Proposing a Novel Method based on Network-Coding for Optimizing Error Recovery in Wireless Sensor Networks

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Abstract

In Wireless Sensor Networks (WSNs), signals are used as channels for communicating data. Wireless channels are inherently insecure; hence, the vulnerability of signals to external destructive factors and to the interference of intruders can result in the production of errors in data to be transferred. On the other hand, in as much as wireless sensors have limited energy, optimal consumption of energy for enhancing network lifetime is of high significance. In this paper, a protocol based on block-level retransmission and network-coding has been proposed which is intended to optimize error recovery in sensor networks. This protocol takes the parameters of reliability and energy consumption into account. In this protocol, data frames are divided into blocks and in the case of error occurrence, the total frame need not to be transferred since only the error containing block is retransferred using the network coding technique. This procedure minimizes the number of transfer and reception in the nodes. Consequently, energy consumption is reduced. The simulation results revealed that utilizing the networking coding technique in the proposed method results in reliability enhancement. Thus, the simulation results indicate that the proposed method leads to higher reliability and lower energy consumption than the LIERMO method.

Keywords: Energy Consumption Optimization, Error Recovery, Network Coding, Reliability, Wireless Sensor Networks (WSNs)

1. Introduction

Recent developments in electronics and wireless telecommunications have facilitated the designing and production of low-power and small sensors which are reasonably cheap and have various applications. These small sensors which are capable of receiving different environmental data (based on sensor type), processing and transmitting data have led to the creation of an idea for developing and extending networks labeled as Wireless Sensor Networks (WSNs). In WSNs, thanks to the presence of sensors in their architecture, sensor nodes receive the environmental data; meanwhile they carry out a primary processing in the nodes and transmit them towards their targets. In this type of networks, signals are used as channels for communicating data. Since wireless channels are unreliable and network energy is limited, it is essential that protocols be designed for optimizing error recovery so that the parameters of reliability, energy consumption and average delivery time[3] are taken into consideration. For enhancing error detectability in received packets, the concept of redundancy should be taken into account. Redundancy refers to the fact that some control bits should be added to the message head so that defective bits can be detected and recovered. It should be noted that this procedure increases the amount of packets which should be transmitted. There are two major mechanisms for recovering error in the network[1]:

In the first method which is called *automatic repeat request*, control bits and redundancy are used to detect error in the message; then, a message is transmitted to the sender asking it to retransmit the message. The second method which is known as F*orward Error Correction (FEC)*, the receiver not only detects the error in the message but also uses the redundant bits and particular techniques to guess the message. However, with respect to the energy limitation in these networks, using these methods results in the consumption of a lot of energy in the network. Hybrid ARQ is deemed to be a promising method for reducing error in WSNs[2]. Transmitting based on this method (HARQ) leads to the reduction of energy in WSN[3].

Recently, a mechanism, known as network coding, has been proposed which can solve the energy consumption in these methods. This mechanism has significantly high reliability[4] and leads to the reduction in the number of transmissions and receptions. Consequently, it reduces energy consumption. In the majority of protocols, in case an error occurs, the entire packet should be retransmitted which leads to an increase in the energy consumption of nodes; consequently, channel efficiency decreases. In this paper, a protocol has been proposed in which the source divides the data frames into blocks and then, it sends the blocks to the receiver. Hence, in the case of error occurrence, there is no need to transmit the whole frame since the error-containing block is only transmitted by the network coding technique; this action enhances the reliability and reduces energy consumption. The reminder of the paper is organized as follows: in section two, the related works are briefly reviewed. The proposed protocol is discussed in section three where the energy consumption model will be explained. The simulations conducted in the study will be reported in section four. Section five summarizes the findings and concludes the study.

2. Related Previous Works

Numerous research has been conducted which aimed at introducing novel protocols for optimizing error recovery in WSNs. Some of the mechanism proposed for recovering errors in WSNs has been mentioned in[5–7]. The main concept in the proposed mechanism combined the defective versions of a packet to recover the original packet; each of the following protocols has adopted a version of this mechanism: EARQ[5], Simple Packet Combining Error Recovery Scheme (SPAC-M)[6]

and Destination Packet Combining (DPC)[7]. Wang[8] proved that when the length of data is large and bit error rate is high, the EARQ will have significantly higher efficiency than the SPAC-M and DPC methods in retrieving data. Singh[9] proposed a method based on FEC technique for preventing retransmission of data and saving energy consumption. This method is capable of bursting errors up to eight bits. Krohn[10] introduced a method for ensuring the accuracy of the communicated data in the network based on homomorphism hash functions. The rationale behind this method is that mid nodes check the accuracy of packets and if a packet has an error, it will be eliminated. This method reduces the network overload. However, the complexities involved in the implementation of this algorithm are still remaining and when the scope of the network is high; the calculations related to hash will cause a delay in the network. Kehid[11] proposed a simple method for detecting and restricting attacks on the packets which is based on NULL; they found that this method is more efficient than the previous methods since it reduces the delay in packet delivery.

Network coding was first proposed by Ahlswede4. In this method, rather than simply transmitting just one packet, the mid node combines and integrates a few input packets into just one packet and then transmits that packet. In recent years, network coding technique has been used for maintaining reliability in WSNs[12–17]. Network coding-based methods have relatively higher reliability than the traditional methods. Using this technique in multi-hop multi-cast networks results in the reduction of energy consumption[18]. Coding linear data is a type of functional implementation of network coding[19]. Koetter[20] introduced a fault-tolerating routing mechanism for mash networks which was based on network coding. Yuhuai[21] proposed a fault-tolerant routing mechanism based on network coding for wireless mesh networks. Antonopoulos[22] proposed a protocol for vehicular ad hoc networks (VANETs) which was based on Novel Network Coding and Automatic Repeat Request (ARQ). This protocol was intended to reduce the number of the whole transmissions. Wenbo[23] proposed a method in which a coding parameter (n, k) in proportion with the pollution status is selected. In this method, when a node detects an error in a packet, it does not eliminate the packet; rather, it sets a value for the syndromes of the error in the packet and then transmits the packet. It should be noted that this procedure will be done if the error is capable

of being detected. After a sufficient number of packets are gathered, the secondary node will be able to recover the defective packet. Indeed, this method which is based on network coding has integrated the error detection and error recovery mechanisms with each other. Guo[24] found that in case network coding is used in underwater sensor networks, error recovery efficiency will be improved. Cai[25] proposed a novel protocol, called Multi Paths and Network Coding (MPNC), based on network coding for enhancing packet delivery rate in this type of networks. Some methods which are based on block-level retransmission in WSNs have been mentioned in[26–28]. Ganti[26] proposed the Seda algorithm for enhancing efficiency in WSNs. In this algorithm, the network layer divides the data packets into data blocks. Then, each block adds one bite as the sequence number and one bite as the CRC-8 code so that it can detect errors. Next, these blocks are categorized and are delivered to the Mac layer for transmission. In the case of error occurrence, there is no need for transmitting the entire packet; rather, the defective blocks which contain errors are retransmitted by the sender. Showail[27] proposed the iFrag protocol which is based on the concept of segment-based retransmission. In this protocol, the number of blocks within each frame is dynamically determined and arranged according to the current conditions of the channel. Showail[27] proved that their proposed method reduces the amount of delay in the noisy networks for 12% which is better than those methods in which the number of blocks within each frame is stable. Moreover, in this method, energy consumption was reduced up to 6% for each useful bit. Thanks to the reduction in the number of frame retransmission, the above-mentioned method reduces energy consumption. Kaikai[28] proposed a protocol based on block-level ARQ and network coding in single-hop wireless networks for recovering errors. In this method, data stream is divided into data blocks and in case an error occurs, only the error-containing blocks are retransmitted rather than retransmitting the entire blocks. Indeed, using the novel network coding technique minimizes the number of blocks to be retransmitted. Kaikai[28] found that their proposed method enhances the efficiency of the channel better than the earlier methods. LIERMO algorithm is an event-based protocol for optimizing service quality in WSNs which uses energy-efficient multi-path routing[29]. The objective for designing this protocol was to improve packet delivery rate, enhance network lifetime and also reduce delay in transmittingpackets to the sink. This protocol uses multi-path

detec tion which has the fewest number of interference between the source node and the sink node. It also uses a balancing algorithm for distributing the source node traffic on multiple paths according to the relative quality of each path.

3. Designing BNC

In this section of the paper, BNC is introduced as a method which can improve error recovery in WSNs. In BNC, the source divides data stream into frames with the length of $n_B l_B$. In general, the transmission of a frame includes two phases: the path determination and transmission phase and the retransmission phase.

3.1 Path Determination and Transmission

This phase includes three parts: 1. Blocking frames, 2. selecting the best neighbor, 3. measuring the reliability and transmitting frame.

3.1.1 Blocking Frames

At first, the source separates the available data of each frame within the N_b block so that each of the blocks have data with the length of L_b. then, it adds a section as the sequence number to each block for showing the sequence and trail of the consecutive blocks. The sequence number begins with 1 and continues up to N_b. in this protocol, instead of one bite, two bites are used for the sequence number since an 8-bit bite can only indicate the communication among 256 different blocks which can result in efficiency reduction in some states and conditions. Thus, for enhancing efficiency, especially when N or N_b is big, using 2 bites can result in relatively better efficiency and performance. The source also adds the CRC-16 control bits to each block for detecting error. Using the control bits for blocks, the receiver can detect the existence of bit error in the block. Figure 1 illustrates the format of data frame.

3.1.2 Blocking Frames

For selecting the best neighbor, each node needs to identify its own neighbors. This operation is accomplished by transmitting a particular packet which is called Hello. The format of Hello packet is given in Figure 2. In Figure 2, Rem_e refers to the remaining energy, ID refer to the unique ID number of the node and (X, Y) refer to the location and position of the node. The source completes the items of the Hello packet with its own
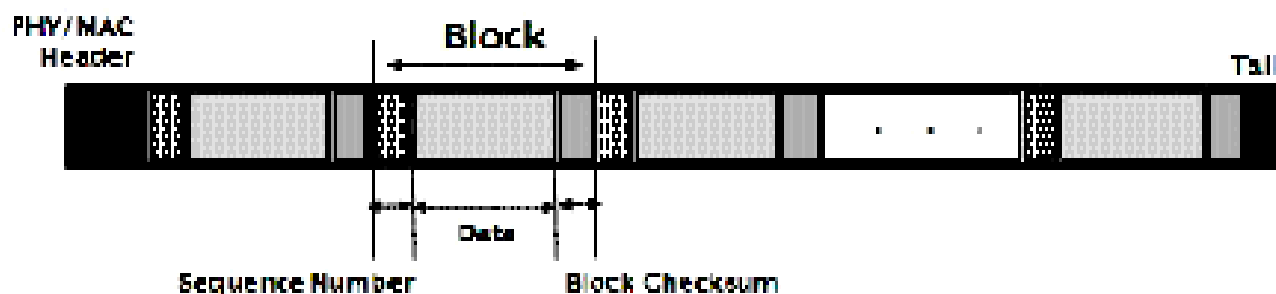
Figure 1. The format of data frame in the BNC method.

(X, Y)	ID	Rem_e

Figure 2. The format of Hello packet in the BNC method.

data; then, it transmits this packet to all of its neighbors as far as the sink. When each node receives the Hello message, it replaces the previous ID number, remaining energy and position with its own data and transmits the packet to the sender of the Hello message. Based on the received replies, the requesting node creates a routing table about its own neighbors. In this method, all nodes occasionally update their own routing table through the Hello packets so that they can use the table when they want to transmit data.

After framing, the source uses the data of routing table and cost function[1] to select the best neighbor for transmitting data. The neighbor node with the higher cost will be selected as the chosen node.

$$Cost(i,j) = \propto \frac{1}{dist_{i,j}} + (1-\propto)Rem_e \quad (1)$$

In equation 1, $dist_{i,j}$ refers to the distance between the current node and the neighbor node Rem_e stands for the remaining energy of the neighbor node, α refers to the distance effect coefficient and 1-α refers to the energy effect coefficient.The distance between the current node and the neighbor node is obtained with respect to the position of the neighbors in routing table. Equation 2 is used for measuring this distance:

$$dist_{i,j} = \sqrt{\left(X_i - X_j\right)^2 + \left[(Y)_i - Y_j\right)^2} \quad ....(2)$$

3.1.3 Measuring the Validity and Transmitting Frame

After selecting the best neighbor node, the transmitter transmits the frame to the selected node; then, after the middle node receives the frame, it uses control bits to measure and evaluate the validity of each block.

As soon as the middle node detects an error in any of the frame blocks, it produces a FAILURE control packet including the number of defective block and transmits it towards the transmitter. Also, the middle node sets the value of zero to data section of the block and then transmits the packet to its best neighbor. Observing the zero value in a block, the next node notes the occurrence of error in that block and hence, it does not retransmit the control packet for announcing error. This procedure continues until the frame reaches the sink.

3.2 Retransmission Stage

In the retransmission stage, the transmitter uses the network coding technique to code the blocks which have not been properly received. After receiving the error-announcement control messages, the source creates a list of improper blocks and the corresponding receivers. Then, the transmitter uses the XOR-bit operator to combine the N number of improper blocks; then, it places the coded blocks as well as the improperly received blocks within one frame. Next, after selecting the best neighbor, the transmitter transmits the frame. This procedure continues until the frame reaches the sink. After the sink receives the coded frame, it starts to decode and retrieve those blocks which had not been properly received in the transmission stage. Comparing the traditional method based on automatic repetition request and the new method based on network coding and automatic repetition request in the block level indicates that energy consumption in the new method is less than that of the old method. This is due to the fact that the source only transmits the inaccurate blocks rather than transmitting the entire frames which include errors. As a result, transmitting inaccurate blocks consumes less energy than transmitting the inaccurate frames. For example, as illustrated in Figure 3, blocks B_1 B_4 and B_7 are inaccurate blocks

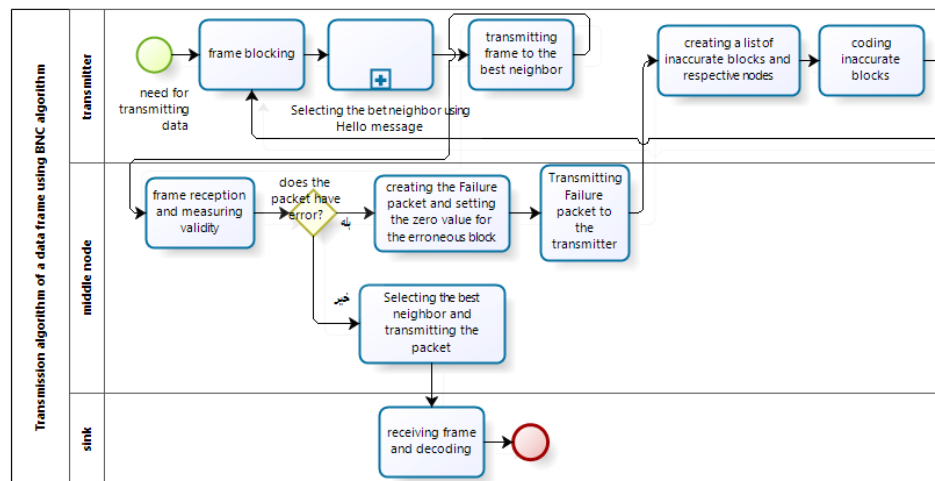which were detected by the three nodes R_1, R_2, R_3 and were reported to the source node.

	B_1	B_2	B_3	B_4	B_5	B_6	B_7	B_8
R_1	1	1	1	1	1	1	0	1
R_2	0	1	1	1	1	1	1	1
R_3	1	1	1	0	1	1	1	1

Figure 3. An instance of block error pattern, zero value indicate error occurrence in the block.

B1	B4	B7	B1⊕ B4⊕ B7

Figure 4. Data frame format for the first example in the retransmission stage.

In case the network coding technique is used, the source node can code the blocks B_1, B_4, and B_7 in the form of $B_4 \oplus B_1 \oplus B_7$ (isolated by the XOR-bit operator). Hence, the source node can retransmit the coded block along with the blocks B_1, B_4 and B_7 in the form of a frame. Figure 4 demonstrates the data frame for the mentioned example in the retransmission stage.

3.3 Energy Consumption Model

Energy is considered to be one of the highly significant parameters in WSNs. The significance of this parameter lies in the fact that the energy of sensor nodes is supplied by battery and the lifetime of batteries is limited. On the other hand, since sensor nodes are distributed in undesirable environments such as forests and desert, access to them encounters some problems. Thus, the probability of replacing batteries is low. Therefore, in proposing routing protocols, energy consumption and consequently network life time should be considered as critical parameters.

Figure 5. The flow chart for transmitting a frame by the proposed protocol (BNC).

For efficient transmission of packets with respect to energy consumption and network lifetime, the available energy of the neighbor nodes and the energy required for transmitting packets should be considered[30]. The energy required for transmitting a K-bit packet to a node with the distance d is measured through equation 3 below:

In this equation, d_0 refers to the threshold level and its value equals $d_0 = \sqrt{\dfrac{\varepsilon_{fs}}{\varepsilon_{fs}}}$ E_{elec} refers to the required energy for digital coding, modulation and filtering. The energy needed for the receiver node for receiving a k-bit packet is measured through equation 4[30]:

$$E_{TX}(k,d) = E_{TX-elec}(k) + E_{TX-amp}(k,d) = k(E_{elec} + E_{amp}d^\alpha) = \begin{cases} k(E_{elec} + \varepsilon_{fs}d^2), d < d_0 \\ k(E_{elec} + \varepsilon_{mp}d^4), d \geq d_0 \end{cases}$$

$$E_{RX} = E_{RX-elec}(k) = E_{elec} \quad\quad\quad ....(4)$$

Therefore, the total energy required for transmitting and receiving a k-bit packet is obtained through equation 5 below:

$$E_{total}(k) = E_{TX}(k,d) + E_{RX}(k) = \begin{cases} k(2E_{elec} + \varepsilon_{fs}d^2) & d < d_0 \\ k(2E_{elec} + \varepsilon_{pm}d^4) & d \geq d_0 \end{cases} .....(5)$$

It should be noted that the values of ε_{fs}, ε_{pm}, E_{elec} are constant.

4. Simulation Results and Analysis

For evaluating the efficiency and performance of the protocol proposed in this study (BNC), the researchers considered 50 nodes in a square working area with the size of 200 m by 200 which is illustrated in Table 1. The proposed method was examined and analyzed with respect to the following parameters: system output, the number of live network nodes, average remaining energy of the network and the number of missing nodes. These parameters were used to compare the proposed protocol with LIEMRO. The simulations were conducted in Matlab software and the impact of independent variables such as the number of produced packets and their initial energy of the nodes were analyzed. In order make the protocols comparable, identical conditions were considered for both of the protocols. Simulation parameters have been mentioned in Table 1.

Table 1. Simulation parameters

| Parameter	Value
Initial energy (Jules)	5
Buffer size (packet)	1.000
Simulation time (minute)	10
Network size	200*200
Sink position	(200,200)
The number of nodes	50
Radio range (m)	80
The number of actors	20
The radius of the actors (meter)	30
Packet size (bit)	$15*10^3$
E_{elec}	50 nj/bit
ε_{amp}	100 pj/bit/m^2
r_{mac}	5
α	0.8

4.1 System Output

One of the most important parameters for service quality is the system output. System output refers to the rate of pacckets which are delivered to the sink. In the proposed method, network coding technique was used to control error in which it is possible to recover the packet in case an error occurs. However, in the case of error ocurrence in LIEMRO method, it is considered that the whole packet is lost. Figure 6 compares the proposed method with LIEMRO with respect to the impact of the number of produced packets on system output. When the network coding technique is used, the increase in the number of produced packets does not reduce algorithm efficiency. In contrast, in the LIEMRO method, an increase in the number of produced packets reduces the algorithm efficiency.
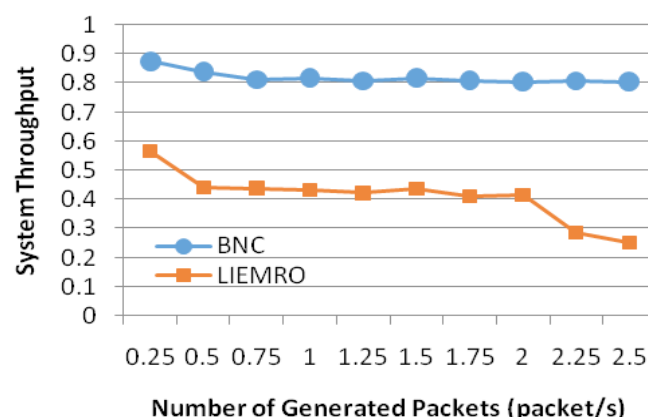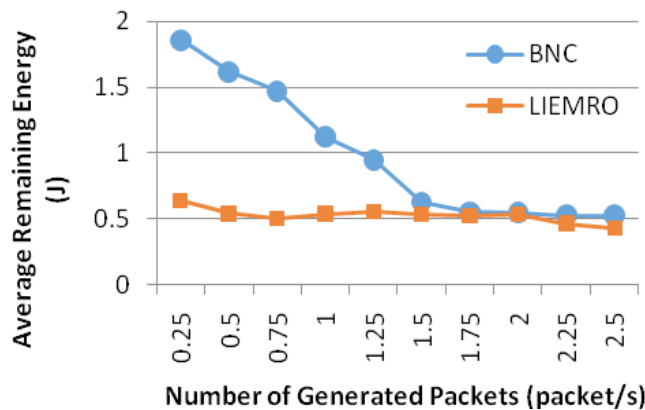

Figure 6. The imapct of the number of produced packets on system throuhput.

In the proposed method, in each node, the priority is to transmit that type of data which has been sensed by the node itslef. In case the node itself has no dat for transmitting, the data related to the neghboring nodes will be transmitted. However, in LIEMRO method, before transmitting data, the route needes to be discovered which results in an increase in the network energy consumption and if the initial energy of the nodes is low, thye cannot receive many packets from the neighboring nodes for transmitting to the neighboring nodes. This condition results in the loss of the related packets and consequently the packet dilevery rate decreases. Figure 7 depicts the impact of the initial energy of the nodes on system output for both the proposed method and the LIEMRO method. As shown in this Figure, By increasing the initial energy of the nodes, the system output in the proposed method increases more than that of the LIEMRO method.
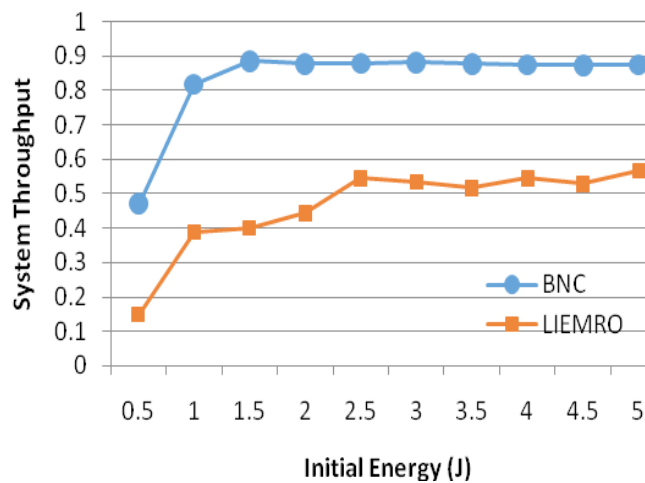
Figure 7. The impact of initial energy of th enodes on the system throuput.

Figure 8. The impact of the number of produced packets on the average remaining energy.
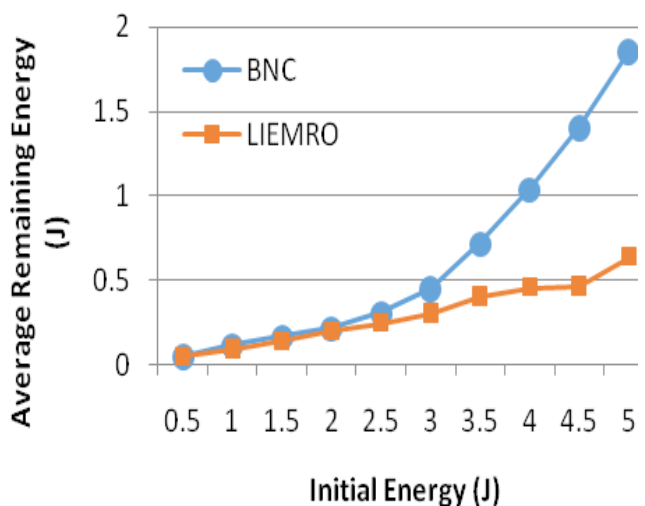

Figure 9. The impact of the initial energy of the nodes on the average remaining energy.

4.2 Energy Consumption

Energy consumption used to refer to the consumed energy in creating a frame in the source node and also the energy consumed in the middle nodes for transmitting packets to the sink. The simulation results indicated thatthe average remaining energy and the number of alive network nodes is higher than those of the LIEMRo method. The higher efficiency and lower energy consumption in the proposed method is attributed to the use of blocking technique which reduces the number of transmissions and receptions in the nodes;moreover, in the proposed method, there is no need for using route discovery before transmitting data which furthr reduces energy consumption. Figures 8–11 demonstrate the impacts of the input parameters on average remaining energy and the number of alive network nodes.

As depicted in Figures 8 and 10, as the number of produced packets increases, the averasge remaining energy and the number of alive network nodes decreases in both methods; this is attributed to the fact that an increase in the number of produced packets requires more energy consumption which should be used for transmitting the packets for from the source node to the sink. Moreover, as illustrated in Figure 9 and Figure 11, as the initial energy of the nodes increases, the average remaining energy and the number of alive network nodes increase.
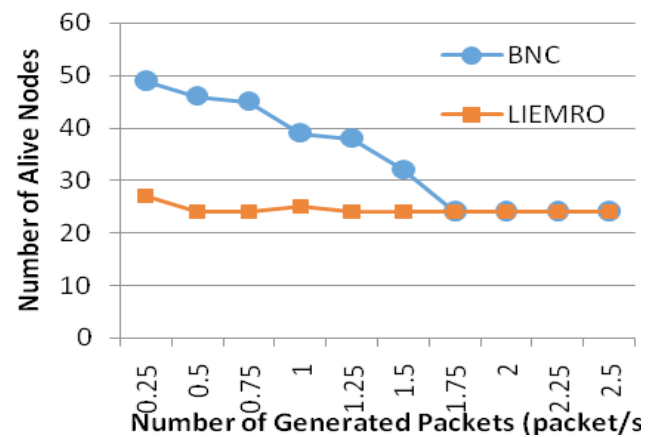
Figure 10. The impact of the number of produced packets on the number of alive network nodes.
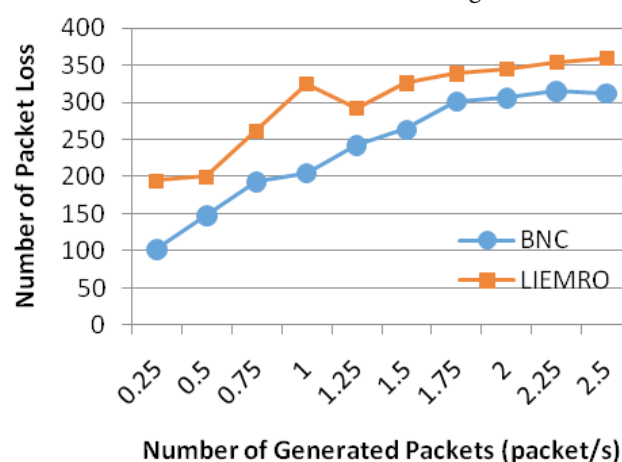
4.3 The Number of Missing Packets

An increase in the number of produced packets and the tranmission of these packets in the network will increase the network traffic. It is obvious that network traffic directly correlates with the interference of the packets.
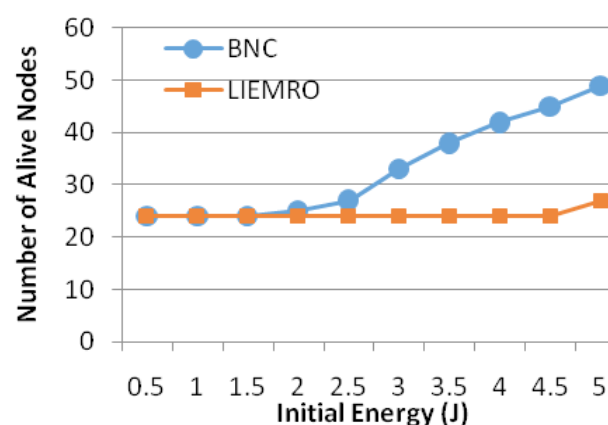
Figure 11. The impact of the initial energy of the nodes on the number of alive network.

That is, as the traffic increases, the probability of packet interference and consequently, errror occurrence goes up. Also, heavy traffic enhances the probabilitiy of data loss which is related to the reduction of the remaining energy of the nodes. In case, the receiver is not able to recover the ocurred error, it is considered that the packetis lost. The impact of the the number of produced packets on the number of missing packets for bothe the proposed methods and LIEMRO is illustrated in Figure 12.
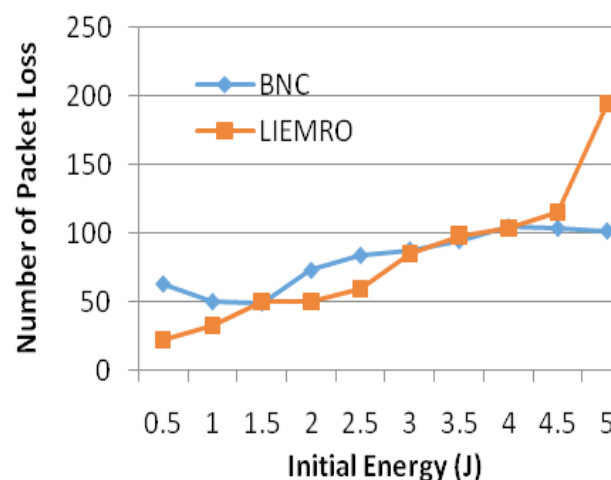

Figure 12. The impact of the number of produced packets on the number of missing.

As indicated in this Figure, as the number of produced packets increases, the behavior of the proposed algorithm becomes better than the LIEMRO method. The better functioning of the proposed algorithm is related to using the network coding technique.In those methods where network coding technique is not used, , if some part of the transmitted packet is destroyed due to any reason, then, the packet should be retransmitted. In contrast, in methods in which network coding technique is used,

it is possible to recover the main packet even though some part of it has been destrouyed. Indeed, on one hand, coding the packets in the retransmission phase and, on the other hand, using blocking techniique leads to the reduction of missing packets in the proposed method. However, this is not the case with the LIERMO method which has lower efficiency and higher energy consumption.

In case the initial energy of the nodes is high, then, the nodes can transmit a higher number of neighboring nodes' packets. This will lead to high network traffic; consequently the number of missing packets will increase. As demonstrated in Figure 13, the impact of initial energy of the nodes on the number of missing packets has a mild slope (less sharper slope) in the proposed method than in the LIEMRO method. That is, it can be argued that in the LIEMRO method, in case the initial energy increases, the number of missed packets will increase.

Figure 13. The impact of the initial energy of the nodes on the number of missing packets.

5. Conclusion

In the protocol proposed in this paper, data frames were divided into blocks and in the case of error ocurrence, there was no need to transmit the entire frame; rather, the network coding technique was used to retransmit only the error-containing block. This procedure minimizes the number of transmissions and receptions in the nodes; hence, the energy cosnumption decreases. The usage of the network coding mechanism results in reliability enhancement. The simulation results indicated that the proposed method is better than LIEMRO with respect to the parameters of reliability and energy consumption.

6. References

1. Jeong J, Ee CT. Forward error correction in sensor networks. Berkeley: University of California; 2003.
2. Datta U, Bharath Kumar D, Ball AK, Kundu S. Performance of a hybrid ARQ scheme in CDMA wireless sensor network. International Journal of Energy, Information and Communications. 2011; 2(3):59–74.
3. Chatterjee M, Nandi A, Basu B. Performance of incremental redundancy-based data transmission in randomly deployed wireless sensor network. Advances in Intelligent Systems and Computing. 2015; 304:167–86.
4. Ahlswede R, Cai N, Li R, Yeung R. Network information flow. IEEE Trans Inform Theor. 2000; 46(4):1204–16.
5. Chakraborty SS, Yli-Juuti E, Liinaharja M. An ARQ scheme with packet combining. IEEE Commun Lett. 1998; 2(7):200–2.
6. Dubois-Ferriere H, Estrin D, Vetterli M. Packet combining in sensor networks. Proceedings of 3rd International Conference Embedded Networked Sensor Systems; 2005. p. 102–15.
7. Zhou Z, Peng Z, Cui JH, Shi Z. Efficient multipath communication for time-critical applications in underwater acoustic sensor networks. IEEE/ACM Trans Netw. 2011; 19(1):28–41.
8. Sheng-Shih W, Pei-Chun L, Kan-Yen L, Tzu-Chang Y. A comparative study of packet combining based error recovery schemes for wireless networks. Journal International Journal of Ad Hoc and Ubiquitous Computing. 2014; 16(3):183–92.
9. Singha A, Kumarb P. An efficient forward error correction scheme for wireless. Procedia Technology. 2012; 4:737–42.
10. Krohn M, Freedman M, Mazieres D. On-the-fly verification of rateless erasure codes for efficient content distribution. IEEE Proceedings of Symposium on Security and Privacy; 2004. p. 226–40.
11. Kehdi E, Li B. Null keys: limiting malicious attacks via null space properties of network coding. IEEE INFOCOM; 2009. p. 1224–32.
12. Yu G, Zhong C, Lan X, Zhang C, Wei L, Liu Y. Research of multi-path routing based on network coding in space information networks. Chin J Aeronaut. 2014; 27(3):663–9.
13. Chi K, Jiang X, Horiguchi S. Network coding-based reliable multicast in wireless networks. Computer Networks. 2010; 11(54):1286–389.
14. Ghaderi M, Towsley D, Kurose J. Network coding performance for reliable multicast. IEEE Conference on Military Communications (IEEE MILCOM); 2007. p. 1–7.
15. Ghaderi M, Towsley D, Kurose J. Reliability gain of network coding in lossy wireless networks. The 27th IEEE Conference on Computer Communications (IEEE INFOCOM); 2008.
16. Nguyen D, Tran T, Nguyen T, Bose B. Wireless broadcast using network coding. IEEE Trans Veh Tech. 2009; 58(2):914–25.
17. Ghaffari A, Babazadeh AS. Multi-path routing based on network coding in wireless sensor. Networks, World Applied Sciences Journal. 2013; 21(11):1657–63.
18. Wu Y, Chou PA, Kung Y. Minimum-energy multicast in mobile ad hoc networks using network coding. IEEE Trans Comm. 2005; 53(11):1906–18.
19. Li SH, Yeung RW. Linear network coding. IEEE Trans Inform Theor. 2003; 49(2):371–81.
20. Koetter R, Medard M. An algebraic approach to network coding. IEEE/ACM Transactions on Networking. 2003; 11(5):782–95.
21. Yuhuai P, Qingyang S, Yao Y, Wang F. Fault-tolerant routing mechanism based on network coding in wireless mesh networks. J Netw Comput Appl. 2014; 37:259–72.
22. Antonopoulos A, Skianisb C, Verikoukisa C. Network coding-based cooperative ARQ scheme for VANETs. J Netw Comput Appl. 2013; 36(3):1001–7.
23. Wenbo Q, Jian L, Jian R. An efficient Error-Detection and Error-Correction (EDEC) scheme for network coding. Proceedings of IEEE Conference on Global Telecommunications (IEEE Globecom); 2011. p. 1–5.
24. Zheng G, Bing W, Peng X, Wei Z, Jun-Hong C. Efficient error recovery with network coding in underwater sensor networks. Ad Hoc Networks. 2009; 7(4):791–802.
25. Shaobin C, Zhenguo G, DeSen Y, Nianmin Y. A network coding based protocol for reliable data transfer in underwater acoustic sensor. Ad Hoc Networks. 2013; 11(5):1603–9.
26. Ganti RK, Jayachandran P, Luo H, Abdelzaher TF. Datalink streaming in wireless sensor networks. Proceedings of the 4th International Conference on Embedded Networked Sensor Systems; 2006. p. 209–22.
27. Showail A, Elrasad A, Meer A. Daghistani A, Jamshaid K et al. iFrag: interference-aware frame fragmentation scheme for wireless sensor networks. Wireless Network. 2014; 20(7):2019–36.
28. Chi K, Jiang X, Zhu Y, Wangd J, Li Y. Block-level packet recovery with network coding for wireless reliable multicast. Computer Networks. 2013; 57(4):910–23.
29. Radi M, Dezfouli B, Abd Razak S, Abu Bakar K. LIEMRO: A low-interference energy-efficient multipath routing protocol for improving QoS in event-based wireless sensor networks. 4th International Conference on Sensor Technologies and Applications; 2010.
30. Wendi Rabiner H, Anantha C, Harri B. Energy-efficient communication protocol for wireless microsensor networks. IEEE Proceedings of the 33rd Annual Hawaii International Conference on System Sciences; 2000. p. 1–10.