Performance of Fountain Codes over Wireless Mobile Relay Network

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Abstract: Cooperative communications, where parallel relays forward information to a destination node, can effectively improve the latency in 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. It is observed that the number of total relay nodes plays a significant role on the performance improvement. Simulation results justify that the proposed feedback based protocol always outperforms its non-feedback counterpart in a variety of metrics.

Key–Words: ad hoc networks, cooperative communications, fountain codes, relay.

1 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 unconscious of channel state information (CSI) can generates 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.

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 relay networks with limited mobility. The mobility is limited in the sense that the movement of the nodes occurs only over short distances. We propose fountain code based feedback and non-feedback protocols and study their performance in a mobile network over Rayleigh 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 receiving acknowledgements of successful reception from all relay nodes, 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 transmission efficiency of these protocols is analyzed in Section IV. Section V presents the simulation results, followed by Section VI to conclude our paper.

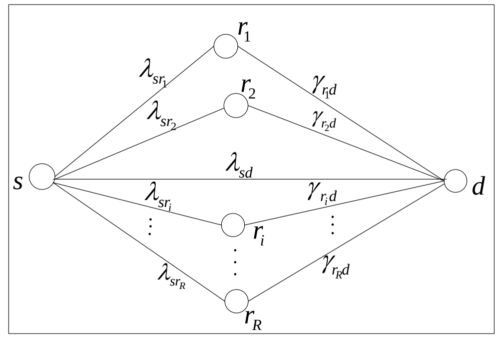

Figure 1: System setup with source s, destination d, and R parallel relays. λ_{sr_i} denotes the channel gain from source to the i-th relay, γ_{r_id} denotes the channel gain from i-th relay to the destination and, λ_{sd} denotes the channel gain between source and destination.

1.1 System Model

We consider a system model consisting of a source node s, a destination node d and R available relay nodes where relay nodes $r_1, r_2.......r_R$ assist s in passing its information to d as shown in Fig.1. 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.

2 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.

2.1 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

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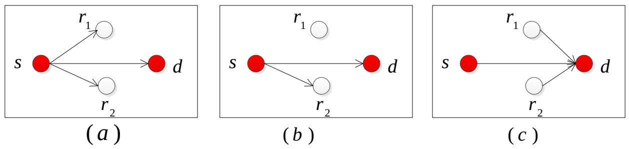

Figure 2: Feedback based data transmission protocol:(a)No relay has decoded the source information. (b)Relay r_2 has decoded source information. (c) Two relays have decoded source information.

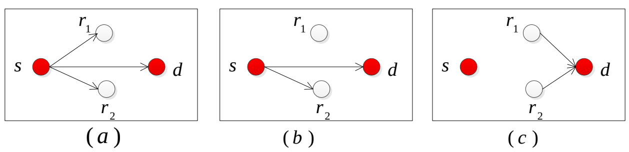

Figure 3: Non-feedback based data transmission protocol:(a)No relay has decoded the source information. (b)Relay r_2 has decoded source information. (c)Two relays have decoded source information and source has terminated its transmission.

from the destination indicating that the reception has been successful. The protocol is presented in Fig 2. and 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.

2.2 Non-feedback Based Protocol

In the first step, the source transmits the data stream encoded by a fountain code. The various relay nodes listen to the source data; as soon as they have acquired sufficient information to decode source data, they transmit an acknowledgment to the source that their reception was successful and at the same time, the relay nodes switch from reception to transmission. Once the source has received acknowledgments from all of the relay nodes, it ceases its transmission hoping that the destination can successfully receive the remaining information from relays and feedback is not required as shown in Fig. 3. The protocol works as follows:

1. Source generates a large number of encoded symbols and transmit its encoded data targeting the destination and relays.

2. Relays and the destination d consistently receives signals from source transmission and accumulate the mutual information.

3. As soon as a relay node has sufficient information to decide on a codeword, it sends acknowledgement to the source and switches from reception mode to transmission mode. It encodes information using its own fountain encoding routine and transmit on the pre-allocated orthogonal channel.

4. As soon as source receives acknowledgement from all relay nodes it ceases its transmission. By this time if the destination d can not accumulate enough partial information from source transmission it depends on the relay nodes to collects the remaining information.

5. The destination d collects mutual information form 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.

3 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.

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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 $\zeta = k/n$. 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

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

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

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

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

$$\sum_{i=1}^{n} CH_{sd}[i] + \sum_{j=1}^{R} \sum_{i=n_j^1}^{n} CH_{r_jd}[i] \geq n\zeta. \tag{3}$$

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

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

The maximum transmission efficiency R is defined as

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

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

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

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

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

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

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

and minimum required time to make the decoding successful is

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

4 Simulation Results

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 $-1 < x < 1$, $-.5 < y < .5$ (see Fig.4). 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 employ Brownian motion model [15] to change the

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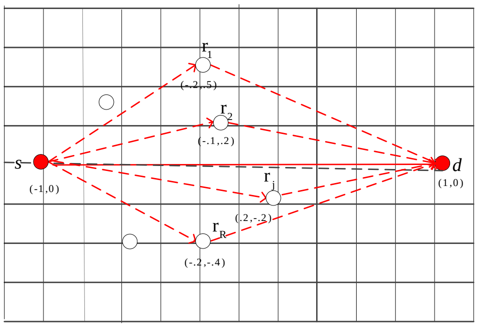

Figure 4: Simulation model

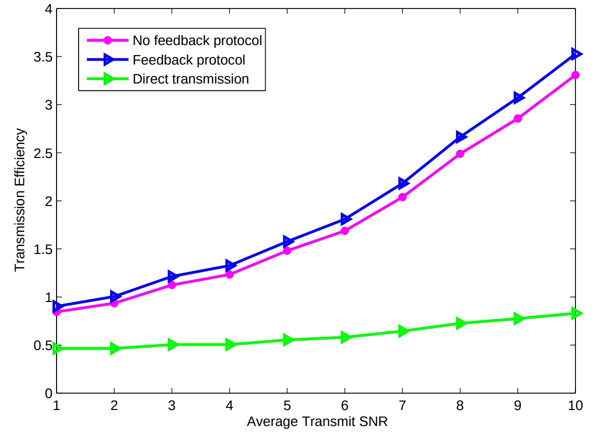

Figure 5: Transmission efficiency vs average transmit SNR in Rayleigh channel

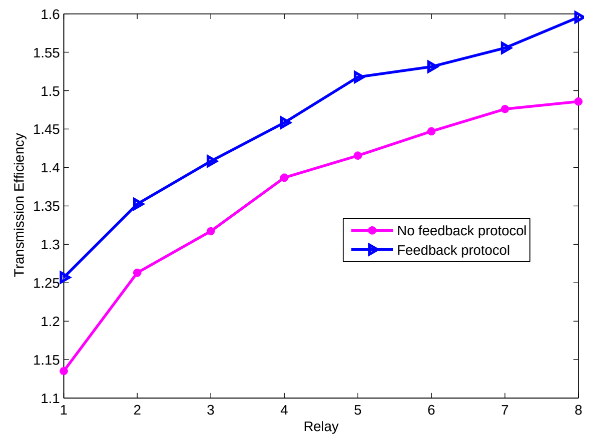

Figure 6: Transmission efficiency vs number of relay in Rayleigh channel

position of the nodes. The position update equation: New_Position = old_Position + Random_Movement is used for updating the position of the nodes. The performance study focuses on the cooperative communication protocols in different channel models.

In our proposed relaying schemes, the source and relays employ a special class of fountain codes, namely Raptor codes. At first the LDPC code encodes k bit message $\{x = x_1, x_2, ...x_k\}$ into k' bit message $\{v = v_1, v_2, ...v_{k'}\}$ and the LT encoder then encodes the vector $\{v = v_1, v_2, ...v_{k'}\}$ to an infinite binary sequence$\{c_1, c_2, ...c_m\}$. 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 the following degree distribution as Equation-11.

$$\Omega(x) = 0.006x + 0.492x^2 + 0.03396x^3 + 0.2403^4 + 0.006^5 + 0.096x^8 + 0.049x^{14} + 0.018x^{30} + 0.0356x^{33} + 0.033x^{200}. \quad (10)$$

The performance study focuses on the cooperative communication protocols. The channel between relay and destination considers Rayleigh fading.

Fig. 5 presents transmission efficiency vs average transmit snr in Rayleigh channel. Without loss of generality, we assume a unit path loss between source and destination , i.e., $G_{s,d} = 1$. We then have $Gs, r_i = d_{s,d}/d_{s,r_i}$ and $G_{r_i,d} = d_{s,d}/d_{r_i,d}$ where d_{s,r_i} and $d_{r_i,d}$ are the distance of source and destination form relay node r_i respectively.The bit error rate 10^-4 is considered as the threshold of successful decoding. It is shown that both feedback and non-feedback protocols outperform the direct transmission. Moreover the performance of feedback protocol is better than the non-feedback 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.

Fig. 6 presents transmission efficiency vs number of relay nodes at fixed transmit SNR $5dB$. It is observed that transmission efficiency is always improved with the involvement of more relay nodes.

5 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

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transmission between two wireless terminals, and then studied their performance in Rayleigh fading channel. Simulation results demonstrate that the feedback based protocol outperforms non-feedback one in terms of transmission efficiency. 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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