Energy Saving Methods in Wireless Sensor Networks
(Based on 802.15.4)

Master Thesis in Computer System Engineering

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Energy Saving Methods in Wireless Sensor Networks
(Based on 802.15.4)

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Preface

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Partha Roy & Syed Jawad Ali
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Abstract

To predict the lifetime of wireless sensor networks before their installation is an important concern. The IEEE 802.15.4 standard is specifically meant to support long battery life time; still there are some precautions to be taken by which a sensor network system application based on the standard can be made to run for longer time periods.

This thesis defines a holistic approach to the problem of energy consumption in sensor networks and suggests a choice of node architecture, network structure and routing algorithm to support energy saving in the network. The idea and thrust of the thesis is that stand-alone measures such as selecting a low-power microcontroller with embedded transceiver will not alone be sufficient to achieve energy saving over the entire network. A comprehensive design study with energy saving as a primary task must be made. Focus given on the design objectives needs to look at different aspects – application code, network configuration code, routing algorithms etc to come up with an energy efficient network.
1 Introduction

Wireless sensor network (WSN) technology is promising and is therefore gaining popularity day by day in a wide area of different applications.

The WSN nodes operate on battery power which is often deployed in a rough physical environment; changing the batteries is therefore a complicated task, as some networks may consist of hundreds to thousands of nodes. Such large physically distributed networks increase the difficulty of changing batteries and makes recharging almost impossible during operations. This problem has forced node, network and system developers to make changes in the basic WSN architecture to minimize the energy consumption especially of the nodes in order make the network and overall system application more energy efficient. Recently the IEEE 802.15.4 standard was developed for low data-rate application which needed to last for longer duration by consuming relatively less energy.

One of the challenging topics in wireless communication techniques to be used for WSN applications is energy efficiency. The life time of a wireless sensor node depends on available energy sources and its overall energy consumption. Further, increasing the capacity of batteries is not possible due to the small size requirement of the nodes.

Zigbee/802.15.4 technology is one of a number of promising technologies for wireless communication due to its low cost, low complexity, and overall energy efficiency. Zigbee/802.15.4 claims to be made to operate using minimum energy, making it suitable for applications which operate on low data rate and that require support for a long lasting energy efficient network.

1.1 Limitation in Wireless sensor network

WSN nodes that are based on the Zigbee over 802.15.4 protocols are increasingly being deployed for a number of applications. The characteristic features of such nodes are their low cost, low energy consumption and deployment in geographically wide areas. The deployment scenarios vary from habitat monitoring, environment monitoring to plant-equipment monitoring. The primary job of wireless communication standards such as Zigbee and 802.15.4 is to do away with the hassle of wires and provide an almost maintenance-free network that delivers data. Since the nodes are wireless, powering them up from the main supply would be counter-productive. Supplying energy through batteries, energy scavenging (reuse) or other local energy sources (such as solar cells) are then the only viable options. However Batteries have limited capacity. Continuous operation will drain batteries and make the nodes inoperable. Frequent changes of batteries are not a practical option since a network might have over a hundred nodes spread over a large geographical area. In this context it becomes imperative that energy be saved so that regular
AA batteries will last for a year or more. However to solve this quite difficult problem there is a need to take a holistic approach to the issue of energy management in sensor nodes and networks. The selection of components of the sensor node, the application program that runs in the node, the protocol configuration, routing algorithms all play a significant role in the energy consumption patterns and the energy conservation capability of the network.

This work aims to identifying and quantifying energy saving methods in WSN. An important prerequisite to carry out this activity is to develop a methodology for the estimation of energy consumption in the individual WSN nodes and in the network as a whole. The purpose of this work will be to suggest node architecture, network infrastructure and protocol configuration that will all minimize the energy consumption of a WSN. In the optimization for minimal energy consumption care should be taken to see that other parameters such as successful transmission of parameters by the network and event detection by the nodes are not sacrificed.

1.2 Problem statement

The following issues will be addressed in this thesis:

- Analysing the architecture of a WSN node to minimize energy consumption. This involves proper selection of the node components with mechanisms to conserve energy such as support for sleep modes. A diverse set of sleep modes will help in programming the node to respond to different event scenarios such as periodic transfer of parameter data, different sleep modes for the different types of nodes in the network – end devices, routers and base stations. The analysis will also focus on the operating system requirements to support activities such as scheduling of tasks, responding to external wake-up calls, modification of execution paths as per available energy in the node, duty cycle for sleep and wake-up.

- Comparing different microcontrollers and RF transceivers on energy level and on different modes of operation.

- Studying network infrastructure, factors influencing energy consumption at network level and things to be look for while making wireless sensor network for more efficiency.

- Estimation methods for energy consumption of a node based on the battery data sheet supplied by the manufacturer can be an estimate on the remaining life of the battery. This information can make use of routing algorithms that favour nodes running with low power so that there is uniform consumption in the entire network.
The approach is basically to delineate/define energy saving methods first and then focus on some energy saving estimates. In addition, the study of energy saving methods will focus on the physical layer, the choice of components and the choice of network topology as the areas where savings can be affected by putting in efforts. The thesis work takes a holistic approach and divides the methods as pertaining to a node or to the entire network. It is probable that only a combination of methods that attempt to reduce energy consumption at the node level and the network level will lead to a practical network that is energy efficient. Some of the methods that were thought of as promising are:

- Allowing nodes in a network to sleep for much longer periods during non-transmission of data
- Minimize the time it takes for nodes to get into sleep mode and to awake from sleep mode
- Allowing node to sleep even in deeper mode as described in [11]
- Configuring 802.15.4 MAC

An integrated scheme that involves the component selection of the node, the operating system that runs in the node, the tasks that run and are controlled by the operating system, the configuration of the MAC and finally a network wide energy efficient application were presented in the present thesis. This thesis is a survey of methods currently available. Further some new methods and techniques have been discussed. This thesis gives a comprehensive solution that can be practically implemented. It is a solution that integrates techniques and components in their individual capacities but not in an integrated manner.

The objective of this thesis is to give some preliminary guidance on how to configure the WSN and extend its services in terms of its life time and in order to make it energy efficient based on the criteria discussed above. Finally we make our recommendations, suggest improvements and conclude with a summary.
2 Background

2.1 Overview of 802.15.4

Wireless technology is largely and increasingly beneficial for industry. According to their demand, industry needs technology that can help to implement local area applications like office, industry, and outdoor environments where often tens to hundreds and even thousands of nodes are needed. The challenge is to maintain each node in a cost, complexity, and energy perspective. Most difficult is to replace the battery of each node in a wide area network. Thus, the IEEE 802.15 working group has taken this responsibility to work on this problem, and to develop technology for this purpose.

The working group that first introduced Bluetooth technology in 1999, based on 802.15.1 [4] later formed two other subgroups to design a high-speed wireless personal area network that is WPAN [802.15.3] but they are not energy efficient according to expectations. Finally, in December 2000 they introduced 802.15.4 low rate WPAN (LR-WPAN) [5]. The 802.15.4 standard supports two modes: beacon and non-beacon.

The IEEE 802.15.4 working group and the Zigbee alliance have been working closely together to specify and improve the entire protocol stack. As both the IEEE 802.15.4 and Zigbee groups are working with the same purpose, the developers are committed to work together to improve this technology. Zigbee alliance group takes the responsibility to define and modify the higher level protocols, whereas 802.15.4 is working on the two lower level protocols (physical Link and data link layer). The working model of 802.15.4 and Zigbee are shown in figure 2.1a. Nowadays the IEEE 802.15.4 works on the specification of the PHY and MAC layers, by offering building blocks for different types of networks like star, mesh, and cluster tree which is aimed at achieving a data rate of 250kbps in the 2.4 GHz Band [3].

Currently existing Zigbee compliant equipment transmits data within a range of 10-75 meters, depending on the RF environment. The existing protocol operates on different frequency bands (2.4 GHz ISM world wide, 915MHz USA ISM band and 868MHz - Europe). This standard offers two PHY options, based on direct sequence spread spectrum (DSSS) [1] for transmission and reception of data.

Zigbee is a new wireless technology supporting WPAN. It has low data rate, low power consumption and low cost as its main goals. The main purpose or target for this technology is remote control and wireless monitoring applications which means to communicate between WSN nodes and/or between base station and WSN nodes. The IEEE 802.15.4 also started their work on low data rate standard. It is part of the IEEE STD 802.15.4 working
group which is developing WPAN standard. The first successful work of this group was the IEEE 802.15.1, commonly known as Blue-Tooth, used to send data without cable for consumer electronic devices. The second phase of this group was high speed WPAN, but now they are working on a Third Standard which should be cheap, have low complexity and low power wireless connectivity to the portable electronic device.

**Figure 2.1a:** The working model of the IEEE 802.15.4 and Zigbee [15]

In the 802.15.4 standard the CSMA-CA (Carrier Sense Multiple Access with Collision Avoidance) method is used to access the radio channel or control the access through the MAC sub layer. It is also used to synchronize data flow as well as entire network and gives support to upper layer for robust link operation. It is responsible for handling retransmission, acknowledgement of data packet, frame validation and also provides Mac layer security (AES-128 encryption based).
2.1.1 Physical Layer

The Physical Layer (PHY) is one of the essential parts of the IEEE 802.15.4 which provides two services, PHY data service and PHY management Service. The main feature of this layer is activation and deactivation of the radio transceiver, sensing channel, link quality determination, energy detection (ED) channel selection and clear channel assessment. It is mainly responsible for sending/receiving data between two devices. It supports three frequency data rates: 20 kb/s in Europe over the 868 MHz band and 40kb/s in North America over the 915 MHz band and for world wide applications at 250 kb/s using 2.4 GHz. The physical layer helps in energy detection (ED) measurement. It estimates the receiver signal power and link quality indication (LQI), measures the strength and quality of the received packet, and on-going activity detected by the clear channel assessment (CCA) and relays the result to the MAC layer.

<table>
<thead>
<tr>
<th>PHY (MHZ)</th>
<th>Frequency Band (MHZ)</th>
<th>Spreading Parameters</th>
<th>Data Parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Chips rate (Kchips/s)</td>
<td>Modulation</td>
</tr>
<tr>
<td>868/915</td>
<td>868-868.6</td>
<td>300</td>
<td>BPSK</td>
</tr>
<tr>
<td></td>
<td>902-928</td>
<td>600</td>
<td>BPSK</td>
</tr>
<tr>
<td>2450</td>
<td>2400-2483.5</td>
<td>2000</td>
<td>O-QPSK</td>
</tr>
</tbody>
</table>

**Table 2.1a:** Frequency Bands and Data Rate [7]
2.1.2 Mac Layer

The Mac Layer provides an interface between the upper layer and PHY layer. The MAC protocol of IEEE 802.15.4 can operate both beacon and no beacon models. It is a simple CSMA/CA Technology. IEEE 802.15.4 LR-WPAN allows super frame structure which is bounded by network beacons and is divided into 16 equally sized slots. Beacons are used to synchronize the attached device and help to identify the PAN coordinates. Actually the super frame starts with the beacon which is a small synchronization packet that contains information relating to the network and notifying the nodes about pending data [6].

The super frame has active and inactive portions as shown in figure 2.1b. When it goes to active portion it is divided into 16 contiguous time slots. It contains three parts: connection access period (CAP), connection free period (CFP) and active portion. Within the connection free period (CFP) there is one part called guaranteed time slot (GTS), which is used for a specific node. When it goes to an inactive portion the coordinator can not interact with PAN, which means node enter into power saving mode.

The duration of different portions of super frame duration (SD) is described by the values of MAC Beacon Order (BO) and MAC Super frame order (SO). The beam interval (IB) and Active super frame duration can be adjusted by BO and SO [9].

\[
\begin{align*}
IB &= A \text{ Base Super frame Duration} \times 2 \\
& [0 \leq BO \geq 14] \text{ the super frame is ignored if } Bo=15 \\
SD &= A \text{ Base Super frame Duration} \times 2 \times SO \\
& [0 \leq SO \geq 14] \text{ the super frame will be inactive if } SO= 15
\end{align*}
\]

![Figure 2.1b: The Super frame structure [6]](image-url)
2.2 Network Topology

The 802.15.4 /Zigbee network layer helps to maintain the device and configure the network. The combination of devices working in Zigbee networks helps to enable the network shown in table 2.2a.

<table>
<thead>
<tr>
<th>Physical device type distinguishes the device hardware complexity and capability.</th>
<th>Logical device type distinguishes the physical device develop in specific in Zigbee network</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Coordinator</strong></td>
<td><strong>Router</strong></td>
</tr>
<tr>
<td>Network Establishment and control</td>
<td>Support data routing functionality, can talk to other routers, coordinator and end device</td>
</tr>
<tr>
<td>Full Function Device (FFD) : Adequate resources and memory capacity to handle all designated task</td>
<td>Yes</td>
</tr>
<tr>
<td>Reduce Function Device (RF D) : Modest resources and memory capacity compare to FFD</td>
<td>No</td>
</tr>
</tbody>
</table>

**Table 2.2a: Device types in Zigbee networks**

In this network data transmission occurs in three different ways: from a device to a coordinator, from a coordinator to a device and from a coordinator to a coordinator. The manner of transmission occurs in two different modes. One is a beacon mode; the other is a non beacon mode. In the beacon mode, the coordinator adds information into the data which is waiting in the device in the frame, then the device analyse or survey the network in CAP and get data from the coordinator. In the non-beacon mode the devices sample the coordinator for data at a distinct rate by application. The device uses the slotted CSMA-CA in CAP from devices to the coordinator. In the case of non-beacon mode the data is transferred using the unslotted CSMA-CA. Optional acknowledge frame from the receiver is sent after receiving data. Transmit modes are shown in figure 2.2a.
(1) From coordinator in beacon  
(2) From coordinator in non beacon  
(3) From device in beacon  
(4) From device in non beacon

Figure 2.2a: Data transmission examples in IEEE 802.15.4 some distinct Network Topologies
- Star
- Mesh
- Cluster Tree (peer-to-peer)

In the star network, the communication is carried out by the PAN coordinator. The communication network is treated as a master device and other devices act as slaves and communicate only with the PAN coordinator. The PAN coordinator can be either a FFD or RFD and it is suitable for small networks like the single hop-network. Figure 2.2b illustrates different types of topologies.

Peer-to-peer structure is good for large networks and also suitable for industrial purposes. In this network any coordinator can communicate with any other coordinator in their range. Peer to peer can be self-controlled, self-healing and also allows multi-hop routing of messages from any to any device in network.

Cluster-tree network is a form of peer-to-peer network. In peer-to-peer networks (e.g. cluster-tree network) one coordinator node acts as a root/parent (PAN) coordinator which initiates the network. The network forms a parent-child relationship. The root coordinator can initiate any new child coordinators to become the cluster head of new network [15].

![Network topologies](image)

**Figure 2.2b:** Network topologies
3 Related work

3.1 Research Area

As energy saving of wireless sensor network is one of the hot topics in the WSN field much research has already been done and more is expected. Much of the recent works has targeted a single factor influencing energy consumption of a network either at hardware or communication level. This project however has been done by identifying and collecting the most influential of the factors effecting energy efficiency in WSN.

To minimize the energy consumption of the entire network, analyses have been focused on the IEEE 802.15.4 using cluster-tree topology. Beacon-enabled structure was used and the result shows 73 µW for the transmission of data at 4 min intervals. In [35] 1560 nodes were used to form beacon-enabled cluster networks. Device and coordinators energy consumptions were evaluated separately. The result shows that BO and SO parameters affect the most on energy efficiency. [24] Has tried to configure MAC layer of 802.15.4 and examine the outcome in terms of performance and power management by using star network topology. They have suggested some configuration for the IEEE 802.15.4 standard and for the applications that used this standard. One of the suggestions they make is to allow GTS to the nodes associating with FFD.

In a typical wireless sensor network scenario paper [23] has determined minimum energy consumption. They have examined in the different phases of data transmission how much energy that is used.

3.2 Applications Field

The IEEE 802.15.4 and Zigbee have a wide range of applications, including industrial control and residential, personal health care, computer peripherals etc. One of the good points of the 802.15.4 and Zigbee is that applications are not limited to one specific market networks can be created from point to point networks.

In a usual home management case sensors provide the control of security systems, lighting and heating of any particular place in home from anywhere in the home. Consumers at both home and industrial level can reconfigure network to add more nodes.

Some of the applications described in the papers [21] are RF-Ultrasound Roboter Guidance, to determine position and control of mobile vehicle, DTOF localisation of IEEE 802.15.4 tags. The [33] paper described the importance of 802.15.4 for building automation applications were 802.15.4 protocols help in reducing energy consumption in building installation and in turn reducing overall energy cost.
3.3 Competing Standards and Technologies

In today’s market of wireless sensor networks where there is so much competition many technologies exist which have similar but not exactly the same goals.

3.3.1 Z-wave

The Z-wave was designed mainly for home applications and common commercial applications. It was developed by Zensys and later joins by the Z-Wave Alliance [9]. Applications like home lighting, home security, meter reading are already in use by many. In Europe where operating voltage is 220v, it is currently available from ACT but only later this year it is said to be available from others as well. Some of the features are as follows:

- Operates in the 900MHz ISM band.
- 30 m of range indoor
- Reliable and low cost
- Up to 232-device in a network

3.3.2 Bluetooth

Most popular all around the world for short-range communication is Bluetooth. Bluetooth is mainly used for computers, laptop PDA, mobile phones and headsets. Some of the features are as follows:

- Data and voice transmission simultaneously
- Data rate for version 1.2 1mbps and for 2.0 up to 3 mbps
- Operates between 10 to 100 meters
- Can penetrates solids objects
- Operates at 2.4GHZ band
- Cost Under $3
3.3.3 Xmesh

X-mesh belongs to one of the products developed by crossbow technology Inc. Unlike Bluetooth, X-mesh protocol supports both ad-hoc and multi-hop. This technology is very similar to Zigbee and designed for keeping in mind extension of network life.

3.3.4 Insteon

Insteon network protocol is developed mainly for home management and home applications purposes. It is one of the products of Smarthome™, Inc [26] and its main competitor is X10.

- Operates with both wires and on RF
- Nodes acts as repeaters
- Nodes per network up to 16,777,216
- Operates on 902- 924 MHz ISM Band
- Up to 10 messages per second
- Uses mesh topology
- Compatible with X10 devices
- Low power consumption
- Price starts from $19.9
4 Energy saving at Node Level

This chapter describes the basic components of wireless sensor node. Suggestions regarding the choice of node components and batteries have been made and the node architecture was studied in detail.

The methods in which energy savings can be affected or can be classified under two heads:

1. Device Level - Hardware component selection and their configuration to achieve low energy consumption in a wireless sensor node.
2. Network Level - Choice of communication methods and protocols to minimize energy consumption.

Overall Design

In a Sensor node there are four essential parts: processing unit, sensing unit, transceiver unit and, power unit. This part of Wireless sensor mote (WSM) is built on the Integrated Chip (IC). One needs to choose proper Peripheral of WSM and configure the entire network which will be more energy efficient. The basic diagram of wireless sensor mote is shown in figure 4a below.

![Figure 4a: The basic block diagram of the WSN](image-url)

Processing unit is a part of microcontroller unit which can read sensor data, perform some minimal computations and make a packet ready for transfer in the wireless communication channel. The local memory requirements will not be high and emphasis will be placed on the
modes of operation to facilitate low-power operation. The Communication module/unit is typically an RF transceiver that should support the 802.15.4. This unit helps in collecting information and to exchange or control data acquisition. The maximum amount of energy is used in communication module when compared to the two other modules. Sharing information between sensor nodes will consume more amount of energy than implementing the calculation within individual node. In Sensing unit, sensors are literally used for sensing temp, images, gas etc. Sensors to sense different things require different amount of energy, but to sense gas, sensors require more amount of energy than any other applications [40]. In Power unit, base stations are more often connected to main power supply, whereas nodes in the network depend on batteries to supply power. Hence there is a requirement to choose power efficient hardware and various efficient-operation modes to make the network more power efficient. Figure 4b reflects power consumption of WSN in various states.

![Figure 4b: Power consumption of sensor](image)

### 4.1 Node Architecture

The architecture of the node can be designed base on the following conditions:

- Criteria for component selection based on the end goal of energy saving
- A viable combination of components that satisfy the end criteria

A WSN node can be described in three parts, processor, sensor and power unit.
4.1.1 Processing unit

Basically the processor is built on the microcontroller which reads sensor data and makes the data ready for transfer. In other words, processor is a core module for the calculation in a wireless sensor node. This part of the node helps to control the task scheduling, to calculate energy, to define communication protocols, to make suitable coordination, and for data manipulation and data transfer. The processor is therefore the most important part, which is why it is necessary to choose a suitable energy-efficient processor for WSM. The power consumption of processor mainly depends on how long it supports sleep mode because sleep mode has a straight connection with the operation of node. The power consumption of node depends on operating voltage, duty-cycle internal logic and above all on efficient manufacture technology.

There are various microcontrollers available that are use for industrial purposes. Different microcontrollers are studied according to their key features, such as operating voltage, channel, RAM, Bits, Flash, and power consumptions (Idle, active and power down mode). Based on their different features and performances, microcontroller MSP430 comes out to be the more prominent choice. MSP430 is quite suitable for wireless sensor network due to its ultra-low power, high performance and its design for the minimum power (MSP430) for portable system. MSP430 has a RISC frame of 16 byte and integrates a large number of registers and data memories which provide good computational power and a full set of analog and digital processors. It has flash programming through a standard JTAG interface and RAM (10 KB) can participate in its operation. MSP430 microcontroller speed can be driven at 8 MHz with 125µs instruction cycle and the range of voltage is 1.8-3.6V. It has five energy-saving mode and a range of current consumption mode of only 0.1 to 400µA and 0.8µA in the waiting mode. A comparison of different microcontrollers is shown in the table 4.1a.
Energy saving at Node Level

Table 4.1a: Comparison of different microcontrollers [16] [17] [25]

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>ATMega 103L</th>
<th>MSP430 F149</th>
<th>AT90LS8535</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bit</td>
<td>8</td>
<td>16</td>
<td>8</td>
</tr>
<tr>
<td>Flash</td>
<td>0.125Kbyte</td>
<td>60Kbyte</td>
<td>8Kbyte</td>
</tr>
<tr>
<td>Ram</td>
<td>4KB</td>
<td>2KB</td>
<td>0.5KB</td>
</tr>
<tr>
<td>ADC</td>
<td>10bit</td>
<td>12bit</td>
<td>10 bit</td>
</tr>
<tr>
<td>Timer</td>
<td>3</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>Operating Voltage</td>
<td>2.7 – 3.6V</td>
<td>1.8 -3.6V</td>
<td>4-6V</td>
</tr>
<tr>
<td>Active Current</td>
<td>5.5mA</td>
<td>0.4mA</td>
<td>6.4 mA</td>
</tr>
<tr>
<td>Current In Power Idle Mode</td>
<td>1.6mA</td>
<td>0.0013mA</td>
<td>1.9mA</td>
</tr>
<tr>
<td>Current In Power Down Mode</td>
<td>&lt;1µA</td>
<td>&lt;0.1 µA</td>
<td>&lt;1µA</td>
</tr>
</tbody>
</table>

4.1.2 Radio and Transceiver

The Radio transmission and reception has proven to be the major energy consumer in the sensor network. In most of the sensor networks, energy conservation involves two methods to minimize communication overhead. Configuring MAC and networking layer is the first method for which the multi-hop communication nodes switch off their radios when they are not in use (Adaptive duty cycle). Data reduction and data aggregation is the second method where exploitation of the correlation in the data is achieved [4] to decrease the size of data and also the communication cost.

Radio needs to be active for longer periods in multi-hop communication more often where nodes send data to one or more base station. In multi-hop routing when node is not required, power conservation policy will switch off radio. However these nodes which are switched off will be unavailable for multi-hop communication and the network region where these nodes are present can become inaccessible by queries because of routing partition. Maintaining the communication stamina and enabling multi-hop routing while powering down radios of the nodes for conserving energy involves other techniques. ‘Wakeup on demand’: multiple radios in nodes are used in this scheme, low-power radio that is used
exclusively to ‘wake up’ the high-power radio when the need arises. In selecting radio one of the areas that need to be considered strongly is turn-off, turn-on time, which will have an effect on the overall system performance. A short time for the radio to go into sleep mode and to wake up from sleep mode is preferable while making the selection of the radio. Transceiver can be described as the combination of receiver and transmitter. Communication between nodes within the network and transfer of data between base stations to node, require a combination of transmitter and receiver.

The selection of different transceivers is made on the basis of their key features such as:

- Power consumption requirements
- Availability of modes to support low power operation
- Throughput
- Transmitted power, current in receiving/transmitting mode
- Ease of interface to microcontrollers
- Range etc.

<table>
<thead>
<tr>
<th>Characteristics</th>
<th>CC2420</th>
<th>XBee</th>
<th>AT86RF210</th>
</tr>
</thead>
<tbody>
<tr>
<td>Operating Voltage</td>
<td>2.1-3.6V</td>
<td>2.8-3.4V</td>
<td>1.8-3.6V</td>
</tr>
<tr>
<td>Transmitter Power</td>
<td>-24dbm</td>
<td>0dbm</td>
<td>6-12dbm</td>
</tr>
<tr>
<td>Current Transmit Mode</td>
<td>17.4mA</td>
<td>45mA</td>
<td></td>
</tr>
<tr>
<td>Current Receive Mode</td>
<td>18.8mA</td>
<td>50mA</td>
<td>14.5mA</td>
</tr>
<tr>
<td>Receiver Sensitivity</td>
<td>-95db</td>
<td>-92db</td>
<td>-95db</td>
</tr>
<tr>
<td>Throughput</td>
<td>250Kbps</td>
<td>250Kbps</td>
<td>20Kbps @868MHz</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>40Kbps@915MHz</td>
</tr>
<tr>
<td>Modulation Type</td>
<td>DSSS</td>
<td>DSSS</td>
<td>DSSS</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>BPSK</td>
</tr>
<tr>
<td>Carrier Frequency</td>
<td>2.4GHZ</td>
<td>2.4GHZ</td>
<td>850-930MHz</td>
</tr>
</tbody>
</table>

**Table 4.1b:** The comparison of XBee and CC2420 Transceiver shown in chart [18][19][20]
In the table 4.1b, we compared different transceivers and Ic’s like AT86RF210 [18] MC13193 Chipcons’s CC2420 [19] and Maxtream’s XBee [32] that supports IEEE 802.15.4. Most of the devices are fabricated using surface mount technology. However CC2420 RF-transceiver comes out as the better option due to low power requirements compared to others [19], because very swiftly it enters into the sleep mode when no communication occurs. In practice CC2420 is used for wireless sensor network to home and building automation, industrial monitoring and control systems. The CC2420 can also be fit for use in 2.4-GHz Zigbee products and based on Chipcons SmartRF 03 technology in 0.18µm CMOS which is highly integrated. The CC2420 also ensures effective reliable and long communication range. CC2420 provides high-level security by providing extensive hardware support for AES-128-based data encryption and data authentications as well as it supports burst transmission, clear channel assessment, link quality indication, timing information and it is very easy to interface with microcontroller.

4.1.3 Sensor

In reality sensor unit is the medium to communicate between the physical world and the conceptual world of processing unit. The sensor unit is one of the important parts of wireless sensor mode, it senses or detects the physical state of the atmosphere and sends the data to processor. Processor manipulates data and decides where it has to promote or else transmit the data to the base station.

Sensor converts energy from one form to another form. In reality sensor acts as a transducer where energy is converted into analog signal or digital signal. Sensor can be distinguished based on what kind of energy they detect or transfer to the system.

4.1.3.1 Optical and radiation sensors

- EOF (Electromagnetic time-of-flight) is an optical sensor normally named RADAR (Radio Detection and Ranging) and LIDAR (Light Detection and Ranging). It produces electromagnetic impulse and broadcast to the object, when impulse reflects back it measures time to return or bounce back of broadcast impulse.

- TOF (Light time –of –flight depth sensor) consists of modulation light source led or Laser, an array of pixel competent of sensing the phase of the incoming light, and an ordinary optical system for focusing the light onto the sensor. The time it takes to bounce back is proportional to the pulse

- (Distance α Pulse) and also related to the atmospheric density.
4.1.3.2 Thermal Energy

- Temperature sensors: Thermometers, Thermistors, thermostat and Bi-metal thermometers.

4.1.3.3 Mechanical sensors

- Pressure sensors: altimeter, barometer, barograph, pressure gauge.
- Gas and liquid flow sensors: flow sensor, anemometer, flow meter.
- Gas meter, water meter, mass flow sensor.
- Mechanical sensors: acceleration sensor, position sensor.

4.1.3.4 Acoustic sensors

- Sound sensors: hydrophones, seismometers, microphones

A wireless sensor node can be built with different types of sensor, and different types of sensor use different amounts of energy. Some of them require a considerable larger amount of energy than others. For example, gas sensors require a comparatively higher amount of energy than temperature sensors, pressure or image sensor because it requires active heating elements. Table 4.2a redrawn from [12] shows power requirement of different sensors. Image sensors also require a higher amount of energy because thousands of conversions (analog to digital) are required to produce images.

<table>
<thead>
<tr>
<th>Sensor Type</th>
<th>Power consumption</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gas sensor</td>
<td>500mW-800mW</td>
</tr>
<tr>
<td>Image Sensor</td>
<td>150mW</td>
</tr>
<tr>
<td>Pressure Sensor</td>
<td>10mW -15mW</td>
</tr>
<tr>
<td>Acceleration</td>
<td>3mW</td>
</tr>
<tr>
<td>Temperature</td>
<td>0.5mW- 5mW</td>
</tr>
</tbody>
</table>

*Table 4.1c: Power Consumption of different sensor [12]*
4.2 Low power mote

Table 4.2b and 4.2c shows power consumption of microcontroller and transceiver in active and sleep mode. Telos mote comes out as the best available option, which is ultra-low power wireless mote available in the market today developed by UC Berkeley. For the use in sensor network it comes with integrated temperature, light, humidity sensors and it has the ability to support a wide range of mesh network applications and it is IEEE 802.1.5.4 and Zigbee compliant.

Some of the key features are:

- Ultra low current consumption
- 250Kbps 2.5GHZ IEEE 802.15.4 chipcon wireless transceiver
- USB programming
- Fast wakeup time
- Msp430 microcontroller
- Antenna Integrated onboard

<table>
<thead>
<tr>
<th>Operation</th>
<th>Mica2</th>
<th>MicaZ</th>
<th>Telos</th>
</tr>
</thead>
<tbody>
<tr>
<td>Minimum voltage</td>
<td>2.7V</td>
<td>2.7V</td>
<td>1.8V</td>
</tr>
<tr>
<td>MCU idle (DCO on)</td>
<td>3.2 mA</td>
<td>3.2mA</td>
<td>54.5µA</td>
</tr>
<tr>
<td>Mote standby (RTC on)</td>
<td>19.0µA</td>
<td>27.0µA</td>
<td>5.1µA</td>
</tr>
<tr>
<td>MCU + Radio TX (0dBm)</td>
<td>25.4 mA</td>
<td>21.0mA</td>
<td>19.5 mA</td>
</tr>
<tr>
<td>MCU + Radio RX</td>
<td>15.1 mA</td>
<td>23.2mA</td>
<td>21.8 mA</td>
</tr>
<tr>
<td>MCU Active</td>
<td>8.0 mA</td>
<td>8.0mA</td>
<td>1.8 mA</td>
</tr>
<tr>
<td>MCU Wakeup</td>
<td>180µA</td>
<td>180µA</td>
<td>6µA</td>
</tr>
<tr>
<td>Radio Wakeup</td>
<td>1800µA</td>
<td>860µA</td>
<td>580µA</td>
</tr>
</tbody>
</table>

Table 4.2b: Comparison of different motes based on current consumption
## Energy Saving Methods in Wireless Sensor Networks

### Table 4.2c: Active and Sleep current of different microcontroller

<table>
<thead>
<tr>
<th>Manufacture Device</th>
<th>Active (mA)</th>
<th>Sleep (mA)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Atmel</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mega128</td>
<td>8</td>
<td>20</td>
</tr>
<tr>
<td>Mega165/325/645</td>
<td>2.5</td>
<td>2</td>
</tr>
<tr>
<td>Microchip</td>
<td></td>
<td></td>
</tr>
<tr>
<td>PIC Modem</td>
<td>2.2</td>
<td>1</td>
</tr>
<tr>
<td>Intel</td>
<td></td>
<td></td>
</tr>
<tr>
<td>8051</td>
<td>45</td>
<td>10</td>
</tr>
<tr>
<td>Motorola</td>
<td></td>
<td></td>
</tr>
<tr>
<td>HC808</td>
<td>6.5</td>
<td>1</td>
</tr>
<tr>
<td>Texas Instrument</td>
<td></td>
<td></td>
</tr>
<tr>
<td>MSP430 14x 16 bit</td>
<td>1.5</td>
<td>1</td>
</tr>
<tr>
<td>MSP430 16x 16 bit</td>
<td>2</td>
<td>1</td>
</tr>
</tbody>
</table>

Table 4.2c: Active and Sleep current of different microcontroller
4.3 Battery

Generally sensor nodes are designed to run on ordinary AA batteries. It is vital to approximate the power consumption needs of the sensor node. Appropriate selection in the design phase of the transceiver and microcontroller will make sure that the hardware platform on which the sensor node is built is power conscious, and this will be useful in managing the power of the system.

We can differentiate batteries in two categories, chargeable and rechargeable. It can be also compare according to their different properties like,

- Electro material (such as NiCd, AgZn, NiMH etc).
- Capacity (how much mile-amp-hours (mAh) of current the cell can store.)

<table>
<thead>
<tr>
<th>Microcontroller</th>
<th>ATmega163 (Rene2,Dot)</th>
<th>ATmega128 (Mica2)</th>
<th>TI MSP430 (Telos)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Program memory(KB)</td>
<td>16</td>
<td>128</td>
<td>48</td>
</tr>
<tr>
<td>RAM(KB)</td>
<td>1</td>
<td>4</td>
<td>10</td>
</tr>
<tr>
<td>Active power(mW)</td>
<td>15</td>
<td>33</td>
<td>3</td>
</tr>
<tr>
<td>Sleep Power (µW)</td>
<td>45</td>
<td>75</td>
<td>15</td>
</tr>
<tr>
<td>Wakeup Time(µs)</td>
<td>36</td>
<td>180</td>
<td>6</td>
</tr>
<tr>
<td>Radio</td>
<td>TR100</td>
<td>CC1000</td>
<td>CC2420</td>
</tr>
<tr>
<td>Data rate</td>
<td>40</td>
<td>38.4</td>
<td>250</td>
</tr>
<tr>
<td>Modulation</td>
<td>OOK</td>
<td>FSK</td>
<td>O-QPSK</td>
</tr>
<tr>
<td>Receive Power(mW)</td>
<td>9</td>
<td>29</td>
<td>38</td>
</tr>
<tr>
<td>Transmit Power at 0dbm</td>
<td>36</td>
<td>42</td>
<td>35</td>
</tr>
<tr>
<td>Minimum Operation(V)</td>
<td>2.7</td>
<td>2.7</td>
<td>1.8</td>
</tr>
<tr>
<td>Total Active Power(mW)</td>
<td>24</td>
<td>44</td>
<td>41</td>
</tr>
</tbody>
</table>

Table 4.2d: Comparison chart of microcontroller and radio
• Energy density (how much energy can be store in the cell per unit volume).
• Battery Mechanical Specifications.
• Battery Environmental Specifications.

There are many commercial batteries available in the market. However it is preferable that batteries are chosen by the three approaches described in [46] developed at the University of Michigan by K: A Cook and A.M Shastry.

1. Specification of a single, aggregate power supply, resulting in a single battery electrochemistry and cell size.
2. Specification of several power supplies, by a priori division of power sources by power range.
3. Specification of an arbitrary number of power “bundles”, based on available space in the device.

This approach helps to select the commercial batteries that are available in the market. A comparison of different commercial batteries is shown in the table 4.3a.
<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Alkaline</th>
<th>Alkaline</th>
<th>Alkaline</th>
<th>Nickel-Cadmium</th>
<th>Alkaline</th>
</tr>
</thead>
<tbody>
<tr>
<td>Manufacturer</td>
<td>Panasonic</td>
<td>Duracell</td>
<td>Maxell</td>
<td>Panasonic</td>
<td>Energizer</td>
</tr>
<tr>
<td>Volume</td>
<td>55.9ml</td>
<td>23ml</td>
<td>8.34ml</td>
<td>23ml</td>
<td>8.34ml</td>
</tr>
<tr>
<td>Voltage</td>
<td>1.5V</td>
<td>9V</td>
<td>3.6V</td>
<td>1.2V</td>
<td>1.2V</td>
</tr>
<tr>
<td>Capacity</td>
<td>2.4Ah</td>
<td>280Ah</td>
<td>1.8 Ah</td>
<td>1.08Ah</td>
<td>2.3Ah</td>
</tr>
<tr>
<td>Gravimetric Density</td>
<td>106</td>
<td>56</td>
<td>102.22</td>
<td>102.22</td>
<td></td>
</tr>
<tr>
<td>(Wh/Kg)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Energy Density</td>
<td>3.5</td>
<td>5.22</td>
<td>1.296</td>
<td>3.3</td>
<td></td>
</tr>
<tr>
<td>(Wh)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Weight</td>
<td>141g</td>
<td>49g</td>
<td>10g</td>
<td>23g</td>
<td>27g</td>
</tr>
<tr>
<td>Rechargeable</td>
<td>No</td>
<td>No</td>
<td>no</td>
<td>Yes</td>
<td>no</td>
</tr>
</tbody>
</table>

**Table 4.33a:** Comparison of different AA Batteries
Table 4.3b: The diagram shows how much Energy Require for WSM.

If the Sampling period or duty cycle is 1 % using TDMA or Low power listing then,

Average drain current = 0.1*(active current) + 0.99*(sleep current)  
Lifetime = capacity / Average Drain current

The life time of MicaZ and Telos wireless sensor motes are shown on the next page.
In some cases battery life can be increase by reducing duty cycle, like if WSM read the data every 3 minute it means that if the duty cycle is 0.5% then same battery will give more life time. The comparison shown in table 4.3c and table 4.3d where vertical axis represents number of days and horizontal axis represent motes.

**Table 4.34.3c:** Life time of MicaZ and Telos wireless sensor motes when duty Cycle is 1

Additionally in the application code which runs in the node, concern should be given to reduce battery drain. The subsequent portion of the flow chart below shows an example of sensor node application. The program polls a sensor and spreads this information to its neighbour if it exceeds a confident significant value.

**Table 4.33d:** Life time of MicaZ and Telos wireless sensor motes when duty Cycle is 0.5
Cycle duration arbitrates the length of the sleep stage. In the meantime the value of threshold has an impact on the amount of network transmissions. These two have an impact on the energy consumption and the equivalent battery lifetime of a node running this simple application. Under different duty cycles the energy consumption of the application can be calculated or derived from simulation. On the other hand before the node is deployed and sensor readings are available the impact of the second parameter on battery lifetime is not recognized.

**Figure 4.3e:** Flow chart show as exemplary sensor node application.
The application could obtain its energy descriptions at run-time and if required be adapted (by itself or one more node). In the instance above, one of the two parameters from thresholds and cycle period can be altered in case where the system lifetime does not reached the expected target. Consequently, the application has to be attentive of its energy consumption. To reconfigure a running system its energy descriptions have to be recognized. The energy descriptions constitute the capacity of the battery and the amount of energy consumption. By monitoring state changes and the incidence of exact events, the energy consumption can be approximated on-line. Environment state also influences system lifetime. An order from a battery sensor can be used to adjust lifetime judgments based on the accounted energy.

It is possible to store the discharge characteristics on the node, resulting in a more precise lifetime. If the discharge characteristics could be approximated the expansion of a battery model would be more feasible.

### 4.4 Conclusion

This chapter has dealt with the evaluation of sensor node architecture in minute details followed by the energy requirements of processor and transceiver has been compared. Power is defined as the rate at which energy is transferred. Most of the evidence provided in the chapter are based on the term power consumption of components rather than energy due to the fact that majority of the data sheets provided by manufactures are power related. Different microcontrollers and transceivers from different manufacturer have been studied. Functions like active power, sleep power, wakeup time, transmit power and receive power of various microcontroller and transceiver have been highlighted which makes Msp40 microcontroller and CC240 transceiver to be the most efficient ones compared to others due to their power requirements. Finally the battery selection was described according to cook & shastry method.
5 Energy Efficient MAC Protocols

Medium Access Control (MAC) synchronizes the channel access in an environment where numerous nodes access a shared communication medium. The MAC Layer provides an interface between the data-link layer and the PHY layer. Furthermore it can handle data service and MAC management service like generating networks beacons if the device is a coordinator, as well as GTS allocation and synchronizing to the beacons which is important for data polling and energy saving purposes. The MAC layer has a major role in making the network more power-efficient. Basically MAC is responsible for the coordination between neighbours. MAC protocol must not only be an energy constrain protocol but should also be able to address scalability issues (handling dynamic changing topology of WSNs, unaffected by node density etc) and take into account the timing constraints of the applications. For example, some applications are more time-sensitive such as military, fire alarm etc and other applications might be more demanding in terms of network lifetime such as environment monitoring. A large amount of energy can be saved at this layer. Some of the causes behind energy wastage in wireless sensor networks related to this layer are mentioned in the short description below.

Collision

Once a collision of packets occurs there is re-transmission of the collided packets that were discarded, resulting in wastage of energy due to re-transmission. This can be saved by avoiding collisions in the first place resulting in conserving network energy.

Idle listening

In contention-based MAC protocols when nodes are neither transmitting nor receiving data, channel tries to sense data in which results in the wastage of energy.

Control-packet overhead

The number of control-packet should be reduced to save energy since the transmission, reception and listening of these packets will result in energy consumption.

Overhearing

When node receives a packet which is addressed to some other node, overhearing occurs. This takes place during high traffic loads. Overhearing unwanted packets is wastage of energy.
All these factors must be taken into account by an energy aware MAC protocol in order to minimize the energy wastage in WSN. In this chapter MAC protocols are categorized into two types: contention-based and contention-free protocols. In this section, we will discuss and group different approaches of MAC protocols which were developed for wireless sensor networks and we will also compare these solutions with the 802.15.4.

5.1 Contention free protocols

Many nodes are present in sensor network, and they are most likely distributed in non-uniform direction. When two sensor nodes attempt to access the communication channel at the same time, contention occurs. Due to contention messages could collide when traffic is frequent. As a result collision has an effect on the network life time of a sensor network A MAC protocol is believed to be contention-free if it does not allow collision. All accessible contention free MAC protocol assumes that the sensor nodes are time-synchronized in some way. In contention-free protocols, the channel is most often divided into time slots. To send the data, each node uses the time slot and thus it provides collision free communication.

5.1.1 Slot-based protocols

The main idea of this protocol [47] is that the time is divided into periods which has a certain number of fixed slots, where some active slot are assigned to keep the nodes active, send the beacons to neighbours’ and to listen for message acknowledgement or listen to requests from neighbour nodes. In slot-based protocol, beacon helps to communicate with any two nodes of a network. Figure 5.1a demonstrate that time is divided in seven periods. Any two neighbours can eventually hear each other if they use an 1101000 activation schedule since they always have at least one overlapping slot.

![Figure 5.1a: If they use a 1101000 activation schedule any two neighbours can eventually hear each other [34]](image-url)
Schedule of the form 1101000 where 1 stand for active stage and 0 for inactive. Nodes are first communicated with each other through beacons and wait for one of them propel data to neighbours. There are no pre-defined activation schedules for slots. But it has been already proved that the number of active slots is \( k \), then \( k = \mu + 1 \), where \( k \) stand for active slots, \( \mu \) for number of overlapping and \( \mu \) is prime number, as a result if \( \mu = 1 \)(minimum overlapping) and number of slots in the period is \( t \) then active schedule exits for \( t = \mu^2 + \mu + 1 \), if number of overlapping is increased then latency will be less, whereas as energy consumption will be high.

5.1.2 Time Division Multiple Access (TDMA) protocols

TDMA is a channel access method that is used to share a radio link. In this technology, different users can share the same frequency channel by dividing the signal into different time slots. Idle listening can be avoided by using TDMA protocol and MAC layer contention issue can be fixed by scheduling transmissions earlier, so that the nodes can have information in advance when the radio should be turned on and doing so they can stay away from collision. Figure 5.1b shows time slot scheme in TDMA protocol where time is organized as sections of signalling slots and transmission slots. In classical TDMA protocols all the nodes can see each other while master node initiates the super frame in specific time interval for network operation. This technology is most suitable for single hop but for multi-hop it is very difficult for multiple simultaneous transmissions.

One of the energy efficiency TDMA protocol is Traffic-Adaptive Medium Access (TRAMA) [58] that was developed based on Node Activation Multiple Access (NAMA) [45] for WSN. In that proposal, time is divided into time slot and each node’s channel access is organized over a fraction of time. In this mechanism each node has information of other two hop neighbourhood and transmits data freely without interferences according to their winning slots, which mean the neighbours who have highest precedence according to their slot number and node ID. TRAMA assume low data rate compared to the time slot. Random access periods are used for time synchronization to exchange the information of the neighbours. First hop neighbourhood information is broadcast in contention-based slots but the actual data transfer takes place according to a contention-free schedule.

To make this protocol energy efficient, TRAMA change nodes to sleep state whenever possible and attempt to reuse transmission slot which are not use in transmission. It is quite possible when one selected node allow his transmission slot to be used by another node if it does not have any packet to send. To make use of low power, idle mode and reuse the transmission slot nodes can share existing traffic with their neighbours.
Contention based

In contention-based protocols, a given transmit chance towards a receiver node can in principle be taken by any of its neighbours. If two or more neighbours try their luck at the same time, they have to compete with each other. In this case a collision might occur, wasting energy for both transmitter and receiver. In Contention-based protocol, stress is made on minimizing collisions rather than avoiding it completely (Schedule-based or collision free protocols). In this technology all node shared single radio channel according to their demand. To reduce the probability of collision or to avoid collision distributed algorithm is used which allocates the channel between nodes. Distributed MAC protocols which are mostly contention-based uses a carrier sensing or collision-avoidance mechanism [60] known as CSMA (carrier sensing multiple access). In this mechanism nodes listen to the channel before sending a message just to ensure that channel status is free before transmission. If all channel are busy then node continuously listen until the medium is free to send data.

However a CSMA-based protocol in multi-hop wireless networks guides towards hidden node problem. Due to insufficient radio coverage such as in figure 5.1c, node n1 is not able to talk directly to node n2, n1 then tries to send data to its immediate neighbour R but node n2 will be unaware about this transmission and in the mean time n2 can also initiate to send data to R. As a result collision will occur on the receiving node R.
To handle this problem additional signalling control messages have been proposed. One of them is out of bound signalling which relies on sending busy tone when transmission is in progress hence preventing other nodes from initiating transmissions. This system is known as Busy Tone Multiple Access [60] which eradicates the hidden terminal problem. Busy tone radio is cheaper than other methods and consumes less power.

5.2.1 Sensor MAC (S-MAC)

S-MAC supports multi-hop operation. Its key features are:

- Periodic listen and sleep
- Collision avoidance
- Overhearing avoidance
- Fixed duty cycle

Sensor MAC (S-MAC) [40] uses three new procedures to decrease energy consumption and support self-configuration. It is a contention-based protocol with low duty cycle. For S-MAC, energy consumption in idle listening is to be reduced by allowing neighbouring nodes of transceiver and receiver to sleep periodically during transmission, by doing so this scheme put nodes into low duty cycle. Fig 5.2 reflects SMAC listen sleep schedule. S-MAC is based on contention. Periodically sleeping is good in low traffic cases. If a node can sleep for longer time it consumes less energy. For example, if the duty cycle is trimmed down to 50%, it means that for each second a node can sleep half a second and be active for the other half, which results in 50% of energy reduction. The S-MAC approach is to split a long message into small parts and send them out in bursts. Nodes in the S-MAC exchange their sleeping schedule and before going to sleep nodes broadcast their schedule to their neighbours as a SYNC packet. Nodes listen to this sync message and follow it. If they do not get the sync message they make their own schedule. If the new scheduler is not used to the neighbour’s nodes, it can be discarded. If two nodes want to talk, the sender first will use single RTS (request to send). When it is received by another node it replies with CTS (clear to send). All the nodes will again go back to sleep mode cycle once the transmission is completed.
5.2.2 Time Out MAC (T-MAC)

The problem with S-MAC protocol is the idle listening time and also the fact that it has a fixed duty cycle. This makes S-MAC unsuitable for varying traffic load. When there is low traffic, a duty cycle wastes large amount of energy which are made or tuned for handling high traffic load. Similarly under high traffic conditions a duty cycle which is made for low traffic load will decrease the throughputs. Hence, an elaboration based on S-MAC, T-MAC has been developed to fix the problem by using adaptive duty cycle. If there is no movement or no event in the neighbours, the node goes to sleep. Apparently T-MAC has the same role as S-MAC under steady traffic, but it is more power-consuming in variable traffic.

**Figure 5.2a:** T-MAC has variable active windows while S-MAC has fixed active windows

S-MAC has fixed active windows while T-MAC has variable active windows that extend as long as messages are received or other activation events occur.
5.2.3 Dynamic Sensor MAC (DS-MAC)

Dynamic sensor MAC protocol is based on SMAC. In heavy traffic load nodes can use dynamic duty cycle [41]. When interval is too large in heavy traffic then SYNC and data message helps node to increase duty cycle and vice versa in case the traffic is low. In DS-MAC, duty cycles are included in the SYNC message that they transmit. To measure the traffic condition each source calculates the queuing delay from message reception to transmission completion and inserts this to an additional field for upcoming data message. In DSMAC SYNC message updates the schedule and then nodes updates their schedule itself and shared equally with period, which helps to decrease latency over heavy traffic. Figure 5.2b shows a DSMAC frame where the sensor node has a duty cycle twice the normal value.

![S-MAC Frame Format](image)

*Figure 5.2b: DSMAC Frame Format*
5.2.4 Dynamic Mac (D-MAC)

Dynamic Mac protocol (D-MAC) works like S-MAC but it adequately manages active/sleep duty cycles and provides real time guarantees. When sending data in multi-hop, sinks are not alerted by the nodes that the data delivery is in progress. Hence some nodes are unaware about this transmission and as a result interruption occurs, which makes sleep delay. As can be seen in figure 5.2d, D-Mac is based on a data gathering tree and a systematic wake-up scheme. Targeted to achieve both energy efficiency and low latency, D-MAC is estimated to give out data along the data gathering tree. In D-MAC nodes wake up sequentially like a chain reaction and synchronize assignments of time slots on different nodes.

![Figure 5.2b: Data gathering and DMAC Implementation](image)

In D-MAC, time interval is divided into sections. Receiving, sending and sleep period. In the receive mode, a node receives a data packet and sends an acknowledgement to the receiver. In the sending period, a node forwards data to the next hop, receives an ACK and the radio will be turned off when the child node does not have any work to do which actually helps to reduce power consumption.
5.3 Other approaches at MAC Level

Data channel and separate signal channel mechanism can help to make the entire network more energy efficient. Data channel can only be used for sending data, manipulate some control message and will be turned on only when it is required. On the other hand, a signal channel will be used only for wakeup notification and it is characterized by a fixed low-duty cycle. This new topology management scheme is called as Sparse Topology and Energy Management (STEM) [59].

STEM is two-radio architecture. When node wants to share data with other node in STEM-B, it broadcasts beacons containing the address of the destination until it receives an acknowledgement and then the radio can be used to send data. In the STEM-T method, nodes are continuously sending a busy tone on the signalling channel so that neighbours node can wake up and get ready to receive original data from the data channel. The STEM-T method will be inefficient in dense network where one of the neighbours will turn off their radio again. In contrast busy tone radio is cheaper and consumes less power. To improve on STEM-T it is suggested that [39] outgoing messages may get buffered by the sender and once the queue for a given destination rises beyond a certain limit, the wakeup procedure will be started and in addition, many attempts will be made by sender to send data at regular intervals. This mean at the expected transmission time receiver automatically gets wakeup and listen to the data radio for a short interval hence saving the energy of the wakeup signal.

![Figure 5.3a: Separate data wakeup using two radios](image-url)
5.4 IEEE 802.15.4 energy efficiency

The IEEE 802.15.4 protocol supports many features with MAC sub layer of the IEEE 802.11 protocol like CSMA-CA (Carrier Sense Multiple Access / Contention Avoidance). To acquire a desired data rate and maximum life time for every sensor node, it is needed to get fix essential features that can make this technology more power efficient. The Mac protocol support slotted CSMA/CA and unslotted CSMA/CA two operational models. Research [51] on “Effective capacity of IEEE 802.15.4 beaconless (unslotted) mode” shows that CSMA-CA design which is used in IEEE 802.15.4, but request to send (RTS) or clear to send (CTS) mechanism are not involve in 802.15.4 like 802.11. In multi-hop data transmission unslotted CSMA–CA has hidden node problem but in performance, unslotted CSMA-CA is better than Slotted CSMA-CA due to its scalability, its ability to self organize and the fact that it can use higher channel.

In multi-hop data transmission there is problem of hidden nodes [34]. Conflicts occur when two transmissions happens at the same time and the receiver is unable to avoid the collision because they cannot see each other. This hidden node problem (HNP) can be solved by using “Group strategy” [36]. The proposed strategy for 802.15.4 LR-WPAN consists of four stages, first is the hidden node discover, second is the hidden nodes relation, and third is the grouping and finally bandwidth allocation of the node. Nodes are divided into groups and contain information from each other. In addition nodes are assigned a guaranteed time slot which help to access the channel using CSMA-CA. Another way to avoid HNP is Busy-Tone Multiple Accesses (BTMA) where node throw a busy tone out of communication frequency bands in order to hear an on-going transmission so that other nodes do not initiate their transmission.

In non beacon enable mode, device can just send data using unslotted CSMA-CA mechanism. This Mechanism does not have a power-saving technique and there is no use of superframe structure and no time agreement between nodes that packet will go to a proper destination at a specific time. In beacon enable mode, which is slotted CSMA-CA mechanism, In beacon enable mode (slotted CSMA-CA mechanism) PAN is associated with the super frame, but these mechanisms are only suitable for master-slave star topology. In this technique node can sleep periodically and send data in a better time plan. Duty cycle is one of the other factors influencing network lifetime. In order to make energy efficient networks, the low duty cycle of this system can be considered which is to keep the radio turned off for a maximum amount of time, allowing it to be switched on only when required.

If node sleeps unnecessarily in slotted CSMA-CA, there will be a problem in sending data periodically, this problem is called contention-inherited sleep delay (CSD) [50]. Due to this problem node fails to grab the sink node because all network traffic surrounds it. If nodes go to several sleep periods that will make delay in packet transmission on the way to sink node.
To ease this difficulty the packet’s main concern is to temporary separate medium access by diverse groups of nodes according to the priority of the related packets’ priority [50]. In this mechanism node can access medium through “pseudo” time division multiple access. Consequently every group of nodes end up experiencing less contention and helps to reduce the probability of contention-inherited sleep delay. The sort of the packet is the strict priority-based type so that high-priority packet can be provided bounded delay and packet can be delivered to the sink node within suitable delay.

In WSNs modulation scheme are designed to reduce noise, congestion, unlawful detection and interference. There are two modulation schemes: the Frequency Hopping Spread Spectrum (FHSS) and the Direct Sequence Spread Spectrum (DSSS). This network (IEEE 802.15.4) is used specially in hostile environments and thus the DSSS modulation scheme is used for narrow band interface. For interface into the wider channel filters and for greater channel spacing, on the other hand, less time is required [52].

The transceivers active power is often less significant than receiver active power in low power systems, due to the large number of active signal processing circuits in the receivers. In star network when no packet is receiving or transmitting, node literally does not have to do anything and on that instance in beacon enable mode the transceiver is completely switched off 15 out of 16 times. However, it remains connected with the network which means that it can perform and is able to send/receive data anytime [50]. As soon as beacon transmission ends, the beacon-enabled mode contention procedure starts to set up a major overhead in energy consumption. LR-WPAN is developed for low data rate applications and therefore contention access will be the sensible choice for energy saving and random back off periods help to avoid collision. In CSMA-CA in contrast, frequent collision occurs due to short back off period (default). In this mechanism collision and back off period are exponentially increased and it can be power efficient due to monitoring procedure when duty cycle is low. In IEEE 802.15.4 the range of the back-off exponent is 0-2 and this helps to reduce duty cycle in low traffic.

In dense networks, the area probability of collision is higher. In [23] the author justifies a scenario (1600 nodes are uniformly distributed) where it is estimated how much energy is required for different size of data packet at a time transmission in rate of 1 byte every 8ms per node over a single hop. In fact that small packet increases the energy per bit because they require more transmission than large packets and also use the same Mac overhead. In the case of large packets, on the other hand, the probability of transmission failure is higher than for small packets and therefore it requires frequent retransmission. In IEEE 802.15.4, the maximum allowed payload packet size is 123 byte and energy per bit decreases monotonically with the packet. Allowing bigger packets would result in additional energy efficiency expansion, but the cost will be the amplified latency. In scenario [56] it has been revealed that for data transmission, 50% of energy is used and in the event of contention, the procedure energy consumed is up to 25%. For waiting and acknowledgement, 15% and 20%
is used for listening to the beacon. The reason for this is the multiplicative outcome of the
CSMA-CA system to the transceiver start-up energy. When doing clear channel assessment,
the overhead of the contention is largely owed to the receiver start-up energy. When waiting
for an acknowledgment, the receiver power consumption leads to acknowledgement
overhead.

Periodically data sending to proper destination is essential than energy saving. For real time
performance time slot GTS protocol is a good choice in low rate WPAN. This method
allocates or de allocate time slot in a super frame and offers expected service guarantees. The
basic ideas of GTS allocation and Time Division Multiple Access (TDMA) are almost
similar in terms of time slot allocation. Periodically data flow is arranged in the reserved
amount of bandwidth and it is determined by the duration of the time slot. But GTS duration
can dynamically adjust (what) by means of some parameters and thus GTS method is better
and more flexible than classic TDMA. GTS mechanism was examined in [35] with respect
to cluster modelling and throughput metrics.

5.5 Conclusion

In this section, we have described different protocol for wireless sensor networks and have
reviewed some proposed MAC protocol to make the network more power efficient. We also
talk about drawback and benefit of each method. Form this section it can be said that there is
no complete protocol solution for wireless sensor network because different application of
WSN has different requirements. For example, in environment monitoring application such
as checking pressure, temperature, humidity etc, where the use of power is more sensitive to
make network more energy efficient as well as to extend network lifetime in that case
802.15.4 will be the better choice but no real-time guarantees are assured in such an
application.

802.15.4 in [61] shows the best performance compare to SMAC and other protocols, the
reason for this is that it does not send RTS/CTS mechanism and thus reduces the energy
consumption of the MAC layer control packet. When traffic load is high RTS/CTS overhead
is proved to be useful but for low data rate application for which 802.15.4 is designed
RTS/CTS overhead could prove too expensive. S-MAC has low packet delivery ratio due to
adaptive sleeping mechanism, but delay is increased when traffic is high because one node
has to wait for others to receive data and latency is also low for periodic sleeping where as in
802.15.4 average packet delay is small. For low data rate 802.15.4 has much lower energy
consumption as the design of 802.15.4 is for low data rate wireless personal area network
where as S-MAC is designed for low rate and low cost wireless sensor networks and for
application such as environment monitoring.
However the performance of the IEEE 802.15.4 protocol is quite satisfactory in large WSN application. It is quite flexible than other protocol for example parameters can be adjusted easily to fulfill their application requirements and also beacon order and super frame order can be adjust dynamically either to make more energy efficient (lower duty cycle) or to shrink communication latencies (higher duty cycle). In IEEE 802.15.4 Mac layer duty cycle scheduling has been proven an efficient approach to make energy efficient network. From research world to industrial application the release of IEEE 802.15.4 has been a major landmark in the evolution of wireless sensor network.
6 Energy saving at Network Level

The network layer is accountable for routing information through the sensor network, which finds the most efficient lane for the packet to travel on its way to a specific destination. This chapter deals with energy-saving methods at network level, the choice of data routing in the network and different protocols which will results in less energy consumption in the network.

In minimizing the overall power consumption of the network, the data routing algorithm plays an important role. It is not necessary that the shortest route is taken for it to be the best option from an energy perspective. Information about the remaining batteries’ life is important and useful input for the routing algorithm. This information can be self-computed by individual nodes and broadcasted over the network for the other nodes so that the best available routing path can be chosen.

Sensor nodes are assumed to be stationary in most of the network architecture. If not it is more challenging to route messages between moving nodes depending on the application: the sense event can be dynamic or static. Traffic is generated only when reporting has to be done in static events; on the other hand most application periodic reporting is required in dynamic events, resulting in the generation of significant traffic that has to be routed to the base station.

One of the factors that affect the performance of routing protocols is the deployment of sensor nodes, which is either deterministic or self-organising. Nodes are randomly scattered creating an infrastructure in an ad-hoc manner [47]. The position of cluster head and base station is also important in terms of energy efficiency, considering the fact that nodes are not placed in a uniform manner. The position of sensor nodes and data routing is pre planned in deterministic situations. Sensor nodes are placed randomly over an area of interest in most of the applications. Energy consumption has a huge impact on the setting up the routes while creating the network infrastructure. For wireless radio transmission, power is proportional to distance square or even to higher order [48].

Data transmission: The transmission of data depends on the application, i.e. it varies from application to application; it can be of any of the following types:

- Continuous-Periodical transmission of data from each sensor node to base station
- Event driven (query driven) - whenever there is an occurrence of event or query by the base station the transmission of data is started.
• Hybrid – the combination of both the above-mention cases [45] included in some networks.

Choice of communication methods: Typically the data that needs to be transferred on a wireless sensor network is non-periodic in nature. For example, if a wireless sensor network is used for monitoring of the environment, each node might have sensors to sense parameters such as temperature, humidity and atmospheric pressure. Often these parameters do not need to be transmitted at a periodic rate. It is only when the parameter value exceeds the define limit that the values need to be transmitted. A good understanding of the application requirement will help in the proper choice of communication methods and protocols. Two types of communication strategies can be considered here.

1. Periodic transmit/receive at a fixed period
2. Event based transmit/receive

Periodic/transmit receive strategy: The following combinations can be tried out

• The microcontroller and the RF module in Active mode. In this combination, data transfer will be guaranteed but at the expense of high power consumption.

• The microcontroller and RF module in Sleep mode: but with event-based wake up. The issue here is to find a way to synchronize the wake-up times of the WSN node and the base station.

Event based transmit/receive strategy: The microcontroller will always be in Active mode and the RF module will be in sleep mode. In the occurrence of an event (limited checking can be done in the microcontroller to trigger an event) the microcontroller can wake up the RF module to transmit data from the WSN node to the base station.

Data aggregation: There is always a possibility of having redundant data in network; these similar data types from different sensors can be aggregated by using functions such as suppression, min, max and average [43] to reduce the number of transmissions thereby reducing energy. Data fusion is similar in the sense that it maintains the signal processing technique.

Minimisation of energy consumption, routing protocol and data transmission are co-related which means that each influences the other. For continuous transmission a hierarchical routing protocol is an efficient choice [46] due to the presence of redundant data, which can be routed after aggregation to the base station resulting in reduced traffic and energy [44]. Cluster head handles the aggregation of data and the transmission of data to base station and
is therefore required to be more powerful than other sensor nodes in a network. A diverse set of sensors may be required by some applications and routing in this type becomes more challenging due to the possibility that sensor reading can be at a different rate.

A diffusion-based routing algorithm can be configured on the assumption of each node’s location geographically, which favours nodes with low battery life. A value can be assigned and the limit of life of the nodes within that value are only included for the routing process; others are excluded. Those which are excluded will be saving power by not taking further action in the process of passing messages from other nodes. Battery life is extended by the transmission of self-generated messages.

6.1 Basic Routing Protocols

Direct: In the direct protocol, data is send directly to base station by each individual sensor in the network. Hence if the base station is close to nodes in the system where this protocol is in used, the energy required for transmission is less. In some applications, such as if the base station is line-power supplied and the receiving data requires large amounts of energy, this protocol is quite sufficient. However, if the above-mentioned conditions are not present and base station is far away from nodes, the transmission power requirement increases and nodes could be drain from power quickly.

Minimum-energy routing protocol: In minimum-energy routing protocol nodes in a network act as a router for other nodes. Transmission to the base station from one node occurs through intermediate nodes. The energy dissipation of the receiver is neglected in some of the protocol [7] and only transmitter energy is taken. The selection of midway nodes is completed in such a manner that transmission energy is minimized. It has been discussed whether this routing protocol perhaps consumes more energy than direct routing algorithm. That is, the energy consumed by each neighbour in order to receive and then transmit data could result in the total energy consumption to be higher.

Self-organizing protocols: The heterogeneous sensors types’ architecture that are stationary or mobile forwards the messages to a set of nodes which acts as routers. These nodes are stationary and are the most important part of the communication. Messages collected are forwarded by these nodes which act as routers to the sink nodes which are more powerful. Router nodes are in range with each sensing nodes that is important to them to involve in the network. This protocol is described in [42].
6.2 Hierarchical protocols

Clustering: In these schemes, nodes in the network form cluster, one node act as a local base station and data is send to this node which then forward the data to the main base station. The local base station will be nearer to all nodes in the cluster, hence reducing the distance of transmission.

6.2.1 LEACH –Low Energy Adaptation Clustering Hierarchy

LEACH is very similar to clustering protocol where nodes formed into cluster in the network. In this hierarchy, one node act as a local base station. Nodes within that cluster will send data to this node, which then transfers data to the main base station. The biggest advantage of this self-organized scheme is the rotation of the local base station nodes. If a low power node is chosen as a local base station, however, there are chances that it will die, making the system unstable. Hence, cluster head nodes (local base station) are chosen depending on their power level and if the chosen node is drained of energy, a different node in that cluster is given the job of cluster head, depending on its energy level. These way nodes are maintained in one standard-energy level. Once the selection of cluster heads is completed in the network the cluster heads transmit their status to each node in the network. After having received this information, nodes in the network decide to which cluster it wants to join, considering which cluster head will be the best for minimum communication energy. After the formation of cluster, each local base station send schedule to the nodes within that cluster allowing the radio of all nodes to be switched on only at the time of transmission. At all other times, the radio of those nodes will be off, thus making this protocol energy efficient. The data from all the sensor nodes in that cluster is transmitted to their local base station and on receiving this data the local base station collects and forwards the data to the main base station. LEACH not only reduces the distance of transmission for the local nodes but it also compresses the data that is sent from the local base station to main base station through data fusion.

PEGASIS (Power Efficient Gathering in Sensor Information System) is an improvement over LEACH. It is chain–based protocol where cluster heads are chosen randomly which means that nodes will die throughout the network in a random fashion. Hence density is maintained stable throughout the network. Node communication is only possible between close neighbours. A chain is formed which starts from the cluster head, the information of network topology is assumed to be known by PEGASIS and the chain is constructed by the use of a greedy algorithm.
6.2.2 Energy-aware routing for cluster based sensor networks

Based on three tier architecture a hierarchical routing algorithm was proposed by Younis [44]. In the beginning itself cluster of sensors are made and in this algorithm cluster heads are named as gateways, which carries information about the location of each node. Multi hop routing is set up for calculating messages by gateways. Messages are sent to gateway by MAC based TDMA. Each node is informed by gateway about the slots for listening to other nodes by which they get schedule for transmission. Gateways are communicated by sink. The radio can be independently switched on and off independently, the sensors can operate in active mode or a low power mode and depending on required range the power for transmission can be programmed. The four states in which sensors nodes can be are: Sensing only, relaying only, sensing-relaying and inactive mode. In the first state that is sensing, the node surveys the surroundings and data is generated at constant rate. In relaying state the target sensing is not done by the node but the radio is on and data is relayed form the active nodes. Both sensing and relaying of messages is done by the node in sensing-relaying state, otherwise node is said to be in inactive state. Figure 6.2a shows sensors states in a typical cluster for a target tracking application.

Figure 6.2a: Cluster network
6.3 Data centric protocols

Due to the amount of sensors nodes in many applications it is hard to assign a global identifier to each node. Thus it becomes difficult to select a particular set of sensors in a network for query. In addition, in some applications sensor nodes are distributed randomly in a network. Hence in this type of network data transmission is done by each sensor node in the deployment region and there is therefore a large possibility of redundancy. Energy is wasted whenever there is redundancy. The routing protocol that defines the selection of nodes and data aggregation is to be considered, which is defined as data centric protocols. The sink waits for data from sensors in a particular region after sending queries to that region. The first data centric protocol is SPIN [48]. Later, the popular protocol Direct diffusion [49] was developed and this has given rises to many more protocols.

SPIN (Sensor Protocol for Information via Negotiation): SPIN uses meta-data which is high-level descriptors. There is data advertisement throughout through which the meta data is exchanged in the network by sensors, which after receiving the data advertise to the surrounding nodes. After this, request is sent by nodes for receiving data for those who have not yet received data. The data is exchanged between nodes in SPIN by the messages which are defined in SPIN. The first message is the ADV message in which a sensor has permission to advertise meta data. The second message is the REQ message in which request is made for specific data. The third message is the DATA message which carries actual data.

6.3.1 Direct Diffusion

Direct Diffusion aims to get rid of non–required operations of network layer routing and by doing this energy is saved. The design of direct diffusion is such that it is suitable for query based network communication. There are multiple paths between each node in a network. Data is diffused through sensor nodes and there is a scheme which provides names for data. It finds the path and if a node fails on the way there are always alternative paths present which are chosen before. Localized algorithm and naming data are the main characteristics of directed diffusion. Filters are used in order for data to flow in the network by applications which are encouraged by Direct Diffusion [49]. In most of the cases only selected data are required by applications, this give total control of routing to direct diffusion protocol. [50] A two-phase algorithm is used in diffusion. In this process receiver nodes seek out data source nodes and then the source nodes reaches through the best available path back to the receiver node. The receiver node identifies data by its set of attributes. Figure 6.3a shows direct diffusion protocol redrawn from [52]. Applications where data needs to be send continuously to sink, Direct Diffusion is not feasible for such applications as it is based on query-driven. The main advantage of Direct Diffusion is that each node can perform caching in addition to
aggregation and sensing, and maintaining global network topology is not required which makes it energy efficient.

![Image of network topology with nodes and connections]

**Figure 6.3a: Direct Diffusion**

6.3.2 Proposed Routing Algorithm

In a WSN, some nodes may have more load and more energy requirement than others, these nodes may die faster making network unstable. The main reason for this instability is uneven energy dissipation among nodes. Based on diffusion the routing algorithm which relies only on spatial information was developed. In this routing algorithm, list of all node neighbours and their preferences based on distance are made by each individual node. Afterward data is send by each node to their corresponding neighbour until the power of receiver is depleted on which the transmitter will choose another neighbour to communicate with. The main disadvantage of this is that nodes which are located nearer to the base station whose task is routing messages for whole network will ‘die’ faster than the other nodes in the network. The nodes that are not close to the base station will communicate with close neighbours and will not be relaying messages for anyone and therefore have a longer lifespan.

An enhanced routing algorithm based on diffusion was suggested in [32]. Estimation of energy based on node location is needed for the definition of algorithm. Factors which are involved in this algorithm are node location, power level and load on the node. The main target is to make sure that most of the nodes in the network consume energy at approximately the same rate regardless of physical location by distributing energy throughout the network. This will result in having better maintenance of the system as there is good predictability. Consequently, the overall system performance is increased as the
network can function at full capacity. Power distribution across nodes and efficiency in energy can be made by taking effective decisions based on the location, power level and node loads. Each node will be forwarding the messages of its peer nodes towards the base station. A decision is made by using radio signal strength, battery power and loads at the neighbouring nodes by each node for communication with its best neighbour. At the system start-up, the selection for main neighbour occurs and updates on battery power and load of each neighbour are carried out by the transmission of synchronized messages between senders and receivers nodes.

An efficient routing algorithm is preferred which not only increases node lifetime but also evenly distributes the energy dissipated throughout the WSN resulting in improving overall system performance. If the node has total information of the network topology and energy level of all the nodes in the network they can make their own perfectly suitable communication decision. If synchronized messages are excluded this technique can produce the best performance result. However, it is clear that there would be more synchronized messages than data since all the nodes need to have complete information about each other and the network. Thus, this algorithm is feasible in a system where communication is cheap.

6.4 Geographical Routing

GPSR (Greedy perimeter stateless routing): The process of GPSR is that it is stateless and topology information within single-hop neighbourhood is required to be propagated. This algorithm is suitable for dynamic networks, where topology change or inaccurate information is tracked down by means of global algorithm. Another big advantage of GPSR is that it uses forwarding algorithm based on the distributed perimeter of packet reaching communication holes, and this helps in routing packet around these obstacles [51]. Greedy forwarding and perimeter forwarding are the two main components of GPSR. In greedy forwarding; a node which forwards data chooses the neighbour that is closest to the data destination for the next hop. Overhead is much reduced in greedy forwarding. In topologies where the packet has to be routed further in distance from the destination, this greedy forwarding method will not work. For enabling perimeter forwarding the planner graphs are made by GPSR, using two algorithm RNG (relative neighbourhood graph) and GG (Gabriel Graph) when greedy forwarding is not possible GPSR uses perimeter forwarding. Figure 6.4a summarize greedy and perimeter forwarding.
6.5 CDS (Connected Domain set approaches)

This idea is based on the approach of selecting some of the nodes as a network backbone which will be active at all times. These nodes provide network connectivity and the ability to talk with non-backbone networks. The nodes which are not part of backbone sleep most of the time to save energy and periodically wake up to exchange information with backbone node and their neighbour. As a result backbone nodes have to consume more energy than other nodes.

The Geographic Adaptive Fidelity (GAF) [46] and Span [57] are the two ways in Connected Domain set approaches (CDS) protocol that interchange between backbone and non-backbone position. Previously GPS systems were used for finding node location and partition into the network. In GAF, a distributed algorithm helps to find the grid leader or the backbone node which uses standard ad-hoc routing protocol AODV [54] [38]. Nodes alternate their states (active or sleep) and detect where they can change or take over the grid leadership.
In GAF the whole sensor field is divided in a small square grid with side \( L = \frac{r}{\sqrt{5}} \) and represents the radio range where backbone node (Grid leader) can talk to each other and other nodes can receive or send data to their backbone node. A Sketch of GAF square grid picture is shown below.

Span is different than GAF. Literally it does not use GPS to find the location of nodes to create the network or to take care of backbone nodes. In Span there are no fixed grid dividers. Based on information from the neighbour, node itself decides where it should join with or leave with backbone node and decide on the transitioning of backbone state. Backbone node also involves some energy resourceful protocol to avoid running the radio all the time and also maintain the network and perfectly exchange data with other nodes.

### 6.6 Adaptive self configuring sensor network topologies

Large sensor network consist of many nodes and in some cases all the nodes do not need to be in active mode. When few of the nodes are in use in the network, the distance between neighbouring nodes may be too long which will cause the packet loss rate to increase. On the other hand data transmission energy over long distance will be scrutinized. Similarly, if all nodes of the network are in use, the system will lose unnecessary energy. ASCENT describes a logical energy efficiency and adaptive procedure for dealing with these kinds of situations. In ASCENT, nodes try to save energy for extending network lifetime by using the
adaptive techniques that permits applications to configure the underlying topology based on their needs. ASCENT is a self-configuration technique reacting to operating condition measured locally. Active nodes from the network are selected by ASCENT which stays awake all the time and performs multi-hop packet routing and the rest of nodes remain inactive. These inactive nodes periodically check whether they should become active or not. These nodes are passive nodes and they remain listening to packets but they do not take part in the transmission.

6.7 Conclusion

In this chapter different network routing protocols such as Direct, Minimum energy routing, Geographical routing and data centric has been discussed. We have drawn the conclusion that the routing protocol influences network lifetime. However, different routing protocols can be efficient depending on the given environment and applications. For relatively big network, LEACH routing protocols driven by the results [43] [44] which are redrawn below in table 6.7 (a, b) and a diffusion based routing protocol on spatial distance turn out to be the most efficient.

<table>
<thead>
<tr>
<th>Algorithm</th>
<th>First Node Dies</th>
<th>Last Node Dies</th>
<th>System Lifetime</th>
</tr>
</thead>
<tbody>
<tr>
<td>Direct</td>
<td>56</td>
<td>122</td>
<td>45.90%</td>
</tr>
<tr>
<td>Leach</td>
<td>690</td>
<td>1077</td>
<td>64.07%</td>
</tr>
<tr>
<td>Pegasus</td>
<td>1346</td>
<td>3076</td>
<td>43.76%</td>
</tr>
</tbody>
</table>

Table 6.7a: Life time comparison of routing algorithm [30]

<table>
<thead>
<tr>
<th>Algorithm</th>
<th>First Node Dies</th>
<th>Last Node Dies</th>
<th>System Lifetime</th>
</tr>
</thead>
<tbody>
<tr>
<td>Direct</td>
<td>217</td>
<td>468</td>
<td>46.37%</td>
</tr>
<tr>
<td>Leach</td>
<td>1848</td>
<td>2608</td>
<td>70.86%</td>
</tr>
<tr>
<td>MTE</td>
<td>15</td>
<td>843</td>
<td>1.78%</td>
</tr>
<tr>
<td>Static Clustering</td>
<td>106</td>
<td>240</td>
<td>44.17%</td>
</tr>
</tbody>
</table>

Table 6.7b: Life time comparison of routing algorithm [31]
Diffusion algorithm [32] has 3425 number of node dying first. The last node dies 4323 and the system lifetime with 100% utility is 79.23%.
Energy saving at Software Level

7.1 Operating System

The performance of the sensor network also depends on the operating system. The operating system has a vital role from different aspects: it has for example an impact on energy consumption. There are several operating systems that are designed for wireless sensor mode, such as SOS, Mantis, Contiki, and TinyOS. According to real time implementation requirements the design of operating system depends on two categories.

1. Depends on the task scheduling capability
2. Depends on multiple execution time, on different task, that deal with thread

Two different operating systems have been discussed in this chapter - Event Driven (Tiny Os) and Multi Threaded (MANTIS). Event driving is suitable for WSN due to its low use of resources. On the other hand, multi-thread has superior event processing capability. Both operating systems literally execute the same application, but on the level of energy efficiency there is a need to decide which operating system is suitable for what application.

7.2 TinyOS

The operating system which is specially designed for WSN is TinyOS. It offer common software platform. TinyOS operating system is an event based operating system written in programming language nesC. It is specially designed for static memory allocation, and to avoid overhead problem which is related to dynamic allocation [27].

A basic Algorithm of TinyOS shown below:

Algorithm (TinyOS structure)

1: component_A
2: task do () {...}
3: command X () {...}
4: event Y () {...}
5: int_A
6: ........
7: post_task (A)
TinyOS algorithms are implemented in a manner for the task to execute sequentially from the queue (TOSH_run_task()) and are run into FIFO. In this OS one task cannot be interrupted by another task. Furthermore it takes a minimum amount of processing time to service the event. When the task is executed, the system will go to sleep and this state will be terminated when an interruption occurs.

7.3 MANTIS

Mantis is a light-weight multi-thread operating system which is written in standard C and is capable of running multi-task processes on energy-efficient sensor networks. Hence it can execute tasks faster under a critical situation because its thread architecture facilities the operating system to switch active thread without waiting.

A basic algorithm of MANTIS is shown below:

Algorithm (MANTIS structure)

1: thread_A
2: while (running)
3: ...; mos_semaphore_wait (A1)...
4: int_A
5: ...; mos_semaphore_post (A1)...
6: dispatch_thread ()
7: PUSH_THREAD_STACK ()
8: CURRENT_THREAD = readyQ.getThread ()
9: CURRENT_THREAD.state=RUNNING
10: POP_THREAD_STACK ()

In this operating system a new thread is introduced and when a task is initialized the process will start (Algo line 2). Algorithm is developed in such a way that when one thread is waiting for resources the other thread will be activated. Also, if no processing is required or no thread is activated, the system will go to idle mode which is handled by a thread called idle task. Mantis was build up with memory protection technique like binary and counting semaphore to handle and coordinates threads. In MANTIS threads are implemented with the kernel with a fixed thread table and it hold other information like priority, the state of each thread and a pointer to the thread stack. The stacks of each thread mange through the kernel
memory manager. If no threads are working mean no event are process then the CPU will go to sleep state to save more energy.

### 7.4 Discussion

MANTIS allows prioritization of thread. Packet processing thread is configured to have a higher priority than the sensing thread [28]. In MANTIS average processing time depends on execution time and in TinyOS processing task depends on length of the sensing task and uses average processing time to forward packet. For predictable behaviour of the system MANTIS has an edge over other operating systems.

On the other hand the TinyOS scheduler code size is less than other thus it doesn’t provide thread switching capability and core consist of an absolute minimum functionality [27] based on FIFO queuing algorithm. The scheduler task run automatically and task will execute with respects to one another. When task finishes it will goes to sleep mode (TOHS_sleep ( )) furthermore its idle time is also more stable which helps to make the network energy efficient. But in Mantis the available time drops faster [41] due to its context switching that mean switching context reduce idle time.

However different experiment [27][28][29] shows that Mantis is better for the scenario where system require deterministic, timely processing in addition it will be the better choice where idle period is long and suddenly required sensing information. In cases where energy efficiency is the first preference of network then TinyOS will be the better option.
8 Summary

The purpose of this thesis is to have an energy efficient sensor network based on IEEE 802.15.4 standard. The project states impact on energy consumption does not depend only on one or two factors instead it requires a suitable combination of factors. Right from the selection of nodes components to the routing algorithm selection, it will have significant impact on energy consumption of a network. Energy consumption of WSN was examined from different levels namely, Node level, MAC level, Network level and Software level.

At the node level, a survey of microcontrollers and RF radios that support energy saving methods such as multiple sleep modes, quick wake-up times was done. Different microcontroller/radio combinations that are promising as likely candidates for the development of a energy efficient sensor node were presented. With VLSI advancing at a fast pace, more and more integration is taking place. Microcontrollers like MSP430 has relatively less energy requirement and so does the transceiver like CC2420, thus energy requirement of each individual node have impact on the entire network energy consumption.

Selection of power source for the nodes which in this case is battery can be done by defined cook and Shastry approach. Telos and Micaz comparison has been studied where AA battery gives more life time for Telos motes. The different tasks that will run in the individual node hold the key to this integrated approach. One of the main tasks that will run in the node is that of acquisition of parameter values. The most important parameter from the point of view of making the node energy efficient is the present battery voltage. The battery curves given by the manufacturer can be stored in the node and the time of running and the current battery voltage can be used to derive a fairly reliable estimate of the remaining life of the batteries of the node. If the node is low on battery voltage the following steps can be activated:

- Increasing the delay at which parameter vales are acquired and transmitted
- The same can also be achieved by reducing the priority of the parameter acquisition task

The current battery voltage of the node can be a parameter transmitted over the entire network and will play a role in deciding routes that will favour low energy nodes (by avoiding these nodes when a new route is required). Thus the Operating System tasks help in implementing an integrated energy management policy that works at both the node level as well as there network level.

Another example of the integrative approach is the issue of putting even route nodes to sleep. The Zigbee/802.15.4 protocol prescribes that only the end node is put in to sleep. We
can place a scheduler in each node and put even the routers to sleep. The implementation of
this scheduler is once again one of the tasks of the operating system that is resident in the
node. A very small active duty cycle compared to the sleep period is what is recommended
for energy conservation. The scheduler is one level away from this simple sleep-awake duty
cycle and ensures that network-wide energy efficiency is achieved. While most of the
methods detailed above deal with how they deal with a dynamic, already active network,
the MAC configuration issues are equally important. The MAC of the IEEE 802.15.4 has a
number of configurable parameters that need to be properly configured.

From network point of view, a routing algorithm based on diffusion was discussed that
makes use of the location, power levels and node loads, the algorithm aims at making the
power consumption uniform in all nodes, although they may be farther/nearer to the central
base station. Based on the criteria suggested in the report, a node will either accept to act as a
relay of messages or will deny this service forcing the sender of the messages to search for a
new neighbours node to act as a relay of data.

The following modification to this scheme can be suggested. If a receiving node finds that its
power levels are low or its computing load is high, it can dynamically change some to alter
parameters the situation. Examples of parameters that can be changed are:

- The polling interval between successive reads of parameter values from sensors
- The sleep time
- Shutting down certain tasks that are not critical

This dynamic restructuring of parameters in the application code will allow the node to still
participate in the communication network without sacrificing its power. Power consumption
can still be kept minimal. The additional burden that will result from adopting this method
will be as follows:

- Application code written to suit parameterized increase/decrease of
  intervals
- Classification of tasks as critical/non-critical

Since these are to be done off-line in the planning phase they will not have an adverse
impact on the performance of the network. Finally operating systems that are to be installed
in the nodes have been discussed in the area of energy efficiency and TinyOS have been
preferred in term of energy saving.
8.1 Epitome / Synopsis

- Node architecture: VLSI advances have shrunk the bill of materials required to build WSN nodes. An example is the TI/Chipcon's CC2430 chip. Future work can start with this chip as the building block rather than look into separate microcontroller + RF transceiver schemes.

- Routing Protocols: Many routing protocols were discussed in the literature and extension was proposed based on direct diffusion. There is scope for the development of many more algorithms which take cognizance of factors such as:
  - Critical/Non-critical nodes
  - Battery voltage of node
  - Classification of nodes as failing/active
  - Shutting down of routes that have a majority of failing nodes

- Node Software: The software architecture can be defined in such a way using an Real Time Operating System (RTOS) like TinyOS that there is graceful degradation of services in the node rather than a sudden switch-off/going dead. The steps in this graceful degradation of service can be directly linked the current level of the battery voltage and an estimate of the remaining life based on battery manufacturer curves stored in the node. The software architecture model which will facilitate such a graceful degradation can itself be taken up as a separate work.

- Network Software: When a node is going down gracefully, it will intimate its precarious state to the other nodes via the network. The response scenarios of other nodes can be taken up as a future course of work. Some response scenarios that can be worked on are:
  - Response based on the failing node's role in the message transmission route
  - Response based on the failing node's parameters. If the failing node gathers non-critical information, the response might simply be to ignore it.
9 References


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http://www.maxstream.net/products/xbee


http://www.futurlec.com/Atmel/ATMEGA103.shtml

[26] Insteon Smart lab technology.  
http://www.insteon.net/


### 9.1 Abbreviations

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>ASCENT</td>
<td>adaptive self configuring sensor network topologies</td>
</tr>
<tr>
<td>AEA</td>
<td>adaptive Election Algorithm</td>
</tr>
<tr>
<td>BE</td>
<td>back off exponent</td>
</tr>
<tr>
<td>BER</td>
<td>bit error rate</td>
</tr>
<tr>
<td>BI</td>
<td>beacon interval</td>
</tr>
<tr>
<td>BO</td>
<td>beacon order</td>
</tr>
<tr>
<td>BPSK</td>
<td>binary phase-shift keying</td>
</tr>
<tr>
<td>BSN</td>
<td>beacon sequence number</td>
</tr>
<tr>
<td>BTMA</td>
<td>busy Tone Multiple Accesses</td>
</tr>
<tr>
<td>CAP</td>
<td>contention access period</td>
</tr>
<tr>
<td>CBC-MAC</td>
<td>cipher block chaining message authentication code</td>
</tr>
<tr>
<td>CCA</td>
<td>clear channel assessment</td>
</tr>
<tr>
<td>CD</td>
<td>clear detection</td>
</tr>
<tr>
<td>CDS</td>
<td>connected Domain set approaches</td>
</tr>
<tr>
<td>CFP</td>
<td>contention-free period</td>
</tr>
<tr>
<td>CID</td>
<td>cluster identifier</td>
</tr>
<tr>
<td>CLH</td>
<td>cluster head</td>
</tr>
<tr>
<td>CSD</td>
<td>contention-inherited sleep delay</td>
</tr>
<tr>
<td>CSMA-CA</td>
<td>carrier sense multiple access with collision avoidance</td>
</tr>
<tr>
<td>CTR</td>
<td>counter mode</td>
</tr>
<tr>
<td>CTS</td>
<td>clear to send.</td>
</tr>
<tr>
<td>CW</td>
<td>contention window (length)</td>
</tr>
<tr>
<td>D-MAC</td>
<td>dynamic Mac protocol</td>
</tr>
<tr>
<td>DSSS</td>
<td>direct sequence spread spectrum</td>
</tr>
<tr>
<td>DSMAC</td>
<td>dynamic sensor Mac protocol</td>
</tr>
<tr>
<td>ED</td>
<td>energy detection</td>
</tr>
<tr>
<td>Abbreviation</td>
<td>Full Description</td>
</tr>
<tr>
<td>--------------</td>
<td>------------------</td>
</tr>
<tr>
<td>FFD</td>
<td>full-function device</td>
</tr>
<tr>
<td>FH</td>
<td>frequency hopping</td>
</tr>
<tr>
<td>FHSS</td>
<td>frequency hopping spread spectrum</td>
</tr>
<tr>
<td>GTS</td>
<td>guaranteed time slot</td>
</tr>
<tr>
<td>GPSR</td>
<td>greedy perimeter stateless routing</td>
</tr>
<tr>
<td>HNP</td>
<td>hidden nodes problem</td>
</tr>
<tr>
<td>IR,</td>
<td>infrared</td>
</tr>
<tr>
<td>LAN</td>
<td>local area network</td>
</tr>
<tr>
<td>LLC</td>
<td>logical link control</td>
</tr>
<tr>
<td>LPL</td>
<td>low power listening</td>
</tr>
<tr>
<td>LQ</td>
<td>link quality</td>
</tr>
<tr>
<td>LQI</td>
<td>link quality indication</td>
</tr>
<tr>
<td>LR-WPAN</td>
<td>low-rate wireless personal area network</td>
</tr>
<tr>
<td>MAC</td>
<td>medium access control</td>
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<tr>
<td>NAMA</td>
<td>node Activation Multiple Access</td>
</tr>
<tr>
<td>O-QPSK</td>
<td>offset quadrature phase-shift keying</td>
</tr>
<tr>
<td>OSI</td>
<td>open systems interconnection</td>
</tr>
<tr>
<td>PAN</td>
<td>personal area network</td>
</tr>
<tr>
<td>PHY</td>
<td>physical layer</td>
</tr>
<tr>
<td>RF</td>
<td>radio frequency</td>
</tr>
<tr>
<td>RFD</td>
<td>reduced-function device</td>
</tr>
<tr>
<td>RTS</td>
<td>request to send</td>
</tr>
<tr>
<td>RSSI</td>
<td>received signal strength indication</td>
</tr>
<tr>
<td>RX</td>
<td>receive or receiver</td>
</tr>
<tr>
<td>SAP</td>
<td>service access point</td>
</tr>
<tr>
<td>SCP</td>
<td>schedule Channel Polling</td>
</tr>
<tr>
<td>SD</td>
<td>super frame duration</td>
</tr>
<tr>
<td>SEP</td>
<td>schedule Exchange Protocol</td>
</tr>
<tr>
<td>SPIN</td>
<td>sensor protocol for information via negotiation</td>
</tr>
<tr>
<td>Abbreviation</td>
<td>Description</td>
</tr>
<tr>
<td>--------------</td>
<td>--------------------------------------------------</td>
</tr>
<tr>
<td>SO</td>
<td>super frame order</td>
</tr>
<tr>
<td>STDMA</td>
<td>sensor division multiply allocation</td>
</tr>
<tr>
<td>STEM</td>
<td>sparse Topology and Energy Management</td>
</tr>
<tr>
<td>S-MAC</td>
<td>sensor Mac protocol</td>
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<tr>
<td>TMAC</td>
<td>Time out Mac</td>
</tr>
<tr>
<td>TRAMA</td>
<td>traffic-Adaptive Medium Access</td>
</tr>
<tr>
<td>TRX</td>
<td>transceiver</td>
</tr>
<tr>
<td>TX</td>
<td>transmit or transmitter</td>
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<td>TDMA</td>
<td>time division multiply allocation</td>
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<tr>
<td>WLAN</td>
<td>wireless local area network</td>
</tr>
<tr>
<td>WPAN</td>
<td>wireless personal area network</td>
</tr>
<tr>
<td>WSM</td>
<td>wireless sensor mote</td>
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