Ultra-Reliable and Energy Efficient Wireless Sensor Networks

Nabeel I. Sulieman, *Student Member, IEEE* and Richard D. Gitlin, *Life Fellow, IEEE*
Department of Electrical Engineering
University of South Florida
Tampa, Florida 33620, USA

Email: nis@mail.usf.edu, richgitlin@usf.edu

***Abstract*— Near instant link failure recovery and lower energy consumption can be achieved via the synergistic combination of Diversity and modified Triangular Network Coding (eDC-NC), an open-loop coding technique, in a wide variety of network architectures. In this paper, eDC-NC is applied to Wireless Sensor Networks (WSNs) to enable very rapid recovering from wireless link/node failures and provide low computational and energy cost, which are very important metrics for WSNs. It is shown that utilizing eDC-NC coding in WSNs can provide ultra-reliability with very rapid fault recovery, decrease energy consumption, and increase the network throughput for broadcasting applications.**

Keywords—Diversity Coding, Triangular Network Coding, reliability, throughput, Wireless Sensor Network

I. INTRODUCTION

A Wireless Sensor Network (WSN) contains one or more gateway nodes (central controllers) and several sensor nodes that are implemented at different locations [1]-[2]. Each sensor node contains a sensor with ability to monitor a specific kind of conditions such as temperature, pressure, noise levels, etc. [1]-[2]. Very low energy consumption [1]-[3], as well as high throughput and ultra-reliability are required for the WSNs [1]. Link/node failures are one of the principle contributors that reduce system throughput and decreases reliability. In addition, a sensor node has limited processing and energy capacity [1]-[3], which weakens the ability of recovery from wireless link/node failures. In this paper, these two challenges are addressed and overcome for WSNs. In [4] reliability was improved by utilizing multiple sensor nodes that transmit the same collected information to multiple gateway nodes. However, this will increase the redundancy by 100% and similarly the power consumption due to multiple transmissions of the same data. A more efficient approach is Diversity Coding (DC) [5]-[6], which is a forward error control technique over diverse routes, that has the ability to recover from wireless link failures as soon as the failure is detected with no need to retransmit messages and perform rerouting. This will improve reliability with low energy consumption and minimal added complexity.

In [7] Diversity Coding was utilized to improve the reliability of WSNs with minimum energy cost. Also, DC was shown to enhance C-RAN (Cloud Radio Access Network) network performance by improving reliability with fast link/node failure recovery [8]-[9]. In addition, it was shown that multiple simultaneous link failures can be recovered via Diversity Coded systems [9]. Although reliability is very important in WSNs, energy consumption and throughput are other important factors that effect WSN performance. Triangular Network Coding (TNC) [10], which is a mode of Network Coding (NC) [11], has the ability to provide minimum energy consumption with higher throughput, since its computational complexity is lower than other NC schemes.

It was shown in [12] that reliability, throughput, and energy consumption are simultaneously enhanced for wireless fronthaul networks by DC-NC coding, a synergistic combination of Diversity Coding (DC) and Network Coding (NC). However, the DC-NC coding scheme depends on deterministically chosen coefficients from a finite (Galois) field [12] and the computational complexity will increase dramatically with an increased number of broadcasted packets and/or the number of link failures that need to be protected. This will increase the energy cost of link failure recovery, as DC-NC coding requires increasing the finite field (GF) size. Consequently, the coding process will consume more energy, as it includes matrix inversion.

Further improvement of DC-NC has been presented in [13] which introduced a new coding technique called Enhanced Diversity and Network coding (eDC-NC), based on the synergistic combination of Diversity Coding and modified Triangular Network Coding. It was previously shown that eDC-NC can enable ultra-low energy consumption systems, improve wireless fronthaul network reliability, and enhance network throughput for broadcasting/multicasting applications. Energy cost is lowered owing to the less computational complexity of eDC-NC coding as it is a coding method over GF(2) [13].

The contribution of this paper is to extend the application of eDC-NC coding to WSNs and enable ultra-low energy consumption, enhance network reliability, and improve network throughput.

This paper is organized as follows: Section II describes the network topology based on WSNs. Section III presents a summary of Enhanced DC-NC (eDC-NC). The demonstration of the ability of eDC-NC coding to provide minimum energy cost, enable higher throughput and faster recovery from multiple simultaneous link/node failures in WSNs is presented in Section IV. The paper ends with concluding remarks in Section V.

II. SYSTEM MODEL

A WSN is a set of distributed sensors that observes and collects environmental information and communicates the recorded data to a central position, often referred to as a gateway [1]-[3]. There are several topologies that can be used to build the WSNs networks such as a star or mesh [see Figure 1] topology and multi-hop wireless mesh topology [1]-[3]. In addition, several wireless techniques can be used for WSN communications such as Zigbee [1], [3]. A sensor node has the ability to receive and forward the information to the gateway either directly or via other sensor nodes [1]-[2]. The gateway, which works as a bridge between the WSN and the other networks, transmits the collected information to the outside network. The WSN can contain a few to several thousands of nodes and a battery is usually utilized as the energy source for these nodes [1]-[3]. Sensor nodes often have limited resources such as memory, energy, and computational capability [1]-[3] that might affect the reliability of the WSN. However, it is necessary to design very low computational complexity and ultra-low energy techniques that improve the reliability of the WSN when link and/or node failures occur.

Since eDC-NC has very low computational complexity and ultra-low energy cost, in this paper eDC-NC is applied to increase the reliability of a WSN with a multi-hop mesh topology where sensor nodes are connecting to each other by wireless links as shown in Fig. 1. The collected data is transmitted from sensor nodes to the gateway node, and commands and other information is transmitted from the gateway to the sensor nodes. In this study, the focus is on an uplink scenario, where a sensor node sends the collected information to the gateway nodes.

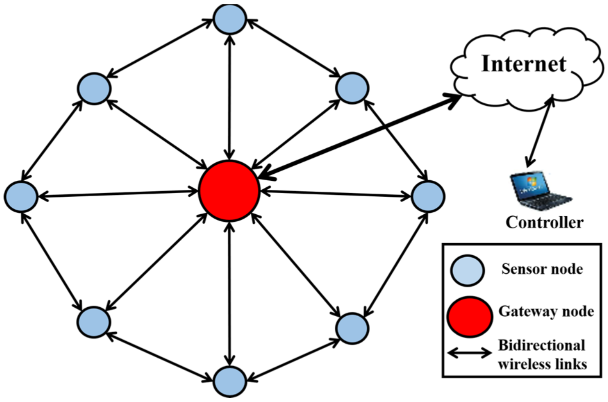

Fig. 1. Wireless Sensor Network with mesh topology.

III. ENHANCED DC-NC CODING

Diversity Coding [5]-[6], Network Coding [11], and DC-NC coding [12] generally use a finite Galois Field, denoted by GF(2^m) where m ≥ 1, to select the required coefficients for coding packets. Therefore, high encoding and decoding computational complexity will be required with an increased number of broadcasted packets and/or the number of coded packets since m increases which means that the field GF(2^m) also increases and the dimension of the coding and decoding matrices will also be increased. However, linear encoding and decoding over GF(2), where m = 1, has the ability to decrease computational complexity, but is not able to generate more than one coded packet. Enhanced DC-NC (eDC-NC) coding [13] can decrease the encoding and decoding computational complexity. The key idea of eDC-NC is similar to that of TNC [10], which is to add a string of "0" bit(s) to each packet such that the XOR operation between the packets will result a new coded packet [13].

To illustrate the principle of eDC-NC coded packets generation and their decoding schemes [13], let us assume that the number of packets $N = 3$, and the packets are p_1, p_2, and p_3. Each packet has B bits so that the packet bit pattern is $p_i = \{b_{i,1} \quad b_{i,2} \dots \dots b_{i,B}\}$, where i is the packet number. To generate the first coded packet, c_1, $N-1$ redundant bits "0", which are called r_{max}, are required. Fig. 2 illustrates the generation of the coded packet c_1 where no redundant bit "0" is added at the head of packet p_1 and hence, it is denoted by $p_{1,0}$. A redundant bit "0" is added at the head of packet p_2 and hence, it is denoted by $p_{2,1}$. In addition, two redundant bits "0" are added at the head of packet p_3 and hence, it is denoted by $p_{3,2}$. To equalize the length of all packets, Two "0" bits are added to the tail of packet p_1 and a "0" bit is added to the tail of p_2. Therefore, in general, each packet will be denoted by p_{i,r_i}, where r_i is the number of redundant bit(s) "0" that are added at the head of packet i. A simple XOR operation between $p_{1,0}$, $p_{2,1}$, and $p_{3,2}$, will generate the first coded packet, c_1. The unique ID of the encoded packet is represented as $[r_1, r_2, r_3]$. Hence, the unique ID of c_1 is $[0, 1, 2]$, which in general is given by $[0, 1, \dots, N-1]$. To generate the second coded packet, c_2, the position of "0" in the first ID will be fixed and all the other terms will be cyclically rotated. Hence, the second coded packet's ID will be $[0, 2, 1]$. In this way, the first group of $N-1$ coded packets can be generated. To generate the second group of $N-1$ coded packets, the new ID will be [0, the smallest integer greater than r_{max} at the previous group (r_{2_α}), $r_{2_\alpha} + \alpha, \dots, r_{2_\alpha} + \alpha(N-2)$], where α represents the group number. In eDC-NC coding, only $(N-1)$ coded packets for NC are required to get the

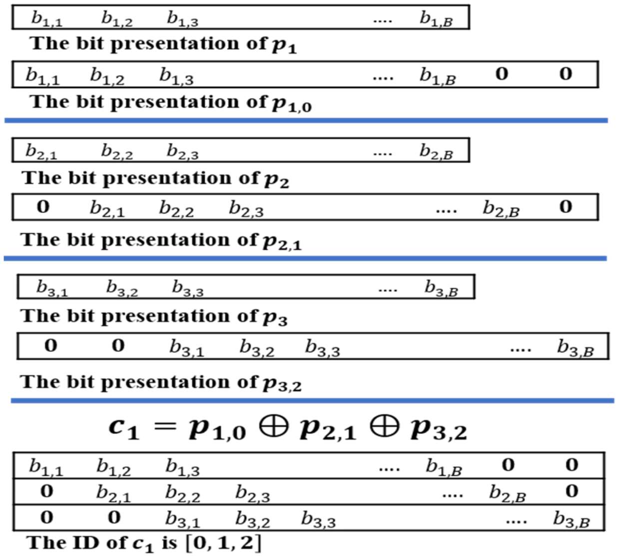

Fig. 2. The eDC-NC generation scheme for the coded packet c_1.

throughput gain and N coded packets for DC are required to get full protection of the network. Hence, the maximnum number of required coded packets will be $(2N-1)$ [13]. Therefore, to broadcast 3 packets and tolerate 2 link failures for each destination node, four coded packets with the following IDs are required:

$$ID_{c_1} = [0,1,2], \qquad ID_{c_2} = [0,2,1],$$
$$ID_{c_3} = [0,3,5], \qquad ID_{c_4} = [0,5,3].$$

Hence, first group of coded packets can be expressed as

$$c_1 = p_{1,0} \oplus p_{2,1} \oplus p_{3,2}, \tag{1}$$
$$c_2 = p_{1,0} \oplus p_{2,2} \oplus p_{3,1}, \tag{2}$$

And, second group of coded packets can be expressed as

$$c_3 = p_{1,0} \oplus p_{2,3} \oplus p_{3,5}, \tag{3}$$
$$c_4 = p_{1,0} \oplus p_{2,5} \oplus p_{3,3}, \tag{4}$$

Due to space limitations, we refer the reader to [13] for the details of the decoding algorithm. However, here, the decoding process is simple and is by bit XOR substitution. Below is an example of recovering the packets p_2 and p_3 in the presence of packet p_1 and coded packets c_1 and c_2. The bit representtion of p_1 and each coded packet is shown in Fig. 3. Each encoded packet is represented by a table where each row lists the bits of a packet involved in the encoding.

$b_{1,1}$	$b_{1,2}$	$b_{1,3}$	....	$b_{1,B}$

The bit presentation of p_1

$b_{1,1}$	$b_{1,2}$	$b_{1,3}$		....	$b_{1,B}$	0	0
0	$b_{2,1}$	$b_{2,2}$	$b_{2,3}$	....		$b_{2,B}$	0
0	0	$b_{3,1}$	$b_{3,2}$	$b_{3,3}$	....		$b_{3,B}$

The ID of c_1 is $[0,1,2]$

$b_{1,1}$	$b_{1,2}$	$b_{1,3}$		....	$b_{1,B}$	0	0
0	0	$b_{2,1}$	$b_{2,2}$	$b_{2,3}$	....		$b_{2,B}$
0	$b_{3,1}$	$b_{3,2}$	$b_{3,3}$	....		$b_{3,B}$	0

The ID of c_2 is $[0,2,1]$

Fig. 3. An example of the decoding process in eDC-NC.

A separate XOR operation between p_1 and both available coded packets will be performed as illustrated below:

0	$b_{2,1}$	$b_{2,2}$	$b_{2,3}$	....		$b_{2,B}$	0
0	0	$b_{3,1}$	$b_{3,2}$	$b_{3,3}$	....		$b_{3,B}$

Coded packet c_1 after XOR operation with p_1

0	0	$b_{2,1}$	$b_{2,2}$	$b_{2,3}$	....		$b_{2,B}$
0	$b_{3,1}$	$b_{3,2}$	$b_{3,3}$	....		$b_{3,B}$	0

Coded packet c_2 after XOR operation with p_1.

Starting from the left, the first bit from both coded packets will be neglected as both are “0”. The second bit of c_1 is encoded by $b_{2,1} \oplus 0$ which equals $b_{2,1}$. Similarly, $b_{3,1}$ can be recovered from the second bit of c_2. Now, the decoding process proceeds to the third bit position of both coded packets. By substituting $b_{2,1}$ into c_2 and $b_{3,1}$ into c_1, $b_{2,2}$ and $b_{3,2}$ can be recovered directly. Going forward to the fourth bit position, bits $b_{2,3}$ and $b_{3,3}$ can be instantly obtained by substitution. All unknown bits can be obtained by continuing decoding process. In this way, the bits of packets p_2 and p_3 can be decoded by back substitution at the bit level [13]. In this way, enhanced DC-NC coding can provide ultra-low energy cost and minimal computational complexity.

IV. APPLYING ENHANCED DC-NC CODING TO WSNS

Wireless Sensor Network resource limitations such as energy and transmission bandwidth, in the presence of link/node failures, can cause degradation in throughput and reliability. Enhanced DC-NC is a promising technology to maximize the reliability of WSNs with enabling ultra-low energy cost for link/node failures recovery and increase throughput in broadcast applications.

The eDC-NC coding is applied to a WSN network as illustrated in Fig. 4. Here, bi-directional wireless links connect sensor nodes and gateway nodes to each other in a mesh topology. An uplink point-to-multipoint network topology models the broadcasting of three packets from the sensor node S1 to two gateways G1 and G2. It is assumed that these two gateways are working in active/stand by (ACT/STBY) mode to eliminate single points of failure and to make sure that the required information is collected from sensor nodes i.e. even if one gateway fails for any reason, the collected data will still arrive to the user. Utilizing the eDC-NC coding scheme, four disjoint routes are needed to broadcast three packets from the sensor node to two gateway nodes. In addition, two more disjoint paths are used to tolerate two link failures at each gateway node. Using direct links, packets p_1 and p_3 are transmitted from S1 to G1 and G2 respectively. To obtain the throughput gain and tolerate 2 link failures for each destination node, four coded packets, $c_1 - c_4$ are formed at S1 as shown in (1)-(4) and then sent to S2, S3, S4 and S5 respectively. To obtain the throughput gains, S2 and S3 transmit c_1 and c_2 respectively to G1 and G2. Coded packets c_1 and c_2 in addition to the packet p_1 are decoded at G1 to obtain p_2 and p_3 as described in section III. Similarly, c_1, c_2 and p_3 are decoded at G2 to obtain p_1 and p_2. In this way, the throughput gains in this example network improve by at least 20% [12].

Wireless sensor network reliability in the presence of link failures, can be improved by transmitting c_3 and c_4 from S4 and S5 respectively to G1 and G2. The coded packets c_3 and c_4 will be ignored when there are no link failures. In the presence of a link failure, for example if the link from the S1 to G1 fails, G1 detects the failure then recovers p_1, p_2 and p_3 by utlizing c_1, c_2 and c_3 using the back-substitution method. In addition, if c_1 is lost, G1 has p_2, c_2 and c_3 then can quickly and easily recover p_1 and p_3. Furthermore, if two links fail at G1, for example p_1 and c_1, G1 detects the failures then recovers p_1, p_2 and p_3 by utilizing c_2, c_3 and c_4 in the same manner that illustrated in Section III. Similarly, any two link failures can be recovered in the same way.

Moreover, not only multiple link failures can be recovered by eDC-NC coding in this example WSN network. Two intermediate node failures such as S2 and S3 can be tolerated since this corresponds to four simultaneous link failures that each pair is associated with different destination node. Also, when failures occur at S4 and S5, c_3 and c_4 will be lost i.e. protection of the network but, if these are the only failures, successful data communication can still be achieved.

In general, eDC-NC networks can tolerate n link failures for each destination node at k destination nodes, however, $kn + n$ redundant links are required, where $n \leq N$.

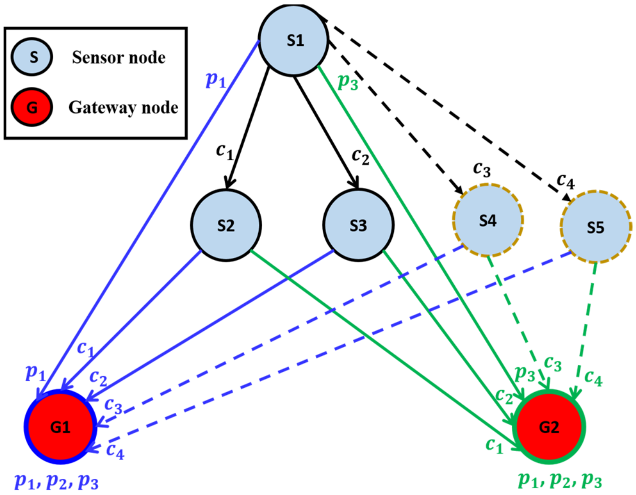

Fig. 4. Example of eDC-NC coding to broadcast three packets to nodes G1 and G2 applied to a WSN, where solid lines represent the links that carry coded packets and are used to improve network throughput whereas dashed lines represent the links that carry coded packets and are used to maximize network reliability. The blue and green links distinguish the different destinations.

There is no need to simulate the results in this paper because the link failure is considered independently of the failure mode and it is mathematically proven how the WSN network can be enhanced and protected by eDC-NC. Of course, the recovery time is lower bounded by the time to detect a failure.

Although in this study, we solely focused on applying the eDC-NC coding scheme in a WSN, our future work will investigate the application of this approach to more general and complex network topologies.

V. CONCLUSIONS

This paper presented the application of the recently introduced coding technique, eDC-NC, that synergistically combines Diversity and modified Triangular Network Coding, to improve the performance of WSNs. It has been demonstrated that eDC-NC can simultaneously recover from multiple link/node failures nearly-instantaneously with minimum energy consumption. Furthermore, eDC-NC networks can tolerate n link failures, where n less than or equals to the number of broadcasted packets for each receiver node at k receiver nodes, with $kn + n$ redundant links. Applying eDC-NC coding minimizes the energy cost of recovering from multiple wireless link/node failures due to its less computational complexity, while simultaneously improving the throughput in the network by at least 20% in this example network.

ACKNOWLEDGMENT

Nabeel I. Sulieman is supported by the Higher Committee for Education Development in Iraq (HCED-IRAQ).

REFERENCES

[1] A. Nayak and I. Stojmenovic, *Wireless Sensor and Actuator Networks*. Hoboken, NJ: John Wiley & Sons, Inc., 2010.

[2] I. F. Akyildiz, W. Su, Y. Sankarasubramaniam, and E. Cayirci, “Wireless sensor networks: a survey,” *Computer Networks journal (Elsevier)*, 38:393–422, 2002.

[3] Silicon Laboratories, Inc. Silicon Labs. <https://www.silabs.com/documents/public/white-papers/evolution-of-wireless-sensor-networks.pdf>.

[4] K. Ozaki, N. Hayashibara, T. Enokido, and M Takizawa, “Fault-Tolerant Semi-Passive Coordination Protocol for a Multi-Actuator/Multi-Sensor (MAMS) Model,” *IEEE Second International Conference on Availability, Reliability and Security (ARES'07)*, Vienna, Austria, April 2007.

[5] E. Ayanoglu, C.-L. I, R. D. Gitlin, and J. E. Mazo, “Diversity Coding: Using error control for self-healing in communication networks,” in Proc. *IEEE INFOCOM’90*, San Francisco, CA, June 1990, pp. 95–104, vol. 1.

[6] E. Ayanoglu, C.-L. I, R. D. Gitlin, and J. E. Mazo, “Diversity Coding for transparent self-healing and fault-tolerant communication networks,” IEEE Trans. Commun., vol. 41, pp. 1677–1686, Nov. 1993.

[7] G. E. Arrobo and R. D. Gitlin, "Minimizing energy consumption for cooperative Network and Diversity coded sensor networks," *IEEE Wireless Telecommunication Symposium,* Washington, D.C., April 2014.

[8] N. Sulieman, K. Davaslioglu, and R. D. Gitlin, “Link failure recovery via Diversity Coding in 5G fronthaul wireless networks,” *IEEE Wireless and Microwave Technology Conference,* Cocoa Beach, FL, April 2017.

[9] N. Sulieman, K. Davaslioglu, and R. D. Gitlin, “Diversity coded 5G fronthaul wireless networks,” *IEEE Wireless Telecommunication Symposium,* Chicago, IL, April 2017.

[10] J. Qureshi, C. H. Foh, and J. Cai, "Optimal solution for the Index Coding problem using Network Coding over GF(2)," *IEEE Communications Society Conference on Sensor, Mesh and Ad Hoc Communications and Networks (SECON)*, Seoul, South Korea, June 2012.

[11] R. Ahlswede, N. Cai, S.-Y. R. Li, and R. W. Yeung, “Network information flow,” IEEE Trans. Inform. Theory, vol. 46, no. 4, pp. 1204–1216, July 2000.

[12] N. I. Sulieman, E. Balevi, K. Davaslioglu, and R. D. Gitlin, “Diversity and Network coded 5G fronthaul wireless networks for ultra reliable and low latency communications,” *IEEE International Symposium on Personal, Indoor and Mobile Radio Communications*, Montreal, QC, Canada, Oct. 2017.

[13] N. Sulieman, E. Balevi, and R. D. Gitlin, “Near-instant link failure recovery in 5G wireless Fog-base-fronthaul networks,” *IEEE Wireless Telecommunication Symposium,* Phoenix, AZ, April 2018, in press.