Binary Joint Network-Channel Coding for Reliable Multi-Hop Wireless Networks

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ABSTRACT

The high and variable packet loss in wireless networks due to the unreliable nature of wireless channels, interference, link or router failure, fading, and shadowing wireless link are the main problems and challenges in implementing a reliable wireless network. Packet loss probability is the most important performance measure for real-time applications. Packet loss is due to errors, congestion in the queue because of high traffic, collision, hidden nodes, and link failures. In this paper, we focus on the links failure problem. To address this problem, improve the performance of wireless networks, and enhance and make the network survivability and availability more reliable, a new efficient binary joint network and channel coding (B-JNCC) technique is proposed. B-JNCC combines low-complexity parity-check (LCPC) channel coding and the wireless network erasure correcting with router code to detect lost packets to reduce the bit error rate and increase the packet delivery ratio over a wireless multi-access channel. B-JNCC is applied at the receiver node. Simulation results show that the proposed B-JNCC outperforms the binary symbol-wise JNCC, non-binary JNCC (NB-JNCC), and NB separate network-channel coding.

Keywords: Wireless Network Coding, Channel Coding, Joint Channel-Network Coding, Multihop Wireless Networks

1. INTRODUCTION

Wireless network communications suffer from packet loss due to the detrimental effect of the fading of wireless channels and link failures. Motivated by this problem, this paper presents a novel binary joint network coding with channel coding (B-JNCC) scheme to provide reliable multi-hop wireless mesh networks. The B-JNCC technique combines low-complexity parity-check (LCPC) [1] channel coding and the wireless network erasure correcting with router detected packet loss (WNEC-RDPL) algorithm. This combination assists in the complete exploitation of the spatial variability and redundancy in both channel and network encoding.

The B-JNCC technique is proposed to reduce the bit error rate (BER) over wireless multi-access channels with a low signal to noise ratio (SNR) and increase the packet delivery ratio (PDR) over multi-access wireless channels. This research focuses on the multi-path, multi-hop wireless network topology that consists of one source router, one destination router, and multiple relay routers. In wireless networks, the packet is dropped if the retransmitted information is still erroneous. This causes retransmission of the data, which is a waste of bandwidth and time and leads to poor network performance [2–4]. In addition, packets can be lost due to errors, congestion in a queue due to high traffic, collisions, hidden nodes, and link failures. The problem of packets dropped is critical in real-time applications, such as video conferencing and remote control in a wireless sensor network (WSN) [5]. In addition to channel coding, wireless network coding (WNC) has been considered a promising solution because it can improve the quality of service of wireless networks by retrieving packets lost [6]. In a traditional store-and-forward network, packets are forwarded hop-by-hop along the intermediate routers from a source to a receiver. An intermediate node forwards the packets as it receives them through a predefined path. WNC is a recent field in information theory that allows intermediate nodes to generate new packets by combining the packets received on their incoming ports before sending the combined data on its output links instead of simply forwarding data [7] to increase the capacity and throughput of each link (path) and increase the PDR.

The aim of channel and network coding techniques is to retrieve the original information [8]. Channel coding is used for point-to-point communication over a single channel. It is implemented at the physical layer to recover erroneous bits through the redundant parity check bits added inside a packet. The error recovery capability for channel coding depends on the specific coding and the number of redundant bits. Network coding can be used to

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handle lost packets for end-to-end communication by using redundant packets to recover the original information [9], [10]. Joint channel-network encoding provides reliable communication and achieves better performance for a network communication system than when channel and network encodings are designed separately [11–14]. The demand for real-time and multimedia applications has increased due to the rapid increase in the number of wireless network users. In addition, providing high-speed and reliable services with the ability to access videos over the Internet and share large files in wireless mesh networks is a fundamental challenge due to interference and the unreliable nature of wireless links (i.e., variable link qualities), which cause packet losses and link failures. Moreover, some applications cannot use automatic repeat-request (ARQ) when the packet is lost because the original packets are no longer available in the source. For example, most of television cameras immediately forget information as soon as it is sent and cannot resend the original packets.

Tuan et al. [11] presented and investigated a joint network and channel encoding technique to increase the bandwidth efficiency of single hop wireless networks, such as WLAN or WiMAX networks. Qiang et al. presented a joint network and channel encoding with retransmissions for broadcast and multiple access channels [13]. Furthermore, the authors in [15] and [16] proposed joint network channel encoding for two-way and multi-access relay channels. The authors in [17] presented a general framework that merges channel and network encoding. Jiafeng et al. [18] proposed a joint network channel encoding algorithm for wireless relay communications to reduce the BER over the wireless multi-access channel. Thobaben proposed a non-binary JNCC (NB-JNCC) for multiuser ARQ [19]. By exploiting ARQ, receiver-side information, and correlated sources, Qiang et al. [20] proposed a JNCC strategy. Guo et al. [21] proposed a practical NB-JNCC for multi-path multi-hop communication in large-scale wireless networks. The authors combined the non-binary irregular low-density parity-check (LDPC) channel encoding [22] and random linear network encoding [23–25] through iterative joint decoding. Zhang et al. [26] employed a JNCC with a specially designed rate loss code. They considered an asymmetric time division multiple access relay system that consists of two sources, namely, one relay and one destination. Liu et al. [27] proposed the JNCC scheme for reducing the energy consumption in WSNs. Christian et al. [28] considered a binary channel encoding on a binary symmetric channel (BSC) and q-ary RLNC for erasure correction in a star network. The authors analyzed the joint design of channel encoding on the physical layer and random linear network encoding on the data link layer for a star network topology.

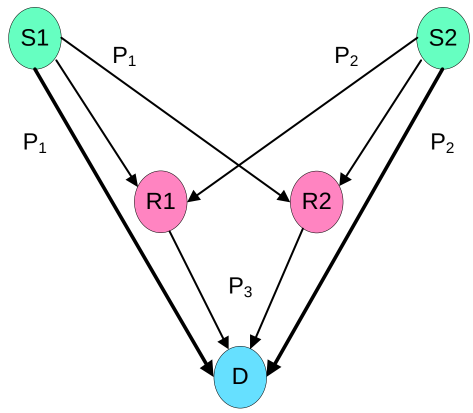

Fig.1: *Simple example of two sources, two relays, one destination network topology.*

In [29], a new joint source channel network encoding (JSCNC) using Quasi Cyclic Low Density Parity Check (QCLDPC) code is proposed for a sensor network with two source nodes communicating correlated information to multiple destinationnodes.A joint iterative channel-network decoder for use at the base station in a system employing a Diversity Network Code (DNC)is presented [30]. The proposed scheme is based on hybrid soft/hardmessage passing between constituent low-complexity low-density parity-check (LDPC) decoders.The authors in [31] proposed a Joint Channel Network Coding (JCNC) scheme applied to Multiple Access Relay Channel (MARC) for correlated sources. Table 1 summarizes the related works in joint network and channel coding (JNCC).

The rest of this paper is organized as follows. The proposed B-JNCC model is described in Section 2. The simulation results and the performance of the proposed scheme are presented in Section 3. Section 4 concludes this paper.

2. BINARY JOINT NETWORK - CHANNEL CODING MODEL

In this section, the encoding and decoding procedures of the proposed B-JNCC are presented. Specifically, B-JNCC combines LCPC [1] and WNEC-RDPL. This combination assists in completely exploiting the spatial variability and redundancy in both channel and network encodings. To understand the rationale behind the joint treatment of channel and network encoding, we provide a simple example in Fig. 1. Supposing we have a simple topology with five routers distributed as two sources, two relays, and one destination. The two source routers (S1 and S2) broadcast two independent packets (P_1 and P_2) after encoding them using the LCPC code to two relay routers (R1 and R2) and a common destination router (D). R1 and R2 encode the packets received using the WNEC-RDPL code, temporarily store the coded

Table 1: *Chronology of research activities on JNCC.*

Reference	Summary of work performed
(Hausl and Hagenauer, 2006) [15]	An extension of the relay channel model, called two-way relay channel was proposed and introduced. Time-division two way relay channel without power control was considered.
(Hausl and Dupraz, 2006) [16]	A joint network-channel coding based on turbo codes was proposed to be used for the multiple-access relay channel. Simulation results confirmed that joint network-channel coding outperformed separate network-channel coding.
(Tran *et al.*, 2008) [11]	A joint network and channel coding technique to increase the bandwidth efficiency of a single hop wireless network such as WLAN or WiMAX networks was presented. Simulation results showed that the proposed technique could increase the bandwidth efficiency for both broadcast and unicast scenarios in a single-hop wireless networks.
(Li *et al.*, 2009) [13]	A joint network and channel coding (JNCC) strategy was proposed, with retransmissions for broadcast channel with receiver side information (BC-SI) and orthogonal multiple access channel with correlated sources (MAC-CS).
(Thobaben, 2010) [19]	A joint network and channel coding scheme for multi-user ARQ was proposed. The proposed JNCC approach outperformed the conventional MU-ARQ significantly.
(Liu *et al.*, 2011) [18]	A joint network-channel coding algorithm for wireless relay communications was proposed, in order to reduce high BER over the wireless multi-access channel with low SNR. LDPC was applied as channel encoding to work together with network encoding in the relay node.
(Li *et al.*, 2011) [20]	A joint network and channel coding (JNCC) strategy was proposed by exploiting ARQ, RSI, and correlated sources. Wireless multicast network with multiple sources, relays, and destinations was considered. A multi-hop decode-and-forward relay protocol was adopted.
(Guo *et al.*, 2012) [21]	Non-Binary Joint Network-Channel Coding (NB-JNCC) for reliable multi-path multi-hop communication scheme was proposed. NB-JNCC combined non-binary irregular LDPC channel encoding and random linear network encoding through iterative joint decoding.
(Zhang and Zhang, 2013) [26]	An asymmetric time division multiple access relay system consisting of one relay and one destination was considered. The channel conditions and message lengths of the two sources were allowed to be different.
(Hernaez *et al.*, 2013) [35]	Joint non-binary network-channel codes for the time-division decode-and-forward multiple access relay channel (TD-DF-MARC) was proposed. The relay linearly combines the coded sequences from the source nodes. Simulation results showed that the proposed scheme outperformed other schemes.
(Koller *et al.*, 2014) [28]	Propose a binary channel encoding on a binary symmetric channel (BSC) and q-ary RLNC for erasure correction in a star network.
(Jesy and Deepthi, 2014) [29]	Proposed joint source channel network coding (JSCNC) using Quasi Cyclic Low Density Parity Check (QCLDPC) code for a sensor network.
(King and Flanagan, 2016) [30]	Presented a joint iterative channel-network decoder for use at the base station in a system employing a Diversity Network Code (DNC).
(Zid *et al.*, 2017) [31]	Proposed a joint channel network coding (JCNC) scheme applied to Multiple Access Relay Channel (MARC) for correlated sources.

packets, and then forward the packets to destination router D. R1 and R2 generate $P_3 = (P_1 \oplus P_2)$ and forward it to D, ($\oplus$ is the symbol of XOR logical gate). We assume that all routers operate with multi-radio, multi-channel techniques and all communications are linked over orthogonal channels, such that mutual interferences can be ignored.

Accordingly, the destination router (D) in the normal case (i.e., no link failure) will receive four packets, that is, two packets from S1 and S2 (i.e., P_1 and P_2) and two packets from R1 and R2 (i.e., P_3). The destination receives P_1 and P_2 from S1 and S2, respectively, and receives double P_3 from R1 and R2. B-JNCC will be implemented at destination router D. At D, the LCPC encoding allows the router to detect and correct signal and double bit errors [1]. In contrast, the WNEC-RDPL code can recover the packets that the LCPC code cannot correct or those lost due to link failure. The capability of detecting and correcting error packets when B-JNCC is used with the topology shown in Fig. 1 is shown in Table 2. Destination router D aims to receive P_1 and P_2 correctly. If D cannot correct the bit errors in P_1 or P_2 directly, then the LCPC tries to correct the P_3 received from R1 and R2. Then, D can use P_3 to recover the packet that cannot be corrected (i.e., P_1 or P_2). In the worst-case scenario, if the LCPC cannot recover P_1 and P_2, then WNEC-RDPL sends NAK to R1 and R2, then the latter sends the packets (i.e., P_1 and P_2) received from S1 and S2, respectively, to D. Thus, D will receive 2 packets of P_1 and 2 packets of P_2 from R1 and R2, respectively. Again, the LCPC code detects and corrects the new packets received to obtain P_1 and P_2.

Table 2: *Capability of error detection and correction for B-JNCC at the destination.*

Index of of Possibility	**Possibilities received packets at the destination router (D)**				States correction error packets at (D)
	P_1 from S1	P_2 from S2	P_3 from R1	P_3 from R2	
1	✓	✓	✓	✓	✓
2	×	✓	✓	✓	✓
3	✓	×	✓	✓	✓
4	✓	✓	×	✓	✓
5	✓	✓	✓	×	✓
6	×	×	✓	✓	✓
7	×	✓	×	✓	✓
8	×	✓	✓	×	✓
9	✓	×	×	✓	✓
10	✓	×	✓	×	✓
11	✓	✓	×	×	✓

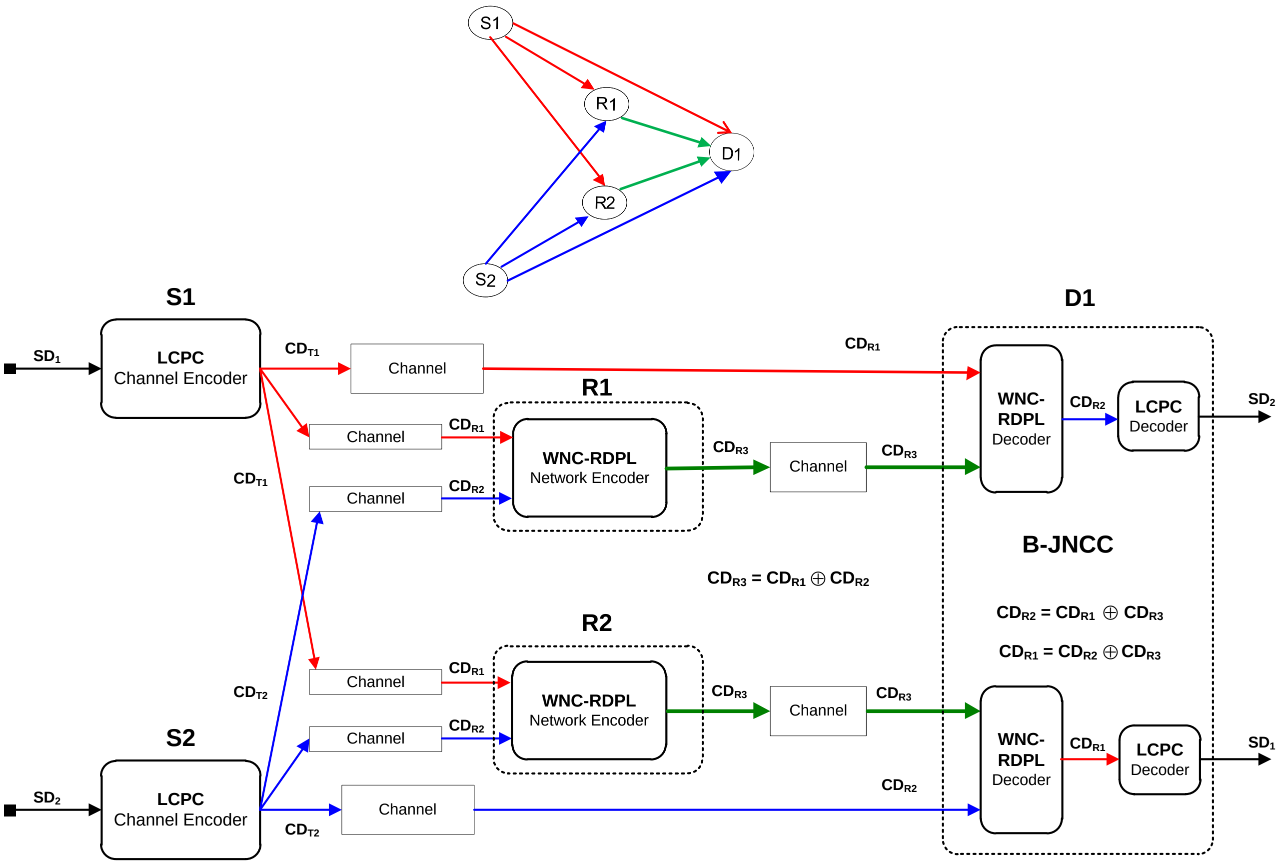

Fig.2: *Architecture of proposed B-JNCC for a simple example with two sources, two relays, one destination.*

Fig. 2 shows more details about the architecture and the functions of each router for our proposed B-JNCC when applied with the topology shown in Fig. 1. All channels are assumed to be lossy, which is one difference between our work and other works that assumed that the channels between the source and relay routers are lossless. S1 generates CD_{T1} from encoding SD_1 (4 bits) using the LCPC code in the same way that S2 generates CD_{T2} from encoding SD_2. S1 and S2 broadcast their encoded data to R1, R2, and D over the lossy wireless channel. Owing to the lossy channel, R1, R2, and D received CD_{Ri} that is considered to be $CD_{Ri} = CD_{Ti}$ + E, where E is the error bits.

2.1 System Model Topology of B-JNCC

In this subsection, the proposed topology consists of one source and one destination routers with multi intermediate (relay) routers as shown in Fig. 3. This

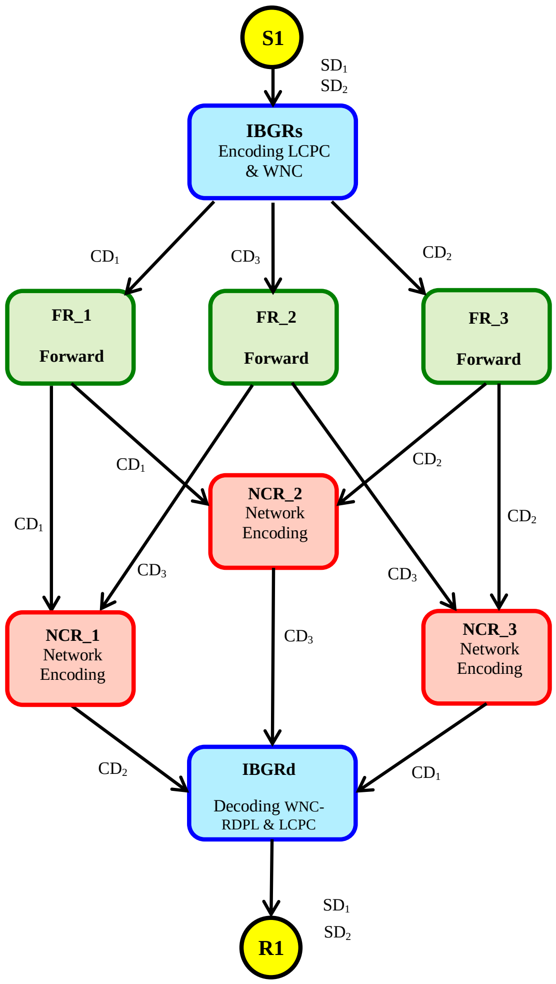

Fig.3: *Joint LCPC channel with WNEC-RDPL network encoding.*

topology has three types of routers that operate with the multi-radio, multi-channel (MRMC) technique as follows. The first type is an internal border gateway router (IBGR, called IBGRs at the source side and IBGRd at the destination side), which encodes the packets using the LCPC encoding and forwards the packets. The second type is a traditional forward router (FR, the current approach), which forwards the packets received. The third type is the coding router (CR), which encodes using WNEC, stores, and forwards the packets. The packets are temporarily stored for a short time until the CR receives an acknowledgement signal (ACK) from the IBGRd at the receiver side. The IBGRd decodes the packets using the LCPC channel encoding and the WNEC-RDPL network encoding.

To avoid the interference between radios for routers operating in the MRMC, a static channel assignment algorithm assigns one channel to each radio for all routers. Channel assignment algorithms allow different nodes in the same wireless network to communicate with one another without causing interference for neighbors [32], [33].

IEEE 802.11a wireless technologies that provide 12 non-overlapping channels (orthogonal channels) [32] are used in the proposed scheme. In the MRMC technique, a router can transmit and receive data simultaneously (as full duplex transmission) on those different channels without the data streams interfering with one another. However, all of the routers within each other's interference range must be on different channels to ensure such interference free communication. Ensuring that all of the potentially interfering routers are assigned different channels is known as the channel assignment problem [33], [34]. The channel assignment problem becomes more challenging to solve when each router is equipped with multiple radios because when a router is equipped with multiple radios and multiple radios operate on the same channel, the interference from a router's own radios leads to packet collisions. However, if each of the multiple radio interfaces on a router operates on a different channel, then the network performance will improve. Therefore, every router in the network can communicate with the others simply by tuning the radio interfaces of the communicating routers to the same channel.

The IBGRs use Ethernet ports to receive symbols for the source node (i.e., SD_1, SD_2) and the three radio interfaces for sending CD_1, CD_2 and CD_3 to the next hop router (FR). An IBGR first encodes SD_1 and SD_2 to obtain CD_1 and CD_2 then it uses the LCPC code, and finally generates CD_3 from XOR-ed CD_1 and CD_2. We assume that all the transmitted packets have a fixed length (L, 1500 bytes) and are under the same modulation scheme (i.e., BPSK).

Fig. 3 shows three FRs (i.e., FR_1, FR_2, and FR_3). This type of routers broadcasts any packets received without any modification to the next hop router. CR has three radios and uses two radios for receiving different packets from FR_1, FR_2, and FR_3 (in our case, CD_1, CD_3 from FR_1 and FR_2, respectively, and CD_2, CD_3 from FR_2 and FR_3, respectively) and one radio to forward the encoded packets after encoding (XOR operation) the packets received from the FR. NCR_1, NCR_2, and NCR_3 temporarily store the packets received from the FR (i.e., CD_1, CD_2, and CD_3) and send these packets when a negative acknowledgement signal (NAK) is received from the IBGRd. The CR deletes the packets stored when an ACK is received from the IBGRd. We assume that the ACK and NAK signals are never lost.

IBGRd works with a MRMC and has four radios. Three radios are used to receive the packets (i.e., CD_1, CD_2, and CD_3) from NCR_1, NCR_2, and NCR_3, respectively, and one radio is used to forward the decoded packets to the receiver nodes. The IBGRd has two functions, namely decoding using the LCPC and the WNEC-RDPL. The IBGRd sends an ACK to NCR_1, NCR_2, and NCR_3 if any two

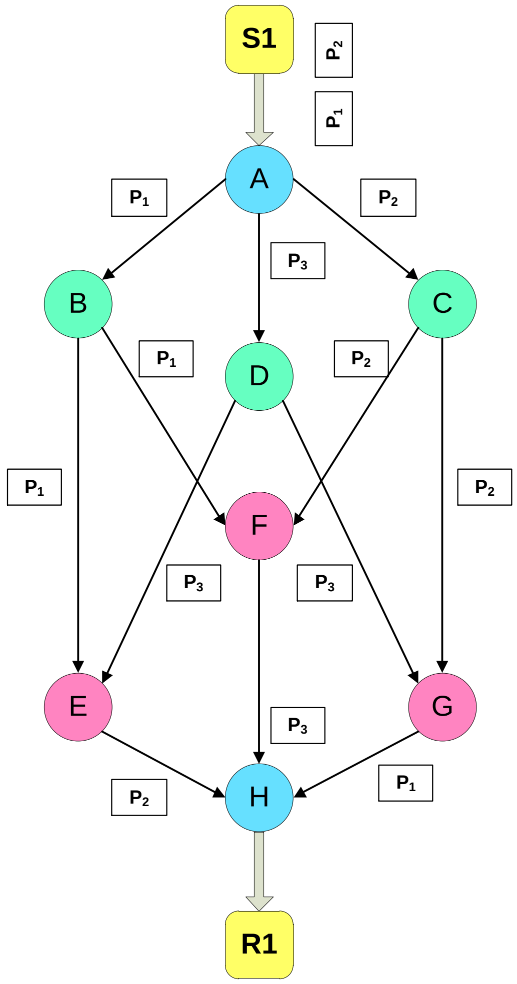

Fig.4: *One source one receiver network topology.*

different packets are received correctly. Otherwise, a NAK is sent. For simplicity, all the ACK/NAKs are assumed instantaneous and never lost. That is, we insist the feedback channel is error free and has no delay.

2.2 Algorithm of B-JNCC

In this subsection, we present the algorithm of the B-JNCC. Fig. 4 shows the proposed network topology scenario that considers one source and one receiver (1S_1R). Fig. 4 shows 8 routers that are connected by 12 links. These 8 routers work with the MRMC technology. Router A (RA) is an IBGR used to encodes and forwards packets. Routers B, C, and D (RB, RC, and RD) forward the packets received without any modification. RE, RF, and RG encode, store, and forward packets. RH is an IBGR and is near the receiver side. This router decodes and forwards packets to receiver1 (R1), which is connected to RH via an Ethernet port.

Source1 (S1) transmits two packets (P_1 and P_2) to receiver1 (R1) through a wireless mesh network backbone. RA receives the packets (i.e., P_1 and P_2) via an Ethernet port as shown Fig. 4. RA generates P_3 by encoding ($P_1 \oplus P_2$). RA forwards three packets (i.e., P_1, P_2 and P_3) to RB, RC, and RD respectively, using the multiple radio technique (three radio interfaces). RB, RC, and RD work as intermediate routers (forwarding packets to the next hop) that have one input and two outputs.

Then, RB, RC, and RD forward (broadcast) the packets received to the next hop routers (RE, RF, and RG), and these routers receive two types of packets via the two radio interfaces. Using the MRMC, the router can simultaneously receive different packets from different routers. For example, RE receives P_1 from RB via the link BE (LBE) and receives P_3 from RD via link DE (LDE). Similarly, RF receives P_1 and P_2 from RB and RC via LBF and LCF, respectively, and RG receives P_2 and P_3 from RC and RD via LCG and LDG, respectively. Network encoding routers RE, RF, and RG, which have two input ports and one output port, implement three functions: encoding of packets received, storing of packets received, and forwarding of encoded packets to the next hop router.

The network encoding router deletes the stored packets when an ACK signal is received from RH. Otherwise, each encoding router (i.e., RE, RF, and RG) sends the packets received to RH when a NAK is received from RH. RH decodes the packets received and forwards them to R1. RH can decode the packets if at least two different packets are received, sending an ACK to RE, RF, and RG. Otherwise, if RH receives only one packet from RE, RF, and RG or the same packet two times (e.g., RE and RF send P_1 while RG did not send any packets because LDG and LCG are failing), it sends a NAK. In this case, RE, RF, and RG send the packets previously stored in RH. RH can recover P_1 and P_2 from the packets received. RH knows (from the initial configuration of the routing table) that the packets received from RE via LEH are P_1 and P_3, those from RF via LFH are P_1 and P_2 , and those from RG via LGH are P_2 and P_3.

If no link failure occurs, RH receives P_1, P_2 and P_3 from RG, RE, and RF via LGH, LEH, and LFH, respectively. For example, when RH receives P_1 and P_3 due to some link failure (e.g., LBE and LDE), P_2 can be retrieved from ($P_1 \oplus P_3$). Fig. 5 shows the algorithm that WNEC-RDPL uses for recovering a lost packet for 1S_1R. Fig. 6 shows the flow chart of the B-JNCC operation at RH.

3. PERFORMANCE EVALUATION

In this section, the performance of B-JNCC is evaluated based on the topology shown in Fig. 4. We compare the performance of B-JNCC with two schemas, namely, direct transmission with relays (DTR) and the LCPC [1]. In the DTR case, the source directly transmits packets to the destination, and relay routers forward the packets received from

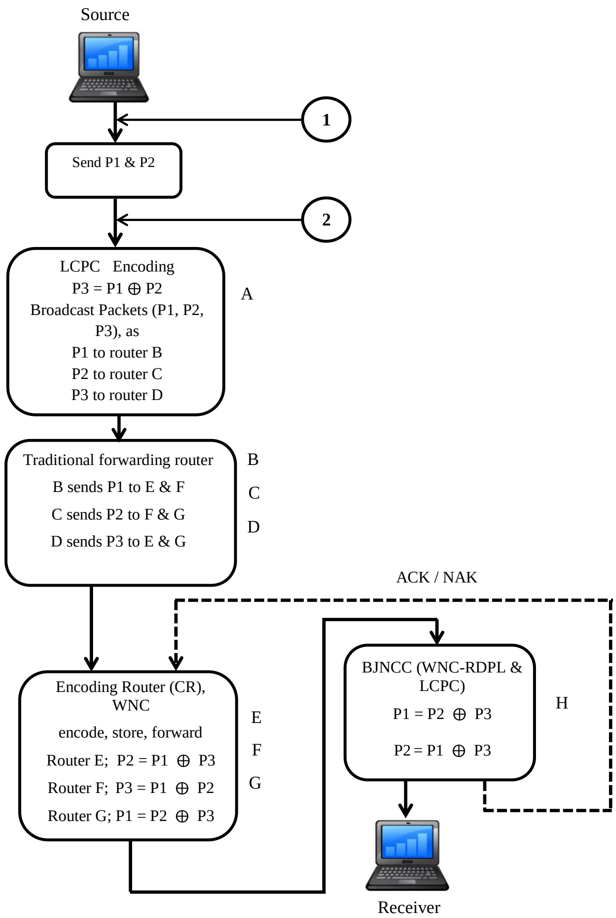

Fig.5: *Architecture of the B-JNCC algorithm.*

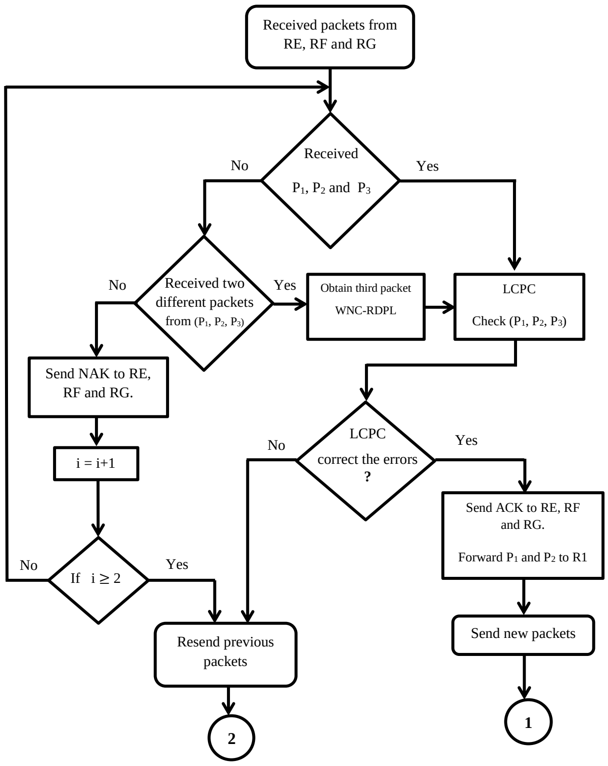

Fig.6: *B-JNCC algorithm for recovering lost packets received by the IBGRd.*

the source to the destination. Verification is performed whenever the proposed systems are simulated using computer programs. The simulation results of the proposed RS coded cooperation schemes are obtained under a slow fading channel, verifying the correctness of the derived mathematical equations for the outage probability. Moreover, the performance of the proposed data systems is evaluated in terms of the BER for various channels' SNR.

3.1 Simulation Results

The topology used in this simulation is the network presented in Fig. 4. The performance of the B-JNCC schema is investigated by computing the PDR, the BER, and the block error rate (BLER). The BLER refers to the number of blocks with at least one error bit. The length of the block is 9 bits (i.e., codeword length) based on the LCPC encoding.

A. Packet Delivery Ratio (PDR) Results

The PDR is the ratio between the number of correct packets received at the destination to the total number of packets sent. The performance of B-JNCC is investigated in the case where 100 packets are sent at different SNRs over the AWGN channel with BPSK. Fig. 7 shows the PDR-SNR curve for the DTR (without encoding), the LCPC code, and the B-JNCC. Fig. 7 shows that the PDR of the three systems increment to different extents with the SNR. However, the PDR reaches 100 % in the LCPC case with B-JNCC at low SNR values (3 dB), whereas in the DTR case, the PDR reaches 100 % at SNR (less than 11 dB). Fig. 7 shows that the PDR values in the B-JNCC case are better than the LCPC at low SNRs (less than 2 dB).

B. Bit Error Rate (BER) and Block Error Rate (BLER) Results

In addition to the PDR performance evaluation, the performance of BER and BLER for the B-JNCC is investigated at different SNRs using BPSK over the AWGN channel when 1000 packets are transmitted. Fig. 8 illustrates the BER versus the SNR for DTR, the LCPC code, and B-JNCC when 1000 packets are sent. Fig. 8 shows that the BER values of the three systems decrease to different extents along with the increment in SNR. However, the performance of BER in B-JNCC is better than that of the DTR and the LCPC, and the BER of the B-JNCC and the LCPC encoding drops rapidly with the increasing SNR. The code gain from using B-JNCC is approximately 2 dB compared with the LCPC code at BER 10^{-5}. Similarly, Fig. 9 shows the BLER versus the SNR for

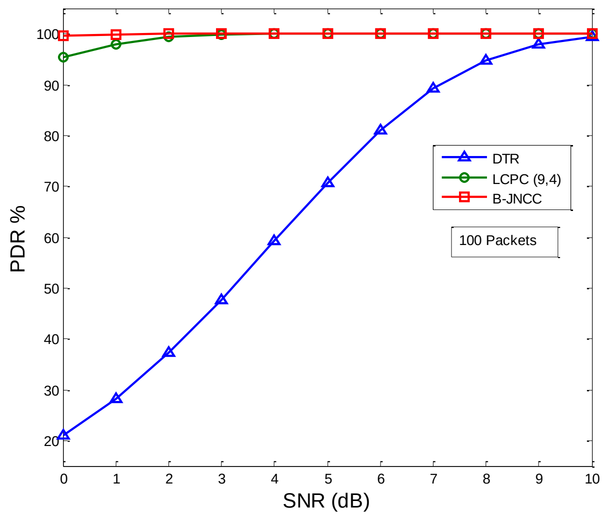

Fig.7: *PDR versus SNR using BPSK over AWGN.*

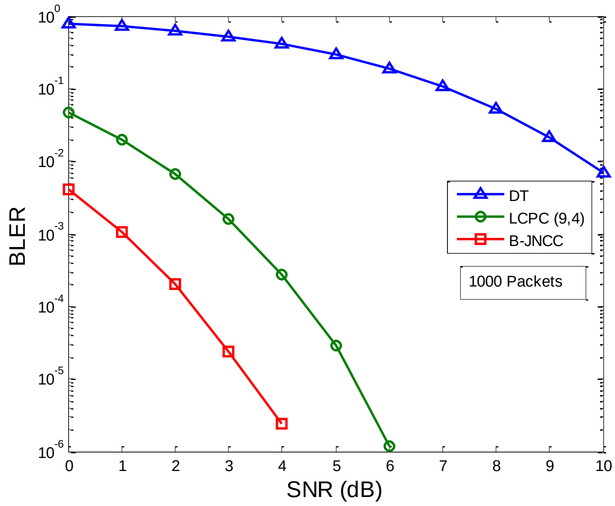

Fig.9: *BLER versus SNR using BPSK over AWGN.*

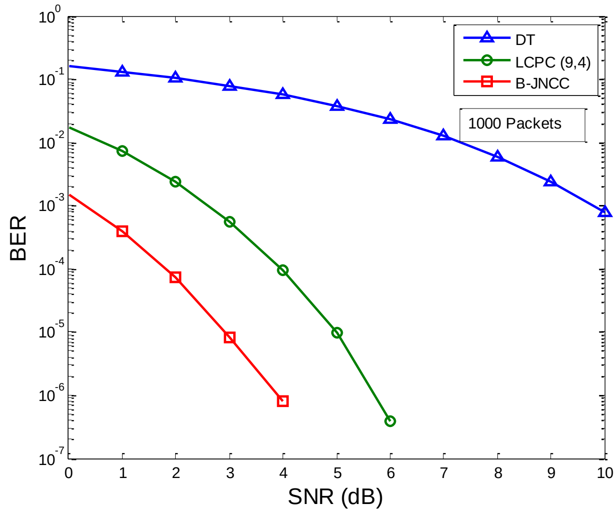

Fig.8: *BER versus SNR using BPSK over AWGN.*

the DTR, the LCPC code, and B-JNCC when 1000 packets are sent. Fig. 9 shows that the BLER of the B-JNCC rapidly decreases and continuously improves with the increments of the SNR compared with those of the DTR and the LCPC. Moreover, the code gain from using B-JNCC is approximately 2 dB compare with the LCPC encoding at BER 10^{-5}. Overall, the simulation results clearly show the benefits of the proposed B-JNCC over the LCPC when the latter is used alone.

3.2 Performance Evaluation Comparison with Various Schemes

The performance of B-JNCC was evaluated over the two-source two-relay topology using MATLAB simulation as shown in Fig. 1. B-JNCC was compared with other schemes, such as binary symbol-wise joint network-channel encoding (BS-JNCC) [21], NB-JNCC [21], and non-binary separate network-channel encoding (NB-SNCC). NB-SNCC schemes treat channel and network encoding separately, where channel decoding is followed by network decoding with no iteration [11], [30]. In DTR, the sources directly transmit packets to the sink, and the relays forward the packets received from the source to the sink. In direct transmission without relays (DT), the sources directly transmit packets to the sink, and the relays do not forward any packets. To demonstrate the benefits of B-JNCC, extensive simulation results are presented based on the network topology shown in Fig. 1. In this simulation, the LCPC (9, 4) and WNC-RDPL encodings are combined, and the results are obtained by using both BPSK and 16-QAM modulation under a fading slow channel. Fig. 10 compares the packet error rates (PERs) of various schemes under varying average received SNR and BPSK modulation. B-JNCC outperforms BS-JNCC, NB-SNCC, and NB-JNCC [17–21]. For example, at a PER of 10^{-3}, B-JNCC outperforms BS-JNCC, NB-SNCC, and NB-JNCC by approximately 10, 9, and 7 dB, respectively.

Figs. 11 and 12 show the comparison of the generation error rate (GER) for B-JNCC with various schemes over a slow fading channel with BPSK and 16QAM modulations. Fig. 11 shows the results with BPSK modulation. Fig. 11 shows that B-JNCC outperforms other schemes in BPSK modulation. For example, at a GER of 10^{-3}, B-JNCC outperforms BS-JNCC, NB-JNCC, and LCPC by approximately 11, 9, and 7 dB, respectively. Fig. 12 presents the results with 16-QAM modulation. In addition, B-JNCC is better than other schemes under 16-QAM modulation. Fig. 12 shows that B-JNCC outperforms other schemes. For example, at a GER of 10^{-3}, B-JNCC outperforms DT, DTR, BS-JNCC, NB-JNCC, and LCPC by approximately 25, 15, 14, 7, and 6 dB, respectively. Simulation results demonstrate

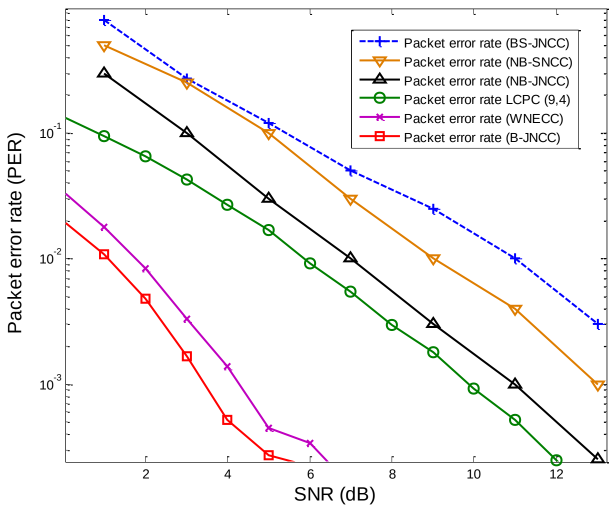

Fig.10: *Packet error rate of B-JNCC and other schemes over fading channel with BPSK modulation.*

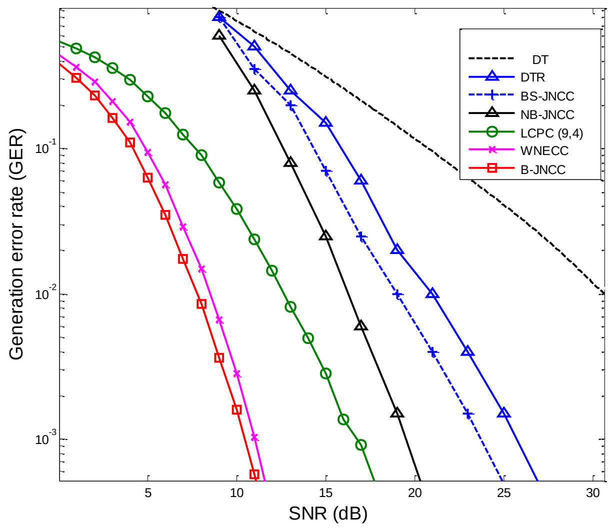

Fig.12: *Generation error rate of B-JNCC and other schemes in the 16-QAM modulation case.*

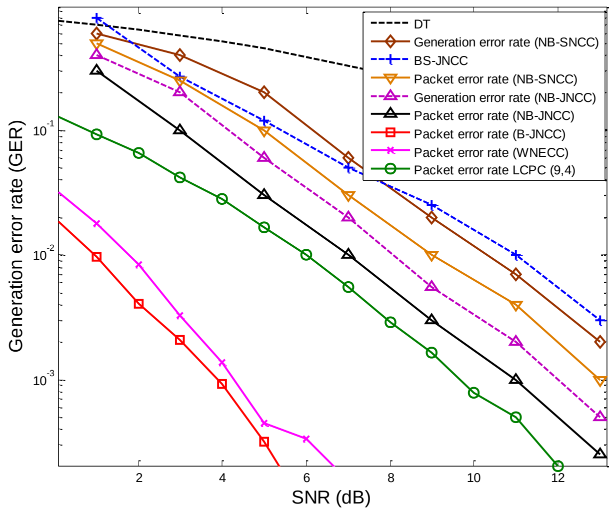

Fig.11: *Generation error rate of B-JNCC and other schemes in the BPSK modulation case.*

the significant benefits of B-JNCC compared to other schemes reported in [21]. Joint channel-network encoding provides reliable communication and exhibits better performance in a network communication system than when channel and network encodings are designed separately [11], [13], [21], [26], [35].

4. CONCLUSIONS

In this paper, a novel B-JNCC scheme for reliable multihop multi-radio multi-channel wireless mesh networks is proposed. B-JNCC combines the LCPC and WNEC-RDPL schemes to reduce the BER and the BLER and increase the PDR over wireless channels. The LCPC encoding is implemented at the physical layer to recover erroneous bits through the redundant parity check bits added inside a packet. Meanwhile, the WNEC-RDPL scheme is used to handle lost packets on the end-to-end connection level by using redundant packets to recover the original information at the network layer for end-to-end communication. The performance of the proposed B-JNCC with BPSK and 16-QAM modulations over the AWGN and slow fading channels was investigated. The performance was then compared with that of previous work. Joint channel-network encoding provides reliable communication and exhibits better performance in a network communication system than when channel and network encodings are designed separately. Simulation results show that the proposed B-JNCC scheme significantly outperforms the conventional and renowned joint channel and networks encoding schemes by increasing the PDR and reducing the BER and the BLER.

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