Enhancement of Lifetime using Duty Cycle and Network Coding in Wireless Sensor Networks

Rashmi Ranjan Rout, *Student Member, IEEE,* and Soumya K. Ghosh, *Member, IEEE*

***Abstract*—A fundamental challenge in the design of Wireless Sensor Network (WSN) is to enhance the network lifetime. The area around the *Sink* forms a bottleneck zone due to heavy traffic-flow, which limits the network lifetime in WSN. This work attempts to improve the energy efficiency of the bottleneck zone which leads to overall improvement of the network lifetime by considering a duty cycled WSN. An efficient communication paradigm has been adopted in the bottleneck zone by combining duty cycle and network coding. Studies carried out to estimate the upper bounds of the network lifetime by considering (i) duty cycle, (ii) network coding and (iii) combinations of duty cycle and network coding. The sensor nodes in the bottleneck zone are divided into two groups: simple relay sensors and network coder sensors. The relay nodes simply forward the received data, whereas, the network coder nodes transmit using the proposed network coding based algorithm. Energy efficiency of the bottleneck zone increases because more volume of data will be transmitted to the *Sink* with the same number of transmissions. This in-turn improves the overall lifetime of the network. Performance metrics, namely, packet delivery ratio and packet latency have also been investigated. A detailed theoretical analysis and simulation results have been provided to show the efficacy of the proposed approach.**

***Index Terms*—Wireless sensor networks, duty cycle, network coding, network lifetime, energy efficiency.**

I. Introduction

Wireless Sensor Networks (WSNs) consist of autonomous sensor nodes that can be deployed for monitoring unattainable areas, such as, glaciers, forest fires, deserts, deep oceans etc [1] [2]. Sensor nodes are generally equipped with a radio transceiver, a micro controller, a memory unit, and a set of transducers using which they can acquire and process data from the deployed regions. The nodes can self organize themselves to form a multi-hop network and transmit the data to a *Sink*. In a energy constraint WSN, each sensor node has limited battery energy for which enhancement of network lifetime becomes a major challenge.

In a typical WSN, the network traffic converges at the *Sink* node *S* (Fig. 1). There is a significant amount of data flow near the *Sink*. The area near the *Sink* is known as the bottleneck zone. Heavy traffic load imposes on the sensor nodes near the *Sink* node. The nodes in the bottleneck zone deplete their energy very quickly, referred as *energy hole* problem in WSN. Failure of such nodes inside the bottleneck zone leads to wastage of network energy and reduction of network reliability. The bottleneck zone needs special attention for reduction of traffic which improves the network lifetime of the whole WSN.

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R. R. Rout is with the G. S. Sanyal School of Telecommunications, and S. K. Ghosh is with the School of Information Technology, Indian Institute of Technology Kharagpur, West Bengal, India, -721302 (e-mail: rashmirsays@gmail.com, skg@iitkgp.ac.in).

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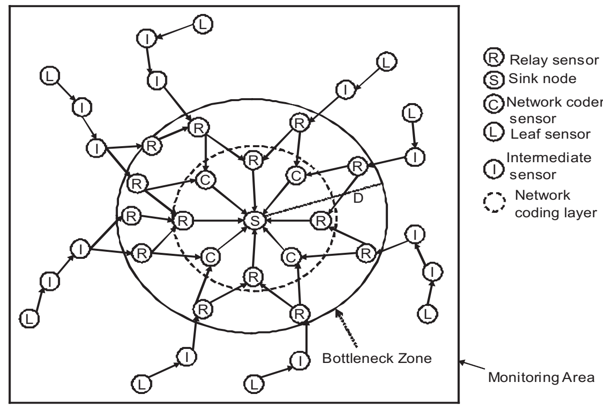

Fig. 1. Traffic flow, bottleneck zone and roles of sensors in a typical WSN.

The *all-node-active* condition is not practical for energy constraint WSN. The sensor nodes save energy by switching between active and dormant (i.e. sleep) states. The ratio between the time during which a sensor node is in active state and the total time of active/dormant states is called *duty cycle*. The duty cycle depends on the node density of the monitored area for better coverage and connectivity. Usually for a dense WSN the duty cycle of a node is very low.

A duty cycled WSN can be loosely categorized into two main types: *random duty-cycled* WSN [3] and *co-ordinated duty cycled* WSN [4]. In the former, the sensor nodes are turned *on* and *off* independently in random fashion. In the later, the sensor nodes co-ordinate among themselves via communication and control message exchanges. They are potentially efficient for communication. However, it requires additional information exchange to disseminate the active/sleep schedule of each nodes. The *random duty-cycled* WSNs are simple to design as no additional overhead is required. In this work, the primarily goal is to gain certain analytical understanding on the upper-bound of the network lifetime. Therefore, the random duty cycle based WSN has been considered for its simplicity in design. Specifically, the problem of reduction of traffic in the bottleneck zone has been considered.

The upper bound on the lifetime has been studied in a previous work [5]. However, the upper bound is not meant for sensor nodes with active and dormant states (i.e. *duty cycle* enabled sensor nodes). In the present work, the upper bound on the network lifetime has been derived for duty cycle based WSN based on [5]. Unlike [5], the multiple reception of the same data bits inside the bottleneck zone for multi-path forwarding [6] has been considered for improvement in reliability and packet delivery in the network. Moreover, energy efficient bandwidth utilization schemes in the bottleneck zone are useful to reduce the extra load on the sensor nodes.

The *network coding* technique [7] improves the capacity of an information network with better utilization of bandwidth. In a multi-hop communication with *network coding*, the intermediate nodes of a network can appropriately encode the incoming data packets before forwarding the coded packets to the next node. The *network coding* technique also improves reliability of the network [8]. A brief description of network coding has been presented in Section I-A. In this work, a *network coding* based communication paradigm in the bottleneck zone has been proposed to reduce the traffic load which enhances the network lifetime. The major contributions of this work can be summarized as follows:

- Estimation of upper bounds of the network lifetime through bottleneck zone analysis in *(a)* random *duty-cycled* WSN *(b) non-duty cycled* WSN using *network coding* in the bottleneck zone *(c)* random *duty-cycled* WSN using *network coding* in the bottleneck zone. The reason is that lifetime upper bounds allow on the design of sophisticated energy efficient protocols.
- It has been shown that the duty cycle and network coding techniques can be integrated to utilize the network resources efficiently. The energy consumption in the bottleneck zone has been reduced to improve the lifetime of the overall WSN.
- Simulations have been carried out to show the efficacy of the proposed approach in terms of network lifetime, packet delivery ratio and packet latency.

A. Network coding

Network coding is a technique which allows the intermediate nodes to encode data packets received from its neighboring nodes in a network [7]. The encoding and decoding methods of linear network coding [9] are described below.

Encoding operation: A node, that wants to transmit encoded packets, chooses a sequence of coefficients $q = (q_1, q_2, ..., q_n)$, called *encoding vector*, from $GF(2^s)$. A set of n packets $G_i (i = 1, 2, 3, 4, ..., n)$ that are received at a node are linearly encoded into a single output packet. The output encoded packet is given by

$$Y = \sum_{i=1}^{n} q_i G_i, \qquad q_i \in GF(2^s) \tag{1}$$

The coded packets are transmitted with the n coefficients in the network. The encoding vector is used at the receiver to decode the encoded data packets.

Decoding operation: A receiver node solves a set of linear equations to retrieve the original packets from the received coded packets. The encoding vector q is received by the receiver sensor nodes with the encoded data. Let, a set $(q^1, Y^1), ..., (q^m, Y^m)$ has been received by a node. The symbols Y^j and q^j denote the information symbol and the coding vector for the j^{th} received packet respectively. A node solves the following set of linear equations (2) with m equations and n unknowns for decoding operation.

$$Y^j = \sum_{i=1}^{n} q_i^j G_i, \qquad j = 1, ..., m \tag{2}$$

At least n linearly independent coded packets must be received by the recipients for proper decode of the original packets. The only unknown, G_i, contains the original packets that are transmitted in the network. The n number of original packets can be retrieved by solving the linear system in equation (2) after getting n linearly independent packets.

The XOR network coding, a special case of linear network coding [9], has been used in this work. The coded packets that are transmitted in the network are elements in $GF(2) = \{0, 1\}$ and bitwise XOR in $GF(2)$ is used as an operation.

The rest of the paper is organized as follows. Section II presents the related work. In Section III, the upper bound of network lifetime with duty cycle through the bottleneck zone analysis has been estimated. Lifetime upper bounds for the WSN with network coding and duty cycle have been presented in Section IV. The performance evaluations of the proposed approaches have been mentioned in Section V. Finally, the concluding remarks are given in Section VI.

II. Related Work

Duty cycle facilitates in reduction of energy consumption in a dense WSN. Furthermore, network coding technique has been drawn its attention for improvement of throughput, bandwidth and energy efficiency in resource constraint wireless networks.

There have been studies on the network lifetime in WSNs. The network lifetime upper bounds have been derived in [10][11][5]. Bhardwaj *et al.* [11] and Wang *et al.* [5] have derived upper bounds on network lifetime for a non-duty cycle based WSN. The network lifetime upper bounds in a cluster based WSN has been estimated by Lee *et al.* [10]. Zhang *et al.* [12] have also derived network lifetime for a non-duty cycle based WSN. A lifetime-aware routing scheme has been proposed by Karkvandi *et al.* [13].

There are also various works in the literature on broadcasting, connectivity and coverage in duty cycle based WSNs. A duty cycle based broadcasting scheme with reliability has been proposed by Wang *et al.* [14]. A recent work which considers duty cycle with respect to communication in an energy harvesting WSN has been proposed by Gu *et al.* [15]. A random duty cycle based WSN has been considered for dynamic coverage by Hsin *et al.* [3]. Futhermore, Lai *et al.* [16] have also proposed an efficient broadcasting scheme in duty cycled WSNs. The coverage and connectivity of low duty cycled WSN has been studied by Kim et. al. [17].

The information theoretic aspect of network coding was introduced by Ahlswede *et al.* [7] for information networks. A random linear network coding based scheme that provides packet-level capacity for both single unicast and single multicast connections have been proposed by Lun *et al.* [18] for wireless networks. Rout *et al.* [19] have also presented a network coding based probabilistic routing scheme which provides gains of network coding in a WSN. Furthermore, Yang *et al.*[20] have presented a network coding scheme for *MANET* using directional antenna. Katti *et al.* [21] have proposed a scheme that uses XOR of packets for practical network coding. However, Keller *et al.* [22] have designed a communication protocol which obtains the trade-off between energy efficiency and reliability in WSN. Hou et al. have proposed a network coding scheme for code updates in WSNs [23]. A network coding based approach for data aggregation has been proposed by Rout *et al.* [24] for distributed WSN. Graph theoretic aspects of network coding for various network structures are studied by Lehman *et al.* [25].

The focus of the present work is to estimate the upper bounds of network lifetime in WSN, considering (i) random duty cycle, (ii) network coding, and (iii) combinations of the duty cycle and network coding. A network coding based communication paradigm has been proposed. Detailed theoretical analysis, simulation and performance analysis have been done to show the efficacy of the proposed approach.

III. Upper bound of Network Lifetime using Duty Cycle

The system model has been described in this section. Based on the system model, an energy consumption model for duty cycle based WSN has been developed. The upper bound of the network lifetime has been estimated and energy savings due to duty cycle has also been shown.

A. System Model

A system is considered with N sensor nodes scattered uniformly in area A. The area A with a bottleneck zone B with radius D is shown in Fig. 1. All the N sensor nodes are *duty cycle* enabled (i.e. switching between active and dormant states). The nodes are named based on their roles in the network as shown in Fig. 1. In the zone B, the nodes are differentiated into two groups, such as, *relay sensor* and *network coder sensor* nodes. The (active) relay sensor nodes (R) transmit data which are generated outside as well as inside the bottleneck zone. The (active) network coder sensor nodes (N) encode the raw native data which are coming from outside the zone B before transmission. The sensor nodes outside the zone B are marked as I and L in Fig. 1. The leaf sensor nodes (L) periodically sense data and transmit them toward the *Sink*. The intermediate sensor nodes (I) relay the data in the direction of the *Sink S*. In the bottleneck zone, the relay nodes can communicate with the *Sink* using a multi-hop communication. However, the network coder nodes use a single hop to communicate with the *Sink*. The radius, D, should be at least equal to the maximum transmission range of a sensor node, so that the data generated outside the bottleneck zone can be relayed through the zone B.

B. Energy Consumption Model with Duty Cycle

A sensor node consumes energy at different states, such as, sensing and generating data, transmitting, receiving and sleeping state. In this work, the radio model [11] has been modified for a duty cycle based WSN. Energy savings are done at the node level through switching between active and sleep states. Energy consumption by a source node per second across a distance d with path loss exponent n is,

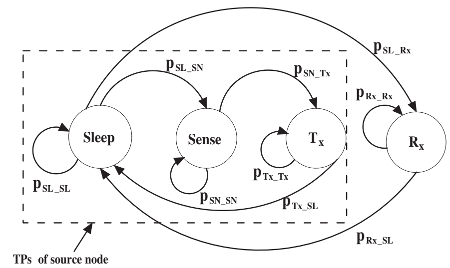

Fig. 2. State transition diagram of a node acting as a source (only inside the rectangle) and a node acting as a relay (the whole state diagram) with transition probabilities (TPs) in a WSN. P_{SL_SL}: *TP* from sleep state to the same state, P_{SL_SN}: *TP* from sleep to sense state, P_{SN_SN}: *TP* from sense state to the same state, $P_{SN\_T_x}$: *TP* from sense to transmit (T_x) state, $P_{T_x\_T_x}$: *TP* from T_x to the same state, $P_{T_x\_SL}$: *TP* from T_x to the sleep state, $P_{SL\_R_x}$: *TP* from sleep to receive (R_x) state, $P_{R_x\_R_x}$: *TP* from R_x to R_x state and $P_{R_x\_SL}$: *TP* from R_x to sleep state.

$$E_{tx} = R_d(\alpha_{11} + \alpha_2 d^n) \tag{3}$$

where R_d is the transceiver relay data rate, α_{11} is the energy consumed per bit by the transmitter electronics and α_2 is the energy consumed per bit in the transmit op-amp [11]. Moreover, the total energy consumption in time *t* (i.e. duration [0,t]) by a source node (leaf node) without acting as a relay (intermediate node) is,

$$E_S = t[p(r_s e_s + E_{tx}) + (1-p)E_{sleep}] \tag{4}$$

where E_{sleep} is the sleep state energy consumption of a sensor node per second, r_s is the average sensing rate of each sensor node and it is same for all the nodes, e_s is the energy consumption of a node to sense a bit, the probability *p* is the average proportion of time *t* (in the duration [0,t]) that the sensor node devotes in active state. Thus, *p* is the duty-cycle. A sensor node remains in the sleep state with probability (*1-p*) till time *t*. The number of active sensor nodes, *g*, out of the total number of nodes *N* deployed in a monitoring area follows a binomial distribution $[{}_NC_g p^g (1-p)^{N-g}]$. The state transition diagram of a source node is shown in Fig. 2 (i.e. in the dotted rectangle). The energy consumption per second by an intermediate node which act as a relay is given by

$$E_{txr} = R_d(\alpha_{11} + \alpha_2 d^n + \alpha_{12}) = R_d(\alpha_1 + \alpha_2 d^n) \tag{5}$$

where α_{12} is the energy consumed by the sensor node to receive a bit. Total energy consumption till time t by an intermediate (relay) node is

$$E_R = t[p(r_s e_s + E_{txr}) + (1-p)E_{sleep}] \tag{6}$$

The state transition diagram of a relay is shown in Fig. 2.

C. Energy Consumption and Upper Bound of Network Lifetime

Total energy consumption in the bottleneck zone are viewed as three parts, namely, energy consumption (i) to relay the data bits which are received from outside of the bottleneck zone (E_1) (ii) due to sensing operation of the (relay) nodes inside the bottleneck zone (E_2) (iii) to relay the data bits which are

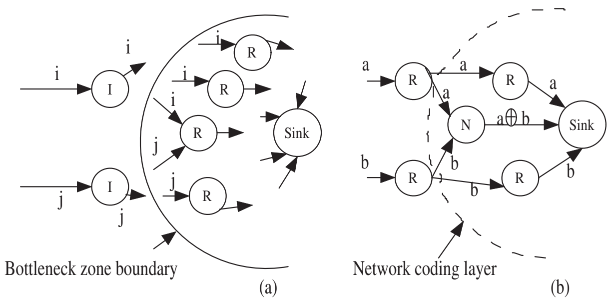

Fig. 3. (a) Reception of redundant data bits by the boundary relay nodes in the bottleneck zone (b) A scenario of *XOR-network coding* in the network coding layer of the bottleneck zone.

generated inside the bottleneck zone (E_3). As shown in Fig. 3 (a), sensor nodes in the bottleneck zone may receive multiple copies of the same data bits transmitted from outside of zone *B*. So, the redundant bits which affect the network lifetime are transmitted inside the zone *B*.

The total number of data bits generated outside the zone *B* is $Np\frac{A-B}{A}r_s t$ [Note: $Np\frac{A-B}{A}$ is the average number of sensor nodes are in active state and $N(1-p)\frac{A-B}{A}$ average number of nodes that are in sleep state in time *t* and follow binomial distribution]. The data bits generated outside the bottleneck zone are relayed through $N\frac{B}{A}$ number of nodes in the bottleneck zone. The total number of data bits which are generated outside and inside of the bottleneck zone in time *t* is given by $Np\frac{A-B}{A}r_s t + Np\frac{B}{A}r_s t = Npr_s t$. The total traffic, $Npr_s t$, is transmitted through $Np\frac{B}{A}$ active relay nodes in the bottleneck zone. Therefore, the average rate of relaying packets by a sensor node in the bottleneck zone is given by $R_d = \frac{Npr_s t}{t\left(Np\frac{B}{A}\right)} = \frac{r_s A}{B}$.

1) Multi-path based packet forwarding: The packet drops, node failures, and errors on wireless links in WSN reduces the reliability of packet delivery in single-path routing schemes [6]. A data packet may travel though multiple paths from source to the *Sink* in a WSN to enhance the packet reception probability [6][26][27]. In the bottleneck zone analysis, multiple redundant receptions may occur inside the bottleneck zone for the same data bits which are generated outside the zone *B* (refer Fig. 3 (a)). Although sensor nodes are uniformly distributed in the monitored area, practically due to deployment constraints and duty-cycle, each node (outside the boundary of the zone *B*) may not have the same number of active neighbors inside the bottleneck zone. While transmitting, any node outside of the zone *B* might have $[1, m]$ number of active neighbors inside the bottleneck zone. Thus, on an average, the number of active neighbors in *B* who received redundant data is $\lfloor (m+1)/2 \rfloor$. The number of forwarding relay nodes need to be reduced (to decrease traffic overhead) based on the required reliability level [26].

The total energy consumption by the nodes in the bottleneck zone to relay the bits that are generated outside the bottleneck zone is

$$E_{1GD} \geq \sum_{i=1}^{\left\lfloor Np\frac{A-B}{A}r_s t \right\rfloor} \sum_{j=1}^{\left\lfloor \frac{m+1}{2} \right\rfloor} E_{ij} \tag{7}$$

where, E_{ij} is the total energy spent by the sensor nodes inside the bottleneck zone *B* to relay one bit data from outside the bottleneck zone. The energy consumption rate to relay a bit over the distance D (bottleneck zone radius) by a relay node with duty cycle in the bottleneck zone is $E_{Rcon} \geq \left(\alpha_1 \frac{n}{n-1}\frac{D}{d_m}\right)$, where d_m is the optimal hop length $\left(d_m = \sqrt[n]{\frac{\alpha_1}{\alpha_2(n-1)}}\right)$ and D is an integral multiple of d_m for equality condition [11]. Now substituting E_{Rcon} in equation (7) gives

$$E_{1GD} \geq \left\lfloor \frac{m+1}{2} \right\rfloor Npr_s t\frac{A-B}{A}\left(\alpha_1 \frac{n}{n-1}\frac{D}{d_m}\right) \tag{8}$$

Inside the zone *B*, energy consumption is basically due to sensing inside the zone and relaying the sensed data. The sensing energy consumption in time *t* by the active nodes in the zone *B* is

$$E_{2GD} = Np\frac{B}{A}r_s e_s t \tag{9}$$

The energy consumption to relay the data bits generated inside the bottleneck zone is

$$E_{3GD} = p\frac{N}{A}r_s t \iint_B l(x)dS$$

$$\Rightarrow E_{3GD} \geq p\frac{N}{A}r_s t \iint_B \left(\alpha_1 \frac{n}{n-1}\frac{x}{d_m} - \alpha_{12}\right)dS \tag{10}$$

where $l(x) \geq (\alpha_1 \frac{n}{n-1}\frac{x}{d_m} - \alpha_{12})$ [Note: The relay nodes do not spend energy for reception of their own sensed data bits [5]]. The total energy consumption in the bottleneck zone in time *t* for a *p* duty-cycle WSN is given by

$$E_D = E_{1GD} + E_{2GD} + E_{3GD} + (1-p)tN\frac{B}{A}E_{sleep} \tag{11}$$

$$E_D = \left\lfloor \frac{m+1}{2} \right\rfloor Npr_s t\frac{A-B}{A}\left(\alpha_1 \frac{n}{n-1}\frac{D}{d_m}\right) + Np\frac{B}{A}r_s t e_s + p\frac{N}{A}r_s t \iint_B \left(\alpha_1 \frac{n}{n-1}\frac{x}{d_m} - \alpha_{12}\right)dS + (1-p)tN\frac{B}{A}E_{sleep} \tag{12}$$

When *p*=1 (*all-nodes-active*) and *m*=1 the energy consumption in the bottleneck zone to relay the data bits that are generated inside as well as outside the bottleneck zone becomes same as in a general or non-duty cycle based WSN [5]. Thus, the equation (12) also covers the general network scenario without considering duty cycle of nodes.

The lifetime of a WSN is significantly depended on the energy consumption at the node level. Let E_b is the initial battery energy available at each sensor node. In a network of *N* nodes, the energy reserve at the start is $N \cdot E_b$.

The performance of a WSN strictly depends on the failure statistics of the sensor nodes. The failure pattern of sensor nodes depends on the rate of depletion of energy. The network lifetime demands that the total energy consumption is no greater than the initial energy reserve in the network. The upper bound on network lifetime can be achieved when the total battery energy (N $\cdot E_b$) available in a WSN is depleted completely. The following inequality holds to estimate the upper-bound of the network lifetime for a duty cycle based WSN.

$$E_D \leq \frac{NB}{A}E_b \Rightarrow t \leq \frac{d_m B E_b}{Q_\chi} = T_{uD} \tag{13}$$

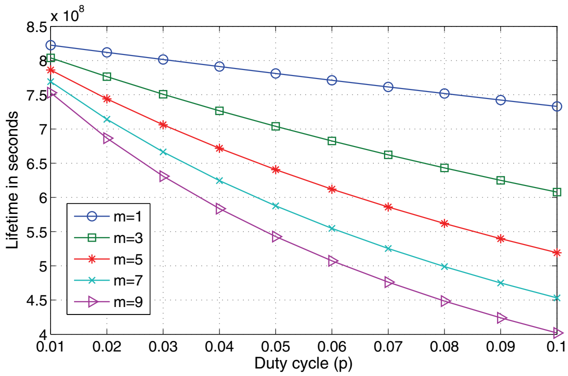

Fig. 4. Network lifetime upper bounds in duty cycle based WSN.

TABLE I
PARAMETER SETTINGS

Number of nodes (N)	10^3
Area (A)	$200 \times 200m^2$
Bottle neck Zone radius (D)	60 meters
path loss exponent (n)	2
α_{11}	0.937 μjoule per bit
α_{12}	0.787 μjoule per bit
α_2	0.0172 μjoule per bit
E_{sleep}	30 μjoule per second
E_b	25Kjoule

where the term Q_χ is given by

$$Q_\chi = p\alpha_1 \frac{n}{n-1} r_s \left[D(A-B) \left\lfloor \frac{m+1}{2} \right\rfloor + \iint_B x dS \right] + Bd_m \left[pr_s(e_s - \alpha_{12}) + (1-p)E_{sleep} \right] \quad (14)$$

and T_{uD} is the lifetime upper bound of the WSN with duty cycle (p). The amount of energy consumption is maximum when *p=1* (i.e. all node active condition) and the lifetime minimizes in a WSN. The energy efficiency of the network increases with low duty cycle which enhances the lifetime of the network.

Analytical results from equation (13) have been shown in Fig.4 which uses the parameter settings given in Table I. The energy consumption parameters are selected based on *MICA* node [28]. The e_s is taken as negligibly small. The area of the bottleneck zone is *B* which is πD^2 while considering it a complete round surface. The value of r_s is set as $H/((A-B) * N/A)$ where H is 960 bits and $\iint_B x dS = (2/3)\pi D^3$. As shown in the Fig. 4, the network lifetime decreases when the value of m increases. The increase of the value of m suggests that more amount of energy has been consumed in the bottleneck zone for transmissions of the redundant bits. The duty cycle varies from 1% to 10% as shown in the Fig. 4. As the duty cycle increases (i.e. more number of nodes are in active state) the lifetime decreases in the network. In a WSN with duty cycle more than 10%, the network lifetime further decreases. For a dense WSN the duty cycle generally varies from 1% to 10%. However, in some special cases the duty cycle may be increased to fulfill the requirement of specific coverage and connectivity in a WSN.

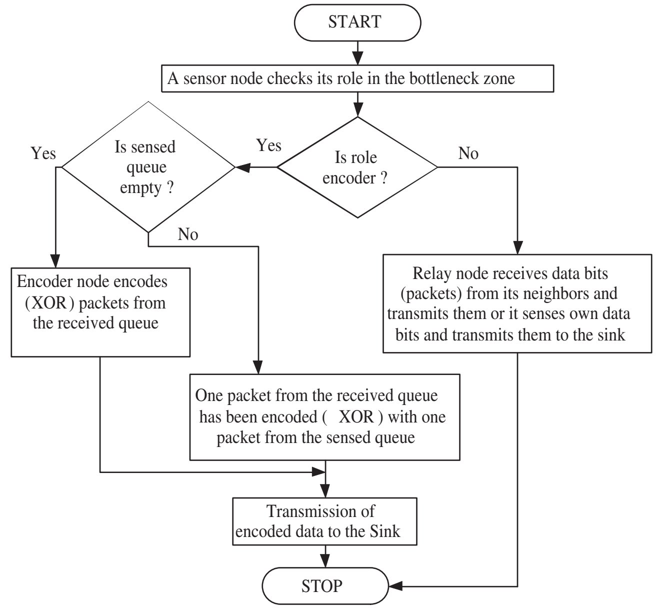

Fig. 5. Functionalities of the sensor nodes in the bottleneck zone.

IV. UPPER BOUNDS OF NETWORK LIFETIME USING NETWORK CODING AND DUTY CYCLE

In this section, the network lifetime has been estimated with a proposed network coding algorithm for a non-duty cycled WSN. Furthermore, network coding and random duty cycle have been combined to estimate the network lifetime in a duty cycled WSN. Here, the lifetime upper bounds have been derived while considering a fraction of total traffic flows through the network coder nodes in the bottleneck zone.

A network coding layer (refer Fig.1 and Fig. 3 (b)) containing network coder nodes has been introduced around the *Sink*. The network coding layer is the most overloaded region (i.e. vulnerable region) of the bottleneck zone. So, reduction of energy consumption of the coding layer leads to higher network lifetime. A group of vulnerable nodes (i.e. the nodes which are nearest to the *Sink* and deplete their energy quickly) in the bottleneck zone transmits using network coding based communication. The other group of nodes in the bottleneck zone acts as simple relay nodes. These relay nodes help the *Sink* to decode the encoded packets. Whenever a node in the bottleneck zone receives a packet, it checks its role (refer Fig. 5). The node follows the *Algorithm-1* to process a packet.

The packet processing procedure of a node in the network coding layer of the bottleneck zone has been given in *Algorithm-1*. Each node in the network coding layer maintains a received queue (*RecvQueue()*) and a sensed queue (*SensQueue()*). On receiving a packet P_i, a node put the packet in *RecvQueue(P_i)*. If the packet is already processed by the node than it is discarded, otherwise the node process the packet further. The node check its role from *EncoderNodeSet()*, whether it is an encoder or a simple relay node. If the packet is a native (non-coded) packet and the node is an encoder, the node invokes the method *XorEncode()*. Detail method of encoded packet generation is given in *Algorithm-2*. On successfully creating an encoding packet, the node transmit the coded packet to the *Sink*. The processed packet is inserted into the forwarding set *ForwardSet()* which stores the forwarded packets and help in restricting further redundant transmissions. However, the received packet P_i is already an encoded packet, it is discarded by the node. Futhermore, if the node is not an encoder, it acts as a simple relay and transmits the received packet P_i to the *Sink*.

ALGORITHM 1: *PacketProcess(P_i) : Packet processing at a node inside the network coding layer*

Require: Packet transmission and reception starts, received packets inserted into the *RecvQueue()*
Ensure: Encoded packet transmitted or discarded
1. Pick a packet P_i from *RecvQueue(P_i)*
2. If Packet $P_i \in$ *ForwardPacketSet(P_i)* exit;
3. If Node *n* $\in$ *EncoderNodeSet()* continue;
4. If *native(P_i)* then
5. C_N =*XorEncode()*;
6. Node *n* transmits the coded packet C_N to *Sink*
7. Insert the processed packet P_i to *ForwardPacketSet()*;
8. else
9 *Discard(P_i)*;
10 endif
10. else
11. Node *n* acts as relay and transmits the packet P_i to the *Sink*;
12. endif
13. endif
14. If (RecvQueue() $\neq$ empty)
15. goto step 1;
16. else exit;
17. endif

Decoding of packets at the Sink: The *Sink* node receives native packets from the simple relay nodes and coded packets from the network coder nodes. In *COPE* [21] the intermediate nodes encode and decode packets. Unlike *COPE*, the decoding procedure is performed only at the *Sink* which processes all the gathered data in WSN. The *Sink* maintains a pool of packets, in which it stores each received native packets. When the *Sink* receives an encoded packet consisting of $\hat{k}$ native packets, the *Sink* retrieves the corresponding native packets one by one from the pool of packets. The *Sink* XORs the $\hat{k}-1$ native packets with the received coded packet to retrieve the missing packet which is totally lost or received with error at the *Sink*.

A. Upper Bound of Network Lifetime using Network Coding without Duty Cycle

The network lifetime for a non-duty cycled WSN has been estimated while considering the proposed network coding algorithm in the bottleneck zone in this section.

The upper bound of network lifetime has been investigated using a network coding layer near the *Sink* in the bottleneck zone. With network coding based relaying in the bottleneck zone, E_1, E_2 and E_3 have been derived and renamed as E_{1NC}, E_{2NC} and E_{3NC}. Energy consumption by a network coder node is assumed to be same as energy consumption by a relay node to transmit one bit data inside the bottleneck zone. The overhead of encoding process is negligible in view of single hop communication between the network coder node and the *Sink*. Let $\frac{1}{h}$ fraction of the total traffic which are generated outside of the bottleneck zone is relayed through the network coder nodes in the direction of *Sink*. So, $(1-\frac{1}{h})$ fraction of the total traffic is relayed through the relay nodes in the bottleneck zone. Energy consumed by a network coder relay node to relay a data bit (generated outside the bottleneck zone) is $E_C(ij) \geq \alpha_1 \frac{n}{k(n-1)} \frac{D}{d_m}$ [Note: for relay node $E_R(ij) \geq \alpha_1 \frac{n}{n-1} \frac{D}{d_m}$], where *k* data packets (fixed size packets) are encoded into one coded data packet by the network coder node. The energy savings per bit due to *network coding* is $E_{NCsv} = \alpha_1 \frac{n}{n-1} \frac{D}{d_m} \frac{k-1}{k}$.

Energy consumption in the bottleneck zone to relay the traffic which are received from outside of the bottleneck zone is given by

$$E_{1NC} \geq \sum_{i=1}^{\lfloor N\frac{A-B}{h\cdot A} r_s t\rfloor} \sum_{j=1}^{\lfloor \frac{m+1}{2} \rfloor} E_C(ij) + \sum_{i=1}^{\lfloor N\frac{(A-B)(h-1)}{h\cdot A} r_s t\rfloor} \sum_{j=1}^{\lfloor \frac{m+1}{2} \rfloor} E_R(ij)$$

$$E_{1NC} \geq \left\lfloor \frac{m+1}{2} \right\rfloor N r_s t \alpha_1 \frac{n(A-B)}{A(n-1)} \frac{D}{d_m} \frac{1+k(h-1)}{kh} \tag{15}$$

Inside the zone *B*, energy consumption is due to sensing inside the zone and relaying the sensed data bits. The sensing energy consumption in time *t* by the network coder sensor nodes are same as relay sensor nodes. Therefore, total sensing energy consumption in the bottleneck zone is given by $E_{2NC} = N\frac{B}{A} r_s e_s t$.

ALGORITHM 2: *XorEncode() : Encoding algorithm*

Require: A received queue *RecvQueue()* and a sensed queue *SensQueue()* is maintained at an encoder node
Ensure: Generation of network coded packet C_N
1. If *SensQueue()* is not empty *then* continue;
2. Pick a packet P_i from head of the *RecvQueue()*;
3. Pick a packet P_j from head of the *SensQueue()*;
4. $C_N = P_i \oplus P_j$;
5. else
6. Pick next packet P_{i+1} from the *RecvQueue()*;
7. $C_N = P_i \oplus P_{i+1}$;
10. endif;
11. return C_N

A fraction of the traffic generated inside bottleneck zone may also relayed through the network coder sensor nodes. Assume that the traffic generated inside the bottleneck zone are not encoded and the network coder sensor node functions as a general relay node. So, the energy consumption in the bottleneck zone to relay the data bits generated inside the zone is given by

$$E_{3NC} = \frac{N}{A} r_s t \int\int_B l(x) dS$$
$$\Rightarrow E_{3NC} \geq \frac{N}{A} r_s t \iint_B \left(\alpha_1 \frac{n}{n-1} \frac{x}{d_m} - \alpha_{12} \right) dS \tag{16}$$

The upper bound of the network lifetime with network coding in WSN is given by

$$E_{NC} = E_{1NC} + E_{2NC} + E_{3NC} \leq \frac{NB}{A} E_b$$
$$\Rightarrow \left\lfloor \frac{m+1}{2} \right\rfloor \alpha_1 \frac{D}{d_m} \frac{n(A-B)}{A(n-1)} N r_s t \frac{1+k(h-1)}{kh} + N\frac{B}{A} r_s e_s t$$
$$+ \frac{N}{A} r_s t \iint_B \left(\alpha_1 \frac{n}{n-1} \frac{x}{d_m} - \alpha_{12} \right) dS \leq \frac{NB}{A} E_b \tag{17}$$

$$\Rightarrow t \leq \frac{d_m B E_b}{Q_\varphi} = T_{uNC} \tag{18}$$

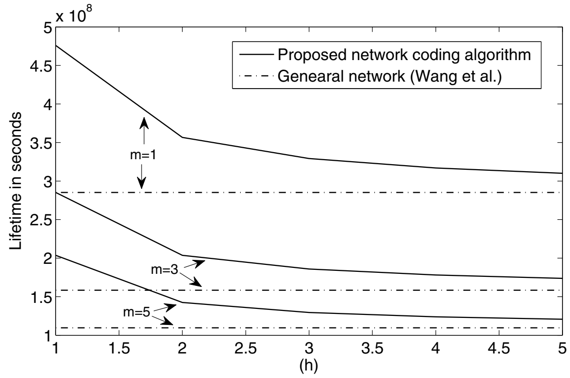

Fig. 6. Lifetime upper bounds using the proposed network coding algorithm and the general network (Wang *et al.* [5]) (with m=1,2,3).

and the term Q_φ is given by

$$Q_\varphi = r_s \alpha_1 \frac{n}{n-1}\left[\left\lfloor\frac{m+1}{2}\right\rfloor D(A-B)\frac{1+k(h-1)}{kh} + \iint_B x dS\right] + r_s(e_s - \alpha_{12}) d_m B \quad (19)$$

In Fig. 6, the analytical results are depicted. The parameter values are taken from Table I and used in equation (18). Some additional parameters are used in Fig. 6, such as, the value of k is set as 2 (i.e. two coded packets are considered). The parameter h has been taken in the *X-axis* and the lifetime has been depicted in the *Y-axis* for the proposed network coding based approach and the general network. As the value h increases, the network lifetime decreases in case of the proposed network coding approach because less traffic flow though the network coder nodes. The network lifetime in case of a general network [5] remains constant irrespective of the value of h and it is significantly less than the proposed approach. Furthermore, on increase of the value of m, the network lifetime decreases in both the cases.

B. Upper Bound of Network Lifetime using Network Coding with Duty Cycle

Lifetime bounds in duty cycle based WSN has been estimated using network coding. With duty cycle of the sensor nodes and network coding based relaying in bottleneck zone, E_1, E_2 and E_3 have been derived and renamed as E_{1NCD}, E_{2NCD} and E_{3NCD} respectively. The energy consumption in the bottleneck zone to relay the bits generated outside of the bottleneck zone is

$$E_{1NCD} \ge \sum_{i=1}^{\lfloor Np\frac{A-B}{h\cdot A} r_s t\rfloor} \sum_{j=1}^{\lfloor\frac{m+1}{2}\rfloor} E_C(ij) + \sum_{i=1}^{\lfloor Np\frac{(A-B)(h-1)}{h\cdot A} r_s t\rfloor} \sum_{j=1}^{\lfloor\frac{m+1}{2}\rfloor} E_R(ij)$$

$$E_{1NCD} \ge \left\lfloor\frac{m+1}{2}\right\rfloor pNr_s t\alpha_1 \frac{n(A-B)}{A(n-1)}\left[\frac{D}{d_m}\frac{1+k(h-1)}{kh}\right] \quad (20)$$

The network coding scheme does not affect the normal sensing energy consumption. The energy consumed for sensing inside the bottleneck zone is same as given in equation (9) i.e. $E_{2NCD} = E_{2GD}$. Furthermore, the network coder nodes do not relay the encoded (XOR) data bits generated inside the bottleneck zone, the energy consumed to relay the bits

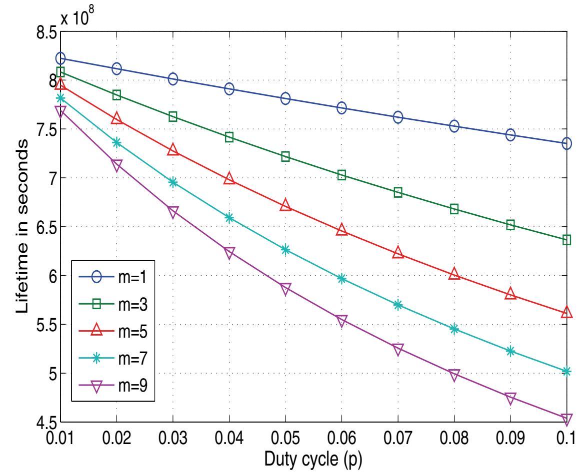

Fig. 7. Lifetime upper bounds by combining network coding and duty cycle.

generated is same as in equation (10) for duty cycle case i.e. $E_{3NCD} = E_{3GD}$. The upper-bound of the network lifetime in duty cycle based WSN with the proposed network coding approach, T_{uNCD}, can be derived as follows. The upper-bound of the network lifetime in duty cycle based WSN with the proposed network coding approach, T_{uNCD}, can be derived as follows.

$$E_{NCD} = E_{1NCD} + E_{2NCD} + E_{3NCD} + (1-p)tN\frac{B}{A}E_{sleep} \le \frac{NB}{A}E_b \quad (21)$$

$$\Rightarrow \left\lfloor\frac{m+1}{2}\right\rfloor pNr_s t\alpha_1 \frac{n(A-B)}{A(n-1)}\frac{D}{d_m}\frac{1+k(h-1)}{kh} + N\frac{B}{A}tpr_s e_s + p\frac{N}{A}r_s t\iint_B\left(\alpha_1\frac{n}{n-1}\frac{x}{d_m} - \alpha_{12}\right)dS + (1-p)tN\frac{B}{A}E_{sleep} \le \frac{NB}{A}E_b$$

$$\Rightarrow t \le \frac{d_m B E_b}{Q_\delta} = T_{uNCD} \quad (22)$$

and Q_δ is given by

$$Q_\delta = pr_s\alpha_1\frac{n}{n-1}\left[\left\lfloor\frac{m+1}{2}\right\rfloor D(A-B)\frac{1+k(h-1)}{kh} + \iint_B x dS\right] + Bd_m\Big[pr_s(e_s-\alpha_{12}) + (1-p)E_{sleep}\Big] \quad (23)$$

The values of the parameters in equation (22) are set from Table I and the analytical results have been shown in Fig. 7. The value of k is set as 2 and the parameter h is set as 2 (i.e. the upper bound of lifetime has been shown in Fig.7 for 50% of the network traffic through the network coder nodes). In the Fig. 7, the duty cycle and the lifetime are shown in the *X-axis* and *Y-axis* respectively. As the duty cycle p increases, the lifetime decreases because more traffic flow in the WSN. The network lifetime decreases when the value of m increases. However, the lifetime in this case is found to be more than the duty cycled WSN without network coding.

C. Performance Analysis and Discussions

In a routing tree based communication, the nodes can forward packets through the path traced by a tree. However, if some of the links fail near the *Sink*, then the entire energy consumption which is required to relay the packet up-to the bottleneck zone is lost. Different kind of *ACK* mechanisms are required for the retransmission of lost packets. This will cause further delay to the delivery of the lost data packets and it needs sophisticated routing protocols. Therefore, multi-path kind of routing strategy gains its importance in WSN for better reliability with less latency of packet delivery [26][27]. However, the numbers of paths need to be restricted to control/reduce the redundant data flow. In such a scenario, the proposed network coding based approach reduces traffic inside the bottleneck zone and provides reliability against data loss due to link failure near the *Sink*.

The performance metrics other than the energy efficiency are packet delivery ratio (*PDR*) and packet latency (*PL*) [29][30]. Thus, the metrics *PDR* and *PL* are used to evaluate the performance of the network with the proposed network coding based algorithm in a duty cycled WSN. *Packet delivery ratio* (*PDR*) is the ratio of the successfully delivered packets to the total number of packets sent to the *Sink* [29]. In case of multi-hop communication with multi-path forwarding strategy, multiple nodes or link disjoint paths exist between a pair of source and the *Sink* [6] [26] to provide certain reliability. However, these paths (some of the links) are shared by the other sources near the *Sink*. The network coder nodes increases the *PDR* by forwarding network coded data on the shared links in the network coding layer (Fig. 3 (b)) near the *Sink* while protecting the native data packets against link failure.

Packet latency(*PL*) is the time taken by a data packet to travel from a source sensor node to the *Sink* [29]. The latency *PL* is expressed as the ratio of the summation of individual data packet latency to the total number of data packets delivered to the *Sink*. In random duty-cycle based networks, each sensor node switch between *on* and *off* independently. Other than the transmission delay, some delay occurs due to the random duty-cycle of nodes where a sensor node holds packets in the sleep state and transmits only at the active state. Also, in the network coding layer, the encoder nodes wait to accumulate k packets from its neighbors. It encodes the k native data packets and transmits the coded packet to the *Sink*. The delay occur due to the wait-and-hold policy and can be reduced by restricting the value of k based on the traffic rate. A network coding node needs at least two packets to encode. However, a network coding node may not get always two such packets to encode. After receiving a packet, an encoder node waits for certain predefined interval of time and forwards the received packet (if the other packet is not available within the stipulated time interval).

1) Selection of network coders: The network coder nodes in the network coding layer (Fig. 1) are one-hop away from the *Sink*. The decoding responsibilities are assigned to the *Sink* which is not usually an energy constraint node. The selection of network coders in the network coding layer is done by the *Sink* by sending control messages. The ratio of the number of network coder nodes to the relay nodes in the network coding layer specify the amount of coded traffic received at the *Sink*. The success rate of recovering the original data from the received encoded data at *Sink* will reduce if more than half of the active nodes are selected as network coder nodes with symmetric traffic flow.

To ensure proper decoding of the network-coded packets at the *Sink*, at least 50% relay nodes are needed. In this work, it has been considered that 50% of the nodes in the bottleneck zone will have network coding capability (refer Fig.1) and they are uniformly distributed. The traffic flow through the nodes in the network coding layer of the bottleneck zone has also been considered to be symmetric. However, if the traffic flows are different, then more than 50% relay nodes will be needed to ensure proper decoding of data packets. In practice, the *Sink* will monitor the decoding rate against incoming traffic rate. If the decoding rate is less, the *Sink* will reduce the number of network-coder nodes.

2) Applications and assumptions: As discussed in the previous sections, sensor nodes are periodically switch on, sense the environment, and transmit the data of interest at constant periodic time intervals. The discussed data delivery analysis is suitable for the applications that require periodic sensing and monitoring such as environmental monitoring [2][31][32]. The random duty cycle based WSN has been considered in the present work. However, for event centric applications, sensor nodes sense and forward data only when the targeted event occurs. Although, the work in this paper focuses on the periodic monitoring applications, the presented analysis can be extended for the event-centric applications. Let $\tilde{e_r}$ be the rate of occurrence of an event and $\tilde{e_g}$ be the average rate generation of bits per event. So $(\tilde{e_r}\tilde{e_g})$ will be the average rate of generation of data from a sensor node for event-centric applications [10]. However, this needs further study on co-ordinated duty cycle based event-centric WSN which is beyond the scope of the present work.

In a WSN, a source transmits packets through multi-hop path to the *Sink*. In an uniformly distributed region, the distance between the sensor nodes may vary with deployment constraints. Similarly, the distance of relay nodes and network coder nodes in the network coding layer may also vary from the $Sink$. In such a case, the average inter node distance such as $d_{av} = \frac{\sum_{i=1}^{U} d_i}{U}$, for large number of hops (U) with hop distance d_i, in the multi-hop path will be used in place of d_m to estimate the energy consumption.

V. Performance Evaluation

This section presents the simulation results and performance analysis of the proposed algorithms. The simulation studies have been made on MICA mote sensors [28]. The energy efficiency and improvement of lifetime of the proposed approach have been discussed. Further, the factors which affect the network performances, such as, packet delivery ratio, latency of packet delivery, routing and MAC layer inefficiencies have also been discussed in this section.

A. Simulation Results

The simulation work has been carried out using a *MATLAB* based event driven simulator known as *PROWLER* [33]. The simulation settings and parameter values are based on the *MICA* mote specification [28]. The radio propagation model is the *free space path loss* model with path loss exponent 2. Fading effects have been considered in the simulation process based on the default parameters as given in [33]. One thousand number of sensor nodes are uniformly distributed in an deployment area of $200 \times 200m^2$. The maximum data rate is 40 Kbps. The packet size is 960 bits. The simulation results are averaged after taking 30 simulation runs.

The radius (D) of the bottleneck zone around the *Sink* is 60 meters. The nodes inside the bottleneck zone are bottleneck nodes. So, the average number of sensor nodes which lie inside the zone is $\frac{N \times \pi D^2}{A}$ while considering a circular bottleneck zone. For simulation the values of h and k are set as 2 (i.e. equal traffic flow though the network coder nodes and the relay nodes). A simple MAC protocol is used in which a sensor node waits for a random duration of time before trying to transmit a packet. The sensor node waits for a random back off time if the channel is in busy state. The node keeps trying until the transmission is performed. The sensed packets from outside of the bottleneck zone have been transmitted to the *Sink* using *flooding* protocol in which data packets travel through multiple paths.

The network lifetimes in a WSN with (a) *duty cycle* and (b) *duty cycle and network coding* have been shown in Fig. 8. The duty cycle p of the WSN has been taken from 1% to 10%. As the duty cycle p increases in the network the lifetime decreases in the network. On the increase of duty cycle suggest that there is an increase in the number of active nodes in the network. As the duty cycle increases from 1% to 10% the number of transmissions and receptions in the network increases. Thus, the energy consumption of the nodes are also increases in the network. It has been observed from the Fig. 8 that the lifetime time *with duty cycle and network coding* is more than only *using duty cycle*. There is an increase of 2.5% to 9.5% of network lifetime by using the proposed network coding based communication algorithm for 1% to 10% duty cycle respectively in the duty cycled WSN. The improvement of lifetime is due to the introduction of network coding nodes near the *Sink*. Furthermore, in Fig. 9 energy consumption (per node) has been shown for a duty cycle based WSN with network coding and without network coding.The per node energy consumption in case of a WSN *with duty cycle* is more than a WSN *with duty cycle and network coding*.

The availability of more volume of data at the *Sink* may facilitate decision making for a sensor application. The *Sink* receives on an average at least two copies of the same packet when the duty cycle $p \geq 0.02$ (Fig.10). The packets received at the *Sink* may also be corrupted in view of multi-hop communication. Therefore, multiple copies of the same packet helps the *Sink* for better decision making. However, with duty cycle $p = 0.01$, the *Sink* is not able to receive at least a packet due to lack of connectivity in the WSN. It can also be seen from Fig. 10 that the proposed network coding based communication approach increases the volume of received data at the *Sink* even with low duty cycle (1% to 10%). The *Sink* receives approximately 50% more data with same number of transmissions (i.e. with same energy consumption) in the bottleneck zone by using the proposed network coding based algorithm.

The *packet delivery ratio* (PDR) and the *packet latency* (PL) have been measured by distributing 100 sensor nodes uniformly with varying the area of the deployment region. The

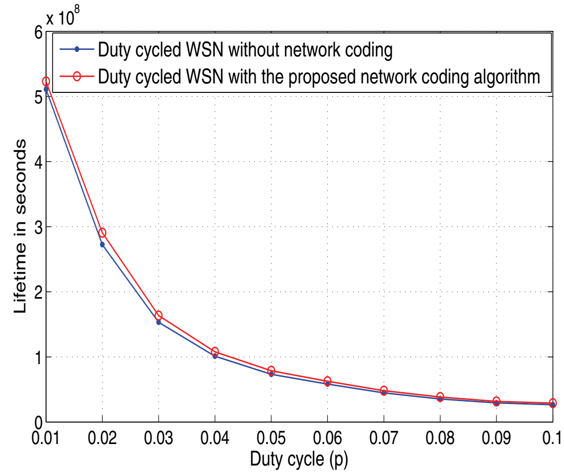

Fig. 8. Network Lifetime (a) with duty cycle (T_{uD}) and (b) with duty cycle and network coding (T_{uNCD}) in a WSN which is deployed in $200 \times 200m^2$ monitoring area.

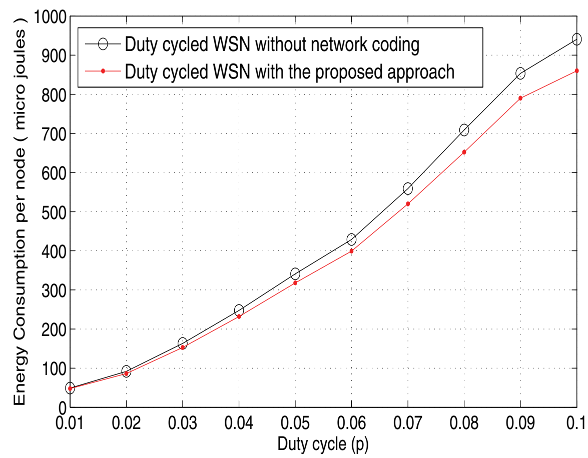

Fig. 9. Per node energy consumption (a) with duty cycle and (b) with duty cycle and network coding in a WSN which is deployed in $200 \times 200m^2$ monitoring area.

node density (i.e. nodes per unit area) is varied by fixing the duty cycle. The improvement in the PDR has been shown in Fig. 11. The PDR has been shown for three cases, namely, (i) $1/3$ (34% approx.) of the total received packet loss at *Sink* with the proposed network coding based approach, (ii) $1/6$ (17% approx.) packet loss, without network coding approach and (iii) $1/3$ (34% approx.) packet loss, without network coding approach. When the density is low, the number of active nodes per unit area is less. Thus, less amount of traffic is successfully forwarded to the *Sink*. In the proposed approach and in the multi-path forwarding without network coding, the PDR is low for low node densities. However, as the node density increases, the proposed network coding approach has significantly more PDR than the the traditional multi-path forwarding. With the proposed approach, up-to 25% PDR improvement can be achieved at the *Sink* by decoding the encoded data packets in case of loss of a fraction of transmitted packets due to link failure (Fig.11).

In Fig. 11, with a very low node density of 0.015, the PDR

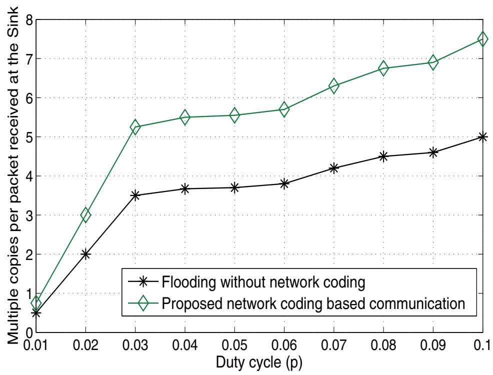

Fig. 10. Multiple copies per packet received at the *Sink* vs duty cycle using (a) Flooding and (b) the proposed network coding based approach.

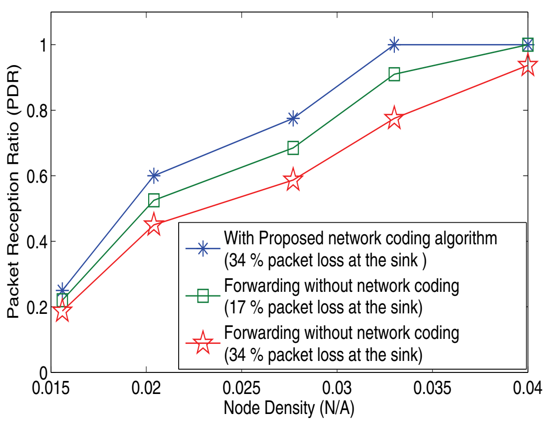

Fig. 11. Packet Delivery Ratio vs node density with duty cycle p=0.05.

is 20% (approx.). With this node density, the nodes in the network are sparsely deployed. However, with node density 0.02, the PDR is improved to 60%, using the proposed network coding based approach. From node density 0.02 to 0.035 the PDR ranges from 60% to 100%. Typically, the PDR is chosen based on an application's requirement.

The variation of network lifetime with duty cycle has been shown in Fig. 8 for fixed node density. The variation of PDR with node density has been shown in Fig. 11 for fixed duty cycle ($p = 0.05$). The PDR improves with the increase in node density for a fixed duty cycle. However, the network lifetime will decrease with the increase in node density due to redundant traffic flow in the bottleneck zone (for a fixed duty cycle). Therefore, the node density needs to be maintained for an appropriate PDR based on the requirement of a given application to achieve a desired lifetime of the network. As shown in the Fig. 11, the PDR saturates after a particular node density (0.035 to 0.04). So further increase in node density will not increase the PDR while the network lifetime will be reduced with redundant reception of data packets at the *Sink*.

The average packet latency (PL) has been depicted in Fig.12. The latency decreases when the node density increases because more nodes are active per unit area while keeping the duty cycle fixed. With low node density and fixed duty cycle, the PL using the proposed network coding based algorithm in the bottleneck zone is higher in comparison to the traditional

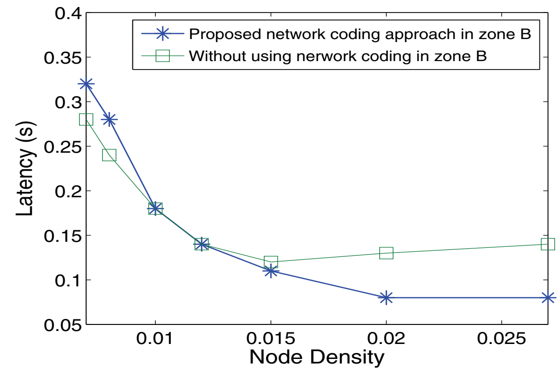

Fig. 12. Latency vs node density with duty cycle p=0.1.

multi-path based communication. The reason is that the traffic flow through the network coder nodes is very less with low node density and the network coder nodes have to wait for sufficient packets in their buffer (i.e. till accumulation of k packets). However, as the node density increases more traffic flow through the encoder nodes and the delay decreases accordingly. On further increase of node density (i.e. node density $\geq$ 0.015 in Fig 12), the latency in the traditional multi-path forwarding increases due to the increase in the multiple copies of data and collided packets near the *Sink*. However, the latency in the proposed approach decreases and remain constant despite of the increase in node density because lost packets are recovered from the encoded packets and the received native packets at the *Sink*.

B. Energy consumptions

It can be observed from equations (13), (18) and (22) that the energy consumptions such as E_G, E_D, E_{NC}, and E_{NCD} conform the following inequalities

$$\begin{aligned} E_{NCD} \leq E_{NC} \leq E_G, E_{NCD} \leq E_D \leq E_G \\ \Rightarrow T_{uNCD} \geq T_{uNC} \geq T_G, T_{uNCD} \geq T_{uD} \geq T_G \end{aligned} \tag{24}$$

where, E_G and T_G are the total energy consumption and lifetime in a non-duty cycle based WSN respectively. As the energy consumption increases in a WSN, the network lifetime decreases. So, the inequalities in equation (24) also can be visualized from Fig. 4, Fig.6, Fig. 7 and Fig. 8. E_G is same as E_D while putting $p = 1$ and $m = 1$ in equation (12). T_G is same as T_{uD} by putting $p = 1$ and $m = 1$ in equation (13). It can be also observed from the simulation results that $T_{uNCD} \geq T_{uD}$ (refer Fig. 8) and the slope of the Fig. 8 suggests that on further increase of duty cycle from (*0.1 to 1*], the network lifetime decreases. Therefore, in case of a non-duty cycle based network [5], the WSN lifetime T_G is very low in comparison to the proposed approaches.

C. Effect of MAC and routing protocols on network lifetime

In randomized duty cycle based WSN, each sensor node randomly generates a working schedule. Energy consumption is also dependent on the working schedule of the sensor nodes. Due to lack of co-ordination among the sensor nodes some amount of energy may be wasted due to collision of data at the receiver. Thus, the network lifetime may be affected by non-ideal MAC (medium access control) protocols. Furthermore, at the physical layer, the realistic conditions of wireless link can affect the intended network lifetime. The wireless link status can change with time and frequency.

Different routing protocols may deal with different forwarding schedule of a node and different paths from the source to destination. An ideal best routing protocol can deliver data to the *Sink* with $\lfloor\frac{m+1}{2}\rfloor = 1$ in equation (22) which is difficult design and it needs significant amount of control packet dissemination in a WSN. In the worst case scenario $\left\lfloor\left(\frac{m+1}{2}\right)^{\frac{\omega+1}{2}}\right\rfloor$ number of redundant data packets will be transmitted in a WSN from a source to destination. Here, the ω is the maximum number of hops from the boundary of a deployed region to the bottleneck zone (where, the data bits generated outside the bottleneck zone follows a uniform distribution in the range of values $[1,\omega]$ for multi-hop communication to reach the bottleneck zone). It has been observed from the simulations that with flood routing the simulated network lifetime upper bounds (as shown in Fig. 8) are less than the proposed analytical lifetime upper bounds (as shown in Fig. 4 and Fig. 7 for $m = 1$). Therefore, the routing protocols affect the intended network lifetime.

VI. Conclusions

In a wireless sensor network (WSN), the area around the *Sink* forms a bottleneck zone where the traffic flow is maximum. Thus, the lifetime of the WSN network is dictated by the lifetime of the bottleneck zone. The lifetime upper bounds have been estimated with (i) duty cycle, (ii) network coding and (iii) combinations of duty cycle and network coding. It has been observed that there is a reduction in energy consumption in the bottleneck zone with the proposed approach. This in-turn will lead to increase in network lifetime. Simulation results reveal that there is an increase of 2.5% to 9.5% of network lifetime by using the proposed network coding based algorithm for 1% to 10% duty cycle respectively in a duty cycled WSN. It has been shown that the *per node* energy consumption in case of a *WSN with duty cycle* is more than a *WSN with duty cycle and network coding*. The *Sink* receives approximately 50% more data with same energy consumption in the bottleneck zone. More volume of data leads to more accuracy of decision making at the *Sink*. The packet delivery ratio and packet latency for the proposed approach have also been investigated with packet losses at the *Sink*. A significant improvement in packet delivery ratio has been achieved with the proposed network coding approach. Although, packet latency is high for low node density but with increase of node density the proposed approach has significantly low latency than forwarding without network coding in a duty cycled WSN.

As an extension of the present work, lifetime time analysis can be done selecting nodes as network coders which are at *k-hops* ($k = 2, 3, ...$) away from the *Sink*. Further, the proposed analysis may facilitate the design of sophisticated MAC and routing protocols for energy-constrained/duty cycled WSN.

References

[1] I. F. Akyildiz, W. Su, Y. Sankarasubramaniam, and E. Cayirci, "Wireless sensor networks: a survey," *Computer Networks*, vol. 38, no. 4, pp. 393–422, 2002.

[2] J. Yick, B. Mukherjee, and D. Ghosal, "Wireless sensor network survey," *Computer Networks*, vol. 52, no. 12, pp. 2292–2330, 2008.

[3] C. F. Hsin and M. Liu, "Randomly duty-cycled wireless sensor networks: dynamic of coverage," *IEEE Trans. Wireless Commun.*, vol. 5, no. 11, pp. 3182–3192, 2006.

[4] X. Y. Wang, R. K. Dokania, and A. Apsel, "PCO-based synchronization for cognitive duty-cycled impulse radio sensor networks," *IEEE Sensors J.*, vol. 11, no. 3, pp. 555–563, 2011.

[5] Q. Wang and T. Zhang, "Bottleneck zone analysis in energy-constrained wireless sensor networks," *IEEE Commun. Lett.*, vol. 13, no. 6, pp. 423–425, June 2009.

[6] D. Ganesan, R. Govindan, S. Shenker, and D. Estrin, "Highly-resilient, energy-efficient multipath routing in wireless sensor networks," *ACM SIGMOBILE Mobile Computing and Commun. Rev.*, vol. 5, no. 4, pp. 11–25, 2001.

[7] R. Ahlswede, N. Cai, S. Y. R. Li, and R. Yeung, "Network information flow," *IEEE Trans. Inf. Theory*, vol. 46, no. 4, pp. 1204–1216, July 2000.

[8] O. M. Al-Kofahi and A. E. Kamal, "Network coding-based protection of many-to-one wireless flows," *IEEE J. Sel. Areas Commun.*, vol. 27, no. 5, pp. 797–813, 2009.

[9] S.-Y. Li, R. W. Yeung, and N. Cai, "Linear network coding," *IEEE Trans. Inf. Theory*, vol. 49, no. 2, pp. 371–381, 2003.

[10] S. Lee and S. H. Lee, "Analysis of network lifetime in cluster-based sensor networks," *IEEE Commun. Lett.*, vol. 14, no. 10, pp. 900–902, 2010.

[11] M. Bhardwaj, T. Garnett, and A. Chandrakasan, "Upper bounds on the lifetime of sensor networks," in *Proc. 2001 IEEE ICC*, pp. 785–790.

[12] H. Zhang and J. C. Hou, "On the upper bound of $\alpha-$lifetime for large sensor networks," *ACM Trans. Sen. Netw.*, vol. 1, no. 2, pp. 272–300, 2005.

[13] H. R. Karkvandi, E. Pecht, and O. Y. Pecht, "Effective lifetime-aware routing in wireless sensor networks," *IEEE Sensors J.*, vol. 11, no. 12, pp. 3359–3367, 2011.

[14] F. Wang and J. Liu, "RBS: a reliable broadcast service for large-scale low duty-cycled wireless sensor networks," in *Proc. 2008 IEEE ICC*, pp. 2416–2420.

[15] Y. Gu, T. Zhu, and T. He, "ESC: Energy synchronized communication in sustainable sensor networks," in *Proc. 2009 IEEE Int. Conf. on Network Protocols*, pp. 52–62.

[16] S. Lai and B. Ravindran, "Efficient oppertunistic broadcasting over duty-cycled wireless sensor networks," in *Proc. 2010 IEEE INFOCOM*, pp. 1–2.

[17] D. Kim, C. F. Hsin, and M. Liu, "Asymptotic connectivity of low duty-cycled wireless sensor networks," in *Proc. 2005 IEEE MILCOM*, pp. 2441–2447.

[18] D. Lun, M. Medard, R. Koetter, and M. Effros, "On coding for reliable communication over packet networks," *Physical Commun.*, vol. 1, pp. 3–20, 2008.

[19] R. R. Rout, S. K. Ghosh, and S. Chakrabarti, "A network coding based probabilistic routing scheme for wireless sensor network," in *Proc. 2010 Int. Conf. on Wireless Communication and Sensor Networks*, pp. 27–32.

[20] S. Yang and J. Wu, "Efficient broadcasting using network coding and directional antennas in MANETs," *IEEE Trans. Parallel Distrib. Syst.*, vol. 21, no. 2, pp. 148–161, 2010.

[21] S. Katti, H. Rahul, W. Hu, D. Katabi, M. Medard, and J. Crowcroft, "XORs in the air: practical wireless network coding," *IEEE Trans. Networking*, vol. 16, pp. 497–510, 2008.

[22] L. Keller, E. Atsan, K. Argyraki, and C. Fragouli, "Sensecode: network coding for reliable sensor networks," EPFL Technical Report, 2009.

[23] I. H. Hou, Y. E. Tsai, T. F. Abdelzaher, and I. Gupta, "Adapcode: adaptive network coding for code updates in wireless sensor networks," in *Proc. 2008 IEEE INFOCOM*, pp. 2189–2197.

[24] R. R. Rout, S. K. Ghosh, and S. Chakrabarti, "Network coding-aware data aggregation for a distributed wireless sensor network," in *Proc. 2009 IEEE ICIIS*, pp. 32–36.

[25] A. R. Lehman, "Network coding," Ph.D. dissertation, Massachusetts Institute of Technology, USA, Feb. 2005.

[26] E. Felemban, C. G. Lee, and E. Ekici, "Mmspeed: multipath multi-speed protocol for QoS guarantee of reliability and timeliness in wireless sensor networks," *IEEE Trans. Mob. Comput.*, vol. 5, no. 6, pp. 738–754, 2006.

[27] M. Hamdi, N. Essaddi, and N. Boudriga, "Energy-efficient routing in wireless sensor networks using probabilistic strategies," in *Proc. 2008 IEEE WCNC*, pp. 2567–2572.
[28] J. Hill and D. Culler, "Mica: a wireless platform for deeply embeded networks," *IEEE MICRO*, vol. 22, no. 6, pp. 12–24, 2002.
[29] P. K. K. Loh, H. W. Jing, and Y. Pan, "Performance evaluation of efficient and reliable routing protocols for fixed-power sensor networks," *IEEE Trans. Wireless Commun.*, vol. 8, no. 5, pp. 2328–2335, 2009.
[30] A. Cerpa and D. Estrin, "Ascent: adaptive self-configuring sensor networks topologies," *IEEE Trans. Mob. Comput.*, vol. 3, no. 3, pp. 272–285, 2004.
[31] B. Gedik, L. Liu, and P. S. Yu, "ASAP: an adaptive sampling approach to data collection in sensor networks," *IEEE Trans. Parallel Distrib. Syst.*, vol. 18, no. 12, pp. 1766–1783, 2007.
[32] Z. Cheng, M. Perillo, and W. B. Heinzelman, "General network lifetime and cost models for evaluating sensor network deployment," *IEEE Trans. Mob. Comput.*, vol. 7, no. 4, pp. 484–497, 2008.
[33] G. Simon, P. Volgyesi, M. Maroti, and A. Ledeczi, "Simulation-based optimization of communication protocols for large-scale wireless sensor networks," in *Proc. 2003 Aerospace Conference*, pp. 1–8.

Rashmi Ranjan Rout is currently submitted his Ph.D. thesis at Indian Institute of Technology Kharagpur, WB, India. He joined as a Research Scholar in G. S. Sanyal School of Telecommunications, January 2009. He received the B.E. degree from F. M. University, Odisha, India and M. Tech degree from Motilal Nehru National Institute of Technology, Allahabad, India, both in Computer Science and Engineering. He is working as an Assistant Professor, Computer Science and Engineering, National Institute of Technology, Warangal, AP, India since June 2012. His research interest includes network coding, data routing, wireless ad-hoc and sensor networks, delay-tolerant networks, P2P overlay networks, mobile computing.

Soumya K. Ghosh did his M.Tech and PhD in Computer Science & Engineering from the Indian Institute of Technology (IIT) Kharagpur, India. He is currently an Associate Professor at the School of Information Technology, IIT Kharagpur. Before joining IIT Kharagpur, Dr. Ghosh worked for Indian Space Research Organization in the area of Satellite Remote Sensing and GIS. His research interests include Ad hoc Networks, Network Security and Spatial Web Services. He has over 70 research publications in journals and conference proceedings. He is a member of IEEE.