Postprint: Cooperative Relay-Based Retransmission Strategy in Communication Networks

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Abstract

This study investigates multicast transmission of information packets in communication networks and proposes a cooperative relay retransmission strategy. When direct transmission of information packets fails, the source node cooperates with multiple relay nodes to perform coded retransmission of multiple lost packets. During the retransmission phase, based on feedback mechanism results, a random access approach is adopted to prioritize the combination of lost packets with coding opportunities, and then by sacrificing nodes that failed during previous retransmission attempts, spatial diversity gain is provided for the information, thereby reducing the number of retransmissions. Finally, under different channel environments, this strategy is compared with non-cooperative NCARQ and traditional ARQ through Monte Carlo simulations. Simulation results demonstrate that when multi-relay channel conditions are superior to source-destination channel conditions, utilizing cooperative network coding for retransmission effectively improves network throughput, and this strategy employs cooperative spatial diversity to mitigate performance degradation caused by coherence.

Full Text

Preamble

Re-transmission Strategy Based on Cooperative Relay in Communication Networks

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Abstract: This paper investigates multicast transmission of information packets in communication networks and proposes a cooperative relay-based retransmission strategy (CRRS). When direct packet transmission fails, the source node coordinates with multiple relay nodes to encode and retransmit multiple lost packets. During the retransmission phase, the strategy employs a random access approach based on feedback mechanism results to prioritize combinations of lost packets that have network coding opportunities. It then provides spatial diversity gain for information recovery by sacrificing nodes that failed in previous retransmission attempts, thereby reducing the number of retransmissions. Finally, Monte Carlo simulations compare the proposed strategy with non-cooperative NCARQ and traditional ARQ under different channel conditions. Simulation results demonstrate that when multiple relay channels exhibit better conditions than the source-destination channel, cooperative network coding for retransmission effectively improves network throughput, and the strategy mitigates performance degradation due to coherence by exploiting cooperative spatial diversity.

Keywords: communication networks; cooperative relay; retransmission; spatial diversity; throughput

0 Introduction

Automatic Repeat Request (ARQ) is an error control mechanism that improves system reliability in communication networks [1]. However, due to fading characteristics of wireless channels and interference from additive white Gaussian noise [2], information packets may be lost or become undecodable during transmission, potentially causing significant ARQ performance degradation and reduced throughput. To address this issue, cooperative communication integrates spatial diversity and channel coherence resistance into ARQ. In this strategy, relay nodes within the coverage area monitor the channel and buffer any successfully decoded packets during transmission, leveraging the broadcast nature of wireless channels [3] without requiring additional bandwidth. When destination nodes fail to receive packets from the source, the source selects optimal relay nodes to minimize channel outage probability and node power consumption during cooperative transmission, reducing retransmissions and effectively improving network throughput while mitigating the poor interruption performance caused by relay nodes [4].

In multicast transmission, retransmission packets are encoded at the source node through a single node without additional cooperative nodes. In cooperative communication, network coding can also be applied at relay nodes, an approach termed cooperative network coding [5][6]. Early cooperative transmission MAC protocols such as CoopMAC [7], rDCF [8], and CD-MAC [9] involve relay nodes cooperating with the source during transmission. Ding et al. [10] proposed a low-complexity strategy for MSMR cooperative communication networks, which effectively reduces complexity but ignores power consumption issues caused by excessive relay nodes. Duy et al. [11] presented a hybrid decode-amplify-forward scheme based on SNR-based relay selection, demonstrating advantages through experiments but with certain limitations. Huang [12] proposed optimization and heuristic scheduling algorithms for relay-assisted wireless broadcast transmission, which suffer from low spectral efficiency, especially when relay nodes fail to decode successfully, leading to idle time-frequency resources. Antonopoulos et al. [13] investigated the impact of cooperative MAC network coding protocols on energy efficiency in deterministic networks. Wang et al. [14] proposed cooperative resource allocation and power control strategies between primary and secondary users under QoS constraints. These studies highlight the critical importance of selecting reasonable and effective cooperation methods during cooperative transmission.

This paper proposes a cooperative relay retransmission strategy for communication networks. In multicast networks, when direct packet transmission fails, the source node selects multiple optimal relay nodes to form an optimization set. With a fixed outage probability, the SNR threshold determines the relay cooperation mode, and available nodes access the random access channel through a feedback mechanism. Under different channel configurations, channel coherence is modeled as a finite-state Markov process, and parameters are varied to compare the average throughput of CRRS, NCARQ, and traditional ARQ algorithms. Experimental results demonstrate that the proposed cooperative relay retransmission strategy can effectively improve system performance in multicast networks.

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1 System Model

The system model in the communication network comprises one source node S, multiple interference nodes I, multiple destination nodes D, and multiple relay nodes R, where relay nodes assist the source in packet transmission. In [Figure 1: see original paper], arrows indicate the direction of packet transmission between nodes. All nodes operate in half-duplex mode, and time is divided into multiple slots. Communication channels are assumed to be flat-fading with channel coefficients remaining constant during a single transmission period but changing independently between periods.

[Figure 1: see original paper] Cooperative broadcast network

The channel coefficient of link l can be expressed as h_l, with corresponding channel gain $|h_l|^2$. P_s and P_r denote the packet transmission power of source and relay nodes, respectively; w represents additional Gaussian noise with power σ^2. $P_s^{\max}$ and $P_r^{\max}$ represent the maximum packet transmission power for source and relay nodes, and μ_0 is the interference threshold.

Assume the source node S transmits packet x in the k-th time slot. The signals potentially received by destination and relay nodes are:

$$y_{sd} = \sqrt{P_s} h_{sd} x + w_{sd}$$

$$y_{sr} = \sqrt{P_s} h_{sr} x + w_{sr}$$
$$y_{rd} = \sqrt{P_r} h_{rd} \tilde{x} + w_{rd}$$

where $\tilde{x}$ represents the relay node' s cooperation mode. The instantaneous received SNR for link l is $\mu_l = |h_l|^2 P/\sigma^2$.

The threshold μ_{th} represents the SNR threshold for successful packet decoding at destination nodes. Based on the reception status at destination nodes, relay nodes are selected for cooperative transmission as follows:

a) The source node S uses a counter to track the number of packets successfully decoded by relay or destination nodes. When S transmits a packet to a destination node, if transmission fails but a relay node successfully receives and decodes the packet, it feeds back the reception status to S and the counter increments by 1. If decoding fails, the counter remains unchanged.

b) After transmitting k subframes, if the counter shows 0 (indicating all relay nodes failed to decode, i.e., $S = \emptyset$), the source node S sends a decoding signal in the $(k+1)$-th subframe and stops all subsequent subframes and relay phase transmissions, initiating a new multicast cycle. Destination and relay nodes attempt to decode previously received packets. If the SNR of the source-destination channel satisfies $\mu_{sd} \geq \mu'_{th}$, then destination or relay nodes can successfully decode packets.

c) If the counter shows a non-zero value (indicating some relay nodes decoded successfully, i.e., $S \neq \emptyset$), the source node S sends a relay selection signal in the $(k+1)$-th subframe. Relay nodes then calculate the SNR μ_{sd} based on the source-destination channel power received during direct transmission and the contained noise power, using feedback from destination nodes.

d) In the next time slot, destination nodes feed back the SNR μ'_{sd} of the source-destination channel to relay nodes in the model. The indices of successfully decoded packets are stored in R_k. Finally, relay nodes calculate the channel gain values $|h_{rd}|^2$ for link $R_k - D$ based on received feedback and compute the corresponding SNR using equation (10).

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2 CRRS Algorithm

The communication process structure includes N subframes from source node S to destination nodes D. Each subframe carries one information packet as payload, verified at destination nodes through redundancy check codes. During frame transmission, when S sends a packet to a destination node, if the destination successfully decodes, it feeds back an ACK signal and the packet leaves the transmission queue. If the destination fails to decode but a cooperating relay succeeds, the relay receives the packet and sends an ACK to S, removing it from the queue. If both destination and relay fail, the packet remains in the transmission queue awaiting retransmission. Each packet transmission occupies one time slot. Due to broadcast characteristics, ACK/NACK feedback transmission time is negligible.

2.1 CRRS Strategy Implementation Mechanism Description

In a new network transmission cycle, the source node S sends a frame to destination nodes D. If no source-destination channel outage occurs during the frame duration (spanning N consecutive packets), the destination successfully receives the frame, completing one transmission cycle. When a cycle finishes and the next begins, if any packet in the frame remains unreceived by any destination node, the retransmission phase begins and continues until all packets are successfully received.

During retransmission, no central control signal exists. Due to destination node ACK/NACK feedback, the retransmission phase includes relay nodes. A random access mechanism selects retransmission nodes. At the retransmission start, a contention period exists where all nodes attempt to retransmit packets through the channel. Each candidate node attempts retransmission after counting down from a timer value, where the random timer value consists of a finite set W_i. In the i-th retransmission, W_i is called the feedback window, initially set to $W_{\min}$ for all nodes during the first retransmission. Expanding the feedback window serves as a penalty mechanism after retransmission failure. Two scenarios cause retransmission failure:

a) Collision when source and relay nodes simultaneously attempt channel access;
b) Packet loss due to channel outage when a retransmission node sends a packet.

In the first case, the feedback window expands by $2W_i$ due to collision. In the second case, when a retransmission node experiences channel outage, the feedback window doubles. Another instance also increases the feedback window: when a candidate retransmission node has no opportunity to combine lost packets using network coding and yields to other nodes for network coding operations, the candidate node also doubles its feedback window, i.e., $W_i \rightarrow 2W_i$. In all cases, the feedback window expands until reaching its maximum value $W_{\max}$.

[Figure 2: see original paper] Algorithm flowchart

2.2 Candidate Forwarding Node Transmission Selection

For each possible pair (i, j), a matrix $S_d(k)$ is formed by included nodes. The goal is to convert as many "0"s to "1"s in matrix $S_d(k)$. To achieve this, all-zero columns and diagonals are identified in $S_d(k)$. An all-zero column indicates a common packet q not received by any destination node; an all-zero diagonal represents two different packets p, q where packet p was received by destination D_i but not D_j, and packet q has the opposite reception status. In the first case, the common packet q is selected for retransmission; in the second case, the network-coded packet $p \oplus q$ is selected. If at least one packet satisfies these conditions, selection is random. Otherwise, the destination node with the highest SNR in a single-row submatrix $S_d(k)$ is selected. As described, candidate retransmission nodes penalize themselves by expanding their feedback windows.

2.3 Cooperative Transmission Mode

This selection follows the destination node priority principle. For each relay node, destination nodes take precedence. This is achieved by detecting the SNR of channels between relay and destination nodes, selecting the two destination nodes with highest SNR. This strategy implies either SNR measurement over a period or using instantaneous SNR measured from the latest ACK/NACK feedback from destination nodes. Given optimal destination nodes, corrective coding operations are performed on selected packets.

Consider a model with 1 source node, 2 relay nodes, 3 destination nodes, and 2 interference nodes. The packet status matrix $S_d(k)$ represents successful or failed packet reception at destination nodes by the end of the k-th time slot. Matrix $S_d(k)$ has 3 rows and N columns, where each row indicates the reception status of the corresponding packet at destination nodes. $S_d(k)_{i,j}$ represents the status of packet j at destination node D_i, where "0" indicates failure and "1" indicates success. Packet success/failure status depends on whether the channel during that specific time slot is in good condition.

During the first transmission, relay nodes that failed to correctly receive certain packets may successfully receive them during the retransmission phase. When this occurs, relay nodes update the corresponding matrix X. The index set of successfully decoded relay nodes is R_k. Each candidate retransmission node (source node and available relay nodes) determines whether packets are correctly received based on $S_d(k)$. The threshold μ_{th} represents the SNR threshold for successful packet decoding at destination nodes. The relay selection process proceeds as follows:

a) The source node S uses a counter to track the number of packets successfully decoded by relay or destination nodes. If transmission fails but a relay node successfully receives and decodes the packet, it feeds back the reception status to S and the counter increments. If decoding fails, the counter remains unchanged.

b) After transmitting k subframes, if the counter shows 0 (all relay nodes failed to decode, i.e., $S = \emptyset$), the source node S sends a decoding signal in the $(k+1)$-th subframe, stops all subsequent subframes and relay phase transmissions, and begins a new multicast cycle. Destination and relay nodes attempt to decode packets received in the previous phase. If the SNR of the source-destination channel satisfies $\mu_{sd} \geq \mu'_{th}$, then destination or relay nodes can successfully decode packets.

c) If the counter shows a non-zero value (some relay nodes decoded successfully, i.e., $S \neq \emptyset$), the source node S sends a relay selection signal in the $(k+1)$-th subframe. Relay nodes then calculate SNR μ_{sd} based on source-destination channel power received during direct transmission and noise power.

d) In the next time slot, destination nodes feed back the SNR μ'_{sd} of the source-destination channel to relay nodes. The indices of successfully decoded packets are stored in R_k. Finally, relay nodes calculate the channel gain $|h_{rd}|^2$ for link $R_k - D$ based on received feedback and compute the corresponding SNR using equation (10).

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3 Performance Analysis

3.1 Channel Transition Probability

Assuming Rayleigh fading channels with strong continuous channel coding, the packet error rate can be approximated as the outage probability of mutual information. Each time slot has duration T_s, with required bit rate $R_b = R_s/T_s$ bits per symbol, where R_s is the symbol rate. The parameter θ represents the amount the channel is allowed to fall below the average value before outage occurs, called the channel fading margin. The received SNR at destination nodes is $\mu_{sd} = |h_{sd}|^2 P_s/\sigma^2$.

The channel model is described by two channel states: poor state A representing packet loss due to channel outage, and good state B representing successful transmission. The Markov chain has the following transition probability matrix:

$$W = \begin{bmatrix} W_{AA} & W_{AB} \\ W_{BA} & W_{BB} \end{bmatrix}$$

where W_{ij} represents the probability that the channel is in state i at time slot k and state j at time slot $k+1$. For circularly symmetric complex Gaussian channels, the transition probability process is:

$$W_{AB} = Q(\theta, \rho) - \rho^2 Q(\theta/\rho, \rho)$$

$$W_{BA} = \frac{1 - W_{AA}}{W_{AB}} W_{AA}$$

where parameters are defined as: ρ is the continuous transmission channel coherence coefficient; f_m is the Doppler frequency; $J_0(\cdot)$ is the zeroth-order Bessel function of the first kind; $Q(\cdot)$ is the Marcum Q-function.

3.2 Two Access Methods

a) Random Access: If source and relay nodes do not have orthogonal time slot distribution during transmission, they access the channel randomly. This creates scenarios where source and relay nodes simultaneously transmit packets to destination nodes, defined as packet collision where transmitted packets cannot be successfully decoded, resulting in transmission failure. The throughput interval for the transmission queue is:

$$\Psi = \left[0, \exp\left(-\min_{l\in\mathcal{L}} \frac{P_s^{\max}}{|h_{sl}|^2}\right)\right]$$

b) Orthogonal Access: Source and relay nodes access the channel orthogonally. The throughput interval for the transmission queue becomes:

$$\Psi = \left[0, \min\left(\exp\left(-\min_{l\in\mathcal{L}} \frac{P_s^{\max}}{|h_{sl}|^2}\right), \exp\left(-\min_{l\in\mathcal{L}} \frac{P_r^{\max}}{|h_{rl}|^2}\right)\right)\right]$$

If the packet arrival rate falls within the throughput interval during transmission, all transmission queues in the communication process remain stable.

3.3 Relay Node Cooperative Outage Probability

Assuming each packet duration remains constant in fading channels and continuous transmission fluctuates only slightly, we analyze the impact of channel coherence on ARQ throughput performance using a finite-state Markov model. The packet duration is T_p, signal duration is T_s, and coherence time parameter is T_c.

The outage probability for destination node D_d is:

$$P_{\text{out}}^{(d)} = \Pr\left\{\min_{k\in\mathcal{K}} \mu_{sd,k} < \mu'_{th}\right\}$$

When relay nodes successfully decode, the outage probability is defined as:

$$P_{\text{out}}^{\text{relay}} = \Pr\left\{\min_{k\in\mathcal{K}} \mu_{sd,k} < \mu'_{th} \mid \mathcal{S} \neq \emptyset\right\}$$

The conditional probability is:

$$\Pr\{\mathcal{S} = \{k_1, k_2, ..., k_m\}\} = \prod_{i=1}^{m} \Pr\{\mu_{sr,k_i} \geq \mu'_{th}\} \prod_{j\notin\{k_1,\ldots,k_m\}} \Pr\{\mu_{sr,j} < \mu'_{th}\}$$

The probability density function of random variable $X = \max_{l\in\mathcal{L}} |h_{sl}|^2$ is:

$$f_X(x) = \sum_{u=1}^{L} \sum_{\substack{j_1,\ldots,j_u \\ \in \mathcal{L}}} (-1)^{u+1} \exp\left(-\sum_{v=1}^{u} x/\Omega_{j_v}\right)$$

where $\Omega_l = \mathbb{E}[|h_{sl}|^2]$.

Substituting into the outage probability expression yields:

$$P_{\text{out}}^{\text{coop}} = \int_0^\infty \Pr\left\{\min_{k\in\mathcal{K}} \mu_{sd,k} < \mu'_{th} \mid X = x\right\} f_X(x)dx$$

After derivation, the final expression for outage probability with relay cooperation is:

$$P_{\text{out}}^{\text{coop}} = \sum_{m=1}^{K} \sum_{\substack{\{k_1,\ldots,k_m\} \\ \subset \mathcal{R}}} \left[\prod_{i=1}^{m} \exp\left(-\frac{\mu'_{th}\sigma^2}{P_s\Omega_{sr,k_i}}\right) \prod_{j\notin\{k_1,\ldots,k_m\}} \left(1 - \exp\left(-\frac{\mu'_{th}\sigma^2}{P_s\Omega_{sr,j}}\right)\right)\right] \times \Pr\left\{\min_{k\in\{k_1,\ldots,k_m\}} \mu_{rd,k} < \mu'_{th} \right.$$

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4 Simulation Results

The simulation environment is a Dell PC with Intel(R) Core(TM) i5-4210U CPU @ 1.70GHz, 2.40GHz, 8.00GB memory, and 64-bit Windows 10 operating system.

Monte Carlo simulations compare the performance of the proposed CRRS scheme under different channel conditions. The communication network contains 8 nodes. System parameters include: destination node successful decoding threshold $\mu'_{th} = 2$, noise power $\sigma^2 = 1$, interference threshold $\mu_0 = 20$, and all link channel gain values equal to 1 (i.e., $\Omega_{sd} = \Omega_{sr} = \Omega_{rd} = 1$). The impact of channel coherence on throughput is analyzed, and throughput performance is compared among CRRS, non-cooperative NCARQ, and traditional ARQ over randomly generated fading channels.

[Figure 3: see original paper] shows average throughput variation under different outage probability functions in non-coherent channels ($\rho = 0$). In this scenario, relay channels (μ_{sr}, μ_{rd}) outperform source-destination channels (μ_{sd}) with fading margins: $F_{sd} = 0$dB, $F_{sr} = 10$dB, $F_{rd} = 10$dB. When relay nodes have better channel conditions than the source, this can be viewed as cooperative relaying. For $\lambda = 0.8$, as μ_{sd} increases, the fading margin of relay-destination channels also increases, and relay cooperation significantly impacts throughput. For $\lambda < 0.8$, throughput decreases as μ_{sd} increases because source-relay channels experience frequent outages and cooperation opportunities diminish. Compared to $\lambda > 0.8$ cases, cooperative conditions have less impact. The main difference between CRRS and NCARQ lies in cooperative conditions and source-relay/relay-destination channels. When $\lambda = 0.8$, NCARQ and CRRS performance becomes similar. For $\lambda > 0.5$, CRRS outperforms traditional ARQ and NCARQ by leveraging cooperation with relay nodes under better channel conditions. As λ increases, source-destination channel conditions gradually deteriorate, increasing the need for cooperative transmission as the probability of continuous successful transmission decreases.

[Figure 4: see original paper] displays average throughput variation under different channel coherence coefficients. As channel coherence strengthens, all schemes exhibit significant performance degradation, especially when the source-destination channel fading margin is very low. The CRRS scheme shows the smallest performance degradation because relay cooperation provides spatial diversity advantages against long-duration outages.

[Figure 5: see original paper] illustrates throughput variation relative to relay node positions in non-coherent channels ($\rho = 0$). Relative position is reflected in fading margins F_{sr} and F_{rd}, where F_{sd} remains constant while F_{sr} and F_{rd} vary with the relative position of source and destination nodes to relay nodes. The relative position parameter is $\lambda = F_{rd}/F_{sd}$. When $\lambda \to 0$, relay nodes approach destination nodes, meaning relay-source channels gradually improve. When $\lambda \to 1$, relay nodes approach source nodes, but the opposite situation occurs. Assuming relay channel conditions are better than source-destination channels, when $\lambda = 0.8$, throughput increases with μ_{sd} because relay-destination channel fading margins increase and relay cooperation significantly impacts throughput.

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5 Conclusion

This paper proposes a cooperative relay retransmission strategy for communication networks. When direct source transmission fails, the strategy selects optimal relay nodes for cooperative transmission, leveraging spatial diversity and network coding to enable successful packet decoding at destination nodes. When relay channel conditions are better than source-destination channels, cooperative relay transmission provides advantages that optimize network performance. Future work will investigate network security to improve transmission safety during broadcast retransmission phases.

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