Joint Forward Error Correction and Network Coding for Wireless Sensor Networks

Dr. Abdulkareem A. Kadhim
Department of Networks Engineering
AL-Nahrain University, Baghdad, Iraq

Maryam K. Abboud
Department of Information and Communications Engineering
AL-Nahrain University, Baghdad, Iraq

Abstract- This paper investigates the combination of two coding schemes; Forward Error Correction (FEC) and Network Coding (NC) to improve the performance of wireless sensor networks (WSNs). Bit error rate (BER), transmission throughput, and consumed energy are the main performance measures considered for WSN. Two different network models are considered; butterfly network with five nodes and a suggested mixed Mesh-Star-Tree (MST) network with eleven nodes. The system is simulated and an energy model is adopted and developed to calculate the consumed energy for each case. Using NC may slightly increase BER under some conditions, while increasing the overall throughput at high Signal-to-Noise power ratios (SNRs). The results show that the combination of RS and NC reduce the consumed energy by reducing the number transmissions and hence improving transmission throughput as well. For some favorite test conditions, the obtained percentage energy saving may be as large as 25% and 62.5% for butterfly and MST networks respectively. This is obtained with the aid of RS and NC coding. Such performance improvements are obtained even when the transmission is performed over a typical model of frequency selective fading channel. In addition to the cost of slight BER degradation in some cases, the practical implementation of the suggested combination remains a real challenge.

Keywords – Linear network coding, Reed Solomon code, WSN, Energy consumption.

I. INTRODUCTION

A small microprocessor integrated with number of sensors to form what is called a sensor node can form a type of wireless networks consist of many of these small, autonomous devices called Wireless Sensor Network (WSN). These nodes are usually working together to solve different problems in many wireless communication applications where the use of WSNs became easy and increased rapidly [1]. Two fundamental characteristics are possessed in WSNs compared to other categories of wireless networks: multi-hop transmission and constrained energy sources. These characteristics are affected by wireless noisy links which leads to information bits changes and hence unrecognizable data reception may occur [2]. In order to solve this problem, FEC coding is used to correct errors and combined with NC to reduce number of transmissions. Many researches cover the two main topics of present paper; the use of FEC and NC to improve WSNs performance. The work in [3] introduced a two-way relay channel coding scheme were two users want to communicate with each other through a relay node that perform NC while the users perform channel coding operations. Zhang et. al. [4] proposed a system where the two schemes (FEC and NC) are combined together. Network coding was performed prior to channel decoding by directly combining the soft/hard decisions at destination side. They showed that the scheme can achieve almost the same channel capacity as the traditional network coding scheme under moderate to high SNR. A highly robust system could be achieved by combining Reed Solomon (RS) coding for wireless networks at the source nodes and the combination of RS coding and NC at the intermediate nodes to enhance robustness and reduce the required resources [5-8]. The same combination is used for star networks in [9], where the source nodes generate packets of size k which is then combined to form one packet using network coding on a Binary Symmetric Channel (BSC) paired with Automatic Repeat Request (ARQ). An adaptive version of channel coding and network coding was proposed in [10] and performed at data link layer to fulfill the requirements of QoS for WSN applications by adjusting RS coding parameters and selecting the optimal relay nodes. Combination of NC with FEC coding is also used for unicast transmission in the presence of fast Rayleigh fading [11-13], where some improvement in performance of WSN is achieved.

In this work, the nodes of WSN are classified into three types which are; source nodes, coding nodes, and destination node. The proposed system performs error correction encoding/decoding in a node to node scenario with end to end NC encoding/decoding. The transmitted packets are first encoded using RS code at the source nodes and transmitted through the network. At the coding node, an intermediate node, packets received from different links are decoded using RS decoder and combined together using NC which is then followed by another RS encoding operation. At the destination node, both RS decoding and NC decoding are performed to retrieve the source transmitted packets. A generalized network topology model having combined star, mesh and tree structure is considered in the work.

The rest of the paper is organized as follows. Clarifying such model together with other system parameters and specifications proposed in section II. Performance evaluation in the form of BER, throughput and consumed energy are then presented in sections III and IV. This is followed by the simulation results in section V. Finally the main concluding remarks are given in section VI.

II. SYSTEM MODEL

The model of the proposed system where the combination takes place is shown in Figure 1. In Forward Error Correction (FEC), Reed-Salomon (RS) code is used as an error correction coding scheme. It has maximum separable property, which provides best error correction capability as compared to other block codes having the same code parameters (n, k, t) [14]. For the network simulated in the present work, node to node FEC coding/decoding operation is considered. Two important parameters of RS code need to be defined; the code word length n and the data block length k. These will determine the error correction capability t of the code where t=(n-k)/2 [14]. The decoding process used for RS code is Berlekamp and Chien's algorithm [15]. The coding parameters for RS code used in the work are given by (255,247, 4) representing(n, k, t).

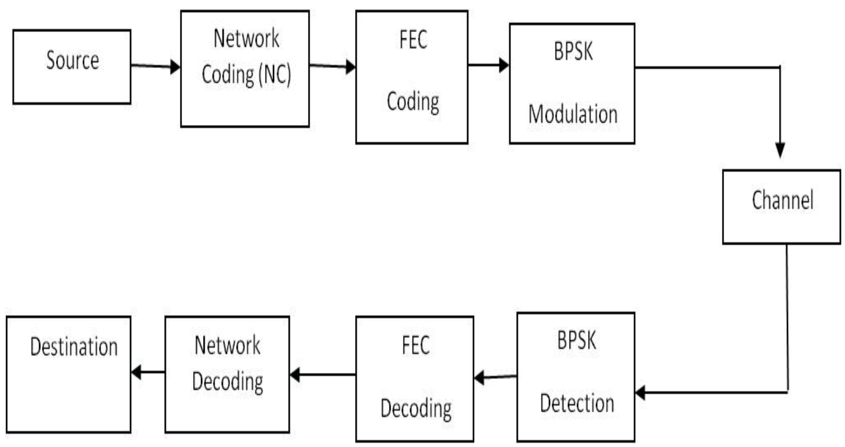


Figure 1. Joint FEC and NC system model in an intermediate node.

The processing involved in Network Coding (NC) block of Figure-1 is based on applying Random Linear Network Coding (RLNC) at each coding node based on generating independent vectors [16]. The process here is an end to end network coding/decoding, where the encoding process performed by the coding nodes is resolved by the decoding process performed at the final destination node (sink node) of the WSN. To improve wireless throughput and simplify the processes of coding and decoding, the coding is performed at the packet level where packets received by the coding nodes are queued in a First in First out (FIFO) rule to be network encoded. The intermediate (coding) node linearly combines packets as given by Equation (1) using independently generated coding vectors with elements being randomly chosen from a finite field of elements called Galois Field (GF) [17];

$$X_k = \sum_{i=1}^{d} g_{i,k} S_k^i \qquad (1)$$

where; S^i represents the source packets ($S^1 \dots\dots S^d$), g_i represents the coding vectors ($g_1 \dots\dots g_d$) of finite field F_2^m elements, and X is the resultant coded packet. X_k and S_k^i are the k^{th} symbols of X and S^i, respectively. The decoding process implemented here applies a simple Gaussian elimination using the encoding vectors in the received packet's header [7,8,10,18].

The modulation method used is Binary Phase Shift Keying (BPSK), where both the demodulation and detection processes are assumed to be performed perfectly. Although, considering more sophisticated modulation schemes could provide some benefits, the aim here is study the effects of FEC and NC on network performance.

The network model is based on two network topologies to be described in the next section. Three wireless channel models are considered; Additive White Gaussian Noise (AWGN), flat fading, and multipath frequency selective fading channels. The latter is known as SUI-3 channel model that represent a moderate level of distortion [19]. SUI-3 channel model considered with three path delays and path gains given by (0, 0.4, and 0.9 μs) as its path delays and (0, -5, and -10) dB as its path gains, respectively [19].

III. Network Model

To show the advantages of NC with FEC, two different networks models are considered. The network required to be built must enable cooperative communication between all its nodes. This means that an opportunity for network coding with some network nodes is possible so that the advantage of NC can occur.

A. Butterfly Network Model-

This model is a wireless network model which consists of five nodes, two sources S_1 and S_2, two destinations D_1 and D_2 , and one coding node V. It is a well-known network used in NC literatures [20-22]. The source packets are transmitted and received by the coding and destination nodes through links as shown in Figure 2. The NC operation is performed at the coding node for the two received packets from S_1 and S_2, where the two queued packets (one from each source node) are XOR-ed. The coded packet is transmitted and then received by D_1 and D_2. The NC decoding operation is performed by the destinations D_1 and D_2 on received packets by the direct link together with NC encoding packets to extract all transmitted packets as shown in Figure 2.

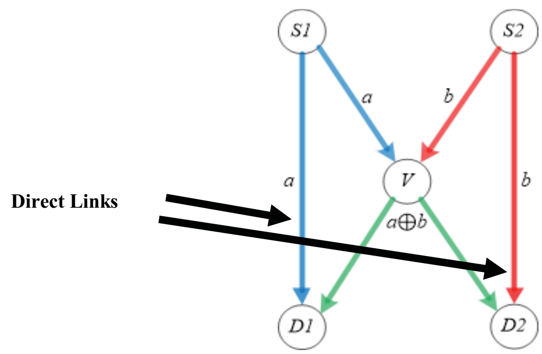


Figure 2. Butterfly Network Model

B. MST Network Model-

Since the performance evaluation of large WSN is a critical point due to the unknown nature of the geographical distribution of the nodes, following a pre specified topology is not a cost effective approach. Thus a more generalized model is proposed and used here. It is a mixed Mesh-Star-Tree network model, and is called here as MST model. The channel model could be any one of the three wireless channel models mentioned previously. Figure 3 provides an overview of MST network. It consists of few source nodes, intermediate (coding) nodes and a base station (sink node). Further, this network can be considered as an elementary sub-network belonging to a large WSN and is used here to simplify the performance evaluation in the work. The intermediate nodes which are the coding nodes perform NC in addition to FEC coding/decoding. The source nodes generate the data packets and perform FEC encoding, while the final destination node (sink node) performs FEC and NC decoding processes.

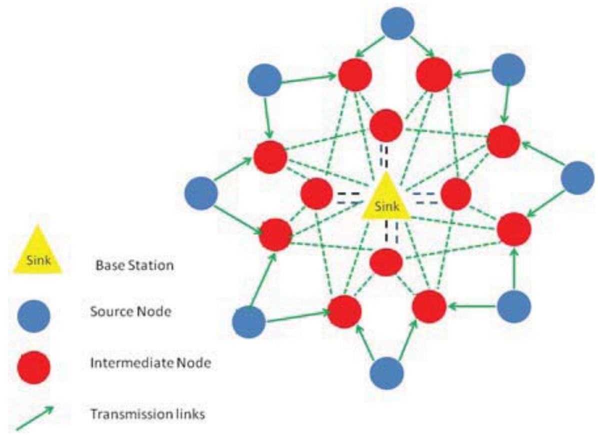


Figure 3. MST network model.

For the above two network models, the processing block for source, intermediate and sink nodes are clarified in processes block diagram shown in Figure 4. The idea behind implementing NC before FEC coding process in this modeling comes from the goal of reducing the required operations as much as possible to reserve energy. Since the source data is requested by the final destination, so, there is no need to perform NC decoding process at the coding nodes, and the implementation of this process done at the final receiving node which is the sink node only. Another point characterized by the number of FEC decoding operations will be implemented if a reverse order considered and each operation consume some power. As a result, this exchange will be time and power consuming. While in the model of Figure 4, the system reserves the right to perform NC decoding at the final destination node and since all received packets are encoded to one packet with NC, it keeps the number of FEC decoding operation to be performed once at each transmission cycle.

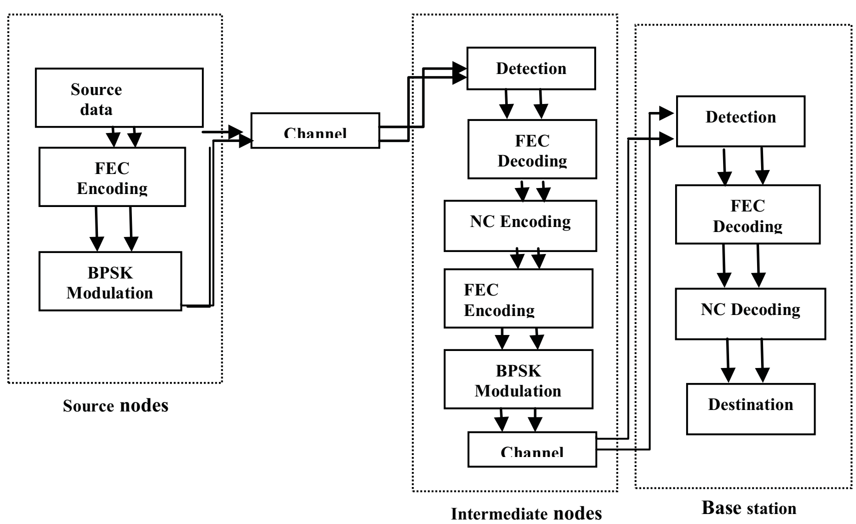


Figure 4. Processing blocks for source, coding and sink nodes.

IV. CONSUMED ENERGY MODEL

An energy calculation model suitable for the mentioned coding is needed to clarify the energy cost caused by each coding process. The required energy for NC and FEC encoding, and NC decoding operations are neglected since they are implemented within GF field where no floating points operations are needed [23]. The energy consumed (E_{cons}) by an intermediate node is given by:

$$E_{cons} = E_{TX} + E_{RX} + E_{FEC_{dec}} \quad (2)$$

where:

E_{TX} , E_{RX}, and $E_{FEC_{dec}}$ are the consumed energy in transmitting, receiving, and FEC decoding operation, respectively (for one packet).
E_{TX} and E_{RX} are given by [24];

$$E_{TX} = \left(E_{elec} + E_{amp} * d^{\gamma}\right) * \text{packet size} \quad (3)$$

$$E_{RX} = E_{elec} * \text{packet size} \quad (4)$$

where, $E_{elec}, E_{amp}, d,$ and γ represent the energy required for sending or receiving one data bit, amplifier energy, distance and the attenuation factor.

As mentioned before, the decoding process used for RS code is Berlekamp and Chien's algorithm [15], and this process consumes some energy represented by [25];

$$E_{FEC_{dec}} = (2nt + 2t^2) * (E_{add} + E_{mult}) \quad (5)$$

where, E_{add} and E_{mult} represent the energy consumption for addition and multiplication operations, respectively in GF [25].
Thus, the consumed energy may differ from node to node according to the role assigned to given node. The following are the three possible cases:

A. Source node-

$$E_{cons} = E_{TX} \quad (6)$$

B. Coding node-

$$E_{cons} = E_{TX} + E_{RX} + E_{FEC_{dec}} \quad (7)$$

C. Sink node-

$$E_{cons} = E_{RX} + E_{FEC_{dec}} \quad (8)$$

V. SIMULATION TESTS AND RESULTS

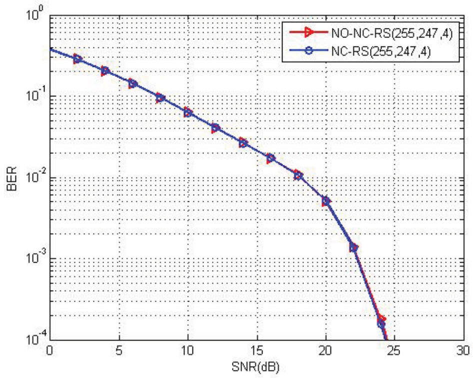
Bit Error Rate (BER), Throughput (Thru), and Consumed Energy (E_{cons}) are the main performance measures used in the work. Mainly two test conditions are considered; with and without NC in the presence of RS coding. BER is determined by calculating the ratio of the total number of erroneous received bits to the total number of transmitted bits. The throughput is determined by the ratio of the total number of correct received bits to the total number of actual bits transmitted in the system for the case where no NC is used. In the presence of NC, the throughput performance has the same definition and multiplied by the gain provided by NC. The latter represents the ratio of the total number of transmissions without NC to the total number of transmissions in the presence of NC. For the energy performance testes, as mentioned in previous section, each node consumed energy depending on the type of the performed process.

In addition to the aforementioned processes and operations, the following assumptions are considered; the capacity of all links is equal to one packet per unit time, all intermediate nodes can perform NC encoding, and the transmission rate is 4 kbps

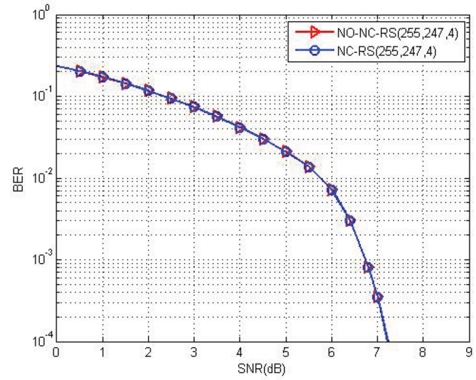
The main test conditions considered in the simulation covered different cases to calculate Bit Error Rate, Throughput, and Consumed Energy, can be summarized by:

A. Transmission without any coding.
B. Transmission with RS, but without NC.
C. Transmission without RS but with NC.
D. Transmission with both RS and NC.

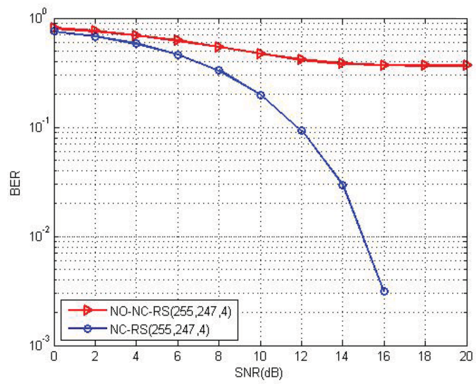
Figure 5 shows BER performance of the butterfly network with and without NC, and with RS (255, 247,4) over different channels. The process of NC for butterfly network is implemented by XOR-ing packets and then combined with RS code. Figure 6 shows the throughput performance for the combination of RS coding and NC over the same network. Regarding the energy performance tests for this network, Table-1 represents the energy consumption results of the combined schemes.



(b) Flat fading

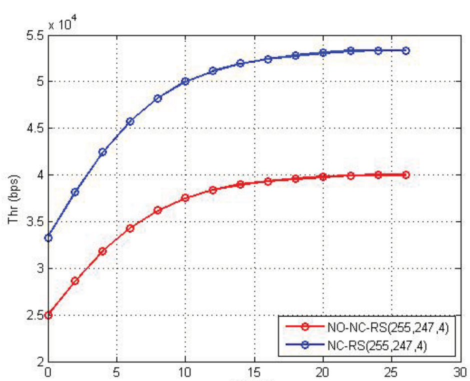


(a) AWGN

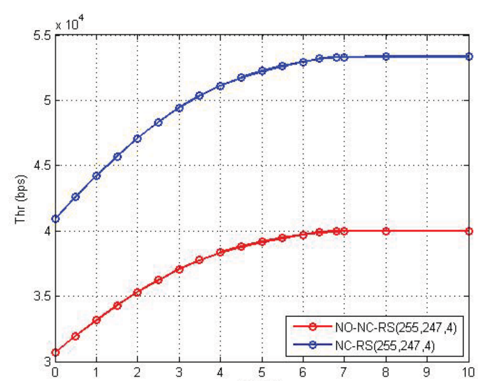


(c) SUI-3

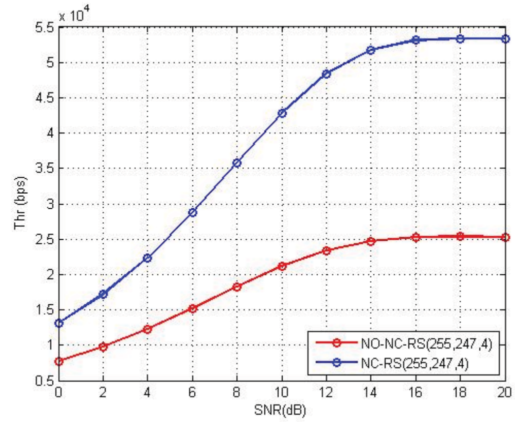
Figure 5. BER Performance of Butterfly Network over Different Channel



(b) Flat fading



(a) AWGN



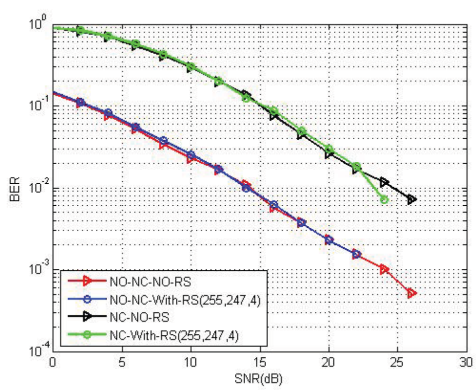
(c) SUI-3

Figure 6. Throughput Performance of Butterfly Network over Different Channels.

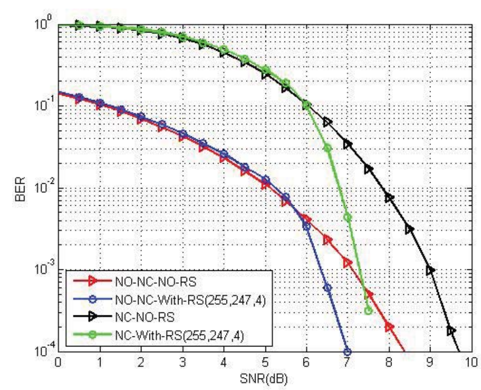
Table -1 Energy consumption results of butterfly network

Case	Energy consumption
Without NC and RS	**41.616$\times 10^{-4}$ J**
Without NC but with RS	**41.652$\times 10^{-4}$ J**
With NC but without RS	**31.212$\times 10^{-4}$ J**
With NC and RS	**31.231$\times 10^{-4}$ J**

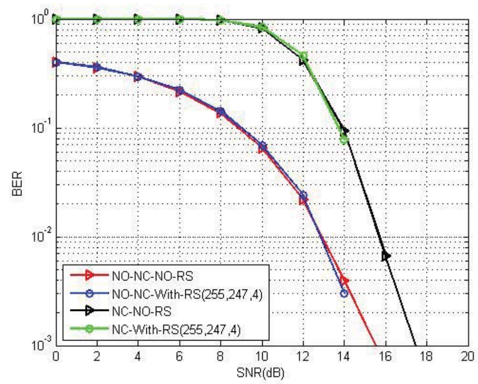
Figure 7 represents the BER performance of NC combined with RS (255,247,4) for MST network model over different channels. The combination of NC and RS coding has a throughput performance shown in Figure 8 and the energy performance tests of this network model is shown in Table -2.



(b) Flat fading

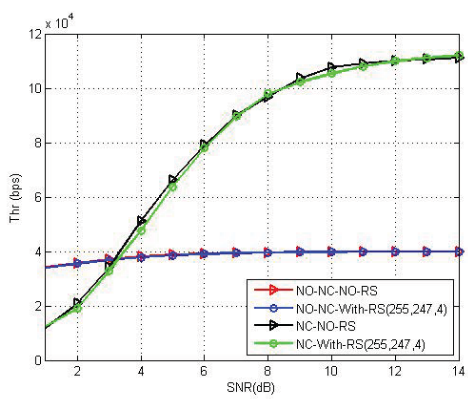


(a) AWGN

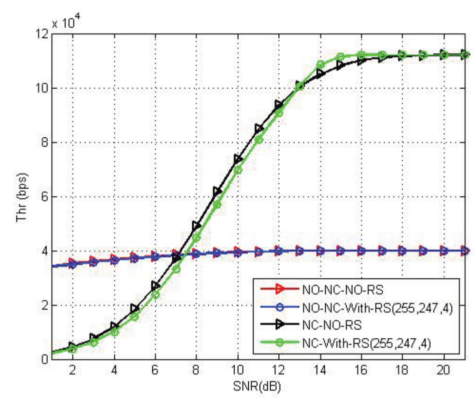


(c) SUI-3

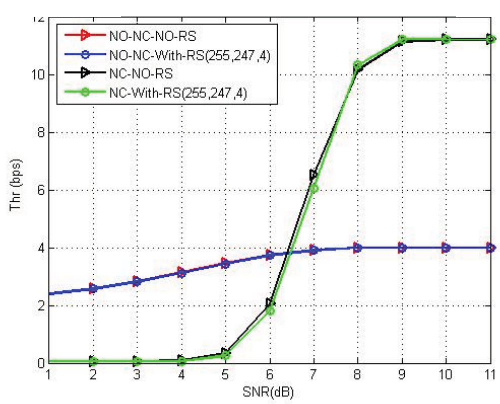
Figure 7. BER performance of MST network over different channels.



(b) Flat fading



(a) AWGN



(c) SUI-3

Figure 8. Throughput performance of MST network over different channels.

Table -2 Energy consumption results of MST network

Case	Energy consumption
Without NC and RS	283.152×10^{-4} J
Without NC but with RS	283.368×10^{-4} J
With NC but without RS	106.008×10^{-4} J
With NC and RS	106.179×10^{-4} J

As seen from the above results, the combination of RS with NC showed a reduction in transmissions leading to reduced energy consumption which saves energy by 25% over butterfly network model. The corresponding throughput gain is about 25% for the test over AWGN and flat fading channels as compared to 53% for SUI-3 channel. The reason behind such large value over SUI-3 is the relatively higher SNR improvement for coded (with NC) case. For the second network model, MST model tests shown that without NC, 28 transmissions is required to deliver packets to their intended receivers as compared to 10 transmissions with NC, which gives a percentage gain of 64% in transmission throughput. RS addition has a useful effect in improving BER, where about 1.7dB is gained by using RS code for the system with NC and RS as compared to that without RS and 0.7dB when RS is used for the system without NC over AWGN channel. Regarding fading channels, a clear decay appears at high SNR beginning from 22dB and 13dB for the system with NC and RS as compared to the case where no RS code is used over both flat fading and SUI-3 channels, respectively.

VI. CONCLUSION

This paper considered a generalized network model as well as butterfly network, where a combination of FEC and NC coding schemes are tested. The test results of the combined RS code with NC over butterfly model show an improved performance even over frequency selective fading channel. The improvements in throughput are ranging from 25% to 53% over AWGN to frequency selective fading (SUI-3) channel used in the work. The corresponding energy saving is about 25%. Such improvements are on the expense of slight degradation in BER performance. The mentioned percentage figures are relative to the case where both FEC and NC are not used.

For the generalized (MST) network model, the used combination of RS and NC provides improvements in BER, throughput, and energy. The gain in SNR due to coding for low BER over AWGN channel is relatively greater than those over fading channels as expected. The number of transmissions is reduced when using NC leading to a considerable improvement in system throughput at high SNR and about 62.5% an overall energy saving.

As a final conclusion, combining RS with NC coding can provide useful energy saving and increased throughput on the cost of slight BER increment. The implementation complexity and how to invoke the considered scheme in the present networks technology remain as the real challenge.

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