ADAPTIVE DUTY CYCLING FOR RECHARGEABLE WIRELESS SENSOR NETWORKS

by

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ABSTRACT

SAYALI SHRIRANG NIMKAR. Adaptive duty cycling for rechargeable wireless sensor networks. (Under the direction of DR. ASIS NASIPURI)

The proposed research addresses development of an adaptive duty cycling scheme to extend the lifetime of wireless sensor networks (WSNs) that are powered by energy harvested from the environment. A key problem of such rechargeable sensor networks is that the energy resources of the nodes vary from one node to another. Moreover, the energy consumption in the sensor nodes are also unequal making their battery lives highly variable. Nodes that are highly loaded and/or have low energy, termed as critical nodes, deplete their batteries faster than the rest of the nodes in the network. We propose a cross layered MAC protocol that allows the critical nodes to adapt their duty cycle to reduce their energy consumption in comparison to other nodes in the network. We employ an utility function, based on game theory, as a decisive condition for adapting duty cycles of selected nodes and allowing them to perform low power operation. In addition, we apply load balancing to shift the data traffic from the highly loaded and energy constrained nodes to its neighbors, thereby conserving their energy further. This increases the lifetime of critical nodes, leading to increase in global network lifetime. Simulation results are presented to analyze the improvement of the lifetime of the network which is the main aim of this research.

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I would like to dedicate my thesis to my father, Shrirang Nimkar, who is my strength and has always been a great supporter. I would like to deeply thank him, my mother and brother for their invaluable love, moral support and blessings that have lead me to be able to successfully complete my Masters degree.

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CHAPTER 1: INTRODUCTION

A Wireless Sensor Network (WSN) is an autonomous network of low priced sensor nodes that monitor the environment and communicate data to a central device thereby interfacing the physical world with the digital domain [1]. Each sensor node is a tiny device that has the capability to sense, process and transmit data to perform different tasks. Sensor nodes can be programmed to configure themselves and interact with the sink node by hopping data packets over other nodes and thus work in different topologies of the network. These tiny devices can continuously and autonomously monitor areas that remain inaccessible to humans. Recent technological advances in low-cost design of microcontrollers, wireless, as well as silicon integration have enabled the implementation of WSNs for applications requiring unique objectives of sensing and monitoring [12].

In recent years, WSNs have gained increasing attention because of its ease of deployment, ability to perform variety of computations and data processing operations. The use of these miniaturized sensor devices has been increasing because of its “deploy and forget” nature and ease of embedding them on to daily used objects for progressive monitoring. WSNs represent a new paradigm of extracting data from the environment and thus finds a wide range of applications, which include military applications for surveillance, environmental monitoring, traffic and transportation control, health monitoring, agriculture, disaster management, industrial monitoring, real-time tracking and various other commercial applications.

1.1 Overview of WSNs

Wireless sensor networks typically comprise of a large number of sensor nodes that are randomly placed over a large region under study. A sensor node includes four basic components: sensing subsystem for observing the events in the physical environment, a processing subsystem for storage and processing of the data to perform various tasks [14], a wireless communication subsystem that includes the RF transceiver and antenna for data transmission and reception, and a power subsystem that forms the energy resource of the sensor device. The major aim of deploying the WSNs is to transmit relevant data to the sink node so that a particular action is taken at the right time. The nearby nodes, where the event occurred, sense and communicate the information to the sink node via multi-hop transmission.

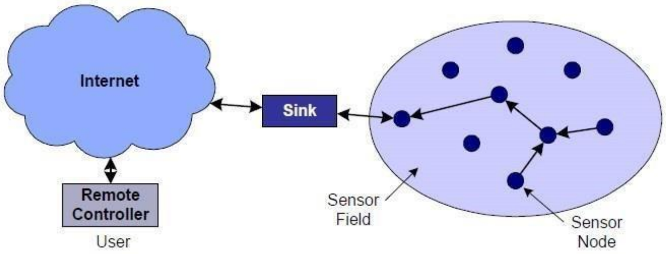

Figure 1.1: Sensor network architecture [14]

A typical wireless sensor network architecture is depicted in Figure1.1, where the sink node acts as the gateway between the sensor nodes and the end user by forwarding information from wireless network to a server. The transmission range of each sensor node is small. However, they can apply multi-hop routing scheme to deliver data to the sink.

1.2 Research Motivation and Objectives

The emerging field of wireless sensor networks merges the sensing, computational and communication abilities in a single tiny device. The advantage of sensor networks is the capability of sensor nodes to monitor the environment for long periods of time without manual intervention. However, the main challenge is that it is difficult to replace their batteries considering their large scale physical deployment. Thus energy stands out to be the most precious resource that demands its usage to be optimum and minimum. The optimization of energy in wireless sensor networks is much more complex as it not only requires to reduce the power consumption of individual nodes but to also balance them in order to achieve higher network lifetime, i.e the time until the first node depletes its energy. This research work addresses these issues by nodes performing adaptive duty cycling, showing improvement in the lifetime of the sensor nodes as well as the global network.

1.2.1 Duty Cycling

The most effective way for energy conservation is to put the radio transceiver to sleep (low power) mode whenever there is no data packet to send or receive. Ideally the radio should be switched off as soon as there is no data packet to send or receive and should be resumed as soon as a new data packet is ready. The alternating between the awake and sleep periods is termed as duty cycling. Duty cycle can be defined as the percentage of time the node remains active in the whole operational time. The active/awake period is the time for which the sensor node is active to receive/transmit a data packet. The sleep period is the time for which the node switches off its radio and thus cannot send/receive anything. One active and one sleep period together form one operational period. As sensor nodes perform cooperative tasks, they need to coordinate their sleep and wake up times for successful transmission and reception of data packets. A sleep/awake scheduling algorithm thus accompanies any duty cycling approach. It is a distributed algorithm based on which it performs transition from active to sleep state and vice versa.

1.2.2 Energy Consumption in Wireless Sensor Networks

In a data collecting sensor networks, sensor nodes are deployed randomly and data packets are required to flow from different locations to a single sink node. Energy being the critical resource, routing techniques that result into energy conservation are widely used. It is beneficial to transmit data packets with multiple hops over shorter distances with low power, than single hop long distance high power transmission. Thus nodes send packets to their neighboring nodes that further forward the data ahead to reach the destination node.

The routing protocol is responsible for determining and maintaining multihop routes between two communicating nodes. A widely used routing protocol for environmental monitoring applications is the collection tree protocol (CTP). CTP is a tree based collection protocol, which forms a routing graph in the network considering expected number of transmissions (ETX) as its routing gradient. An ETX is the expected number of transmissions required to successfully deliver a data packet to the receiver. Thus, a lower value of ETX indicates a good end to end quality of a route and vice versa. The root node broadcasts an ETX = 0. The other nodes further calculate their ETX as ETX of its parent node plus ETX of its own link to the parent node. CTP considers the link quality estimates of the nearby nodes to calculate the number of transmissions a data packet has to be sent for it to be delivered successfully. However, CTP does not consider energy conservation since its primary purpose is to maintain adequate route quality.

A wireless sensor node spends highest of its energy in communication task. The radio, used for communication, consumes energy in the following different modes:

- Transmit mode: The antenna radiates energy while transmitting a packet. For Micaz motes, the current drawn in this mode is [15]
    - At 0 dBm = 17.4 mA
    - At -5 dBm = 14 mA
    - At -10 dBm = 11 mA
- Receive mode: The processing of received signal takes place in this mode. For Micaz motes, the current drawn in this mode is 19.7 mA [15].
- Idle mode: The radio is ready to receive but is not receiving anything, some parts are switched off. For Micaz motes, the current drawn in this mode is 20 µA [15].
- Sleep mode: The significant parts of the transceiver are switched off. The node in this mode consumes lowest of the energy in comparison to all the other modes. For Micaz motes, the current drawn in this mode is 1 µA [15].

From the above values of current consumption, it indicates that the current consumed by a node can vary mA to µA depending on its mode of operation. Thus, enabling radio to be in sleep mode for more amount of time results into lower power consumption. Typically, CTP is implemented with a constant sleep-awake duty cycle that allows all nodes to periodically wake up for brief intervals of time to check for radio activity before returning to sleep. When radio activity is detected, the radio remains in active mode for receiving the packet. This method, known as Low Power Listening (LPL), is an asynchronous duty cycling technique for conserving energy. In order to enable nodes to detect transmitted packets successfully, all packets include a long preamble that spans the period of sleep durations. For energy conservation and prolonging the lifetime of the network, we design an adaptive duty cycle approach which allows nodes to sleep for longer duration thus consuming less energy.

In asynchronous LPL, nodes are woken up for all transmissions in its neighborhood irrespective of the destination address. Thus, a lot of energy is wasted in overhearing, receiving of data packets destined to other nodes. A node, if radio is on, receives the whole preamble and finds only after it checks the header of the data packet, whether the packet is destined for itself or some other node. This contributes to increase in the current consumption of the nodes. The computation of current consumption is done using the following equation [2]:

$$\mathrm{I} = \frac{I_{Rt}T_{Rt}}{T_{RUI}} + \frac{I_{Dt}T_{Dt}}{T_D} + N\left(\frac{I_{Rr}T_{Rr}}{T_{RUI}} + \frac{I_{Dr}T_{Dr}}{T_D}\right) + FI_{Dt}T_{Dt} + \frac{I_S T_S}{T_D} + N_P I_P \tag{1.1}$$

where

I_{Rt} = Current drawn for route update packet transmissions

T_{Rt} = Duration of RU packets transmitted

T_{RUI} = Route update interval

I_{Dt} = Current drawn for transmission of it's own data packets

T_{Dt} = Duration of data packet transmission

T_D = Data packet transmission

N = Number of neighbors of the node

I_{Rr} = Current drawn from route update packet reception

T_{Rr} = Duration of RU packets received

I_{Dr} = Current drawn for reception of data packets

T_{Dr} = Duration of data packet

F = Forwarding rate

I_S = Current drawn for sensing

T_S = Duration for sensing

N_P = number of times the node wakes up in one second

I_P = Current drawn for processing

T_p = Duration of processing time

The term $N\left(\frac{I_{Rr}T_{Rr}}{T_{RUI}}+\frac{I_{Dr}T_{Dr}}{T_D}\right)$ denotes the overhearing of packets from N number of neighboring nodes. The first part denotes overhearing of route update packets and the second part denotes the overhearing of data packets.

1.2.3 Rechargeable Wireless Sensor Networks

The most effective and emerging technology to overcome the energy limitation problem is energy harvesting from different ambient renewable energy sources. This includes energy from sunlight, vibrations, heat, wind, magnetic fields and others. The harvested energy can be converted to electrical energy for recharging the batteries of the sensor nodes. The development of these renewable sources is gaining increasing importance for achieving long term reliable operations of wireless sensor networks. However there are limitations for the use of these resources due to their spatial and temporal variations. There are various factors that would make the availability of these resources differently to different nodes. In a large scale WSN, the sensor nodes are placed geographically at random locations which leads to some nodes being in shadow regions and others in extended sunlight. Also node’s orientation will affect the irradiance collected by the solar panels.

Changes in weather and sun orientation, direction of wind and other such factors lead to variations in the energy harvested, over a period of time. Consequently, for rechargeable sensor networks, it is critical to employ energy adaptation schemes that allow the energy consumption in the nodes to be controlled based on their available energy resources.

1.3 Proposed Approach

To achieve the objective of adapting the energy consumption of nodes in order to balance their remaining battery lives, we propose an approach of reducing the duty cycles of nodes that have critically low energy resources. In addition to reducing the durations for which the radio is active, this also reduces the average energy wastage for overhearing. As the sensor share a common medium (channel) for communication, overhearing dominates the energy consumption in the sensor nodes. Consequently, introducing a mechanism that controls the amount of overhearing will have a significant effect on the energy consumption, and therefore, the lifetime of the sensor nodes. Our approach to balance the lifetimes of all nodes is by adaptively reducing the duty cycles of the nodes that have lower energy. This means that the nodes will be in active state for less amount of time compared to other and will probabilistically overhear data packets destined to others. We also route the traffic away from the weaker nodes by increasing the route costs which would further preserve their energies. Also low power listening performed by the nodes reduces the idle listening further adding on to the energy savings. Thus, by cutting down on these energy wastage, we significantly improve the lifetime of the critical nodes leading to increase in the network lifetime.

1.4 Organization of Thesis

This thesis report is organized into five chapters. Chapter 1 provided information regarding the basic overview of wireless sensor network and the motivation for this research. In Chapter 2, a review of different energy efficient MAC protocols is discussed. Chapter 3 presents the novel protocol proposed for energy conservation and improvement of lifetime of the wireless sensor network. In Chapter 4, we demonstrate the results of our simulation and its advantages. Chapter 5 concludes the thesis work and suggests future work for further research in improving the performance of the network.

CHAPTER 2: RELATED WORK

In wireless sensor network deployments, the ultimate goal is to reliably report the data to destined nodes while consuming least amount of power. Medium Access Control (MAC) layer is responsible for the communication of data packets over a shared medium. To meet the requirements of the sensor network applications, some generalized goals for the MAC protocols can be defined as follows [5]:

- Energy efficiency: Low power operation
- Effective collision avoidance
- Efficient channel utilization at low and high data rates
- Global: network optimization techniques to improve global performance
- Scalability: easily expandable to large numbers of nodes
- Adaptability: Tolerant to changing RF/Networking conditions
- Reconfigurable by network protocols

To achieve the primary goal of energy efficiency, energy conservation mechanisms should be implemented on the factors that contribute to energy wastage. The major sources of energy waste are:

1. Collision: As communication takes place on a shared medium, when two nodes transmit data packets at the same time, there is collision. This results into retransmission of those data packets causing to spend double energy to transmit the same data packet thereby increasing the energy consumption per node.

2. Overhearing: Sensor nodes pick up data packets destined to others thus wasting their energy in staying active and receiving the unwanted packets.
3. Control packet overhead: Transmission and reception of control packets consumes energy too.
4. Idle listening: This happens when the node remains in active state to receive when there is no transmission on the channel i.e listening to possible traffic that is not sent. Many measurements have shown that idle listening consumes 50-100% of the energy required for receiving [4].

Various MAC protocols have been proposed in the recent years. The next section will describe a few of them.

2.1 Sensor-MAC (S-MAC)

The main aim of S-MAC is to reduce energy consumption, while supporting good scalability and collision avoidance. To achieve this, S-MAC focuses on three major components: periodic listen and sleep, collision and overhearing avoidance, and message passing [4].

A. Periodic listen and sleep

Figure 2.1 Periodic listen and sleep [4]

- Basic scheme:

Each node goes to sleep for some time, and then wakes up and starts listening the channel to check if some other node wants to send data to it. During sleep mode, the node turns off its radio, and a timer is set after which it wakes up and switches the radio on again. The time duration for listening and sleeping periods is selected in accordance with different application scenarios. This scheme requires periodic synchronization amongst the neighboring nodes as a remedy to their clock drifts.

- Choosing and maintaining schedules:

Each node can choose its own listen/sleep schedule. Nodes maintain a schedule table that stores the schedules of all its known neighbors. At the beginning of each active period, SYNC period is present during which the nodes exchange their synchronization information. Following this, the data fragment is transmitted using RTS/CTS scheme. Request To Send (RTS) is sent by a sender node requesting the receiver to acknowledge back when it is ready to receive the packet. The acknowledgement to RTS is Clear To Send (CTS) sent by the receiver node indicating that it is ready to receive the data packet.

To establish the initial schedule:

- ➢ A node first listens to the channel for a certain amount of time.
- ➢ If it hears a schedule, it follows it and becomes a follower.
- ➢ If it does not hear a schedule, it randomly chooses its own schedule, broadcasts it and becomes a synchronizer. B.

- Collision avoidance

S-MAC adopts a contention-based scheme. As multiple senders may wish to transmit to a receiver at the same time, they need to contend for the medium to avoid collisions. S-MAC adopts the RTS/CTS mechanism to address the hidden terminal problem [16].

A duration field in each transmitted packet indicates how long the remaining transmission will be. When a node receives a packet destined to another node, it records this value in a variable called the network allocation vector (NAV) and sets a timer for it.

Every time when the NAV timer fires, the node decrements the NAV value until it reaches zero. A node sends data only if its NAV value is zero, if not it determines that the medium is busy. This process is termed as virtual carrier sensing.

- Overhearing avoidance:

S-MAC protocol tries to avoid overhearing by letting interfering nodes go to sleep after they hear an RTS/CTS packet. Thus it prevents neighboring nodes from overhearing long DATA packets and the following ACKs as DATA packets are much longer than control packets.

Shortcomings: As the network expands, the maintenance of schedules increases which results into additional control overhead. Thus it is not tolerant to changing network.

2.2 B-MAC

B-MAC is a carrier sense media access (CSMA) protocol that obtains low power operation, effective collision avoidance and optimum channel utilization. To achieve low power operation, it employs an adaptive preamble sampling scheme to reduce the duty cycle of nodes and thereby minimize idle listening. In this protocol, the sensor nodes sleep and wake up periodically and independently as shown in figure 2.2. As it is an asynchronous scheme, there has to be some mechanism for nodes to coordinate amongst themselves in order to exchange data packets. To achieve successful transmission of data, the sender node appends a long preamble to the data packet which is long enough to last for an entire duty cycle. The receiver node detects the ongoing transmission when it wakes up and remains in the active state for the rest of the time for reception of the data packet [5].

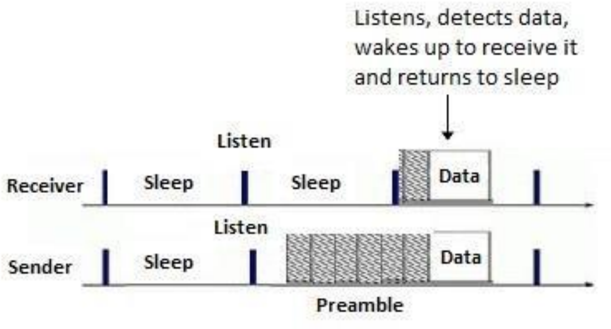

Figure 2.2: B-MAC overview

When compared to S-MAC, B-MAC provides better results in terms of packet delivery rates, throughput, latency and energy consumption. For effective collision avoidance, B-MAC uses the clear channel assessment (CCA) scheme. The ambient noise changes with the environment, therefore B-MAC employs an automatic gain control mechanism for estimating the noise floor. Signal strength samples are compared with this threshold value of the noise floor. If the signal strength received is greater than the threshold value, B-MAC assumes the channel to be busy, else the channel is assumed to be clear (free). If the channel is declared to be busy, the node will back off for some time (wait for random amount of time before transmitting a packet). This CCA and backoff schemes lead to effective utilization of the channel.

B-MAC features a simple, predictable yet scalable implementation and is tolerant to changes in the network. It may be configured to run at extremely low duty cycles and does not force the applications to incur the overhead of synchronization and state maintenance [5].

2.3 Timeout-MAC (T-MAC)

T-MAC protocol proposes an adaptive protocol to change the sleep and listen periods in a novel way. It dynamically ends the active part which is nothing but ending the awake period of the node dynamically. It reduces idle listening by transmitting all messages in bursts of variable length, and sleeping in between bursts. For variable load, the length of the message is determined dynamically to maintain an optimal active time. The active time is ended in an intuitive way, by simply timing out on hearing nothing. This reduces the amount of energy wasted on idle listening, in which nodes wait for potentially incoming messages, while still maintaining a reasonable throughput [11].

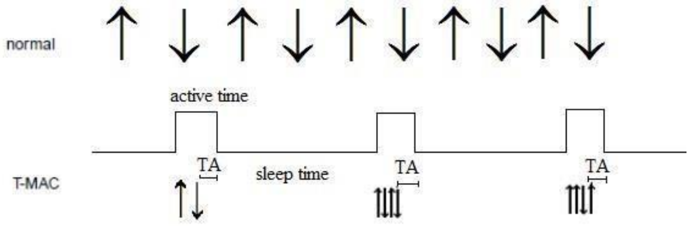

Figure 2.3 Basic T-MAC protocol scheme, with adaptive active times [11]

Figure 2.3 shows the basic scheme of T-MAC. Each node wakes up periodically to communicate with its neighbors, and then goes to sleep again until the next frame. In the meantime, new messages are queued. Nodes communicate with each other using a Request To Send (RTS), Clear To Send (CTS), Data, Acknowledgement (ACK), which provides both collision avoidance and reliable transmission. A node will keep listening and potentially transmitting, as long as it is in an active period. An active period ends when no activation event has occurred for a time TA.

An activation event is:

- firing of a periodic frame timer
- reception of any data on the radio
- sensing of communication on the radio, e.g. during a collision
- end-of-transmission of a node’s own data packet or acknowledgement

- by overhearing prior RTS and CTS packets, having the knowledge that a data exchange of a neighbor has ended.

A node will sleep if it is not in an active period. Consequently, TA determines the minimal amount of idle listening per frame. The described timeout scheme moves all communication to a burst at the beginning of the frame.

A. Clustering and Synchronization:

It uses the same technique as used by S-MAC for synchronization by virtual clustering. It sends SYNC packet to follow a schedule or introduce a new one as discussed in the previous section. It urges nodes to form virtual clusters with same schedule and allows efficient broadcast and obviates the need to maintain information of individual neighbors.

B. Choosing TA:

A node should not sleep while the channel has ongoing transmission as it may be the possible receiver of the subsequent message. The start of RTS/CTS is enough for renewal of the TA interval. The TA interval must be long enough to hear the CTS packet because a node may not hear the RTS packet, of its neighbor, if it is not in range. Thus the lower limit of TA interval can be defines as follows:

$$TA > C + R + T$$

where C → the length of the contention interval,

R → length of an RTS packet, and

T → turn-around time (short time between end of RTS and beginning of CTS)

C. Asymmetric communication

T-MAC protocol revealed an early sleeping problem when traffic through the network is mostly unidirectional, like in a nodes-to-sink communication pattern. This problem can be followed considering the following figure 2.3.

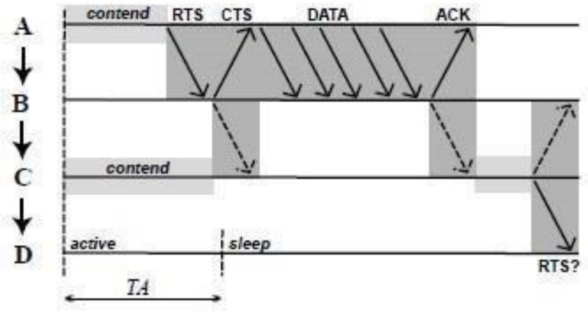

Figure 2.4 Early sleeping problem. Node D sleeps before C can send RTS to it [10]

Nodes A through D in the figure 2.4 forms a cell with its neighbors. Messages flow from top to bottom, so node A sends only to B, B only to C, and C only to D. Now every time node C wants to send a message to D, it has to contend for the medium and may loose to either node B (by receiving an RTS packet) or to node A (indirectly, by overhearing a CTS packet from node B). If node C looses contention because of an RTS packet from node B, it will reply with a CTS packet, which can also be heard by node D. and D will be awake when the communication between C and B ends. However, if node C looses contention because it overhears a CTS packet from B to A, C must remain silent. Since D does not know of the communication between A and B, its active time will end, and it will sleep. Only at the start of the next frame will node C have a new chance to send to node D. Thus for every packet that node C wants to send to node D, it may either succeed or fail (by loosing to node A) with equal probability. Solution to this problem is to send FRTS packet.

D. Future request-to-send(FRTS)

The idea is to let the receiver node know that it still has a message to receive. If a node overhears a CTS packet destined for another node, it may immediately send a future request-to-send (FRTS) packet, like node C in above discussion. The FRTS packet contains length of the blocking data communication (this information is present in the CTS packet).

2.4 X-MAC

Standard MAC protocols developed for duty-cycled WSNs such as BMAC, employ simple, asynchronous and energy efficient approach by using an extended preamble and preamble sampling. But these long preambles introduce excess latency at each hop and thus the approach suffers from excess energy consumption at nontarget receivers. X-MAC proposes solutions to each of these problems by employing a shortened preamble approach that retains the advantages of low power listening, namely low power communication, simplicity and decoupling of transmitter and receiver sleep schedules.

X-MAC’s shortened preamble approach significantly reduces energy usage at both the transmitter and receiver, reduces per-hop latency, with additional advantages such as flexible adaptation to both bursty and periodic sensor data sources [6].

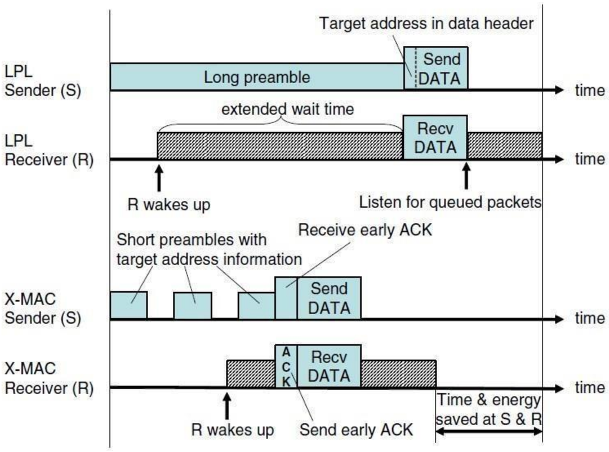

Figure 2.5 Comparison of timelines between LPL's long preamble and X-MAC's short preamble approach [6]

In this protocol, a series of shortened preamble packets are sent each containing the target address information which helps in reducing the overhearing problem of low power listening. X-MAC inserts pauses into these short preambles, creating a strobed preamble, which enables the receiver to send an early acknowledgment (ACK). When the transmitter receives early ACK from the receiver, it stops sending the preambles and transmits the actual data packet, as can be seen from figure 2.5. When a transmitter is attempting to transmit a packet, but detects a preamble and is waiting for a clear channel, the node listens to the channel and if it hears an ACK frame from the node that it wishes to send to, the transmitter will back-off a random amount and then send its data without a preamble. The randomized back-off is necessary because there may be more than one transmitter waiting to send, and the random back-off will mitigate collisions between multiple transmitters. After receiving the data packet, the receiver remains awake for a maximum duration of sender's backoff period and sleeps if nothing is detected.

In X-MAC, truncating the preamble saves energy at both transmitter and receiver and allows for lower latency. This strobed preamble approach can be readily adapted to the packetized radios that are emerging as the standard in today's sensor motes [6].

2.5 Energy Aware Adaptive Low Power Listening (EA-ALPL)

EA-ALPL is a cross layer protocol that has its design built over the B-MAC protocol. EA-ALPL enables each individual sensor node running B-MAC to set its own listening mode according to its duty cycle and its number of descendants in the routing tree. The sensor nodes learn the listening modes of their neighbors and choose their transmit mode accordingly to ensure correct reception of data packets. EA-ALPL introduces the following novel contributions [10]:

1. Enables each node to set its own listening mode on the basis of its current state information.
2. It allows each node to dynamically learn its routing parent's listening mode and then locally set its appropriate transmit mode.
3. It proposes dependence of listening mode on both duty cycle and topology related information (to ensure adaptability to a dynamic sensor network topology).

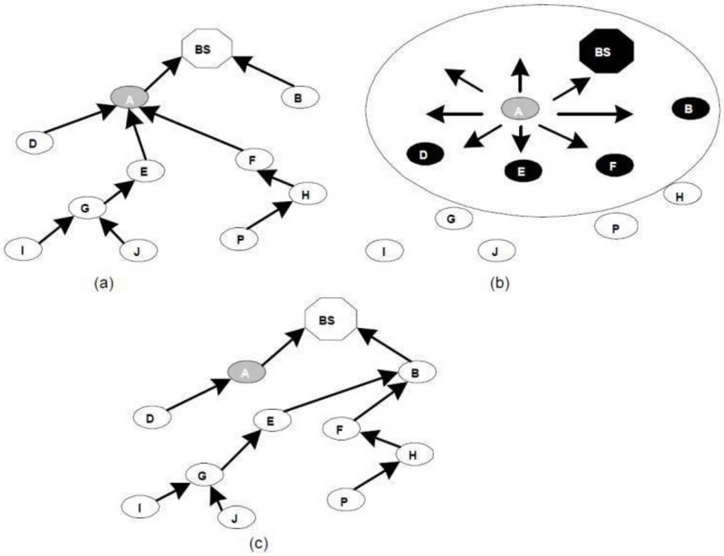

Figure 2.6 (a) Nodes for their routing tree. (b) Each node periodically announces its current state and listening mode, enabling neighbors to use appropriate transmit mode.(c) A high duty cycle at A causes neighbors to increase A's routing cost and choose B as new parent node [10].

EA-ALPL assumes a pro-active routing protocol in which nodes periodically send route update messages to declare its presence to the neighbors. Once nodes learn about their neighbors' presence, a routing graph is formed with data flowing towards the base station and each node learns about its descendants. Parent node sets the optimal listening mode for its current topology position and sends route update message that includes its new listening mode and its power state along with other routing information. All the neighbors store this information and periodically update it in their local routing table. Consequently, all the nodes always have up-to-date information on the state of its neighbors. A node favors neighbors with better power state while making routing decisions. So whenever a node chooses its routing parent, it checks the local neighbor table and matches its own transmit mode to that routing parent's listening mode and then send the data packets. Thus, all nodes hear the updated listening mode information of their parent nodes through the route update messages and accordingly adapt their transmit modes.

In the routing tree, the nodes with heavy traffic load deplete their battery resources faster compared to the rest of the nodes. As can be seen in figure 2.6 (a), node A is the most burdened node. In order to reduce its forwarding load and conserve its own energy, the highly loaded nodes (node A in above case) will increase its duty cycle and announce it in their next route update message. The neighboring nodes will thereby increase node A's routing cost. This in turn causes the children nodes of A to choose another parent node having better power state than A. As can be seen in the figure 2.6 (c), the children nodes choose node B over A, and A starts listening with a longer check interval (sleeps for a long time) to reduce its listening power consumption. Consequently, the highly active nodes will listen less often and there is load balancing in the network.

The adaptive nature of EA-ALPL supports the dynamic nature of the sensor networks and can exploit information about the present, the past and the predicted future state of individual sensor nodes to reduce power consumption.

2.6 Wireless Sensor MAC (WiseMAC)

WiseMAC is an energy efficient MAC protocol based on synchronized preamble sampling. This protocol works for downlink of infrastructure network topology instead of the commonly considered ad-hoc network. An infrastructure network is composed of a number of access points (A.P) that are interconnected through a backbone network. These access points are usually energy unconstrained and each of them serves a number of sensor nodes. This protocol proposes an idea of minimizing the length of wake-up preamble by exploiting the knowledge of the sensor nodes sampling schedules.

This protocol is based on continuous sampling of the medium to check for any activity. The sensor nodes sample the medium for a constant period of time Tw. If medium is found busy, they continue to listen until a data packet is received or wait for the medium to become idle again. A.P learns the sampling schedules of all the sensor nodes. A.P waits till the destined node wakes up and adds a minimized wakeup preamble with the data packet and transmits it to the receiver just before the receiver’s wake up time. The schedule time is piggybacked via the ACK packet. The duration of wake up preamble is computed considering the clock drifts between sensor nodes and A.P from the information received in the last ACK. This drift is proportional to the time since the last resynchronization [7].

The required duration for the wakeup preamble can be given by the following equation:

$$TP = \min(4\theta l, Tw) \tag{2.1}$$

where θ is the frequency tolerance of the time base quartz and l is the interval between two communications. If the traffic is high, the interval l will be small and so the wake-up preamble (4θl) will also be small. If the traffic is low, the interval is large but maximum upto T_w. Overhearing is thus mitigated when the traffic is high, by the combined use of the preamble sampling technique and the minimization of the wake-up preamble duration.

When the traffic is low, the wake-up preamble length can exceed the data packet length. To solve this, the wakeup preamble has padded bits added which are followed by repetitions of data packet. If the medium is found busy, the node waits to check the start of frame delimiter located at the start of each data frame. If the header indicates the sensor node to be the destined node, it waits to receive the packet and sends an ACK, else goes back to sleep.

An important aspect of WiseMAC, which is inspired from IEEE 802.11and IEEE 802.15.4 ZigBee protocols, is the presence of a frame pending bit in the header of data packets. If this bit is set, it indicates that the A.P has more data packets to send. When the sensor node finds this bit to be set, it sends an ACK and waits for further data frames. This technique allows to use a wake-up interval that is larger than the average interval between the arrivals for a given node. It reduces queuing delay at A.P, especially in the event of traffic bursts. Finally, it has an advantage of having no collisions for a downlink channel, as the access point is the only initiator of communication.

2.7 Routing Enhanced MAC (R-MAC)

RMAC protocol exploits cross layer routing information in order to problems like end-to-end delivery latency and poor traffic contention handling without sacrificing energy efficiency significant. In RMAC, a setup control frame is made to travel across multiple hops through a route and the receivers nodes are made to know that they have a data packet upcoming along that route. Each intermediate relaying node for the data packet along these hops sleeps and intelligently wakes up at a scheduled time, so that its upstream node can send the data packet to it and it can immediately forward the data packet to its downstream node. When there is high contention for the medium, RMAC delivers data packets over multiple hops in a single cycle and moves contention traffic away from the busy area thereby reducing the contention in that area quickly [9]. RMAC sends a small control frame with the information about when a node should be awake for the incoming packet to be received correctly from the upstream node and forwarded to the immediate downstream node. RMAC divides an operational cycle of a sensor node into three stages: SYNC, DATA, and SLEEP.

SYNC: In this stage, synchronization of clocks on the sensor nodes takes place with required precision.

DATA: Nodes send a pioneer control frame called PION. Instead of RTS/CTS, PION frame is used to request and confirm communication between nodes. PION includes all the fields that are considered in RTS like current node's address, next-hop address, and the duration of the transmission. PION also includes some cross-layer information: the final destination address, address of the current flow, the number of hops the PION has travelled.

SLEEP: In this stage, nodes go to sleep except for those that need to communicate, as set up by the PIONs. The interesting point to note is that there data frames transmitted in this stage by nodes who relayed by a PION and these nodes wake up at some specific time to transmit or forward the data frames. Each node goes back to sleep after completing its communication task. The PION mechanism increases the complexity in packet handling, which may have some negative effects in a real implementation on sensor network platform.

The design and evaluation of RMAC as a duty-cycle MAC protocol is capable of multihop data delivery in a single operational cycle. RMAC exploits cross-layer routing information to allow PION frame to set up a multihop schedule for subsequent forwarding of a data packet. The advantages of this protocol include reducing delivery latency and better handling of contention, which helps in achieving energy efficiency asa well as throughput improvement.

2.8 Hop Extended MAC (HE-MAC)

This protocol is similar to R-MAC with additional advantage of enabling the data packets to travel through more number of hops in a single duty cycle compared to RMAC. It employs an EXP (Explorer) frame, similar to PION in R-MAC, to set up the route for multiple hop transmission, containing the information about the maximum hop that a packet can travel through in a single duty cycle. EXP includes a maxHop field, along with other fields, which indicates how many maximum hops that data packet can reach. Using the information in EXP and an internal state of Ready-to-Receive (RTR), HE-MAC extends the relay of a packet beyond the termination of the data period by two more hops compared to RMAC and thereby reduces the power consumption and packet latency. This protocol also introduces adaptive sleeping which further reduces the power consumption [8].

Based on the information of EXP frame, corresponding nodes do not change their radio state from active to sleep at the beginning of sleep period which enables to relay the packet to another hop. When a node receives EXP reply from the next node, it adaptively sleeps. It is assumed that the interference range is two or greater times the transmission range. When an EXP is relayed by a node, if another node in the vicinity gets a strong interference due to this relaying transmission, without decoding the frame, it changes its internal state from IDLE to RTR (ready to receive). This change of state is intended for the nodes that possibly participate in the 'Hop Extend Operation'. If nothing is detected for constant duration, they go back to sleep.

HE-MAC significantly reduces latency compared to RMAC. Furthermore, with the exploit of adaptive sleeping, HE-MAC performs better than RMAC in terms of power consumption and average latency. The reduction of energy consumption in random topology can be slightly less as there would be some nodes that do not participate in the 'Hop Extend Operation'.

2.9 Summary

All the protocols discussed in the previous sections enable the variation (adaptation) of listen and sleep periods of the nodes to meet the basic objective of reducing the energy consumption of the network. Duty cycling is considered differently in different protocols that provided results having gain in one sector, like decrease in idle listening, collision avoidance, no synchronization required and so on. But this was achieved at the cost of loss in the other sectors like increase in latency, preamble length, cost of overhead, overhearing etc. Each of the above discussed protocols provide solutions that meet a subset of our goals. Motivated by monitoring applications for wireless sensor networks, we build upon ideas from previously published work to propose a cross layer approach as discussed in the next chapter.

CHAPTER 3: ADAPTIVE DUTY CYCLING FOR LIFETIME IMPROVEMENT

We propose a cross layer framework for optimizing the global power consumption and improving the network lifetime using adaptive duty cycling and route cost adaptation. At the MAC layer, we adapt the duty cycle of the sensor nodes, and at the routing layer we modify the route costs according to the information obtained from the MAC layer. In this chapter we discuss the assumptions of the network model, design objectives, followed by the proposed approach.

3.1 Assumed Network Model

The proposed network model considers a data gathering wireless sensor network in which the nodes collect information and forward it to the base station called sink. The sink node is capable of performing the further desired computations and is assumed to have no power constraints. Each node is assumed to have a specific range (distance) around itself upto which it can hear the neighboring nodes. The nodes within the range are connected with a link cost of 1. In data collecting networks, the forwarding scheme follows a tree structure that connects all the nodes to the sink. The nodes away from the sink, leaf nodes, transmit information by hopping data over other nodes termed as multihopping. The communication of data on a common single channel results in nodes listening to data packets of all the other nodes that are in the receiving range of that node. Based on different forwarding and overhearing rates, the depletion in batteries of nodes are also different.

The network model involves periodic transmission of beacons (route update packets) and data packets. These beacon packets include node information like the node id, ETX, distance information, duty cycle and other basic information of the particular node. By receiving the beacon messages, each nodes has information about the duty cycle and route costs of its neighboring nodes. In our research, we use Dijkstra's algorithm to find the least cost routing path from each node to the base station thereby forming a routing tree for the whole network. Dijkstra's algorithm is a graph search algorithm that finds the shortest path considering distance as metric (lowest distance route to the destination). In our case, this algorithm finds a route towards a destination node with the least route (link) cost as the routing gradient. A routing graph is thus formed and the forwarding and overhearing rate of nodes is calculated according to the number of children nodes and neighboring nodes, respectively. As it is an asynchronous scheme, the basic requirement for successful transmission and reception of data packets is to properly match the sender's preamble length and the receiver's listening mode [1].

The children nodes adapt their preamble length according to the parent node's duty cycle for successful data transmission. This is achieved by attaching a preamble of size equal to the sleep period of the receiver node. The preamble size varies as per the variation in the duty cycle i.e variation in the awake and sleep periods of a node.

All the nodes initially have same duty cycle in the network (assumed to be 2.4 % in our case). The node with the lowest remaining battery lifetime in the network is considered to be the critical node. This critical node is allowed to go to a lower duty cycle thereby allowing it to sleep for a longer duration. As radio transmission/reception forms to be one of the major energy consuming source, switching it off for longer duration contributes significantly for conservation of energy. We propose to improve the lifetime of the critical nodes iteratively, where in each iteration we address the needs of the corresponding critical node.

3.2 Design Objectives

The major objective of a successful design of wireless sensor network is to maximize the lifetime of the network after its deployment in the field under study. The lifetime of the network is defined as the time span from the deployment of the sensor network to the instant the first node dies (drains off its battery completely). Energy consumption has perhaps been the most crucial aspect because of its limited and irreplaceable nature. The main aim of this research is to reduce the energy consumption and improve the remaining lifetime of the network. To achieve this, we implement following two mechanisms:

- Increase lifetime by adaptive duty cycling

The node with the lowest battery lifetime in the network is allowed to go to a lower duty cycle. This critical node will now sleep for a longer duration and will wake up less number of times compared to other nodes reducing its current consumption. This helps in majorly reducing the overhearing, as the critical node now probabilistically overhears fewer of its neighbors. Also energy wastage in radio communication is considerably reduced as the radio is switched off in the sleep state. The reduction in energy increases the remaining lifetime of the node which in turn increases the global lifetime of the network.

- Reduce traffic on energy constrained nodes by route adaptation

The average current consumption of a node depends on the number of data packets transmitted and received by the node. A node which is highly loaded i.e has high forwarding traffic will consume more of energy and its battery is depleted faster compared to other nodes in the network. To address this problem and further reduce the power consumption on the critical node we enable the critical node to increase the link costs. Thus the children nodes of critical node would now adapt their route via a different node to the sink. This allows the critical node to have light forwarding load resulting into improvement of its own and network's lifetime.

The proposed protocol aims at reducing the power consumption and maximizing the lifetime of the wireless sensor networks. We place the sensor nodes randomly in an area of 500×500 meters with random but fixed battery levels. Each node has a radio range of 150 meters. On the basis of the various events like transmission, reception, overhearing, forwarding, the node calculates its own current consumption. The remaining battery lifetime is computed by the node considering the current consumption and the battery level.

Using Dijkstra's algorithm, the nodes configure themselves into a routing network and communicate information to the sink. We enable the critical node, node with lowest remaining battery lifetime, to go to a lower duty cycle.

When non-uniform duty cycled nodes are present in a network, i.e both higher and lower duty cycle, all the HDC nodes will wake up more number of times compared to those at LDC. The nodes will sleep and wake up periodically and check the channel for any activity (perform LPL). As shown in figure 3.1, the HDC nodes transmit packet with a lower preamble, whose length equals to the sleep period of HDC nodes. If the receiver is at a lower duty cycle, it will sleep for longer durations and may miss some packets as depicted in figure 3.2. For a LDC receiver, a longer preamble is required to be sent along with the data packet, for its successful reception.

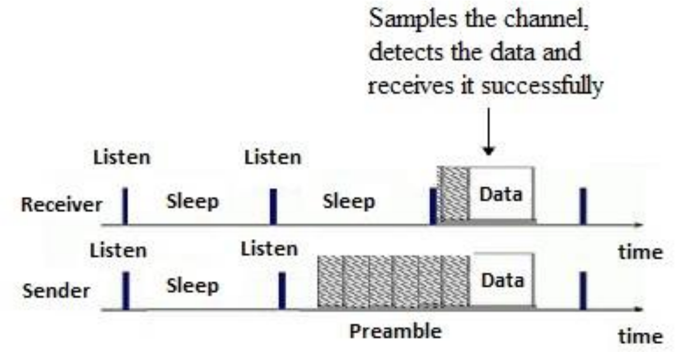

Figure 3.1 Timeline of sender and receiver nodes. Sender and receiver both are at higher duty cycle (2.4%).

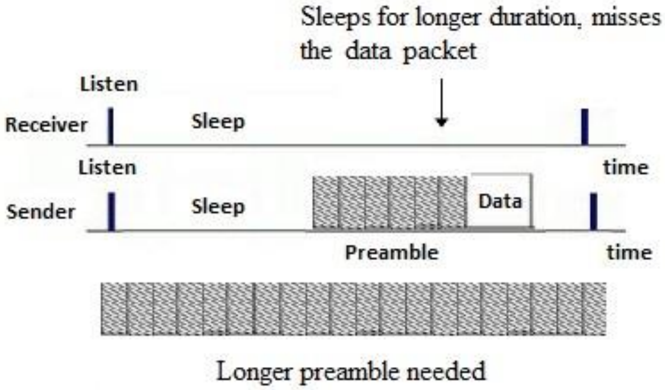

Figure 3.2 Timeline of sender and receiver nodes. Sender is at a higher duty cycle (2.4%) but receiver is at a lower duty cycle (0.3%), thus misses the packet.

When the node goes to a lower duty cycle, the nodes are affected as follows:

- Effect on the critical node
  - The node goes to a lower duty cycle, meaning it will be awake for less duration compared to before (at higher duty cycle), and will now sleep for longer duration.
  - As the node wakes up at different and less number of times compared to its neighbors, it will probabilistically overhear data packets that are intended for other nodes.

- The processing current reduces, as it is dependent on number of times a node wakes up in one second.
- Increase in link cost reduces load on the critical node allowing it to be less utilized for forwarding data packets.
- The current consumption of the node decreases and thereby its lifetime is increased eventually making it no longer a critical node.

➢ Effect on critical node’s neighbors

- If a parent node goes to a lower duty cycle, its children nodes have to transmit their data packets with a longer preamble.
- The nodes in range of the critical node will overhear a longer preambled data packet received by the critical node, which increases the current consumption of the neighboring nodes.

The effects of route adaptation can be seen by considering an example as shown in figure 3.3 (a) and 3.3 (b). In the given network, node G (in blue) is assumed to go to a lower duty cycle and thus it increases the link costs on all its outgoing links from 1 to 2. It broadcasts this in its next route update, thus enabling all the neighboring nodes about the change. As can be seen in figure 3.3 (a), the children nodes K, L and M now have a total routing cost of 5, to the base station (B.S). The children nodes after learning this increase in link cost look for another routing parent who provides a lower cost routing path to the sink node (Base Station, B.S). Node L and M, as shown in figure 3.3 (b), find node H in range that provides a total routing cost of 3. Thus they shift their routing parent from node G to node H. This reduces the forwarding load on node G and further reduces its energy consumption.

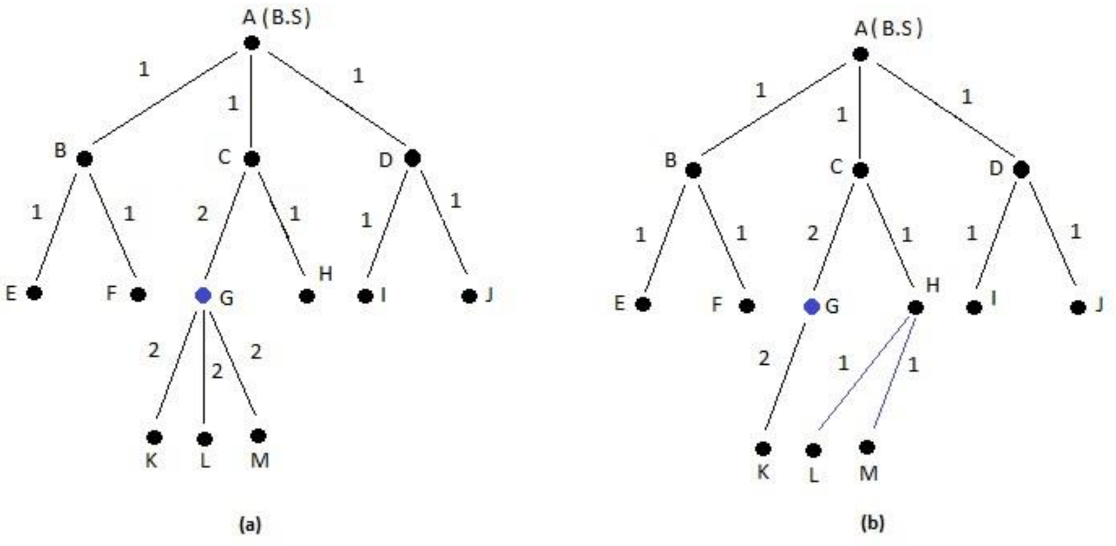

Figure 3.3 Route adaptation (a) Node G (in blue) goes to LDC and doubles all its outgoing link costs from 1 to 2. (b) Children nodes L and M find another parent node H in range with lower route cost to base station A (sink node).

3.3 Evaluation of effects of duty cycle adaptation

- Preliminary results:

To assess the effects of adapting the duty cycles of a few nodes to lower duty cycle, we simulate results for a network comprising of nodes with variable duty cycle (D.C). An example with N=10 nodes in a network having a routing tree as shown in figure 3.4 is considered. The nodes in blue (B, C, G and H) are at a lower duty cycle (0.3%) and rest of the nodes in the network are at higher duty cycle (2.4%). The children nodes E and F are required to transmit data packets with a higher preamble to routing parent B. Nodes G and H have their routing parent C at the same duty cycle as their own (0.3%) and thus behave similar to being in a uniform duty cycled environment for forwarding of packets. In addition, the LDC nodes will probabilistically all the neighboring HDC nodes and thereby save their energies.

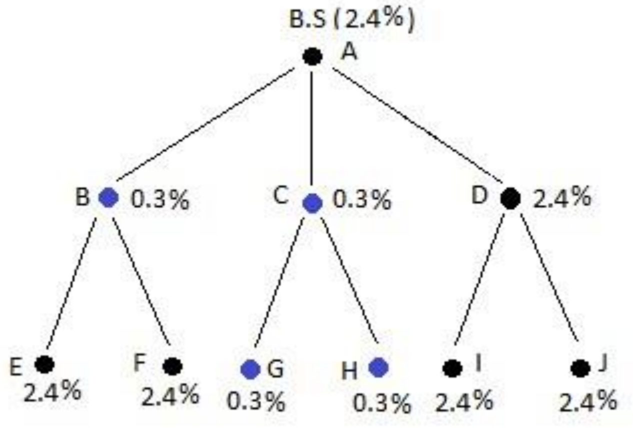

Figure 3.4 Routing tree for N=10 nodes with 4 nodes at LDC

The above depicted routing network is extended to a total of N=20 and N=40 nodes. Initially we assume all the nodes in the network to be at higher duty cycle (2.4%). This case is termed as Case O (H-H), where transmission of data packets takes place between higher duty cycled nodes (H). After sometime, we allow a certain fraction α of nodes to go to a lower duty cycle (i.e go from 2.4 % to 0.3% D.C). For example if α = 5% and the total nodes in the network are N= 40, then 2 nodes adapt their duty cycle to a lower value. We assume route update (RU) interval (interval at which RU packets are sent) and data interval (rate at which data packets are transmitted) to be 3840s (64 mins).

For these evaluations, we assume forwarding rate to be N/4, overhearing rate to N/2. We observe three types of nodes in the network which can be explained as below:

1. Type A (H-H): The nodes that are at higher duty cycle (H) transmitting data packets to other nodes which are also at higher duty cycle (H).
2. Type B (L-H): The nodes that are at lower duty cycle (L) transmitting data packets to nodes which are at higher duty cycle (H).

3. Type C (H-L): The nodes that are at higher duty cycle (H) transmitting data packets to nodes which are at lower duty cycle (L).

In type A (H-H) nodes, the sender node and receiver node, both are at higher duty cycle. But these nodes will have definite overhearing from the lower duty cycled (LDC) nodes of the network. This is because the LDC nodes receive data packets with higher preamble length, as discussed before, that will be overheard by the higher duty cycled (HDC) nodes. As the preamble size equals the sleep period (wake up interval) of the LDC node, the HDC node wake up in this duration and overhears the packet. The current consumption of types A (HDC) nodes thus increases compared to when it was present in Case O scenario.

In type B (L-H) nodes, the sender node is at a LDC and receiver node is at a HDC. The LDC node will spend same amount of energy in data transmission as in case O. It further saves on energy in terms of overhearing and processing. It wakes up less number of times saving on the processing current and also sleeps for longer durations avoiding the overhearing from HDC nodes. When the LDC node is in active state, it will probabilistically overhear HDC nodes because it wakes up at different times compared to other HDC nodes in the network. As a result, the overall current consumption of type B (LDC) nodes reduces compared to when it was present in Case O scenario.

In type C (H-L) nodes, the sender node is at a HDC and receiver node is at a LDC. In this case, the HDC nodes have to send data to LDC nodes and thus will transmit data packets affixed with a higher preamble. The HDC nodes will spend higher energy on data transmission as compared to Case O. Thus their current consumption increases. To reduce this energy on data transmission, in our game theoretic approach, discussed in the next section, we introduce route adaptation by increasing route cost of the critical so as to enable their children nodes to possibly choose a different parent node.

We consider two scenarios, N=20 and N=40, where N is the total number of nodes in the network. For preliminary results, we assume all nodes can overhear all the other nodes in the network. We define the following modified equation 3.1 for current consumption of a node:

$$I = \frac{I_{Rt}T_{Rt}}{T_{RUI}} + \frac{I_{Dt}T_{Dt}}{T_D} + N\left(\frac{I_{Rr}T_{Rr}}{T_{RUI}}\right) + P_{HL}O_H I_{Dr}T_{Dr1} + P_{HH}O_H I_{Dr}T_{Dr2} + P_{LL}O_L I_{Dr}T_{Dr1} + P_{LH}O_L I_{Dr}T_{Dr2} + F I_{Dt}T_{Dt} + N_P I_P T_P \qquad (3.1)$$

where the new parameters included can be defined as follows:

P_{HL} = Probability of overhearing data packet sent from higher D.C node to lower D.C node

P_{HH}= Probability of overhearing data packet sent from higher D.C node to higher D.C node

P_{LL} = Probability of overhearing data packet sent from lower D.C node to lower D.C node

P_{LH} = Probability of overhearing data packet sent from lower D.C node to higher D.C node

T_{Dr1} = Duration of data packet received by LDC node = 1015 ms (D.C = 0.3%)

T_{Dr2} = Duration of data packet received by HDC node = 140 ms (D.C = 2.4%)

F = Forwarding rate = (N/4)*(1/T_D)

O_H = Overhearing rate of higher node duty cycle nodes = (N/4)*(1/T_D)

O_L = Overhearing rate of lower node duty cycle nodes = (N/4)*(1/T_D)

For representing the remaining battery life, i.e the estimated time until a node's battery is depleted considering its current estimated energy usage, we define remaining lifetime (L) as follows[3]:

$$L = \frac{B}{I} \qquad (3.2)$$

where B represents the remaining battery capacity and I represents the current consumed by the node.

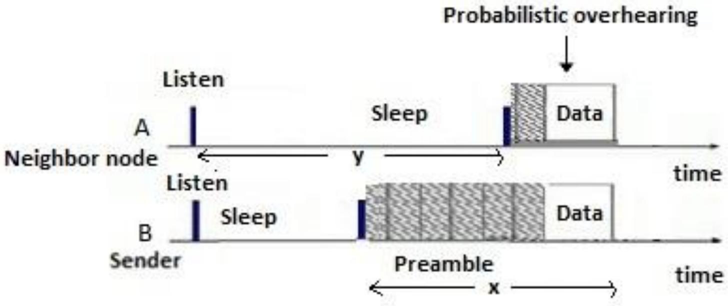

Figure 3.5 Probabilistic overhearing by node B (who is at HDC) from neighboring node A (who is sending data packet to a HDC node).

As mentioned in previous sections, the LDC nodes will have probabilistic overhearing from the neighboring HDC nodes. As can be seen in figure 3.5, a sender node B transmits a data packet with preamble which small compared to the wake up interval (y) of LDC node A. If the data packet falls in the sleep period of node A, it will not overhear the data packet at all. But if the data packet transmission falls in the listen period of node A, it will start overhearing (receiving) the data packet from in between the preamble and further read the data packet to know about it not being the intended receiver. Similarly, nodes will completely overhear data packets from other nodes that are present at the same duty cycle as their own (i.e HDC nodes from other HDC nodes and LDC nodes from LDC nodes). This is due to the preamble length being equal to their own wake-up interval (sleep period), so whenever they wake up and listen to the channel they receive the data packets. Considering this, we compute the probabilities for each type of node as follows:

- For type A (HDC) nodes, the probabilities $P_{HL} = P_{HH} = P_{LL} = P_{LH} = 1$, as it overhears from HDC as well as LDC nodes completely.

- For type B (LDC) nodes, the probabilities $P_{HL} = P_{LL} = 1$ (definite overhearing from LDC nodes).
- The nodes at HDC (2.4%) will wake up 8 times in one second, the length of data packet (including) preamble = 140 ms (for HDC nodes). The nodes at LDC (0.3%) will wake up once in one second, the length of wake up interval = 1000 ms. Thus, the probability $P_{HH} = P_{LH} =$ (x/y) = (140/1000) = 0.14 (probabilistic overhearing from HDC nodes as can be seen in figure 3.5). Also we consider expectation of overhearing duration (considering equal probability) T_{Dr2}= E[overhearing duration]=[1/2*(140)]= 70ms, as the LDC node can wake up and overhear anytime in between the reception of the shorter preambled data packets sent (destined) to its neighboring HDC nodes.
- For type C (HDC) nodes, sending to LDC nodes, the probabilities $P_{HL} = P_{HH} = P_{LL} = P_{LH} = 1$. Also the preamble affixed with the data packet is of higher duration, $T_{Dt} = 1015$ms (considering the node wakes up once every second) .

- Scenario 1 (N=20):

  We compare the results for 3 values of α (5%,10% and 15% of N)

- For the first value, α = (5% of N) = (5% of 20) = 1 node goes to a lower duty cycle and rest of the 19 nodes remain at higher duty cycle.
- For the second value, α = (10% of N) = (10% of 20) = 2 nodes go to a lower duty cycle and rest of the 18 nodes remain at higher duty cycle.
- For the third value, α = (15% of N) = (15% of 20) = 3 nodes go to a lower duty cycle and rest of the 17 nodes remain at higher duty cycle.

- The current consumption of the nodes for each value of α is calculated considering the above parameter values in equation 3.1. The comparison of results for all the above three values of α is depicted in figure 3.6. Observing the results, it clearly shows that as the value of α increases i.e the number of nodes going to lower duty cycle increases, the current consumption of nodes also increases.
- We depict the current consumed, for various events, by the node separately to notice the difference in them after a node adapts to a LDC. The type B (LDC nodes) have considerable reduction in overhearing current of data packets due to probabilistic overhearing. It is noticeable that the processing current also reduces significantly as it is dependent on the factor N_p, number of times a node wakes up in one second.
- If we observe a single case of α, it is interesting to note that the current consumption of type B (LDC) nodes is significantly low compared to when it was in the case O (before adaptation) scenario. This has a greatly improves the remaining lifetime of the critical node and consequently results in increase in lifetime of the overall network.
- But we also notice that the type A and C (HDC) nodes in the network are negatively affected and their current consumption increases. This is due to their increase in overhearing current from LDC nodes.
- It therefore becomes necessary to consider a tradeoff between the number of nodes going to LDC and increase in overhearing of neighboring nodes.

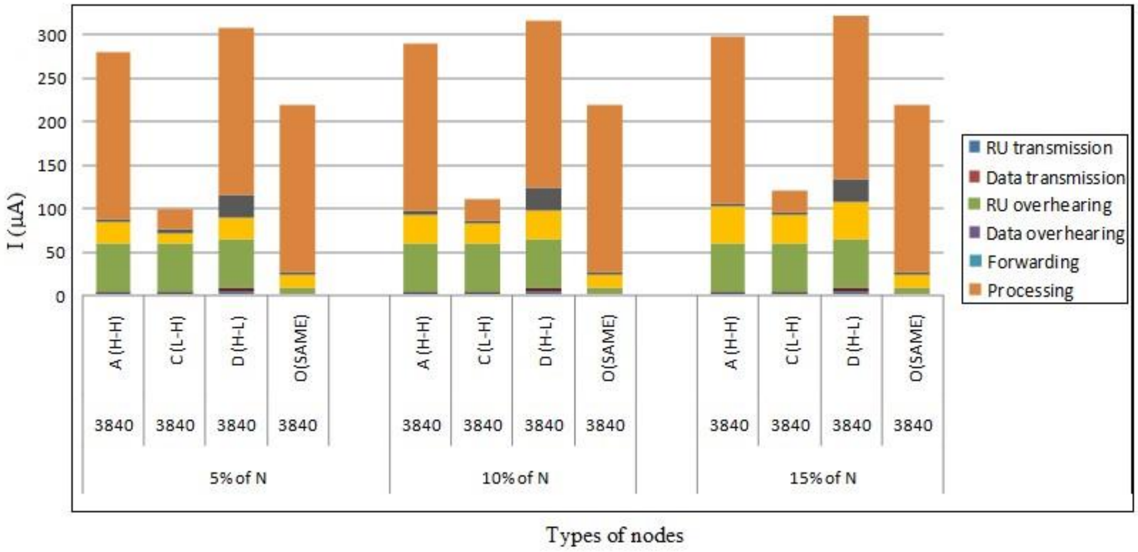

Figure 3.6 Comparison of results for A, C, D and O types of nodes. From N=20 nodes, α nodes go to LDC. (a) α =5% of N, (b) α =5% of N and (c) α =5% of N.

- Scenario 2 (N=40):

  We compare the results for 3 values of α (5%, 10% and 15% of N)

- For the first value, α = (5% of N) = (5% of 40) = 2 nodes goes to a lower duty cycle and rest of the 38 nodes remain at higher duty cycle.
- For the second value, α = (10% of N) = (10% of 40) = 4 nodes go to a lower duty cycle and rest of the 36 nodes remain at higher duty cycle.
- For the third value, α = (15% of N) = (15% of 40) = 6 nodes go to a lower duty cycle and rest of the 34 nodes remain at higher duty cycle.
- The current consumption of the nodes for each value of α is calculated considering the above parameter values in equation 3.1. A comparison of results for all the above three values of α is depicted in figure 3.7. These results also follow the similar observations as in scenario 1 with N=20 nodes.

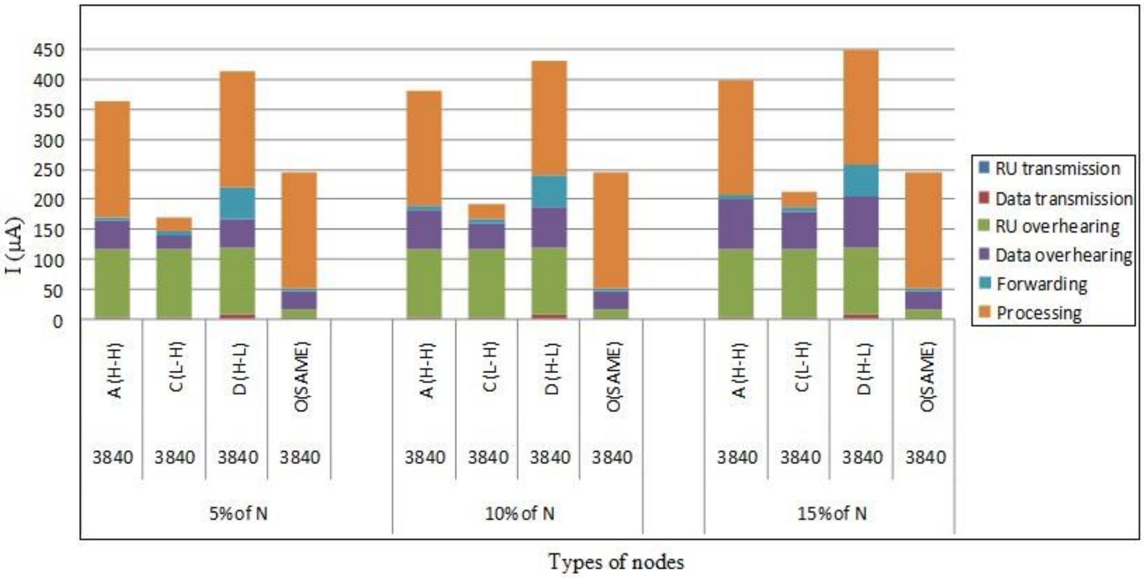

Figure 3.7 Comparison of results for A, C, D and O types of nodes. From N=40 nodes, α nodes go to LDC. (a) α =5% of N, (b) α =5% of N and (c) α =5% of N.

- ➢ The results of N=40 when compared to N=20, indicate that as the number of nodes increases in the network, the current consumption of each node increases. It should be noted that we consider worst case scenario, that all nodes overhear everyone else in the network which is not the case in actual implementations. In physical world applications, nodes that are in the radio range of each other will only be overheard, thereby improvising our results further, which is considered in the next section.
- ➢ To sum up the observations, we conclude that the current consumption of node going to a lower duty cycle experiences significant reduction in its current consumption thereby improving its lifetime but at the cost of increasing the current consumption of the neighboring nodes. Thus a tradeoff needs to be considered to balance the two for the benefit of the network.

3.4 Proposed Distributed Duty Cycle Adaptation Scheme

We now propose a distributed model in which duty cycle of critical nodes is adapted and decisions are taken at individual sensor nodes to improve the network lifetime. From the observations of the preliminary results, we address the tradeoff required for increase in lifetime of LDC nodes at the cost of increase in overhearing of HDC nodes. If the number of nodes going to LDC goes on increasing, after a point, it starts adversely affecting the network due to its downside effect on the neighboring nodes there by reducing the network lifetime. Thus we consider a multi-player game where in only those nodes who are energy constrained and whose neighbors are capable of bearing the overhearing increase are allowed to go to LDC. To perform this task we implement the game theory approach.

3.4.1 Game Theoretic Approach

Game theory, also known as interactive decision theory, is a study of strategic decision making. Specifically it is "the study of mathematical models of conflict and cooperation between intelligent rational decision-makers" [19]. A multiplayer game comprises of the following elements: players of the game, information and actions available to each player at each decision point, and the payoffs for each outcome. We formulate the proposed duty-cycle adaptation and routing problem as a multiplayer game, where

- Players of the game → to be the sensor nodes
- Information and action available to each player → lifetime of nodes and their routing cost information to take the action of going to a LDC

- Payoffs → the gain and loss obtained for the overall network in terms of lifetime if a node takes the action to go to a LDC.

The above elements are typically used to deduce a set of equilibria for each player such that, when these strategies are implemented, no player can profit by unilaterally deviating from this strategy. These strategies determine a stable state (equilibrium) in which one or more outcomes occur with known probability.

A pure strategy Nash equilibrium is a profile of strategies that each player's strategy is a best response which results in the highest available payoff against the equilibrium strategies of the other players. A set of strategies, if each represents a best response to the other strategies, is termed to be Nash equilibrium. So, if all the players are playing the strategies in a Nash equilibrium, they have no unilateral incentive to deviate, as their strategy is the best they can do given what others are doing. So in our case, when there is no node left that can lead to improvement in the network, by going to a lower duty cycle, that state will be termed as Nash equilibrium [20].

The payoffs of the game are generally taken to represent the utility of individual nodes (players). The utility function of a node is defined by the gain and loss of the network when that node takes a particular action. In our approach, the proposed action is going to LDC, and the corresponding utility is obtained by considering the following three parameters:

- Lifetime increase of the critical node (N_c) going to LDC
- Lifetime decrease of N_c's neighboring nodes
- Increase in route cost of N_c's neighboring nodes

The first parameter formulates the gain part of the utility function as it contributes to the improvement of the network lifetime. The other two parameters denote the negative effects on the other nodes which thus contribute to the loss part of the utility function.

The utility function for our approach can be defined as follows:

$$U_i = w_g \times Gain_i + w_l \times Loss_i \qquad (3.3)$$

where U_i= the utility function for a node i

w_g= weightage for gain

w_l= weightage for loss

$Gain_i$ = gain achieved, when node i goes LDC, in terms of lifetime

$Loss_i$= loss, when node i goes LDC, in terms of lifetime and route cost of neighbor nodes

$$Gain_i = \frac{\Delta L^i}{L_{avg}} \qquad (3.4)$$

where increase in lifetime of critical node L^i is,

$$\Delta L^i = L^i_{LDC} - L^i_{HDC}$$

L_{avg} =average lifetime of all the nodes in the network before adaptation (when all nodes are at same (higher 2.4%) duty cycle).

$$Loss_i = \frac{\Delta L^j}{L_{avg}} + \frac{\Delta RC^j}{RC_{avg}} \qquad (3.5)$$

where decrease in lifetime of neighbors of critical node ΔL^j is,

$$\Delta L^j = \sum_{j=1}^{k} (L^j_{LDC} - L^j_{HDC}) \qquad (3.6)$$

k = number of neighbors of critical node i

$$\Delta RC^j = \sum_{j=1}^{k} (RC^j_{HDC} - RC^j_{LDC}) \qquad (3.7)$$

RC_{avg}= average of route costs (to the sink) of all the nodes in the network, before adaptation.

The utility function thus denotes the benefit obtained by the network if a particular decision is taken and thus acts as the decision criterion. We define a threshold value above which the nodes take the desired action, else there is no action taken. Thus a node goes to a lower duty cycle only if its utility value is above the threshold, which implies that gain is more than the loss for the given action. If the criterion is not met, the node stays in the higher duty cycle and its lifetime remains to be the network lifetime in future.

3.4.2 Formulation of Algorithm

We consider a network of N nodes placed randomly in a w×w meters square area where each node has a radio range of R meters. The nodes in range are connected to each other with a link cost of 1. Each node is assigned with random but fixed battery level (B). Now using cost as a routing gradient, we employ the Dijkstra's algorithm to form a routing tree (of the nodes) to the sink. Each node is assigned a least cost path and data packets are forwarded by multiple hopping via parent nodes to the sink. With all link costs set to 1, the least cost routes obtained would lead to shortest path routes and not necessarily those that optimize (or balance) the lifetimes. The current consumption of each node is then computed using equation (3.1).The overhearing rate of a node is considered according to the number of neighbors in range of a node. The forwarding rate is calculated on the basis of children nodes of each node. The remaining lifetime of each node is calculated from equation (3.2), using the battery level (different for different nodes) and its current consumption. The energy (battery) levels is assumed to vary from node to node (random assignment of battery values) such as in energy harvesting schemes. For example in solar harvesting, the nodes present in extreme sunlight will harvest more energy compared to those located in the shadowed region of the network.

The node which has the lowest lifetime in the network, termed as the critical node (N_c), is thus the most energy constrained node and thus its lifetime needs to be improved for increasing the network lifetime. We enable this node to virtually go to a lower duty cycle and the critical node increases (doubles in our simulation) the cost on all its outgoing links. By this we make the route via this node to be relatively more expensive enabling the children nodes to choose a different parent node. This helps to reduce the load on the critical node further reducing its energy consumption. This results in load balancing of the network especially when the critical node is a node near to the sink. After the increase in costs, we determine least cost routes by applying the Dijkstra'a algorithm again for possible route changes in the network. The current consumed on route update transmission/reception, data transmission/reception, overhearing, forwarding and processing is recalculated, combining to give the current consumption. These parameters are calculated considering all the changes that occur in the network when a node goes LDC, as discussed in previous sections.

We further calculate the utility value of this critical node using equation (3.3). For calculating utility function, the $Gain_i$is computed considering increase in lifetime of the critical node, after going to LDC. In the calculation of ΔL^j, the decrease in lifetime of all the neighboring nodes, in range of N_c, is considered with reference to average lifetime of the network. The corresponding increase in their route costs, with reference to average route cost, is included for computing ΔRC^j. The average lifetime and average route cost considered in above calculation is calculated for the initial network (before adapting nodes to a LDC).

If the utility value of N_c is above the threshold value (assumed to be 0.5 in our case), then the node is allowed to go to a LDC and remains in this state for the rest of the time, now no longer being the critical node. We repeat this process iteratively by finding the next critical node, node with the lowest lifetime in current scenario where one node is at the LDC. Thus for each critical node, its utility value is computed which acts as a decisive factor whether a node should go to LDC or not. The process continues for a number of iterations, with each iteration having only one node (the critical node) going to a lower duty cycle. The nodes continue to adapt their duty cycle until the utility function of any node drops below the threshold value at which the process stops. At this point, that critical node's lifetime remains to be the network lifetime and no further improvement is possible and thus we stop the nodes from going to LDC any further. The flowchart for the above process is depicted in figure 3.8.

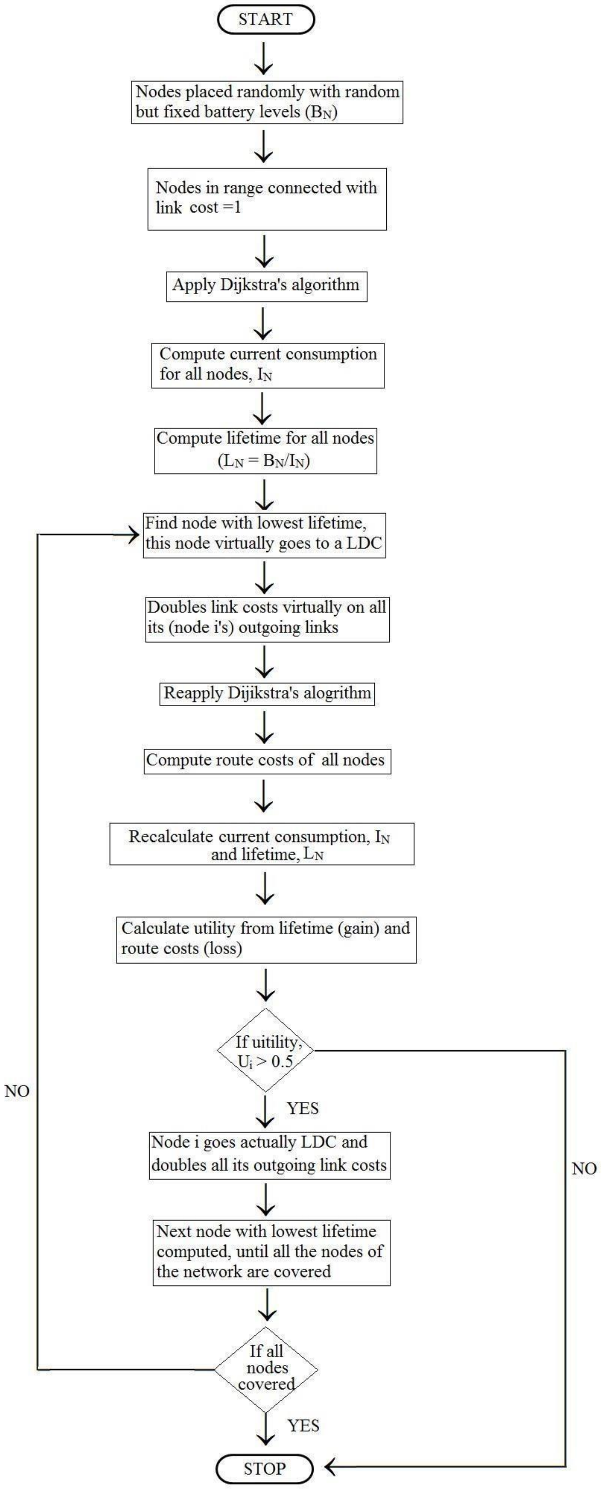

Figure 3.8 Flowchart for game theoretic approach of adaptive duty cycling and route cost adaptation

CHAPTER 4: SIMULATION RESULTS

In this chapter we present the computer simulations performed for our proposed protocol and the results obtained. In the simulator, we place 40 nodes at random positions in an area of 500 x 500 meters. Each node has a radio range of 150 meters, outside of which it cannot transmit/overhear/receive any data packets directly. The process of adapting the duty cycle can run maximum upto (N-1) rounds, N being the number of nodes in the network. The process stops whenever the utility value of the critical node does not meet the defined criterion. The criterion indicates that the neighboring nodes are not burdened by the critical node going to LDC and the decision is taken in favor for improvement of the network.

The utility function considers the gain of the critical node in terms of lifetime increase and the loss of the neighboring nodes in terms of lifetime decrease and route cost increase. We consider these terms with reference to the average values of all the nodes in the network, as seen in equations (3.4) and (3.5).

4.1 Lifetime of Critical Node

The result for the increase in remaining lifetime of a critical node (that goes LDC) is depicted in figure 4.1. At each stage of the adaptation, the lifetime of the critical node in that stage prior to adaptation (blue) as well as after adaptation (red) are shown. These values are obtained using equation (3.2). As the current consumption reduces, when node goes to a LDC, the lifetime increases. The process of adaptation is run iteratively, as discussed in previous chapter, with each round of adaptation having only one critical node going to a lower duty cycle. We show, in the figure 4.1, the values of different nodes that go to LDC in different rounds of adaptation for one scenario of network. It clearly indicates that there is significant amount of increase the battery lifetime of the critical nodes which eventually improves the lifetime of the network.

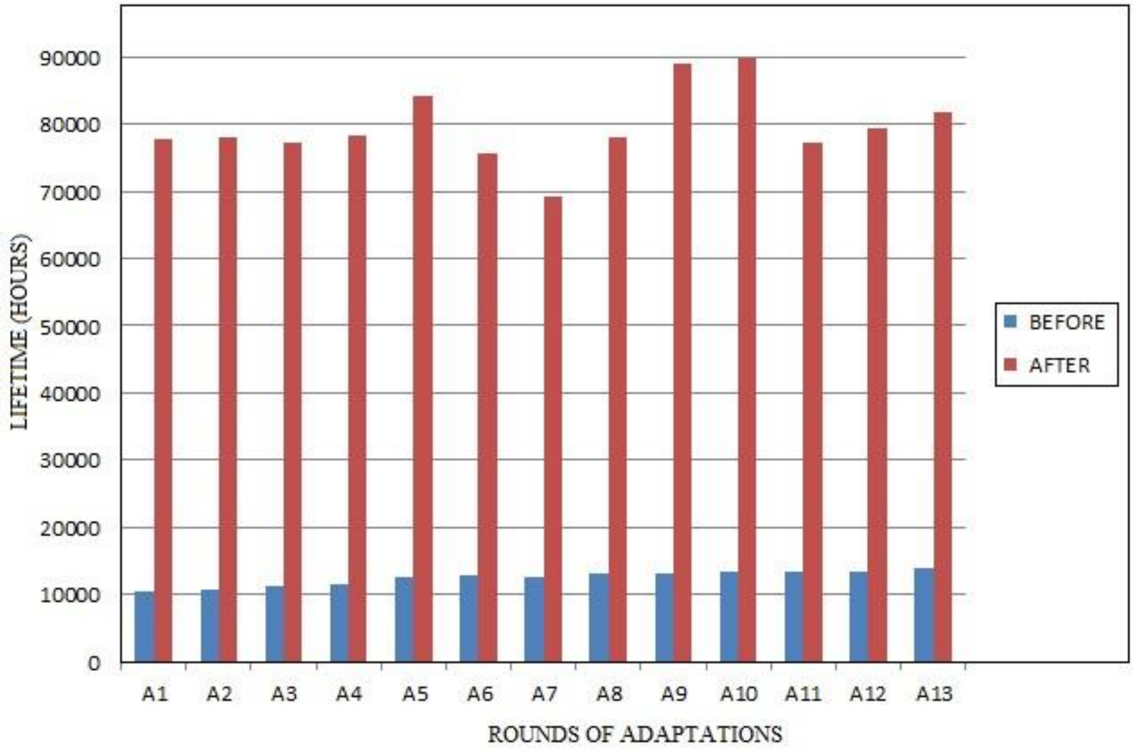

Figure 4.1 Lifetime of critical nodes before and after adaptation of duty cycle

4.2 Improvement in Lifetime of the Network

The result for the increase in average of the network lifetime over different rounds of adaptation is depicted in figure 4.2. We simulate the algorithm for different rounds with each round having only one critical node going to a lower duty cycle. This simulation is run considering different scenarios, i.e considering different topologies of node placement (location). Each scenario has nodes placed at random locations with random battery levels, having no relation with the other scenarios. Every scenario gives different locations to nodes and we average the results of all the scenarios over different rounds of adaptations.

Network lifetime is the lifetime value of that node which has the lowest remaining lifetime (N_c), at that particular round, in the network. If this node goes to a lower duty cycle in the next adaptation, it no longer remains to be the critical node and its strength in terms of energy is improved. We have taken average of the values of network lifetime from 10 different simulation runs, each run stating with different (random) node locations and battery lives. As seen in of figure 4.2, the results show that the average network lifetime increases considerably with the implementation of our designed approach and also helps in balancing the energies of different nodes in the network. The upper threshold (max) and lower threshold (min) values of the average values have also been plotted. The upper threshold indicates the maximum value of lifetime achieved by averaging the network lifetime (critical node lifetime) for different rounds of adaptations considering over 10 different scenarios. Thus each round of adaptation in the result shows the averaged values of network lifetime of 10 different scenarios for that particular round of adaptation. Similarly, the lower threshold indicates the minimum value of lifetime achieved by averaging the lifetimes of all nodes in the network considering over 10 different scenarios. The threshold values eventually stabilize to the average value by the end of the process which indicates that there can be no further improvement in the lifetime of the network.

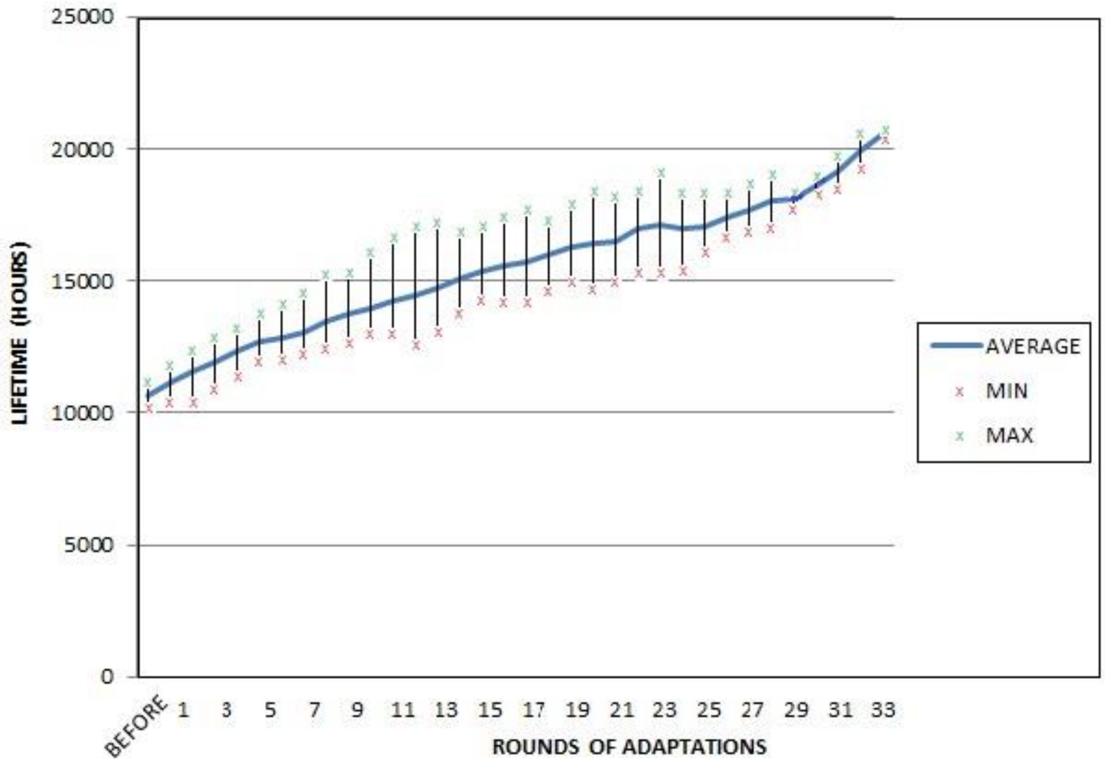

Figure 4.2 Increase in average network lifetime over different rounds of adaptations from 10 different scenarios of network

Whenever a node is not allowed to go to a LDC, i.e it does not satisfy the utility criterion, it indicates that there is more loss than gain to the network, and thus we stop the process. Thus in the above result of figure 4.2, for a particular scenario, after round 33 of adaptation the next critical node obtains utility value below the threshold level and thus the process is stopped. Thereafter, the lifetime of this particular node will remain to be the network lifetime in future.

4.3 Improvement in Average Lifetime of the Network

Average lifetime is defined as the average of remaining battery lifetimes of all the nodes in the network. The significant increase in the remaining lifetime of the critical nodes, as observed in figure 4.1, greatly affects the average lifetime of the network to increase in each round of adaptation. Thus we see a graph with linear increase of values in figure 4.3. The increase in average lifetime of the network indicates the benefits of adaptive duty cycling in terms of energy conservation. As we considered the average, upper and lower threshold values for network lifetime for 10 different scenarios in previous section, we similarly take the average of average lifetime of all the nodes in the network for 10 different scenarios. Thus each round of adaptation in the result of figure 4.3 shows the averaged values of average lifetime of 10 different scenarios for that particular round of adaptation.

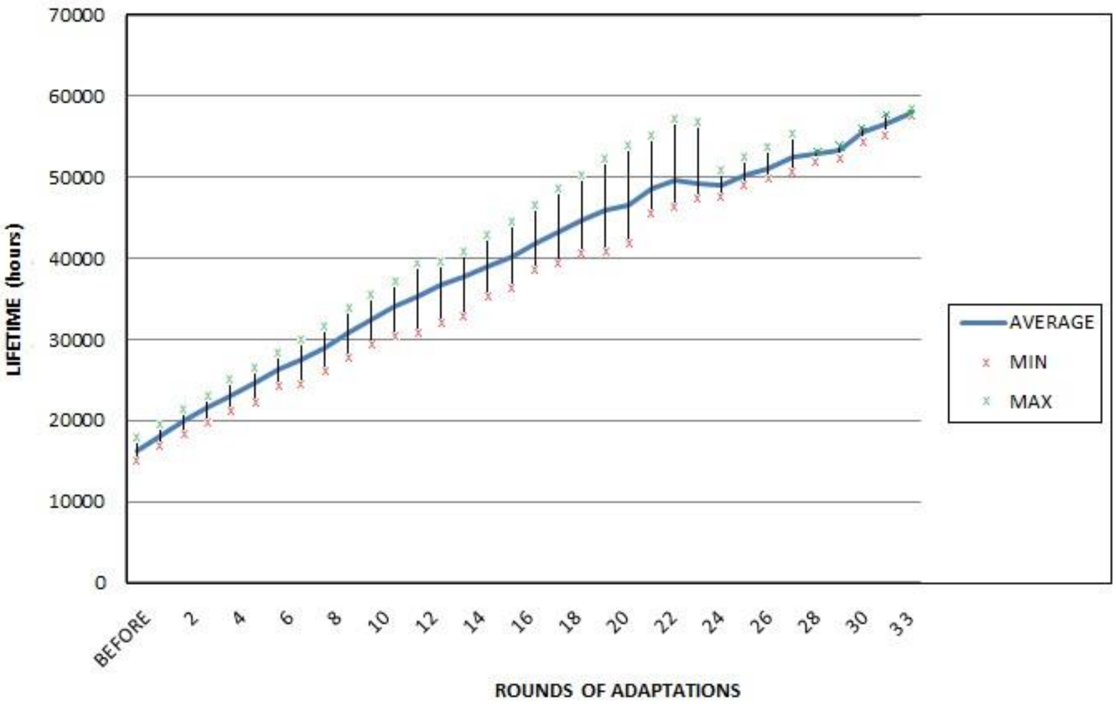

Figure 4.3 Increase in average lifetime over different rounds of adaptations for 10 different scenarios

4.4 Route Cost Adaptation

The adaptation of duty cycle of the critical node has two negative effects as discussed earlier:

- Children nodes need to send data packet with higher preamble length
- Overhearing of neighboring nodes increases

To address these issues, we perform route adaptation, i.e increase the route cost on all outgoing links of the critical node. Due to this, the children nodes choose a different possible parent node and consequently overhearing of neighboring nodes is relatively reduced. Also the load on critical node is reduced further decreasing its energy consumption. But this results into increase in route costs of nodes to the sink, especially those children nodes who will not have another parent node to hop over packets to the sink. The increase in average of route costs of all nodes for 10 different scenarios is depicted in figure 4.4. We can see that the graph goes on increasing as we move further with the rounds of adaptation. It is indicated that as the nodes go to a LDC and increase their link cost, the total route cost to the sink node from each node gradually increases.

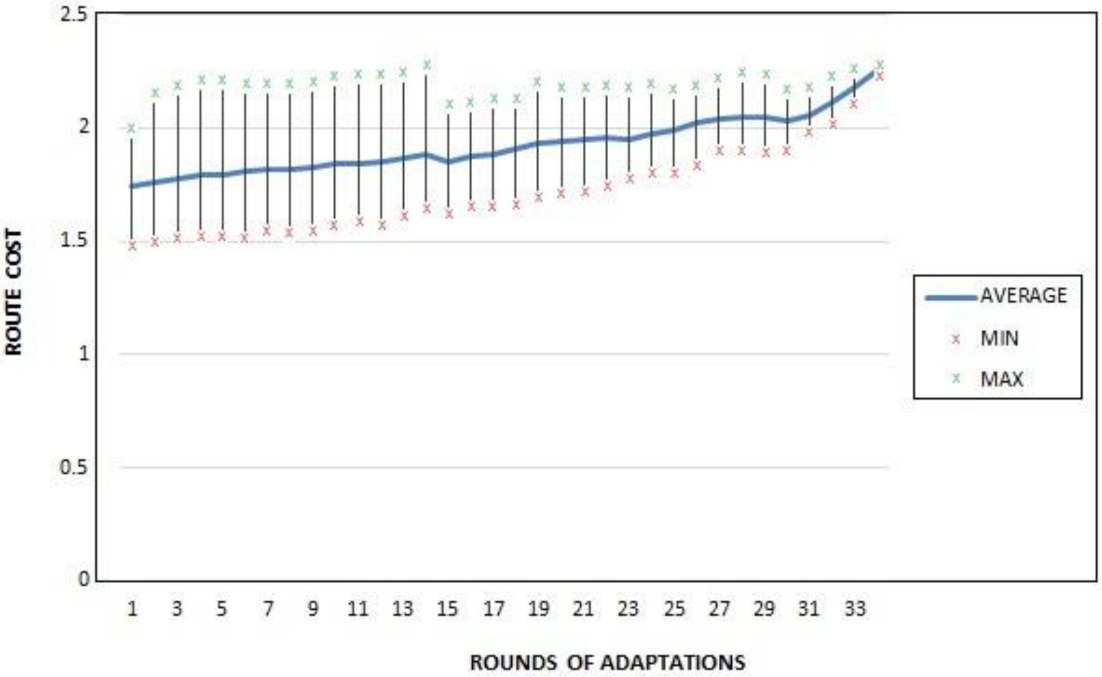

Figure 4.4 Increase in average route cost of neighboring nodes going through adaptations for 10 different scenarios .

CHAPTER 5: CONCLUSION AND FUTURE WORK

5.1 Conclusions

Energy efficiency is of paramount importance in wireless sensor networks, as sensors have limited power resources. This results into design of various techniques for maximizing the lifetime of the networks considering the challenge of resource constraints. Existing protocols typically apply fixed duty cycles of sleep and awake periods for energy conservation. Our research proposes to adapt the duty cycle of the sensor nodes so as to reduce the radio activity of nodes that have relatively lower energy resources at the cost of other nodes that have higher energy resources. This is an effective approach for balancing the lifetime of nodes that may have different energy resources, such as energy harvesting.

We focus to improve the state of the weaker sensor nodes, the most power constrained nodes, by enabling them to go to a lower duty cycle as well as shift their load on to other neighboring nodes. The critical nodes save energy on the radio transmission/reception which results into less current consumption and improvement in the battery health. Improvement in lifetime of each of the critical nodes leads to the improvement in the overall global network lifetime.

The downside of adapting a sensor node to a lower duty cycle is its effect on the neighboring nodes. As we assume it to be an asynchronous approach, the neighbors of a LDC node are required to bear the transmission of a longer preambled data packet. As a solution to it, we increase the link cost on all the outgoing links of the critical node which enables the children nodes to choose a different parent node thereby maintaining a load balance in the network. Our adaptation is based on a game theoretic formulation where actions on duty cycle adaptation are decided using an utility function that is based on the gain and loss (cost) of the actions. Results from computer simulations show the benefits of the proposed approach.

5.2 Future Work

As the proposed protocol is asynchronous, there are lot of limitations involved in its design. Idle listening is another source of energy wastage that can be addressed to further improve the network's lifetime. Also different mechanisms can be applied to reduce the preamble length and conserve radio energy consumption further. Considering synchronization techniques for the above approach can result into a great opportunity of research. As the nodes overhear data packets because of the shared common access medium, synchronization can considerably further reduce energy consumption of the sensor nodes in the network.

REFERENCES

[1] R. Jurdak, P. Baldi and C. V. Lopes, "Adaptive Low Power Listening for Wireless Sensor Networks," in *IEEE Transactions on Mobile Computing, Vol. 6, No.8*, 2007.

[2] A. Nasipuri, R. Cox, J. Conrad, L. V. d. Zel, B. Rodriguez and R. McKosky, "Design Considerations for a Large-Scale Wireless Sensor Network for Substation Monitoring," Proceedings of IEEE SenseApp'10, October, 2010.

[3] A. Pal and A. Nasipuri, "A Joint Power Control and Routing Scheme for Rechargeable Sensor Networks".

[4] W. Ye, J. Heidemann and D. Estrin, "An Energy -Efficient MAC Protocol for wireless Sensor Networks," in *IEEE INFOCOM*, NY, 2002.

[5] J. Polastre, J. Hill and D. Culler, "Versatile Low Power Media Access for Wireless Sensor Networks," in *SenSys'04*, 2004.

[6] M. Buettner, G. V. Yee, E. Anderson and R. Han, "X-MAC: A Short Preamble MAC Protocol for Duty-Cycled Wireless Sensor Networks," in *SenSys'06*, 2006.

[7] A. El-Hoiydi and J. D. Decotignie, "WiseMAC: An Ultra Low Power MAC Protocol for the Downlink of Infrastructure Wireless Sensor Networks," in *ISCC'04*, 2004.

[8] K.-T. Cho and S. Bahk, "HE-MAC: Hop Extended MAC Protocol for Wireless Sensor Networks," in *IEEE "GLOBECOM"*, 2009.

[9] S. Du, A. K. Saha and D. B. Johnson, "RMAC: A Routing-Enhanced Duty-Cycle MAC Protocol for Wireless Sensor Networks," in *IEEE INFOCOM*, 2007.

[10] R. Jurdak, P. Baldi and C. V. Lopes, "Energy-Aware Adaptive Low Power Listening for Sensor Networks".

[11] T. V. Dam and K. Langendoen, "An Adaptive Energy-Efficient MAC Protocol for Wireless Sensor Networks," in *SenSys'03*, 2003.

[12] P. H. Puthran, "Current Consumption Analysis of wireless sensor nodes used for health monitoring of substation equipment".

[13] F. Bouabdallah, Minimizing the energy consumption in Wireless Sensor Networks.

[14] G. Anastasi, M. Conti, M. D. Francesco and A. Passarella, "Energy Conservation in Wireless Sensor Networks: a Survey".

[15] O. Gnawali, R. Fonseca, K. Jamieson, D. Moss and P. Levis, "Collection Tree Protocol," in *SenSys'09*, 2009.

[16] V. Bharghavan, A. Demers, S. Shenker and L. Zhang, "Macaw: A media access protocol for Wireless LANs," in *in Processfdings of the ACM SIGCOMM Conference*, 1994.

[17] Wireless Sensor Networks, wiki/Wireless_sensor_network

[18] “Xmesh user manual, Crossbow technology” xbow.com/Products, 2007

[19] Roger B. Myerson (1991), *Game Theory: Analysis of Conflict,*Harvard University.

[20] Game theory, wiki/Game_theory