper investigates the performance of fountain codes for cooperative communications over mobile relay networks. We developed both feedback-based and non-feedback based protocols to improve the data transmission between two wireless terminals, and then studied their performance with different channel models. Simulation results demonstrate that the feedback based protocol outperforms non-feedback one in terms of transmission efficiency over not only the BEC, but also the AWGN, Rayleigh and Rician fading channels. It is also shown that the achievable transmission efficiency is above 78% in noisy channels, where the use of rateless codes appears

more practical. Moreover, regardless of the protocols used, the transmission efficiency can always be improved by involving more relay nodes for cooperation, at the costs of additional signaling overhead.

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