Cooperative Communications for Reliable Data Transport with Fountain Codes

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***Abstract*—Providing efficient and reliable data transport is a challenging problem for a variety of emerging applications which require reliable data packet delivery in wireless networks. In this paper, we propose to incorporate fountain codes at transport layer in the notion of cooperative relay communications to provide reliability and robustness for data transmission in wireless networks. Our basic idea is to exploit the joint merits of fountain codes and cooperative relay communications. We first derive the achievable rate of cooperative communications with fountain codes based on a general 3-node relay model and find that substantial improvement can be achieved compared with direct transmission and conventional AF and DF relay approaches. Inspired by this finding, we develop two cooperative communication strategies and analyze their performance. Numerical results show that our proposed approaches can achieve significant performance improvement in terms of data transport efficiency. In addition, the proposed approaches exhibit strong robustness to packet losses on wireless links for data transfer.**

***Index Terms*—fountain codes, cooperative relay, robustness, transmission efficiency**

I. Introduction

Wireless data access for nomadic users is a key enabling service for the wireless networks, ranging from third-/fourth-generation (3G/4G) cellular radio systems to wireless local area networks (WLANs). One major challenge in deploying this growing service is to provide reliable and robust high-rate data delivery in the system. For example, 3GPP LTE and LTE Advanced[11] suggest four classes of applications, of which "background" applications including file transfer and email download, normally require reliable data transport but are not highly sensitive to inter-packet jitter and can also tolerate a high round-trip time (RTT). For such applications, the main performance goal is high reliability and transmission efficiency in data transport.

Efficient reliable data transport services has been hindered by low quality and frequent service disruptions on wireless links, which tend to be unreliable due to factors such as interference, attenuation, and fading [10]. Additionally, link quality is marked by significant variability due to user mobility and changes in the environment. Previous protocols for reliable data communication have tried to use two approaches to recover from corrupted packets, namely, ARQ based packet transport and forward error correction (FEC). Both approaches are sensitive to link quality. When links are poor, packet retransmissions are expensive since the resource consumed on a failed transmission is completely wasted. Receiver needs to send ACK or NAK feedbacks to source in the retransmission mechanisms. In addition, the packets loss probability is usually high when the wireless link is poor. This causes frequent ACK or NAK feedback exchanging between the sender and the mobile user as the receiver, and thus incurs high communication overhead. Similarly, FEC could be also expensive since it must be designed for the worst case if channel conditions change frequently. Despite that the recent progress in wireless transmission technology, such as OFDM, MIMO and space-time coding, has effectively improved the error performance and channel capacity at physical and MAC layer, it is still imperative to design transport protocols to achieve reliable data transport and high transmission efficiency, in response to the challenges posed by a variety of emerging data access applications in wireless networks.

Recently, a very promising class of approaches has been proposed to exploit the broadcast nature of wireless communication and spatial diversity to improve the error performance, transmission efficiency and robustness. The concept of cooperative communication (relay) belongs to this class and has received considerable research attentions in academy, industry, and standard organizations[1]. Cooperation communication makes use of a new form of spatial-temporal diversity, namely co-operative diversity, which is formed by exploiting the single antenna devices within the close vicinity in combination with employing distributed channel coding schemes. Recent research has shown that cooperative communication is able to achieve significant improvement in error performance and transmission efficiency in wireless networks. In parallel with the development of cooperative communications, in recent years, fountain code has been intensively investigated as an excellent solution in a wide variety of situations, especially in data communications [3-6]. The idea of fountain codes can be summarized as follows. Each data block is fragmented into m fragments. From these m fragments, r other redundancy fragments are computed. From these $m + r$ fragments, any m fragments are sufficient to rebuild the original data block. Therefore, in reliable data transmission, source keeps sending coded packets until receiver receives sufficient coded packets to

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reconstruct the original packets. Due to the elegant features of fountain code, it has been well explored and implemented in communication systems.

Taking inspiration from the merits of cooperative communications and fountain codes, in this paper we propose to use fountain coding at transport layer in the notion of cooperative communications. Our basic idea is to exploit the temporal diversity in cooperative relay and the capability of fountain codes. We expect that the combination of the two techniques can potentially improve the transmission efficiency and robustness of data transport in wireless networks.

Although the theoretic capacity for conventional relay communications including AF, DF, has been carefully studied [13], a key question still remains: what theoretical capacity gain can be achieved by using cooperative relay with fountain codes? The answer to this question is of vital importance for the motivation of the development and deployment of cooperative relay schemes using fountain codes. In this paper, we first take steps to obtain a fundamental understanding of the achievable rate of cooperative relay with fountain codes. In particular, we consider a general three-node relay channel model and a general cooperative communication approach, called Fountain Coding and Forward (FCF). We compare the theoretical achievable rate of FCF with that of AF and DF, and numerical results show that the achievable rate of FCF is considerable higher than that of AF, DF and conventional direct transmission, even up to quite high SNR. The significance of this result lies at the insight into the potential transmission rate gain of cooperative relay using fountain codes. Motivated by this result, we further develop two cooperative relay strategies inherently working in conjunction with fountain codes. In Strategy 1, both source and relay nodes use transport layer fountain codes to ensure reliable data transport, while in Strategy 2 the source node employs transport layer fountain codes but relay node uses traditional ARQ-like mechanism to ensure reliable data transport. Strategy 1 has a very simple transmission mechanism while Strategy 2 has a higher source transmission efficiency. Compared with traditional ARQ-like mechanisms, our proposed approaches can provide higher transmission efficiency and robustness for reliable data transport. We mathematically analyze the performance of the proposed cooperative relay strategies based on a general 3-node relay model. Numerical results show that source node in cooperative mode has higher transmission efficiency than non-cooperative transmission mode. In addition, as our proposed strategy is not sensitive to the bit error (and thus packet loss) pattern due to the features of fountain codes.

To the best of our knowledge, there is only very little existing work on cooperative communication by exploiting fountain coding. Molisch et al. uses fountain coding to provide "energy accumulation" in multi-relay nodes system [6]. The receiver can recover original data as long as the total receive energy exceeds a certain threshold. In [7], the authors use fountain coding in three nodes cooperative relay networks to provide reliable data transmission. But the focus is using fountain coding at physic layer. Our idea in this paper is different in that we introduce fountain codes at transport layer into the notion of cooperative communications, with design goal of providing an efficient yet simple mechanism for reliable data transport.

The rest of the paper is structured as follows. Section II presents the system model. We derive the achievable rate of FCF and compare it with that of AF and DF in Section III. We propose a cooperative relay strategy in Section IV. We present the performance analysis In Section V, followed by the numerical results as well as discussions in Section VI. We finally conclude the paper in Section VII.

II. SYSTEM MODEL

We consider a three nodes relay model, as shown in Fig.1, where source node, relay node, and destination node are denoted by S, R, and D, respectively. The desired transmission is from S to D, while the relay node R aids the communication by using its "capture" of the transmission between S and D due to broadcast nature of wireless communication. We attention that D cannot simultaneously receive signals from S and R in the same frequency band. Therefore, S and R need to use orthogonal channels to communication with D. In this paper, we use time division orthogonal channels. R works in half duplex mode.

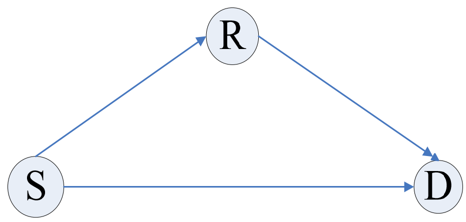


Fig.1 three-node relay model

We assume that the channels between the nodes are modeled as independent slow fading channels which can be deemed as quasi-static [14]. Therefore, as shown in [17], we can employ h_{ij} to denote the shadowing and fading of channels between S, R and D, where $i \in \{S, R\}$ and $j \in \{R, D\}$. When node *i* sends a signal x, node *j* receives it as

$$y_{ij} = h_{ij} x + z_{ij} \tag{1}$$

Where y_{ij} denotes the received signal at node *j*. z_{ij} is the zero-mean channel noise of channel from i to j, with variance σ_{ij}^2. Therefore, we can obtain the Signal to Noise Ratio (SNR) at receiver j which is denoted by γ_{ij} as

$$\gamma_{ij} = \frac{P_i}{\sigma_{ij}^2} \left| h_{ij}^2 \right| \tag{2}$$

Where P_i is the transmission power at node *i*. We assume the nodes have enough power to complete transmission. Without loss of generality, we assume the bandwidth of the three wireless channels is unified as one unit. Let the

SNR of signals which are transmitted from S to D, S to R and R to D be denoted by γ_{sd}, γ_{sr} and γ_{rd}, respectively. Using Shannon formula, the transmission capacity of three wireless channels are given by

$$C_{sd} = \log_2(1+\gamma_{sd}) \tag{3}$$

$$C_{sr} = \log_2(1+\gamma_{sr}) \tag{4}$$

$$C_{rd} = \log_2(1+\gamma_{rd}) \tag{5}$$

where C_{sd}, C_{sr} and C_{rd} denote the transmission capacity of channel S to D, S to R and R to D, respectively.

III. ACHIEVABLE RATE OF COOPERATIVE RELAY COMMUNICATIONS

In this section, we analyze the achievable rate of FCF relay strategy. For comparison purpose, we give the achievable rate of AF, DF first.

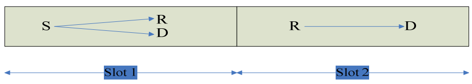


Fig.2 Transmission process in AF and DF

A. AF relay

In AF relay, the transmission process is composed by two time slots with equivalent length. As shown in Fig.2, S transmits data to D in the first slot and R can overhear it. In the second time slot, R amplifies the data which is received in the first slot and forwards it to D. D can combine the data signals which are received in two slots by employing maximum ratio combiner. The achievable transmission rate of AF relay strategy is [13]

$$C_{af} = \frac{1}{2}\cdot\log_2(1+\gamma_{sd}+\frac{\gamma_{sr}\cdot\gamma_{rd}}{\gamma_{rd}+\gamma_{sr}+1}) \tag{6}$$

B. DF relay

The transmission process of DF relay is similar to that of AF relay, as shown in Fig. 2. The only difference between AF and DF is that R decodes the received data instead of simply amplifying it before forwarding the data to D in slot 2. The achievable transmission rate of DF relay strategy is given by [13]

$$C_{df} = \frac{1}{2}\cdot\min\{\log_2(1+\gamma_{sr}),\log_2(1+\gamma_{rd}+\gamma_{sd})\} \tag{7}$$

C. FCF relay

In FCF relay, we employ fountain codes to encode the information which is transmitted at S and R. The receiver can recover the original data if the received information of the code-stream exceeds a certain threshold equal to the amount of information of original data [15], [16]. We use T to denote the value of the threshold.

The transmission process of FCF relay strategy can be described as follows. Referring to Fig.2, in the first slot, S sends coded information to D. R overhears the information. If $\gamma_{sr} > \gamma_{sd}$, which means the quality of link S to R is better than that of link S to D, R receives T amount of information to recover the original data before D dose at the end of slot one. On the other hand, if $\gamma_{rd} > \gamma_{sd}$, which means the quality of link R to D is better than that of link S to D, R replaces S to send coded information to D. D collects T amount of coded information in two slots to recover the original data.

Whether R is able to assist S in the information transmission to D is subject to two conditions $\gamma_{sr} > \gamma_{sd}$ and $\gamma_{rd} > \gamma_{sd}$. If $\gamma_{sr} > \gamma_{sd}$ is not true, D receives T amount of coded information before R dose at the end of slot one and slot two is unnecessary. If $\gamma_{rd} > \gamma_{sd}$ is not true, the transmission rate of direct channel is greater than that of channel R to D. S is unnecessary to cooperate with R. Therefore, if either of the two conditions does not hold, S transmits coded information to D directly without the help of R and the achievable transmission rate of system equals to C_{sd}, which is given in (3).

If $\gamma_{sr} > \gamma_{sd}$ and $\gamma_{rd} > \gamma_{sd}$, the transmission process contains two slots and D receives T amount of coded information from either S or R at the end of the transmission process. The transmission rate is defined by the amount of information which is successfully transmitted from S to D in unit bandwidth and unit time. Therefore, we gain the achievable transmission rate of FCF relay strategy as

$$C_{fcf} = \frac{T}{t1+t2} \tag{8}$$

where $t1$ and $t2$ denote the length of the first and second time slots respectively in the transmission process.

In the first slot, R receives T amount of information from S. Therefore, $t1$ is given by

$$t1 = \frac{T}{C_{sr}} = \frac{T}{\log_2(1+\gamma_{sr})} \tag{9}$$

where C_{sr} is the transmission capacity given in (4).

In the second slot, R replaces S to send coded information to D. $t2$ can be computed as

$$t2 = \frac{T - C_{sd}\cdot t1}{C_{rd}} = \frac{T\cdot(\log_2(1+\gamma_{sr})-\log_2(1+\gamma_{sd}))}{\log_2(1+\gamma_{sr})\cdot\log_2(1+\gamma_{rd})} \tag{10}$$

where C_{sd} and C_{rd} are the transmission capacity given in (3) and (5) respectively.

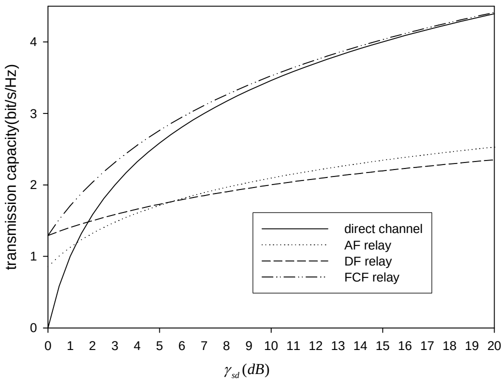
Substituting (9) and (10) into (8), for $\gamma_{sr} > \gamma_{sd}$ and $\gamma_{rd} > \gamma_{sd}$, we have

$$C_{fcf} = \frac{\log_2(1+\gamma_{sr})\cdot\log_2(1+\gamma_{rd})}{\log_2(1+\gamma_{sr})+\log_2(1+\gamma_{rd})-\log_2(1+\gamma_{sd})} \tag{11}$$

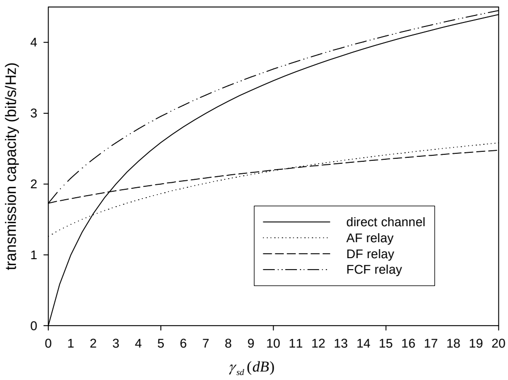
Therefore, we can obtain the achievable transmission rate of FCF relay strategy as

$$C_{fcf} = \begin{cases} \dfrac{\log_2(1+\gamma_{sr})\cdot\log_2(1+\gamma_{rd})}{\log_2(1+\gamma_{sr})+\log_2(1+\gamma_{rd})-\log_2(1+\gamma_{sd})} & \gamma_{sr} > \gamma_{sd},\ \gamma_{rd} > \gamma_{sd} \\ \log_2(1+\gamma_{sd}) & \textit{otherwise} \end{cases} \tag{12}$$

Based on above derivations, we present the numerical results of the achievable transmission rate for AF, DF and FCF relay strategies and compare them to that of direct channel transmission (without relay cooperation). We assume γ_{sr} and γ_{rd} are equal and both of them are greater than γ_{sd} .



a) $\gamma_{sr} = \gamma_{rd} = \gamma_{sd} + 5dB$



b) $\gamma_{sr} = \gamma_{rd} = \gamma_{sd} + 10dB$

Fig.3. achievable transmission rate of different strategies.

Fig.3.a and Fig.3.b show the achievable transmission rate of AF, DF, FCF and direct transmission under the condition that γ_{sr} (or γ_{rd}) is 5dB or 10dB greater than γ_{sd} . We can observe that FCF has the highest achievable rate. When γ_{sd} is small, AF and DF can provide cooperative diversity gain compared with direct transmission. However, when γ_{sd} increases, say greater than 1dB for case a) and 1.5dB for case b) of AF and greater than 1.5 dB for case a) and 2.5dB for case b) of DF, the achievable rate of AF and DF is even worse than direct transmission. This is because that R must use the channel which is orthogonal to direct channel to send information to D. This halves the system transmission bandwidth. It indicates that AF and DF are only appropriate for the case that SNR of direct link is small and the quality of links S to R and R to D is better than that of the direct link. For example, AF and DF can be used at the edge of a cell to improve the transmission rate. This result is known and well understood. However, the achievable rate of FCF is always higher than that of AF, DF and direct transmission. The difference between the achievable rate of FCF and direct transmission is more significant when γ_{sd} is small. When γ_{sd} increases, the difference between the achievable rate of FCF and that of AF and DF becomes greater and more significant.

Next, let us discuss how fountain codes improve the rate of cooperative systems. In general cooperative systems, such as AF and DF, R relays the "captured" signal from S to D. D combines the two signals which are received respectively from S and R to improve the SNR of received signal by exploiting the channel diversity. Nevertheless, as mentioned above, R must use the channel which is orthogonal to direct channel to send information to D, which halves the system transmission bandwidth. Therefore, AF and DF are only appropriate for the case that SNR of direct link is low and the quality of links S to R and R to D is better than that of the direct link. On the other hand, in FCF relay strategy, the two code streams which are sent from R and S are independent, although they are encoded from the same original information. D can accumulate the coded information from S and R. In addition, the durations of $t1$ and $t2$ can be adjusted according to channel states in FCF. In this way, FCF can achieve better bandwidth efficiency compared to AF and DF. Due to aforementioned two reasons, FCF can achieve higher transmission rate compared to AF and DF.

IV. Two Cooperative Relay Strategies by Using Foutain Codes

In this section, addition to analysis the achievable transmission rate of cooperative relay system, we propose two cooperative relay strategies to support reliable and robust data transport in wireless networks by applying fountain codes at transport layer. We assume that the channels between the nodes are modeled as discrete memoryless erasure channels. Packets delivered through the erasure channel are received by a receiver without error or are erased with a specific probability. Let the erasure probabilities on links S to D, S to R, and R to D be denoted by p_{sd} , p_{sr} , and p_{rd} respectively.

We consider that a data block is to be delivered from S to D. Let the data block be segmented into *m* packets and we use fountain coding technique to reliably transfer these *m* packets from S to D, where R may relay signals to D after overhearing signals transmitted from S. The receiver can recover the original data as soon as receive m coded packets.

By using fountain codes at transport layer, we design two cooperative relay strategies as follows.

Strategy 1

In this strategy, R replaces S to send packets to D if R first receives *m* coded packets. Data delivery is successful when D receives *m* coded packets in total from both S and R. Receiver notifies the sender via feedback channel whenever it is able to reconstruct the *m* original packets. The details of this strategy can be described as follows

1. S encodes the *m* original packets and sends the coded packets to D. R also overhears the transmission due to the broadcast nature of wireless communication.

2. If D receives *m* coded packets earlier and reconstructs the *m* original packets, it sends a feedback to S. S stops sending upon receiving the feedback. The data delivery is successful and the algorithm ends.
3. If R receives *m* coded packets earlier and reconstructs the *m* original packets, it also sends a feedback to S and S stops sending.
4. R re-codes the *m* original packets and sends the coded packets to D.
5. D sends a feedback to R when it successfully receives *m* coded packets from both S and R. R stops sending upon receiving the feedback from D. Thus, D can reconstruct the *m* original packets. The algorithm ends.

In this relay strategy, the relay node needs to perform coding. In the following, we present a simpler relay strategy.

Strategy 2

Based on the similar idea of Strategy 1, we further develop a simpler relay strategy. We claim that this strategy is simpler than strategy 1 according to the coding complication. In this strategy, the relay node does not need to perform coding as it dose in strategy 1. As shown in Fig.4, R and D are deemed as one “virtual” receiver denoted by R1, when S sends packets. A packet loss perceived by R1 implies that both R and D lose it. When a packet is received by either R or D, it is deemed that R1 receives the packet. S keeps sending until R1 receives *m* coded packets. Then, R sends the packets that D has not received from S. By successfully receiving all the packets R sends, D eventually receives *m* coded packets from both R and D. The details of this strategy are described as follows.

1. S encodes the *m* original packets and transmits the coded packets to R1.
2. D sends a feedback to R when it receives a coded packet. The feedback indicates which packet D has received. R notifies S when R1 receives *m* coded packets, and S stops sending. If D receives *m* coded packets, it can reconstruct the *m* original packets and the data delivery is successful.
3. If the number of coded packets that D receives is less than *m*, R sends to D those coded packets which have been received by R but missed by D.
4. When the total number of coded packets received by D from either S or R is *m*, D can reconstruct the original *m* packets. The algorithm ends.

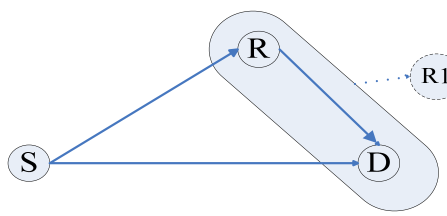


Fig.4 illustration of Strategy 2

Note that in this algorithm, R and D may receive some identical coded packets. But the reconstruction of the original data needs *m* different coded packets. Thus in Step 3, R needs to send those packets missed by D.

V. Performance Analysis of Cooperative Relay Strategy

In this section, we evaluate the performance of the proposed relay strategies and validate their effectiveness via mathematical modeling and analysis. We compare the data transmission efficiency by comparing the mean number of packet transmissions for successfully delivering the *m* original packets from S to D.

A. Performance Evaluation of Strategy 1

At the beginning of transmission, S sends coded packets to both R and D. Let N_s denote the number of packets that S sends in total. From the data transmission process described in Section II, we can find N_s is no less than *m*. Let R_1 and D_1 denote the number of packets that R and D receive from S. The probability density function (pdf) of N_s is given by

$$P(N_s=k)=(1-p_{sd})I_{n-1}^{m-1}(p_{sd})\sum_{k=0}^{m-1}I_n^k(p_{sr})+(1-p_{sr})I_{n-1}^{m-1}(p_{sr})\sum_{k=0}^{m-1}I_n^k(p_{sd})$$
$$+(1-p_{sd})(1-p_{sr})I_{n-1}^{m-1}(p_{sd})I_{n-1}^{m-1}(p_{sr}) \quad (13)$$

where $k \geq m$ and $I_i^j(x)=C_i^j(1-x)^j x^{i-j}$.The mean number of packets that S sends is given by

$$E(N_s)=\sum_{n=m}^{+\infty} nP(N_s=n) \quad (14)$$

In Strategy 1, if Step 3 is executed, D_1 is an integer variable between 0 and $m-1$. In this case, R_1 must be *m*. The pdf of D_1 is

$$P(D_1=c)=\sum_{n=m}^{+\infty} I_n^c(p_{sd})(1-p_{sr})I_{n-1}^{m-1}(p_{sr}) \quad (15)$$

where $0 \leq c \leq m-1$.

In Step 3, R replaces S to send coded packets to D. Let R_s denote the number of packets which R sends, using (15), the pdf of R_s is given by

$$P(R_s=d)=\sum_{c}^{m-1} P(R_s=d \mid D_1=c)P(D_1=c) \quad (16)$$
$$=\sum_{n=m}^{+\infty}\sum_{c=0}^{m-1}(1-p_{rd})I_{d-1}^{m-c-1}(p_{rd})\cdot I_n^c(p_{sd})(1-p_{sr})I_{n-1}^{m-1}(p_{sr})$$

where $d \geq m-c$. Using (16), we have the mean number of the packets that R sends

$$E(R_s)=\sum_{n=m}^{+\infty}\sum_{c=0}^{m-1}\frac{m-c}{1-p_{rd}}\cdot I_n^c(p_{sd})(1-p_{sr})I_{n-1}^{m-1}(p_{sr}) \quad (17)$$

Using (14) and (17), we can obtain the mean number of packets which are sent in whole data deliver process as

$$n_1=E(N_s)+E(R_s) \quad (18)$$

where $n_1 \geq m$.

B. Performance Evaluation of Strategy 2

In Strategy 2, R1 loses a packet when both R and D lose it. Since the channels S to D and S to R are independent, the packet loss probability of “virtual” channel S to R1 equals to $p_{sr} \cdot p_{sd}$. The pdf of N_s is given by

$$P(N_s = n) = (1 - p_{sr} p_{sd}) I_{n-1}^{m-1} (p_{sr} p_{sd}) \quad (19)$$

Thus, we have the mean number of packets which S sends

$$E(N_s) = \sum_{n=m}^{+\infty} n \cdot (1 - p_{sr} p_{sd}) I_{n-1}^{m-1} (p_{sr} p_{sd}) = \frac{m}{1 - p_{sr} p_{sd}} \quad (20)$$

In Strategy 2, if the number of coded packets that D receives in Step 2 is less than *m*, Step 3 is executed. Let $R1_r$ denote the number of packets that R1 receives at the end of Step 2, and R_2 denote the number of packets that R receives only at the end of Step 2. R_2 is a variable which is between 0 and *m*. We can obtain the pdf of R_2

$$P(R_2 = i) = C_m^i \left(\frac{(1 - p_{sr}) p_{sd}}{1 - p_{sd} p_{sr}}\right)^i \left(1 - \frac{(1 - p_{sr}) p_{sd}}{1 - p_{sr} p_{sd}}\right)^{m-i} \cdot P(R1_r = m) \quad (21)$$

where $1 \le i \le m$. From the details of Strategy 2 described, $R1_r$ must be equal to *m* if Step 3 is executed. Thus, we have $P(R1_r = m) = 1$

In Step 3, R replaces S to send packets to D. R keeps sending until D eventually receives all packets that R receives only in Step 2. Let R_s denote the number of packets that R sends in total. We can find that R_s is no less than *i*. Thus, the pdf of R_s given that R_2 equals to *i* is given by

$$P(R_s = h \mid R_2 = i) = (1 - p_{rd}) I_{h-1}^{i-1} (p_{rd}) \quad (22)$$

where $h \ge i$. Using (21) and (22), we have the mean number of R_s given that R_2 equals to *i* as

$$E(R_s \mid R_2 = i) = \sum_{h=i}^{+\infty} h \cdot (1 - p_{rd}) I_{h-1}^{i-1} (p_{rd}) = \frac{i}{1 - p_{rd}} \quad (23)$$

Thus, the mean number of R_s is given by

$$E(R_s) = \sum_{i=0}^{m} \frac{i}{1 - p_{rd}} \cdot C_m^i \left(\frac{(1 - p_{sr}) p_{sd}}{1 - p_{sd} p_{sr}}\right)^i \left(1 - \frac{(1 - p_{sr}) p_{sd}}{1 - p_{sr} p_{sd}}\right)^{m-i} \quad (24)$$

Using (20) and (24), the mean number of packets which are sent in the data deliver process in Strategy 2 is

$$n_2 = E(N_s) + E(R_s) \quad (25)$$

where $n_2 \ge m$.

VI. Numerical Results and Discussions

In this section, we present the numerical results for evaluating the performance of the proposed two relay strategies and validate their effectiveness by comparing their performance with the non-cooperative communication mode. We assume the data block to be delivered is partitioned to packets, i.e., $m = 10$.

We employ two performance metrics for the comparison: (1) Source transmission efficiency, denoted by η, which is defined as the ratio of the number of original packets and the mean number of packets that S sends: $\eta = m / E(N_s)$; (2) System transmission efficiency, denoted by ρ, which is defined as the ratio of the number of original packets and the mean number of packets that both S and R sends upon the completion of data transport: $\rho = m / n$, where *n* equals to n_1 in Strategy 1 or equals to n_2 in Strategy 2.

Fig. 5 shows source transmission efficiency η as a function of packet loss probability of link S to R for different p_{sd} values. We can see that for both relay strategies η increases monotonically with p_{sr} for cooperative relay mode while it is a constant for non-cooperative mode, as the relay node is not involved in the data transmission. For a specific p_{sd} value, η of cooperative relay mode is always greater than that of non-cooperative mode. The difference is more significant when p_{sr} is small. For example, for Strategy 2 when $p_{sd} = 0.1$, the difference of η increases from 0.06 to 0.1 when p_{sr} decreases from 0.4 to 0.

Next let us compare η of different relay strategies in Fig.5.a and Fig.5.b. In Strategy 2, R and D are deemed as one "virtual" node R1. The packet loss probability of the virtual channel from S to R1 is $p_{sr} p_{sd}$. Note $p_{sr} p_{sd} \le p_{sd}$ and $p_{sr} p_{sd} \le p_{sr}$, thus η in Strategy 2 is always higher than that in Strategy 1 under the same p_{sd} and p_{sr} value. For example, for $p_{sd} = 0.1$ and $p_{sr} = 0.4$, the source transmission efficiency for Strategy 1 is 0.912 while it is 0.96 for Strategy 2. This indicates that Strategy 2 can achieve a higher η, with the expense of higher implementation complexity, as ARQ-like mechanism should be performed between R and D in Strategy 2.

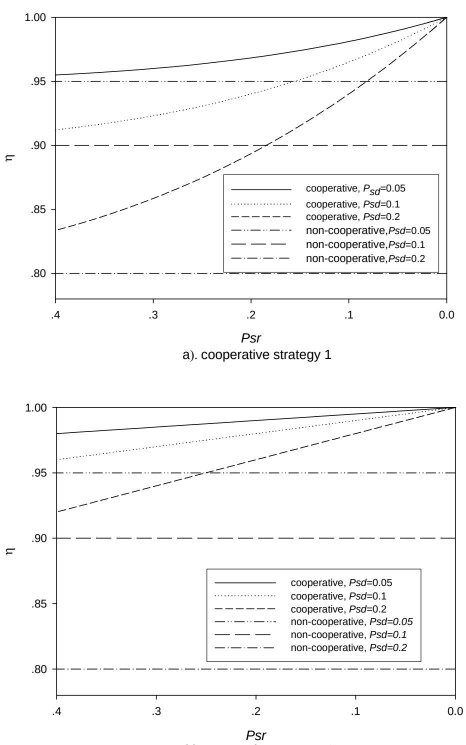
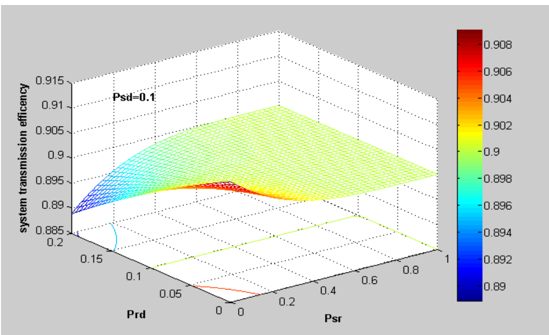


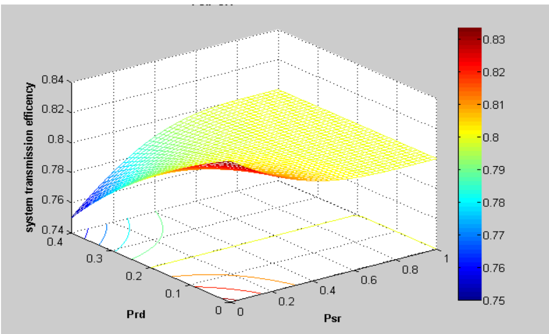
Fig.5. Source transmission Efficiency as a function of γ_{sr} (p_{sd} =0.05,0.1,0.2)

Fig.6 and Fig. 7 show the system transmission efficiency ρ as a function of both p_{sr} and p_{rd} for

Strategy 1 and Strategy 2 respectively. For both Strategies, ρ decreases with both p_{sr} and p_{rd}. Please note we have not depicted ρ for non-cooperative mode which is a constant $\rho = 1 - p_{sd}$, for the sake of clarity. In cooperative systems, a part of packet transmissions are undertaken by the relay node. The amount of packets which are relayed by R are determined by p_{sr}. Therefore, in the figures, ρ becomes insensitive to p_{rd} when p_{sr} value is large. We can also observe that ρ in two strategies is greater than $1 - p_{sd}$ under the condition that $p_{rd} \geq p_{sd}$. This implies that the proposed strategies always outperform the non-cooperative mode. But the improvement on system transmission efficiency is not as significant as on source transmission efficiency. Then, we compare ρ of different strategies in Fig.6 and Fig.7. We can find that the value of ρ in Strategy 2 is higher than that in Strategy 1 under the same p_{sr} and p_{rd}. For example, for $p_{sd} = 0.2$, the system transmission efficiency for strategy 2 is 0.83 while it is 0.82 for strategy 1 under the condition that $p_{sr} = p_{rd} = 0.1$.



a. $p_{sd} = 0.1$

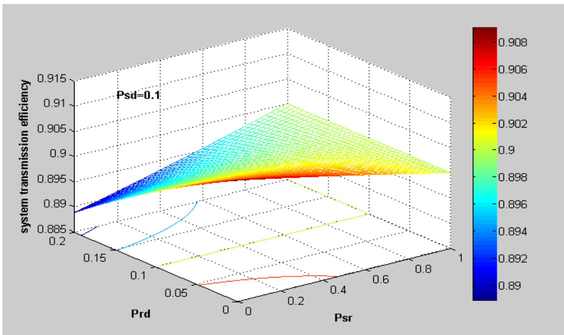


b. $p_{sd} = 0.2$

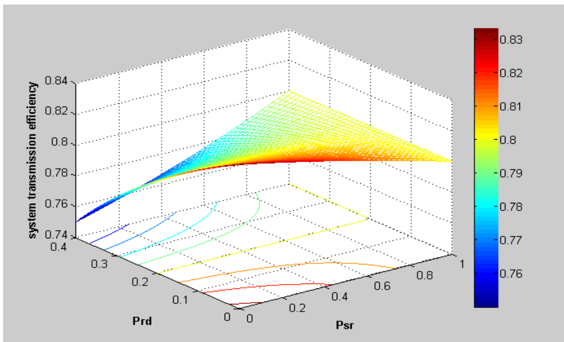
Fig.6. System transmission efficiency of cooperative strategy 1

VII. Conclusion

In wireless networks, poor wireless channel could cause severe packet losses for data delivery, which is a challenge for data access applications that require high reliable and robust data transport. In conventional ARQ-like mechanisms, substantial overhead could be incurred by the feedback/retransmissions to ensure the transmission reliability and robustness. In this paper, we have proposed to make use of the benefits of fountain codes at transport layer in conjunction with cooperative relay for reliable data transport to address the challenge. We have derived the achievable rate of our proposed approach and have found significant gain can be achieved. Based on our finding, we have designed two relay strategies according to the relay operation manner and mathematically analyzed their performance. Numerical results show that our proposed data transport strategies can provide performance improvement in terms of data transmission efficiency. In addition, our schemes are more robust to the link data loss, by means of using fountain codes at transport layer. Our idea of integrating fountain codes and cooperative relay provides an effective solution for supporting data access applications in future wireless networks.



a. $p_{sd} = 0.1$



b. $p_{sd} = 0.2$

Fig.7. System transmission efficiency of cooperative Strategy 2

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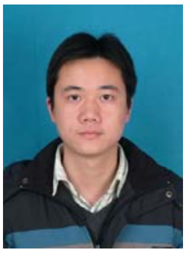

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