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Joint Cooperative Diversity and Network Coding for Wireless Video Streaming

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***Abstract*-The letter introduces random linear network coding (RLNC) based cooperative diversity transmission scheme to guarantee reliable wireless video streaming transmission. For Rayleigh block fading channel, RLNC assisted direct communication method increases packet reliability at high signal-to-noise ratio (SNR). Whereas, cooperative relay transmission achieves diversity gain through cooperative protocols at low SNR. So we merge packet-level RLNC encoding with signal-level cooperative diversity and establish the model to minimize the cost of proposed transmission scheme. According to the quality of service (QoS) requirements of wireless video streaming, numerical results show that the proposed design decreases packet error rate (PER) and end-to-end delay significantly.**

Keywords-cooperative diversity; random linear network coding; block fading channel; video streaming

I. INTRODUCTION

Wireless video traffic increases greatly with the development of broadband wireless transmission, especially for video surveillance in battlefield and emergency communication scenario. Cooperative diversity enhances the link reliability in fading channel via decode-and-forward (DF) protocol in [1], which makes use of resources in the relay node. Alternatively, [2] introduces random linear network coding (RLNC) as packet erasure code, which decreases the packet error rate (PER) in erasure channel at high signal-to-noise ratio (SNR) values. In this letter, we design the optimal adaptive transmission scheme for varying SNR by exploiting the rateless characteristic of RLNC and spatial diversity of DF protocol, which is defined as RLNC based cooperative diversity scheme.

Research in [3] demonstrated that hybrid automatic repeat request (HARQ) was the efficient strategy for link transmission in low SNR. Then delay characteristic of cooperative HARQ was studied extensively under block fading channel with the metric of delay outage probability in [4], and [5] studied the adaptive transmission for HARQ. Under low SNR condition, [3] [4] indicated that transmitting the same packet through different channel could drastically diminish the number of retransmission. Rateless codes were introduced into dynamic DF protocols to improve the transmission rate under different listening time in [6]. RLNC, first introduced in [7], was algebra code and was used to guarantee the reliability of data transmission at high SNR values in [2], which combined channel coding and RLNC. [8] utilized RLNC as broadcast erasure code.

The motivation of this letter is the desire to diminish the acknowledge (ACK) in HARQ and increase link quality under erasure code based transmission scheme at low SNR values. Under indoor environment, the channel model is the combination of erasure characteristic and memoryless bit error trait. Packet level RLNC is adopted to conquer the packet error in Rayleigh block fading channel under high SNR. Cooperative diversity among transmission nodes is adopted to enhance the signal strength for low SNR. Then we propose the adaptive RLNC based cooperative diversity scheme. The optimal model is established to minimize the cost of different combination scheme, and the optimum mode switch algorithm is proposed to solve the problem efficiently.

II. SYSTEM MODEL

A. Network Scenario

In military and disaster communication scenario, as illustrated in Fig. 1, obstacles separate the source node S and the destination node D. We focus on the scenario where the relay nodes R_i, $i = 1,...,M$ are in the same side with S. For example, S transmits video steaming to D in disaster circumstance, and R_i assists S to establish the reliable communication with D.

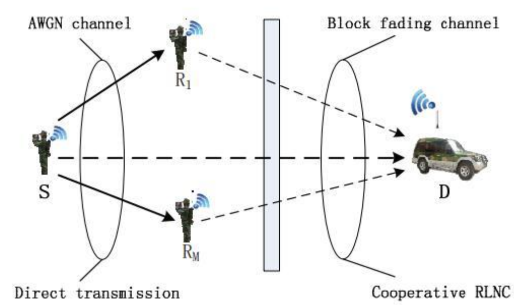

Figure 1. Communication scenario for video surveillance.

B. Channel Model

The transmission links between S and R_i are modeled as additive white Gaussian noise (AWGN) channel, for they have short distances and line-of-sight transmission between any two nodes. On the other hand, the cooperative link between R_i and D is supposed as block fading channel due to the obstacles between relay nodes and D. The direct link between S and D is also modeled as block fading channel.

For Rayleigh block fading channel, we suppose that SNR keeps constant during per packet transmission. Between different packet transmission, however, SNR is independent identical distributed. The probability distribution of SNR can be expressed as:

$$f_{\gamma}(\gamma) = \frac{1}{\bar{\gamma}} \exp(-\frac{\gamma}{\bar{\gamma}}) \quad (1)$$

where γ denotes the instantaneous SNR and $\bar{\gamma}$ represents the average SNR.

C. Brief Introduction of RLNC

RLNC is algebra coding scheme for reliable data transmission in [7] [8] and can be used as erased code for block fading channel in [2]. Let $P_{K \times L}$ denotes the transmitting packet matrix and $G_{N \times K}$ is the random coefficients matrix. The encoding process can be depicted as following:

$$C_{N \times L} = G_{N \times K} \times P_{K \times L} \quad (2)$$

where $C_{N \times L}$ is the encoded packet matrix. K denotes block size of original information packets, N represents the number of coded packets, and L is the bytes of per packet. Since each packet linearly independent with another among C , receiving K correct packets is adequate for implementing decoding process.

III. BASED COOPERATIVE DIVERSITY SCHEME

The direct transmission between S and D encounters large packet errors due to interference from the same frequency band networks under Rayleigh block fading channel. For high SNR, RLNC recovers error packets efficiently as the packet erasure code. With the decrease of SNR, the performances of direct communication with RLNC decay significantly, which incurs long delay and packet delivery failure. For low SNR, the performance of signal-level cooperative diversity is more efficient than that of packet-level RLNC. So joining RLNC with cooperative diversity is adopted to conquer bursty packet error in block fading channel. The naturally arising question is: how to make the optimal mode switch between RLNC assisted direct transmission and cooperative RLNC diversity with the SNR varying.

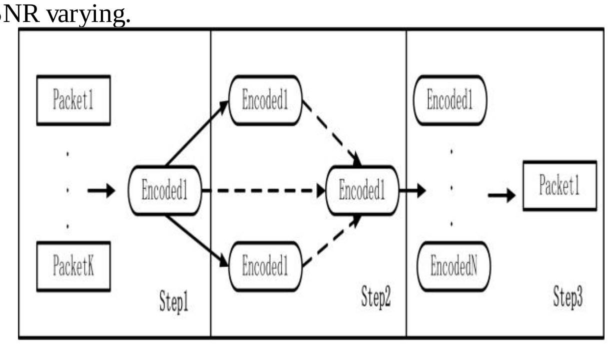

Figure 2. Packet flow of our proposed RLNC based cooperative diversity.

Our proposed RLNC based cooperative diversity scheme is composed of three steps: RLNC encoding, cooperative transmission and cooperative RLNC decoding, as the packet flow in Fig. 2. First, S collects K real-time video packets into one information block matrix $P_{K \times L}$. The encoding delay increases linearly with $O(KL)$, so adjusting K and L parameters could satisfy the system requirement. Second, according to the mode selection, S transmits each coded packet in $C_{N \times L}$ to R_i . Due to the short distance between any two transmitting nodes, the reliability of receiving packets in R_i can be guaranteed. Third, D implements two tiers: maximalratio-combing (MRC) receiver and RLNC decoding. MRC receiver exploits the performance of spatial diversity, which increases the link quality in low SNR [9]. Whereas RLNC guarantees the required PER at high SNR, which is time diversity in essence.

The goal of our proposed scheme is to deliver the real-time video packet effectively from S to D . From the perspective of time evolvement, RLNC based cooperative diversity scheme is divided into two phases: broadcasting phase and relaying phase. The relying phase is optional, which is attributed to the selected mode. RLNC incurs redundance in time domain and cooperative diversity utilizes more number of channels in space. At the beginning of transmission of each packet block, the transmission mode, whether to perform cooperative, needs to be determined.

IV. PROBLEM FORMULATION AND ALGORITHM

A. Performance Analysis

For (K, N) RLNC as the erasure code, PER of direct communication scheme from S to D can be gotten as following:

$$P_D = 1 - \sum_{i=K}^{N} \binom{N}{i} P_P^{N-i} (1 - P_P)^i \quad (3)$$

where K is the number of information packets and N is the number of coding packets. P_P is the error probability of per packet, which is determined by symbol error probability $P_s(\gamma)$ as following:

$$P_P = 1 - (1 - P_S(\gamma))^L \quad (4)$$

where L denotes the length of packet in link layer. Then we obtain average PER as:

$$\overline{P_D} = E(P_D) = \int_0^\infty P_D f(\gamma) d\gamma = 1 - \int_0^\infty \sum_{i=K}^{N} \binom{N}{i} \left(1 - P_t(\gamma)^L\right)^{N-i} P_t(\gamma)^{Li} f(\gamma) d\gamma \quad (5)$$

where $P_t(\gamma) = 1 - P_s(\gamma)$. From (5), given the mean value of γ , we obtain that $\overline{P_D}$ is determined by K , N and L . Without loss of generality, we suppose that L is constant for video transmission.

The end-to-end delay from S to D is composed of three elements, which is depicted as following:

$$D_t = D_{enc} + D_P + D_{dec} \quad (6)$$

where D_{enc} is RLNC encoding delay and D_{dec} is decoding delay. The computation complexity of D_{enc} and D_{dec} is $O(KL)$. With the powerful calculating capability of modern processor in mobile device, D_{enc} and D_{dec} are trivial in the total delay.

The destination D needs collecting at least K correct packets to decode RLNC encoding data, and the last receiving packet is correct packet. We write $\overline{D_P}$ as follows:

$$\overline{D_P} = P_D N d_t + E\left(\sum_{i=K}^{N} P_{si} i d_t\right) \quad (7)$$

The first term $P_D N d_t$ denotes the maximum delay due to failure of RLNC decoding, which means the whole information block is discarded. d_t represents the per packet transmission time and is defined as:

$$d_t = \frac{L}{C_l} \quad (8)$$

where C_l is the capacity of physical layer transmission. P_{si} is defined as the probability of decoding the K block packets successfully when receiving i packets. It is known that $i \geq K$ and P_{si} is geometric distribution, which can be defined as follows:

$$P_{si} = \binom{i-1}{K-1}(1-P_P)^K P_P^{\,i-K} \quad (9)$$

Substituting (9) into (7) we have the final $\overline{D_P}$ as follows:

$$\overline{D_P} = P_D N d_t + \int_0^{\infty} \sum_{i=K}^{N} \binom{i-1}{K-1} d_t (1 - P_P(\gamma))^K P_P(\gamma)^{i-K} f(\gamma) d\gamma \quad (10)$$

From (3), when K/N is constant, PER decreases significantly with increasing K. From (7), however, large K causes large delay due to limited transmission rate of wireless channel.

In Rayleigh block fading channel, low average SNR leads to frequent packet error. From (5) and (10), PER increases significantly and average end-to-end delay is also extended dramatically. On this condition, we propose RLNC based cooperative relay scheme to increase the link reliability, by making each packet transmission through different channel. In [9], symbol error probability of cooperative diversity with m virtual antennas under binary phase shift keying (BPSK) is described as:

$$\overline{P_s}(\overline{\gamma},m) = \frac{1}{\pi}\int_0^{\frac{\pi}{2}} \left(1 + \frac{\overline{\gamma}}{\sin\varphi^2}\right)^{-m} d\varphi \quad (11)$$

where $\overline{\gamma}$ is the average SNR of per link in this cooperative relay network. m is the number of cooperative terminals. Substituting (11) into (5) and (10), we get the performance expression of cooperative RLNC transmission scheme. The values of $\overline{P_D}$ and $\overline{D_P}$ is relevant to $\overline{P_s}(\overline{\gamma},m)$, and larger m get lower $\overline{P_s}(\overline{\gamma},m)$, but incurs more channel resources.

B. Optimal Model for Mode Switch

We minimize additional cooperative RLNC cost under the condition that selected transmission scheme satisfies the minimum delay and PER requirement for video transmission. The optimal model is described as following:

Algorithm 1. Optimal RLNC based Cooperative Mode Selection Algorithm

1: Initialization:
   Initialize RLNC candidates: $\Omega(K, N), m$
2: while $m < C_{\max}$ do
3:     calculate $\overline{P_s}(\overline{\gamma}, m)$ by (11)
4:     for $(K, N) \in \Omega(K, N)$ do
5:         calculate $\overline{P_D}$ by (5) and $\overline{D_P}$ by (10)
6:         if $\overline{P_D} \leq P_{\min}$ && $\overline{D_P} \leq D_{\min}$ then
7:             break;
8:         end if
9:     end for
10:    $m = m + 1$
11: end while
12: Output transmission mode m and (K, N).

$$\min_{m,K,N} g\left(K/N\right) + h(m)$$
$$\text{s.t.} \begin{cases} \overline{P_D} \leq P_{\min} \\ \overline{D_P} \leq D_{\min} \end{cases} \quad (12)$$

The objective function is to minimize the cost of link transmission. $g(\cdot)$ is the cost function of RLNC method and $h(\cdot)$ is the cost of cooperative diversity. In this paper, RLNC based direct communication has high priority. The cooperative relay network is adopted when RLNC assisted transmission could not satisfy the requirements.

From (12), we obtain that single selected scheme is not suitable for real-time video surveillance in Rayleigh block fading channel. According to different $\overline{\gamma}$, we select transmission mode to minimize cost under the condition that video streaming is transmitted efficiently. So we give the following optimal selection strategy, which is described extensively in Algorithm 1.

As in Algorithm 1, this strategy is divided into two stages. At the beginning we search the optimal solution among all encoding schemes. When there is no available solution which satisfies the requirements, we increase the number of cooperative devices. Under the renewed average symbol error probability, we research the transmission scheme.

V. PERFORMANCE EVALUATION

In this section, we evaluate the performance by adopting the network scenario depicted in Section 2. According to the

QoS requirements of wireless video streaming, the parameters can be set $P_{min} = 0.01$ and $D_{min} = 200ms$ [10]. In our experiment, we use MPEG-4 Transport Stream (TS) as the tested video traffic. Based on TS standards, the packet length is set $L = 1504bit$, which is equal to the length of each TS frame. The link capacity is $200kbps$ in our model design, which adopts time division multiple access (TDMA) protocol. RLNC is used in the finite selected candidates, and the parameter design in [2] is also referenced. MRC is perfectly utilized due to AWGN channel among transmitters.

We propose RLNC based cooperative diversity scheme in Section 3. Then the proposed scheme is composed of three design parameters: the number of cooperative devices m, the number of information packets block K and the number of encoded packets N. We optimize these three parameters to minimize the system cost under the condition that QoS of real-time video streaming is satisfied. $M(m,K,N)$ is defined as the tuple of three adjusted parameters. PER and end-to-end delay is calculated from (5) and (10).

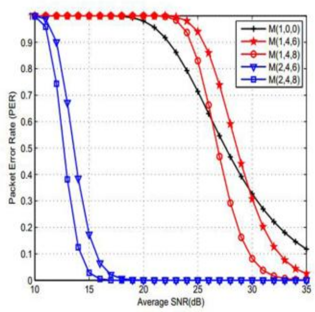

Figure 3. Numerical results of packet error rate.

Fig. 3 shows numerical results of PER by varying SNR. $M(1,0,0)$ denotes the transmission scheme that no cooperative relay and RLNC is adopted. From the results, we can observe that in low SNR, RLNC assisted direct transmission from S to D performs even worse than $M(1,0,0)$. With the increase of SNR, above about 27dB, PER of $M(1,4,8)$ is smaller than that of $M(1,0,0)$. In low SNR, we need to use the cooperative relay to conquer the bit error. From Fig. 3, we conclude that only one additional antenna can decrease PER drastically.

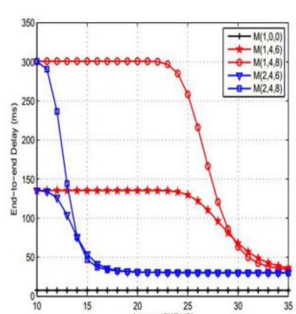

Figure 4. Numerical results of end-to-end delay.

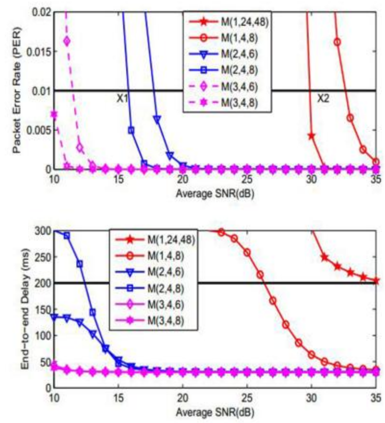

Figure 5. Selecting $M(m,K,N)$ adaptively by varying SNR.

Fig.4 shows the end-to-end delay for different transmission scheme. From the results, we get that end-to-end delay is determined by average SNR. When SNR is above some threshold, the value of end-to-end delay diminishes significantly. In low SNR, we should use the cooperative terminals to assist transmission from S to D. Fig.5 is the example for our proposed optimal RLNC based cooperative mode selection algorithm. The upper figure shows PER of available candidates, and the lower is end-to-end delay. Following the Algorithm 1, we may select the cross point between the line of $PER = 0.01$ and each transmission scheme, such as X_1 and X_2. At X_1, $M(2,4,8)$ is selected; at X_2, $M(1,24,48)$ is selected. However, X_2 is not available because the end-to-end delay for X_2 is more than $200ms$. So the proposed RLNC based cooperative diversity scheme can minimize the cost of transmission system and satisfy the QoS of video streaming.

VI. CONCLUSION

In this letter, we proposed RLNC based cooperative diversity transmission scheme. The key problem was to select the appropriate transmitting mode for given average SNR. We established the optimal model which minimized the cost of link transmission scheme and satisfied video streaming requirements. Furthermore, we gave the optimal RLNC based cooperative mode selection algorithm. Theory analysis and numerical results indicated that the proposed algorithm decreased PER and end-to-end delay significantly.

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