CUSTOM DESIGN AND IMPLEMENTATION OF A WIRELESS SENSOR NODE, ENERGY-EFFICIENT MAC AND ROUTING PROTOCOLS

BY

FAROOQ SULTAN

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The thesis, written by FAROOQ SULTAN under the direction of his thesis advisor and approved by his thesis committee members, has been presented to and accepted by Dean of Graduate Studies, in partial fulfillment of the requirements for the degree of **MASTER OF SCIENCE IN TELECOMMUNICATION ENGINEERING**.

Thesis Committee

Dr. SALAM A. ZUMMO (Advisor)

Dr. MOHAMED ADNAN LANDOLSI
(Member)

for

Dr. MUNIR AL-ABSI (Member)

31 JAN 2011

Dr. SAMIR H. ABDUL-JAUWAD
(Department Chairman)

Dr. SALAM A. ZUMMO
(Dean of Graduate Studies)

2/2/11

Date

This thesis is dedicated to my family

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ABSTRACT

Name: Farooq Sultan

Title: Custom design and implementation of a wireless sensor node, energy-efficient MAC and routing protocols.

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The use of wireless sensor networks in environmental monitoring applications has increased rapidly. Due to the presence of extremely versatile as well as low cost devices in the market, setting up a network now has become easy. A custom build wireless sensor node, named the KFUPM node, has been successfully designed, implemented and tested with the network for monitoring temperature and light. An expansion port for adding external sensors has been provided to ease the need for sensing multiple phenomenon. Widely employed MAC protocol, S-MAC, has been implemented with unique algorithm which exhibits much better energy conservation as compared to basic S-MAC. A routing protocol based on cluster head rotation has been designed and implemented. By employing a cluster head rotation policy, the new protocol promises better energy consumption as compared to the existing protocols thus leading to the enhancement of the overall network life. A network design utility has been created to provide complete specifications for a network setup for a given network cost and an acceptable message reception rate.

ABSTRACT (ARABIC)

خلاصة الرسالة

الاسم الكامل: فاروق سلطان

عنوان الرسالة: العرف تصميم وتنفيذ عقدة استشعار لاسلكية، 'MAC كفاءة في استخدام الطاقة وبروتوكولات التوجيه.

التخصص: هندسة الاتصالات

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وقد ازداد استخدام شبكات الاستشعار اللاسلكية في تطبيقات الرصد البيئي بسرعة. بسبب وجود متعددة للغاية ، فضلا عن الأجهزة منخفضة التكلفة في السوق ، وإقامة شبكة وأصبح من السهل الآن. مخصصة لبناء اللاسلكية العقدة الاستشعار، واسمه عقدة KFUPM ، وقد تم تصميم بنجاح وتنفيذها واختبارها مع شبكة لرصد درجات الحرارة والضوء. وقد تم توفير منفذ لإضافة أجهزة استشعار التوسع الخارجي لتخفيف الحاجة للاستشعار عن ظاهرة متعددة. استعمالا MAC البروتوكول ، S-MAC، نفذت مع الخوارزمية الفريدة التي يسلك أفضل بكثير الحفاظ على الطاقة مقارنة الأساسية S-MAC. وقد تم تصميم بروتوكول توجيه على أساس التناوب رئيس الكتلة وتنفيذها. عن طريق استخدام سياسة التناوب رئيس الكتلة، وبروتوكول جديد وعود أفضل استهلاك الطاقة بالمقارنة مع البروتوكولات القائمة مما يؤدي إلى تعزيز شبكة الحياة العامة. تم إنشاء أداة تصميم الشبكات لتوفير مواصفات كاملة لإعداد شبكة لتكلفة شبكة معينة واستقبال رسائل معدل مقبول.

CHAPTER 1

INTRODUCTION

Human centric networks are designed to process the data provided by humans and consist of computers. Such networks usually do not have any interaction with the outside world and operate on the data provided to them. On the other hand embedded systems, interact with the environment to control some part of a device. Embedded systems usually do not interact with humans and are designed to repeat a task as required by the application. Human need is fueling the convergence of both form of systems leading to a network that has the ability to interact with machines as well as the humans simultaneously. This combination has given rise to the ambient intelligence, which includes thousands of tiny devices that can form networks and have the abilities to interact with both the humans and machines alike. This has led to the introduction of a new kind of network called *Wireless Sensor Network* or *WSN*. Sensor networks trace back to 1986 when DARPA announced the Distributed Sensor Networks Program [1]. Since then the advances in

microcontroller and sensor technology have led to the design of extremely small wireless sensor nodes providing high degree of energy efficiency while ensuring sufficiently long distance wireless communications. A typical WSN consists of two parts as shown in Fig. 1.1.

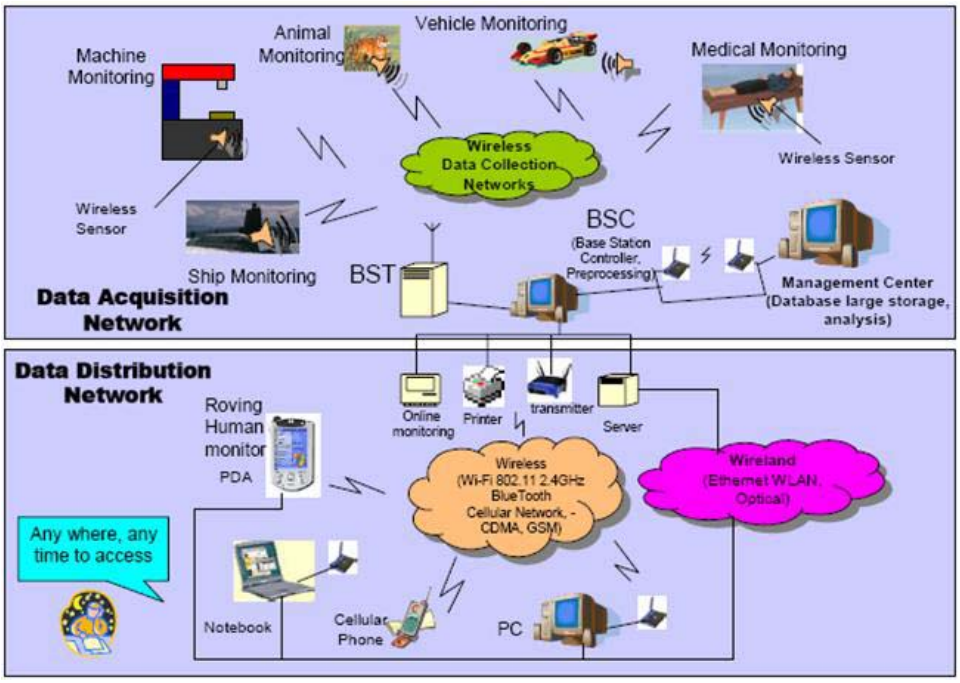


Figure 1.1: Wireless sensor network operational distribution.

The data acquisition part of the WSN comprises of a large number of tiny wireless devices, called nodes, deployed over a physical environment that actively cooperate in order to accomplish one or more tasks. A typical sensor node consists of four main parts; power supply, sensors, micro controller unit (MCU) and a transceiver to send and receive data. The power supply is used to power the node. The sensor circuitry can transform physical quantities into an electric signal. An analog-to-digital converter (ADC), typically a part

of the MCU, changes the analog signals generated by the sensors into digital signals and sends them to the processing part. The processor can then perform simple operations on the received digital signal, and can store it into memory. Finally, the transceiver sends and receives data to different destinations as and when required. The sensor nodes relay their sensed data through each other or directly to the base station depending on the scale of the network and their position with respect to the base node. The base station may send control commands (downstream messages) down into the networks, for example a request to increase their sampling frequency. Sensors are designed to support unattended operation for long durations, frequently in remote areas, in smart buildings or even in hostile environments. A set of sensing components forms an essential part of the device; popular examples include temperature, accelerometer, humidity, infrared light, pressure, and magnetic sensors, as well as chemical sensors. WSN have applications in all fields such as structural monitoring [2, 3], environmental monitoring [4] and object tracking. Owing to the hostility and remoteness of the operating region, [6, 7] have highlighted some critical factors for the efficient operation of a WSN. Power efficiency for longer network life, fault tolerance for network integrity, scalability for variable network topologies and dynamic network setup are just some of the desirable features for a practical WSN.

The data distribution part of the network is responsible for collecting the data from the base station node and distributing it through different mediums. WiFi, LAN and even long distance radio communication techniques are used to accomplish this task. The work presented in this thesis is done at the data acquisition level of the WSN. Designs at

hardware level (sensor node) as well as protocol level are done to ensure cost as well as energy efficiency.

This chapter introduces the motivation behind the work in Section 1.1. Section 1.2 sheds light on the the WSN applications. Section 1.3 presents the details of challenges faced in the design of WSN. Sections 1.4 and 1.5 present the literature survey of the existing technologies at MAC and routing layers for WSNs. Results of the literature review are presented in Section 1.6. Section 1.7 presents the adopted methodology and the proposed objectives of this work are presented in Section 1.8. Section 1.9 contains the achievements and contributions of this thesis and the report concludes with Section 1.10 which gives the report organization.

1.1 Motivation

To meet the challenges presented in the previous section, one needs to have a thorough understanding of the operation cycle of a WSN. Moreover, the implementation requires devising ingenious ways to put a designed protocol into work on actual sensor nodes.

Because of a wide variety of applications, a wireless sensor node has to be "general purpose". It should have the ability to interface multiple types of sensors and must be interoperable with the different brands available in market. This task is a challenge in itself, as the existing IEEE802.15.4 based wireless sensor nodes have a limited interface ability. Proprietary sensors can only be interfaced and the manufacturer requires sufficient time to produce the desired product. In addition, some of the devices available in the

market require special downloading boards for application code transfer which requires dedicating a part of the budget for buying the downloading device itself.

As far as the protocols are concerned, this thesis emphasizes on the design of protocols aimed at increasing the network operating time. To fulfil this requirement the selected medium access control (MAC) and routing protocols must be energy efficient and should have the ability to provide an acceptable data throughput for the network to be meaningful. As far as the routing protocols go, cluster based hierarchical protocols have proved to provide a much better data throughput for large networks [6, 7]; comprising of 100 of nodes. The issue of selecting a permanent cluster head leads to higher energy dissipation and therefore a reduced network life; since the death of the cluster head causes issues in the selection of the new cluster head. When the cluster head runs out of power, until the selection of the new cluster head, the cluster remains out of touch from the rest of the network and in doing so leads to multiple packet loss. This head selection procedure should be streamlined so that the network is not disrupted while providing an acceptable level of end to end throughput.

The implementation of the designed protocol on hardware presents multiple challenges. Although the design details are presented in detail in literature, no mention of implementation process is done. Due to the unavailability of implementation details, unique methods must be devised while ensuring the network operation is not compromised.

In order to deploy a WSN in a given area, the least number of nodes required to cover a major part of the area must be determined. Since the number of nodes is directly related

to the cost of the network, the process becomes a crucial part of the network deployment stage.

1.2 WSN Applications

The wide range of applications of WSNs mentioned in literature are:

Building automation

WSN can be deployed in buildings to monitor live activities like temperature/humidity and in turn operate the heating/cooling equipment depending upon the sensed values. In addition, intrusion detection can be accomplished to enhance the security situation of a locality. Intelligent buildings [1] employing systems like BACnet are examples of this approach.

Environmental monitoring

WSNs have been used to monitor environmental phenomenon like volcanic activity [9] to alert evacuation teams beforehand. This type of system has also been used to monitor temprature/humidity condition in tea plantation [10] to operate the irrigation system autonomously.

Health sciences

WSNs in the form of body area networks (BANs) have been used to monitor health activity of patients remotely. The network gathers the vital information and sends it to the doctor over the internet. Thus the doctor has the complete up to date information about the patient without any dedicated monitoring.

1.3 WSN Design Challenges

As mentioned earlier, to ensure proper operation of a WSN, efficient power consumption must be ensured throughout the network. In addition, self healing ability of the network, cost efficiency and flexible network architecture must also be provisioned to enable seamless operation of the network. A brief detail of the above identified challenges is given below:

Power Consumption

Power consumption is the most important design factor for WSNs. Conserving power at each node, eventually leads to the extension of the overall network life. On the hardware front, efficient design of the node could serve as a major factor in deciding the power consumption figures. At the application level, power conservation can be incorporated into the design of the protocols by introducing novel design and implementation procedures that take the energy reserves into account. For example, minimizing the number of collisions or choosing the shortest path to the destination can help save power. A major part of the power is wasted during transmission and reception of radio packets. Since transmission and reception is inevitable, short distance transmission and simple circuitry for modulation\demodulation can be employed to save power [6, 7]. It is important to know the causes of energy wastage so that appropriate action must be taken to overcome or reduce them. In WSNs energy wastage occurs in three domains namely; sensing, data

processing and communications [12]. However, the losses during communications are considered to be the major factor of the network life [7]. The different causes of energy wastage have been identified and discussed in the following text.

1. **Packet collisions**

   Packet collisions cause nodes to retransmit [13], which in turn results in wastage of the battery power. A collision occurs when multiple nodes transmit at the same time [13]. Since all the nodes share the same channel, collision avoidance must be ensured for proper delivery of packets within the network. The situation becomes even worse when multiple packets start to arrive at a receiving node simultaneously.

2. **Overhearing**

   Over-hearing means that a node starts receiving packets that are not destined for it. In normal operation, a node receives a packet and then starts to parse it. In this process, the node determines the destination address in the packet header and discards it if the receiving node is not the destination of the packet. The time required to complete this process depends on the length of the packet header and also on the location of the destination address in the header.

3. **Control packet overhead**

   The main objective of the WSN is to relay information to the sink. Control packets are, however, necessary for establishing and efficient performance of the system. A large number of control packets decrease the effective data throughput of the

network and also cause an increase in energy dissipation. So there is a tradeoff between the number of control packets that need to be sent and the throughput of the network. Ideally control packets should be sent when absolutely necessary to ensure that the network is productive with respect to data packets.

Fault Tolerance

The network must have a high level of fault tolerance in order to be of any practical value [11]. In the setup of a WSN, the nodes are scattered so that the sensed parameters reported by individual nodes represent the situation at different physical locations. Usually individual nodes cannot directly communicate with the sink node. In such cases, data must be relayed through intermediate nodes until it reaches the sink. In case of failure of multiple nodes in the network, the data should still reach the sink node by re-routing or variable power adjustment methods. In short, failure of individual nodes should not affect the operation of the network.

Scalability

WSNs may include hundreds if not thousands of sensor nodes. New nodes may join the network and older nodes may die out without informing the administrator. In such scenarios, the network must be flexible enough to occupy the changes and to accommodate the variable size while maintaining an acceptable level of integrity [6].

Cost of Network Deployment

The deployment cost is a very important design factor for sensor networks because of the large number of nodes required, as well as the fact that in most networks the nodes are disposable [7]. The cost includes both the hardware and the software required to monitor the network.

1.3.1 Causes and Implications of Energy Wastage

As mentioned in 1.3, the limited power supply of the nodes make it inevitable to use energy conservation techniques to design the network that lasts a longer period of time. It is, therefore, important to know the causes of energy wastage so that appropriate action must be taken to overcome or reduce them. In WSNs energy wastage occurs in three domains namely; sensing, data processing and communications [12]. However, the losses during communications are considered to be the major factor of the network life [7]. The different causes of energy wastage have been identified and discussed in the following text.

Once the packets collide, the data gets corrupt; such packets have to be discarded [13] and retransmissions have to be requested, increasing the energy consumption in the network. Moreover, when the control packets collide, the complete network setup is affected. The delay in packet delivery also increases due to collisions. As an indirect consequence of retransmissions, the effective throughput of the system decreases, since majority of the time is wasted in retransmissions.

Over-hearing wastes valuable energy in reading and receiving packets that are not intended for the desired node. Moreover, until the completion of this process, all the other packets intended for the node are not received, thus increasing the latency in the network and resulting in collisions.

Over-emitting causes high power dissipation and must be avoided by time synchronization schemes or scheduling. Although the losses in idle listening are not severe but, they must also be minimized to increase the network life time.

1.4 Literature Survey - WSN MAC Layer Protocols

Literature has been extensively reviewed for existing work in the field of MAC and routing protocols to establish the basic understanding of the WSN protocol design. Protocols in WSNs have some unique challenges that are not present in general wireless networks. The two main challenges are the varying topology nature, and the low power requirement of the sensor networks [16, 17]. The authors in [7, 13] have presented comprehensive survey and comparison of various MAC protocols proposed for WSNs. The authors have summarized the key requirements for MAC protocol design, analyzed the advantages and disadvantages of some popular MAC protocols and also outlined promising directions for future work.

In order for all the nodes to communicate, medium access is the most important factor. Keeping all the energy wastage causes discussed in Section 1.3.1 in mind, the MAC protocols must be able to reduce latency and provide fair access to all the nodes in the network.

Based on the method of medium access, the MAC layer protocols can be widely divided into two main categories:

Characterization-Based Protocols

In characterization-based protocols, nodes are provided access based on a schedule that is maintained at the setup of the network. This schedule can be created in any of the following three forms:

1. Time Division Multiple Access (TDMA)

   According to the TDMA scheme, time slots are created and assigned to individual nodes (see Figure 1.2). The node can communicate only in the time slot assigned to it. The advantage of this scheme is that the probability of packet collision is almost negligible [18] and consequently power conservation is much better than any of the other schemes. Also, the end-to-end delay for the packets is deterministic but usually high [19]. On the down side, this scheme suffers from intense latency issues. TDMA-based MAC protocols require a central administrative body for strict time synchronization and slot allocation.

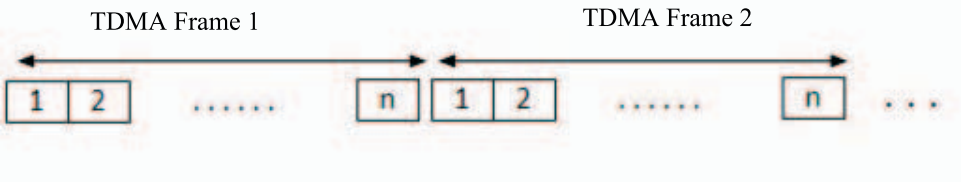


Figure 1.2: Slots assigned in TDMA frames.

2. Frequency Division Multiple Access (FDMA)

FDMA-based MAC protocols divide the available bandwidth into channels which are allocated to the nodes throughout the network. Unlike the time based protocol (TDMA), the latency is much less for these class of protocols [18]. The disadvantage of FDMA approach is the use of highly complex and sophisticated radios that have the ability to operate at multiple frequency bands. In addition, there is a need for a central administration unit that allocates the frequencies to the nodes and implements reuse strategies for dense networks.

3. Code Division Multiple Access (CDMA)

   CDMA-based protocols are good candidates for WSN owing to their ability to tackle interference issues. Each node assigns itself a pseudo noise (PN) code which is then used for communications over the channel. Considering the limited power and computational abilities of the sensor node, this assignment becomes an issue in highly populated networks [20]. Broadcast communications do not work well with CDMA, since each node can decode the information sent using its code. So separate radio channels along with separate PN codes are required to accomplish the broadcast operation in CDMA-based protocols [20].

Contention Based Protocols

In contention-base protocols, unlike the scheduling based, nodes are not bounded by time slots, frequency channels or PN codes. Instead, a node continuously scans the channel [18] and transmits the data as soon as it gets a vacant slot. Although, the control packet overhead associated is high, but the resulting latency is much lower as compared to the

scheduling based counterparts.

In [16], the authors proposed a medium access protocol called the sensor medium access control (S-MAC) for ad-hoc WSNs. This protocol depends on the request-to-send (RTS)/clear-to-send (CTS) mechanism of the IEEE 802.11 to avoid collisions. It was shown that S-MAC had 2-6 times less power consumption than IEEE 802.11. In [17] timeout-MAC (T-MAC) protocol has been proposed to solve the problem of idle listening in a wireless sensor network. The T-MAC dynamically adapts a listen/sleep duty cycle in a novel way, through finely grained timeouts, while having minimum complexity. Both S-MAC and T-MAC operate on the principle of adopting sleep-wake schedules to synchronize the wake timings of all the nodes within a vicinity.

To further reduce the energy wastage due to idle listening, low-power listening (LPL) has been employed to reduce the duty cycles to less than 0.1%. WiseMAC [21] and B-MAC [22] are examples of this implementation. In LPL, nodes wake up for a very brief period to check the channel activity without actually receiving data. This is called channel polling. The work in [23] puts forward power control mechanism based on S-MAC protocol and modifies the competitive mechanism of S-MAC resulting in enhanced S-MAC (ES-MAC). The energy-efficient and high throughput MAC (ET-MAC) protocol proposed in [24] embeds some extra information in long wake up preamble frame and it also uses collision avoidance signaling and handshaking. These ideas help wireless nodes to stay at sleep mode as much as possible. Their simulation results and analysis showed that with dynamic traffic load, this protocol achieves improvement in energy-efficiency

and throughput, over well known MAC protocols like S-MAC and B-MAC.

In [25], the authors have proposed a new MAC protocol for WSNs for environmental monitoring applications. The proposed MAC scheme is specifically designed for WSNs which have periodic traffic with different sampling rates. Moreover, in [26], the authors have proposed an event based MAC (EB-MAC) that is tailored for event-based systems like environmental monitoring. EB-MAC arranges data transfer dynamically using an election based scheduling technique. Trathnig et. al. have presented elastic-MAC (E-MAC) protocol in [27], which has been shown as energy efficient protocol for low-traffic delay-tolerant WSNs. The proposed protocol uses asynchronous distributed transmission scheduling to achieve high energy efficiency. In [28], a novel cluster network topology-based adaptive MAC protocol for WSNs was proposed. In [33] demand wakeup-MAC (DW-MAC) protocol has been presented that allows nodes to wake-up on demand during the sleep intervals to receive or send the data to ensure that the collision in data packets are minimized. This demand wake-up increases the effective channel capacity at increasing loads.

From the above discussion, we conclude that there are a wide variety of MAC layer protocols available. A few contention based MAC protocols have been selected based on their popularity and will be discussed in more detail in the following text.

1.4.1 Sensor-MAC (S-MAC)

The S-MAC [16] protocol is regarded as one of the most energy-efficient protocols at the MAC layer. It trades off some performance reduction in both per hop fairness and latency for energy efficiency [29]. S-MAC achieves its efficiently by utilizing a combined scheduling and contention scheme. The basic idea behind the S-MAC protocol is the locally managed synchronization and periodic sleep-listen schedules employed in the CSMA technique. The S-MAC protocol requires the periodic sleep of all the nodes throughout the network. This design reduces energy consumption, but increases latency, since a sender must wait for the receiver to wake up before it can send out the data. Each node sleeps for some time, and then wakes up and listens to see if any other node wants to talk to it. During sleeping, the node turns off its radio, and sets a timer to awake itself later. A complete cycle of listen and sleep is termed as a frame and the duty cycle is defined as the ratio of the listen interval to the frame length. The sleep interval can be changed according to different application requirements, which actually changes the duty cycle and these values are the same for all nodes.

For multiple access control, the collisions are avoided by virtual and physical carrier sense (CS). There is a duration field in each transmitted frame that indicates how long the remaining transmission will be for. If a node receives a packet destined to another node, it knows how long to keep silent from this field. The node records this value in a variable called the network allocation vector (NAV) and sets a timer for it. Every time when

the timer fires, the node decrements its NAV until it reaches zero. Before initiating a transmission, a node first looks at its NAV as indicated by the flowchart in Figure 1.3. If its value is not zero, the node determines that the medium is still busy. This is called virtual carrier sense. Physical carrier sense is performed at the physical layer by listening to the channel for possible transmissions. Carrier sensing time is randomized within a contention window to avoid collisions and starvation. The medium is determined as free if both virtual and physical carrier sense indicates that it is free. All sender nodes perform carrier sense before initiating a transmission. If a node fails to get the medium, it goes to sleep and wakes up when the receiver is free and listening again. Unicast packets follow the sequence of RTS/CTS/DATA/ACK between the sender and the receiver. After the successful exchange of RTS and CTS, the two nodes will use their normal sleep time for data packet transmission. In order to explain this protocol some assumptions have been considered.

Assumptions

This protocol assumes that all the nodes in the network are stationary and are able to transmit at variable levels of power. The nodes are deployed randomly and have the ability to communicate with neighboring nodes. To conserve energy [29], most of the data communications is done between neighbors rather than between end points. This means, to transmit data between two locations, nodes transmit to their neighbors and the data reaches the destination over a multi-hop path.

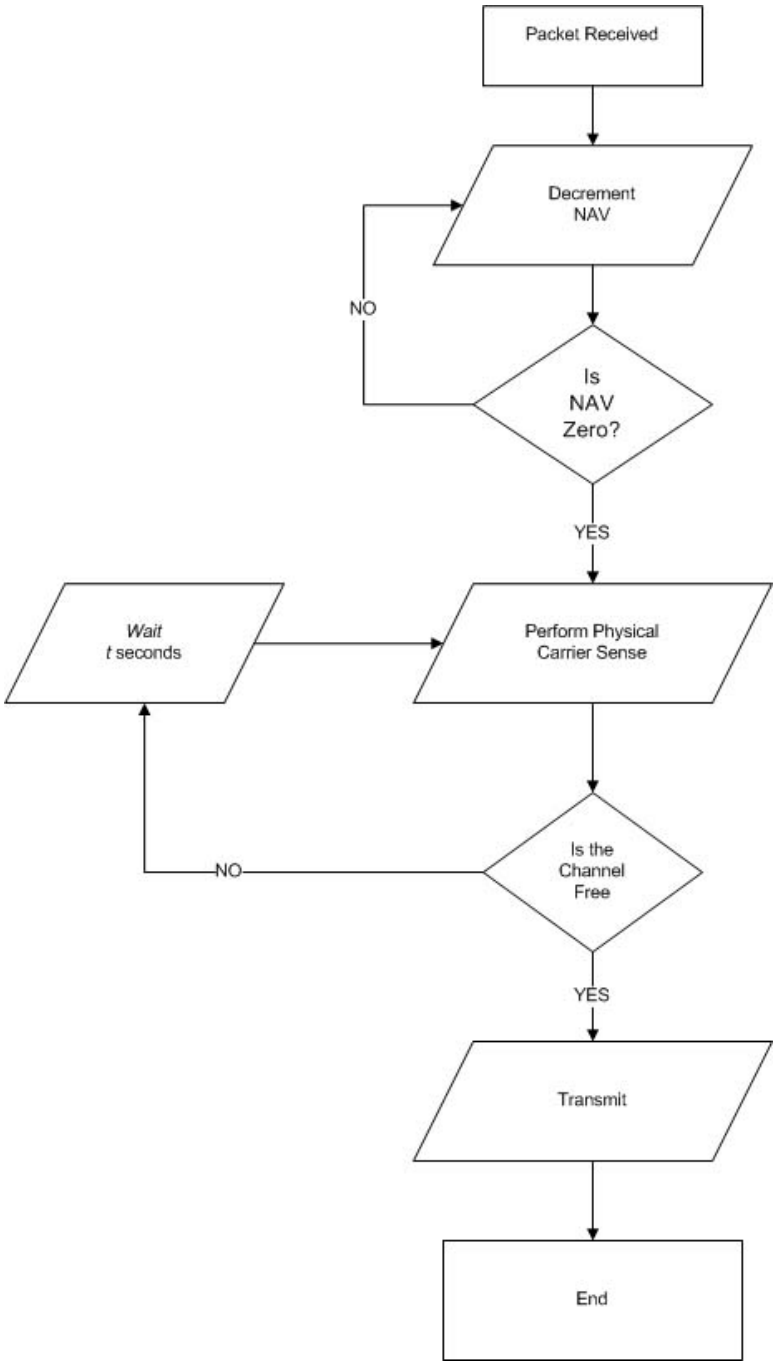


Figure 1.3: Virtual and physical carrier sense mechanism.

The nodes are assumed to operate dedicated applications that result in the activity being reported. This enables the nodes to be hard-coded rather than generally programmed. Every node has the ability to aggregate redundant data before transmission to avoid congesting the network by sending copies of the same packet. The applications are assumed to tolerate some level of latency since environmental monitoring will have long idle periods followed by data bursts in case of alarm.

Protocol Definition

In WSNs, the network is idle most of the time when there is no activity. However, in conditions of alarm, the network becomes highly congested. During the idle state, it is not wise to keep the nodes constantly powered on as this results in the depletion of energy resources. Instead, as shown in Figure 1.4, schedules are created [30] for each node to turn them on (wake-up) and turn them off (put them to sleep). Schedules are created such that every node goes to sleep periodically after some time and then wakes up. The wake time is usually very small as compared to the sleep period. During the wake period, the node continuously listens to its surroundings and also transmits any packets that it needs to during this time. During the sleep period, the nodes turns off its radio, and in some cases the MCU, to save energy. As shown in Figure 1.4, the wake period is usually fixed at the time of programming, however, the sleep period can be flexed depending on the amount of information that needs to be sent.

Individual nodes are given the liberty to choose their schedules independently [29] but

Figure 1.4: S-MAC frame.

it is usually preferred that a group of nodes follow the same schedule to reduce the control overhead [30]. Neighboring nodes synchronize their schedules and make sure that all wake up at the same time so that data is routed (with minimum latency) to the sink node.

Maintaining Synchronization

Nodes maintain their synchronization by broadcasting SYNC packets. The SYNC packets are very concise and contain the address of the sending node and the time of its next sleep. When any node receives this SYNC packet, it adjusts its timers so that it sleeps at the same time as the node that sent the SYNC. The timer adjustment is all done relative to the received SYNC, the absolute times are not important. **Schedule Selection Criterion**

When selecting a schedule for a node, there are three cases that could arise;

1. When a node wakes up initially, it starts to listen the medium for synchronization (SYNC) packets. If it does not receive a SYNC packet within the desired time, it broadcasts its own SYNC packet.

2. If, during the initial listen period, the node receives a SYNC packet from a neighbor, it starts to follow it.

3. If a node receives a new schedule (SYNC packet) when it has already adopted one, then if the node does not have any neighbors, it will discard the old schedule and

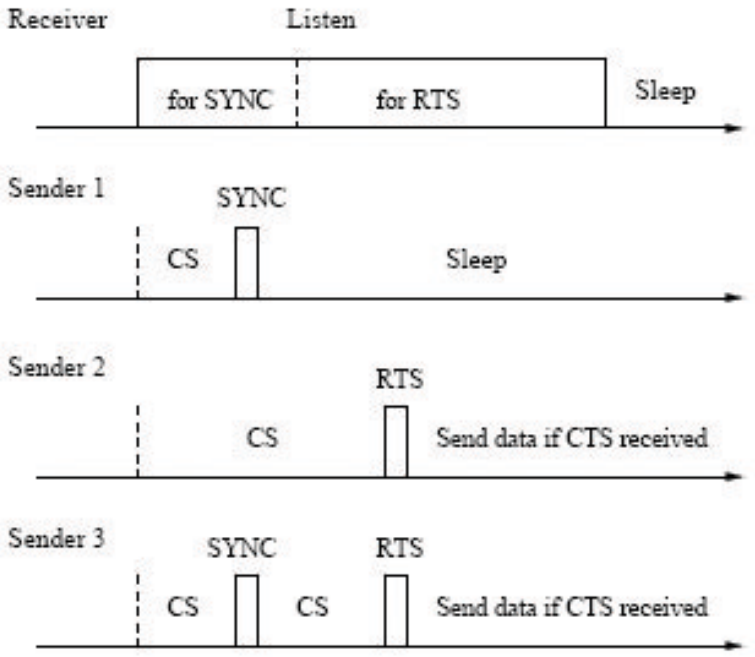


Figure 1.5: Channel contention procedure.

will start to follow the new one. If, on the other hand, the node has neighbors that are following the same schedule, then the node can either discard the new schedule or follow both the schedules. In case when the node is following both schedules, it will wake up twice as much and energy consumption will also increase two times.

Data Sending

In order to avoid collisions between the SYNC and the data packets, the wake period is further divided into slots specific for SYNC and data (see Figure 1.5). During the SYNC period, only the SYNC packets are broadcast and the data packets are sent in the data slot only. When a node has data to send, it contends for the medium first by sending a RTS to the destination. If the destination is free, it responds by transmitting a CTS

packet. When the sending node receives the CTS, it sends its data to the destination node and waits for the acknowledgement (ACK). If the ACK is not received within some predefined time, the complete procedure is repeated again. The nodes whose RTS are rejected back off, go to sleep and try again in the next wake period.

Collision and Over-Hearing Avoidance

Collision and over-hearing avoidance is accomplished by carrying out both physical and virtual carrier sensing. In physical carrier sensing, the node scans the channel for the presence of any signal and if a signal is found, it backs off for a random amount of time and repeats again later. In virtual carrier sensing, the node reads the network allocation vector (NAV) field of the packet it receives. When a node hears an RTS or a CTS not destined for itself, it reads the NAV and starts to decrement it until it becomes zero. When the NAV becomes zero, only then the transmission can be done. Physical and virtual carrier sensing is done before transmitting every packet to ensure that collisions are avoided.

1.4.2 Scheduled-Channel Polling (SCP-MAC)

In SCP-MAC, the concept of LPL is utilized [31]. In LPL, the nodes wake up for small intervals of time and listen for activity on the channel without receiving anything. If the channel is idle, the nodes go back to sleep, otherwise they receive the data and then examine or process it. This complete process is referred to as channel polling. Unlike S-MAC, the polling time is very brief and is synchronized between all the nodes. Due to

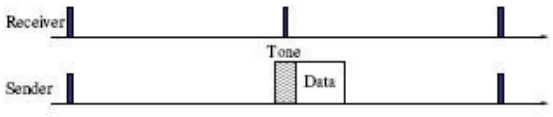


Figure 1.6: Polling synchronization.

the extremely small size of the polling windows, this method is far more energy efficient as compared to the standard S-MAC [31].

Synchronizing Channel Polling

Channel polling reduces the cost of discovering the presence of information since it is far cheaper than actually knowing what the information is [31]. The interval of polling is usually several times less than the actual wake period used in S-MAC. Unlike the ordinary LPL scheme in which senders send a long preamble before the actual information, the preamble in SCP-MAC is very small and serves the purpose of informing the receiving node to wake up for packet reception (Figure 1.6). The length of the polling period is designed in conjunction with the length of the wake-up signal as both are related to the network size. The wake-up period is chosen to be slightly larger than the polling period to ensure the listening node gets the wake-up signal. The primary purpose of synchronizing the polling times is that short wake-up signals are required to be transmitted by the senders before the actual packet. The scheduling of polling periods reduces the energy cost due to over-hearing but increases the cost of maintaining and transmitting schedules.

Adaptive Polling Scheme

In event-driven applications, the network remains idle most of the time and is flooded

by data packets in the event of an activity. If the normal polling schedules are used, the per-hop latency increases and the collisions also increase since bursts of data are being transmitted between nodes simultaneously.In order to counter this, the network intelligently detects traffic flow and adds additional polling slots if the data is thought to have increased (Figure 1.7). This results in a decrease in per-hop latency and enables the network to operate at varying traffic loads [31].

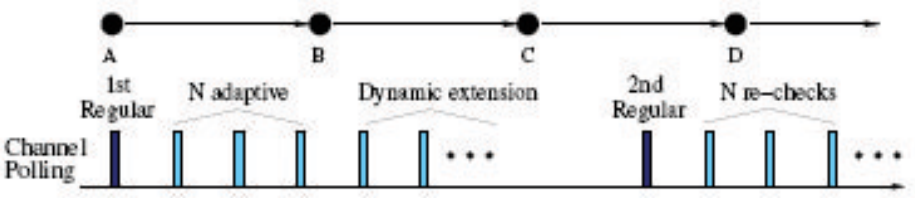


Figure 1.7: Adaptive polling.

Contention

The contention in SCP-MAC involves two steps:

1. In the first step, the sending node sends a wake-up tone that coincides with the polling period of the destination. This wake-up packet is extremely small and serves the purpose of waking up the destination to be able to receive data.

2. Once the destination node wakes up, the sender transmits the data packet.

One advantage of this two-step contention phase is that the probability of collision in data packets decreases as only the nodes that pass the first step proceed to send the data, other nodes will back off. Moreover, it is considered that the collision in the wake-up

tones can be tolerated and the retransmission of such tones does not increase the energy consumption by a considerable amount.

Overhearing Avoidance

SCP-MAC protocol enables overhearing avoidance by using either RTS/CTS or by employing packet headers. When the RTS/CTS scheme is used, the process is the same as that in S-MAC. In case of message headers, upon receiving a packet, the node starts to read the destination address in the packet header. If the current node is not the destination, the reception is stopped.

1.4.3 Medium Reservation Preamble-Based MAC (MRP-MAC)

MRP-MAC is based mainly upon the S-MAC protocol with a few modifications for efficient data transmission. In S-MAC, the wake period is divided into SYNC and data intervals, this makes the wake period excessively long. Moreover, if a node does not get access to the medium, it stays awake for the remainder of the wake period. This extra listening in back-off situation is a cause of energy wastage. To counter these problems, [32] have devised MRP-MAC which introduces separate contention windows for the transmitting nodes and enables the nodes to sleep during the contention period when they do not have data to transmit.

Protocol Definition

MRP-MAC is a synchronized duty-cycle protocol [32] like S-MAC. However, unlike S-MAC, the complete cycle of a node is divided into three windows rather than two. There is an additional contention window as shown in Figure 1.8. The transmitting nodes

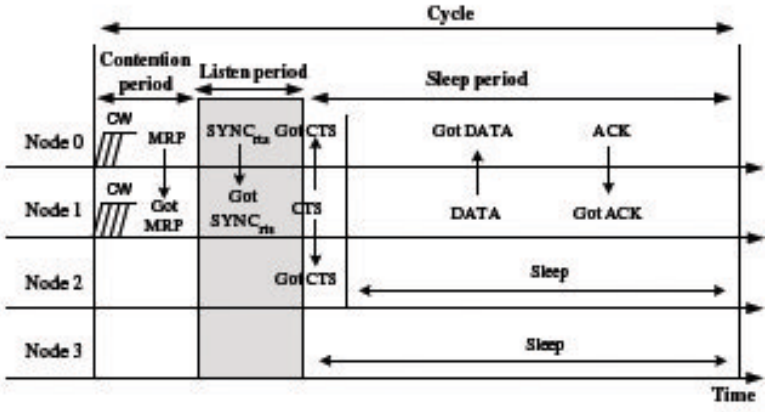


Figure 1.8: MRP-MAC transmission mechanism.

contend during the contention period while all the other nodes sleep. The neighboring nodes wake up during the brief listen period to check for activity and go to sleep again if the channel is idle.

Unlike S-MAC, MRP-MAC does not have separate slots for SYNC and data packets within the wake period. Instead, both types of packets are received in the brief listen window. To contend for the medium, the nodes with data packets are given priority as compared to the nodes that are sending SYNC packets [32]. To save energy, the synchronization information is carried in both the SYNC as well as in the data packet. The RTS packets are combined with SYNC packets to produce a combined $SYNC_{RTS}$ packet. This packet

serves as RTS and also contains the SYNC information, thus reducing the number of SYNC packets that are transmitted.

Packet Transmission

In MRP-MAC, nodes have two wake-up points, the transmitter wakes up at the start of the contention period while the receiving nodes wake up in the listen period. When the transmitter wakes up, it has to contend for the channel by using carrier sense multiple access (CSMA). The successful node that gets the channel broadcasts a MRP packet. The MRP contains a predefined sequence of bits and its sole purpose is to make the other nodes realize that the channel has been occupied. At the end of the contention period, the listen interval starts. The length of the listen interval is chosen to be slightly larger than the contention period so that the nodes can receive the CTS or the data. Both the nodes involved in communication remain awake in the listen period until the transmission is finished.

Node Synchronization

To synchronize the neighboring nodes, SYNC packets are exchanged periodically between the neighboring nodes. Also the SYNC information is contained in the data and the $SYNC_{RTS}$ packets which reduce the number of SYNC packets transmitted thus increasing the effective throughput of the system.

1.4.4 Demand-Wakeup MAC (DW-MAC)

Unlike the previously discussed schemes, this protocol allows nodes to wake-up on demand during the sleep intervals to receive or send the data to ensure that the collisions in data packets are minimized. This demand wake-up increases the effective channel capacity at increasing loads [33].

Protocol Description

In this protocol, each duty cycle is divided into SYNC, data and sleep intervals. The basic concept of this protocol is that nodes wake-up during the sleep intervals and transmit data. In DW-MAC scheduling and contention is integrated. When a node has some data to send, it contents for the channel access first by using CSMA. Once the channel access is complete, the node transmits a special scheduling (SCH) frame instead of the RTS. The length of this frame is adjusted such that the corresponding length of the sleep interval can be determined from the SCH duration. Essentially, there is a one-to-one mapping between the SCH duration and the sleep interval duration. SCH has no other information than the address of the intended receiver so that only the destined node wakes up. Moreover SCH has no timing information and just replaces the contention packets RTS/CTS. This decreases the control packet overhead and decreases collisions at the receivers.

Single-hop Packet Flow

Considering an example from Figure 1.9 in which node A wants to transmit to node B. After performing CSMA, node A contends for the channel and sends an SCH frame to

B. Depending on the length of the SCH frame and the start of the SYNC interval, both

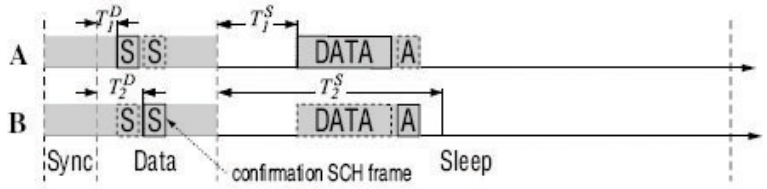


Figure 1.9: Single-hop packet flow in DW-MAC.

A and B decide to schedule their wake-up times to T_1^S seconds after the beginning of the sleep period. If the transmission is broadcast, node B will transmit no other packets and will simply receive the transmitted packet after waking up at the set time. However, in case of unicast, node B will respond by sending an SCH packet that serves a similar purpose to the CTS and data packets are exchanged.

Multi-hop Packet Flow

When transmitting packets over multiple hops SCH packets are used in the same manner as in single-hop. Considering the example in Figure 1.10 in which node A wants to send a packet to node C through the intermediate node B. Node A sends the SCH packet to node B, upon receiving this packet, B schedules a time to wake up and sends an SCH in response to A. This SCH serves dual purpose of acknowledging the receipt of node A's SCH and also alerting node C so that it can wake up after some time. This makes it possible to use smaller number of SCH packets over a multi-hop path as compared to the S-MAC and SCP-MAC.

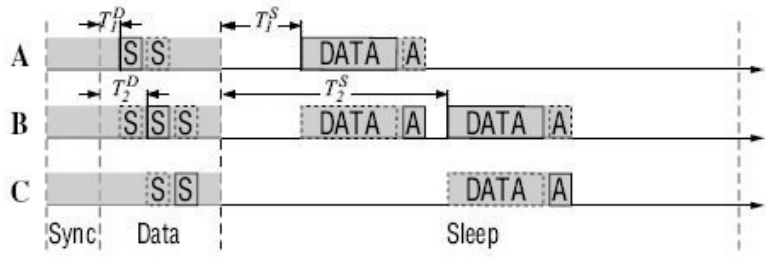


Figure 1.10: Multi-hop transmission in DWMAC.

1.5 Literature Survey - Routing Layer Protocols

The MAC layer serves the purpose of enabling the multiple nodes to transmit while giving equal opportunity to all the member nodes. In order for the data to reach the sink node, the packets must be routed over multiple hops to conserve transmission power. Routing layer protocols ensure the timely delivery of the packets to the sink while keeping in view the scalability and the constantly changing topology of the network .

In [6] a comprehensive survey is presented for the routing protocols for WSNs. Further, very recently in [34, 36] the authors have presented a review and comparisons of recent routing protocols in WSNs and classified them into categories based on the network structure in WSNs. In [37] Schurgers et al have derived practical guidelines to enhance the routing in WSNs based on the energy histogram and have developed a spectrum of new routing techniques. Their first approach aggregates packet streams in a robust way, resulting in energy reductions by a factor of 2 to 3. In the second approach, which relies only on localized metrics, the network lifetime increases up to 90% as compared to the

first approach.

Heinzelman et. al. has proposed one of the most popular hierarchical routing algorithms for WSNs called low-energy adaptive clustering hierarchy (LEACH). LEACH has been shown to achieve a factor of more than 7 reduction in energy consumption compared to direct communication type of routing protocols and a factor of 4-8 compared to the minimum transmission energy type of routing protocol. Later, Lindsey et. al. proposed an improvement of the LEACH protocol in [38], referred to as power-efficient gathering in sensor information systems (PEGASIS). The difference from LEACH is the use of multi-hop routing by forming chains and selecting only one node to transmit to the sink instead of using multiple nodes. PEGASIS has been shown to outperform LEACH by about 100-300% for different network sizes and topologies.

Another very attractive routing protocol; namely, the threshold-sensitive energy efficient sensor network protocol (TEEN), has been proposed in [39]. This is a hierarchical protocol designed to be responsive to sudden changes in the sensed attributes such as temperature and humidity etc. TEEN pursues a hierarchical approach along with the use of a data-centric mechanism. However, TEEN is not good for applications where periodic reports are needed since the user may not get any data at all if the thresholds are not reached. The same authors later proposed an improvement in the TEEN protocol by making it adaptive to the requirements of the application in use [40]. The adaptive-threshold sensitive energy efficient sensor network protocol (APTEEN) is an extension to TEEN and aims at both capturing periodic data collections and reacting to time critical events. Simulations of

TEEN and APTEEN have shown them to outperform LEACH in several aspects.

Another energy-aware WSN routing protocol called reliable and energy efficient protocol (REEP) [41], in which sensor nodes establish more reliable and energy-efficient paths for data transmission. The authors have evaluated the performance of REEP under different scenarios, and have shown it to be superior to the popular data-centric routing protocol, directed-diffusion (DD). Yabin et al proposed a redundancy-based directional reliable multi-hop clustering routing algorithm (DRMC) [42]. DRMC mechanism is claimed to keep the proper lifetime, the stability and expansibility of the network, in addition to improving the speed and reliability of the routing process.

Since TEEN and LEACH have influenced the actual hardware implementation of this thesis, a brief review of these two protocols in given in the coming text.

1.5.1 Threshold Sensitive Energy Efficient Sensor Network Protocol (TEEN)

Threshold sensitive Energy Efficient sensor Network protocol (TEEN)[39] is a hierarchical protocol designed to be responsive to sudden changes in the sensed environmental attributes such as temperature. Responsiveness is important for time-critical applications, in which the network operates in a reactive mode.

The network architecture in TEEN is based on a hierarchical grouping where closer nodes form clusters and this process goes on the second level until base station (sink) is reached. After the clusters are formed, the cluster head broadcasts two thresholds to the nodes.

These are hard and soft thresholds for sensed attributes. The Hard threshold is the minimum possible value of an attribute to trigger a sensor node to switch on its transmitter and transmit to the cluster head. Thus, the hard threshold allows the nodes to transmit only when the sensed attribute is in the range of interest, thus reducing the number of transmissions significantly. Once a node senses a value at or beyond the hard threshold, it transmits data only when the value of that attribute changes by an amount equal to or greater than the soft threshold. As a consequence, soft threshold will further reduce the number of transmissions if there is little or no change in the value of sensed attribute.

Packet Flow Mechanism

This model uses hierarchical clustering scheme [39, 44] in which the nodes are classified into clusters as shown in Figure 1.11. Nodes are grouped into clusters and a cluster head is selected from amongst them. The selection of cluster head can be fixed but is usually taken as dynamic to distribute the energy consumption evenly throughout the network [44]. Once the cluster head has been selected, the remaining nodes become its members. All the member nodes sense and forward the data to their respective cluster heads. Once the head node gets the data, it needs to forward it to the next head in the upper level. This process continues until the packet reaches the sink.

Hard threshold (HT) and soft threshold (ST) are defined by the user and serve as the limits of the forwarded data [43]. HT defines the limit for the minimum sensed value after which the data should be transmitted, whereas ST defines the minimum difference

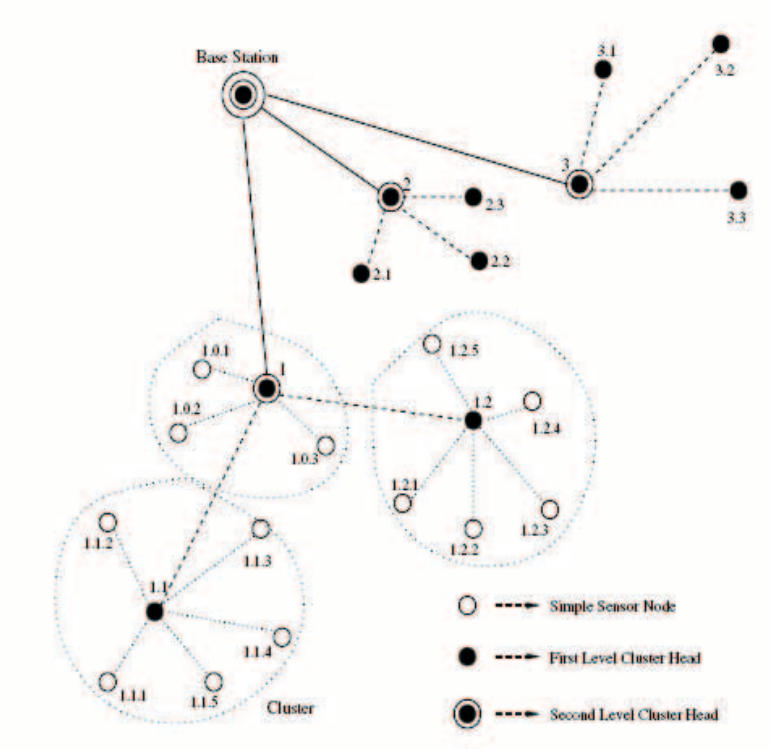


Figure 1.11: Network topology set-up in the TEEN protocol.

between the sensed value and HT. By using HT and ST together, excessive transmissions are avoided.

1.5.2 Low Energy Adaptive Clustering Hierarchy (LEACH)

LEACH belongs to the proactive family of routing protocols. This protocols enables all the nodes to sense at regular intervals, turn on the radios, transmit the information and go back to sleep. In other words, a snapshot of the sensed values is provided after a particular time [39].

Since sensor nodes may die randomly, LEACH employs the concept of dynamic clustering

where the cluster memberships keep varying from time to time. LEACH is completely distributed and requires no global knowledge of the network. However, LEACH uses single-hop routing where each node can transmit directly to the CH and the sink. Therefore, it is not applicable to networks deployed in large regions. Furthermore, the idea of dynamic clustering brings extra overhead, e.g. head changes, advertisements etc., which may diminish the gain in energy consumption.

When the network is set-up, the nodes are distributed into clusters. Once the clusters have been created, the head node transmits TDMA-based schedules to notify the member nodes of their respective time slots during which communication takes place. When all the nodes have sent the data to the cluster head, the head node aggregates the data and forwards to the cluster head in the second level. Due to time slots, the cluster heads has to be awake for a larger amount of time as compared to the member nodes. Also the aggregation of data requires processing, which in turn consumes valuable energy.

Due to the high energy dissipation at the cluster head, it is expected to die out early. To prevent this event from happening, the cluster head responsibility is rotated among the member nodes [45]. This enables uniform energy consumption in the network ensuring that no single node dies out earlier.

1.6 Results of Literature Survey

After surveying the literature for the existing MAC and routing layer protocols, we conclude that the reduction of energy consumption on individual nodes results in an increase

in the overall operating life of the network. This increase in lifetime is highly desirable and can be achieved by the following two methods:

1. Making the hardware design more energy efficient.

2. Designing protocols that aim to reduce energy wastage.

Redesigning the hardware for energy efficiency is usually not preferred unless special requirements on the design are not available on the already offered devices. Usually protocols are tuned to behave in an energy efficient manner.

As for the hardware itself, all the devices currently available in the market are limited in terms of the activity they can sense. This limitation has been put forward to enforce the monopoly of the corporations manufacturing the nodes. Sensing some special phenomenon using the present hardware is not possible without requesting the manufacturer for a modification of the device; resulting in increase in cost.

1.7 Adopted Approach

Traditional WSN design focusses on improving energy efficiency and data throughput by adopting design methods for MAC and routing protocols. However, the energy consumed by the wireless node during the operation of the application is usually side lined. The approach adopted for the design and implementation of the MAC and routing protocols ensures energy efficiency on the application level by using programming platforms like TinyOS which insure a high degree of energy efficiency by limiting the resources being

used.

The protocols have been simulated and fine tuned before implementing them on actual hardware. The implementation details have been devised after intense brainstorming and after extensive testing of the network. The network has been tested with 30 nodes for a sufficient period of time to confirm the operation of the programmed protocols.

In order to create a model to provide an approximation on the network size, received radio power measurements have been performed at two different locations. This data has been used to construct a model that can provide the approximate network size for a given region of interest.

1.8 Proposed Objectives

The main objective of this thesis is to design and implement an energy-efficient WSN for monitoring applications that will help industrial as well as environmental activity monitoring in the big cities of the Kingdom. The design of the prototype WSN will involve the following two phases:

1.8.1 Hardware Design

1. We intend to design our own, custom created hardware nodes, called the KFUPM nodes. The desired features of KFUPM nodes are given below:

    - Using off-the-shelf sensing devices (sensors).

- Designing appropriate conditioning circuits for the sensors used.
- Using off-the-shelf micro-controllers and RF transceivers.
- Provision of extension ports for connecting multiple sensors.
- Onboard power supply to last for sufficiently long time.

2. An analysis of the energy consumption of the KFUPM nodes in different operating modes will be presented in this thesis.

3. A study of the relationship between the transmission power and the covered distance for the transceivers used for KFUPM nodes will also be carried out.

4. On field experimentation will be carried out at different locations to investigate the effect of environment on the radio coverage. This analysis will, in turn, pave the way to the formulation of guidelines for an efficient network design using the KFUPM nodes.

1.8.2 MAC and Routing Layer Protocol Design

The second part of this thesis will emphasize on the design and implementation of MAC and Routing protocols to set-up a network. Our literature survey has concluded that although several protocols have been presented and analyzed, no hardware implementation details for either MAC or routing protocols is presented. The aims for this part of the thesis are:

1. Unique implementation strategies will be formulated to ensure an exact translation of the protocols on KFUPM nodes.

2. An attempt to implement an energy efficient routing protocol will be done.

3. We also plan to present a methodology to determine a rough estimate of the network life based on the protocols designed.

4. The software that runs the protocol stack, application firmware, and data processing application will be designed and coded in a manner that is efficient in terms of memory resources and power consumption.

5. Finally, we will attempt to design and implement the core of the WSN technology to be application and hardware independent so that other applications can utilize the same WSN structure with minor changes in the sensor node design.

1.9 Summary of Achievements and Contributions

This thesis has led to the successful design and fabrication of a one-of-a-kind wireless sensor node (KFUPM node) at a reasonable price and having the same if not higher sensing abilities. KFUPM node can be programmed by a cheap off-the-shelf programmer rather than using special sensor boards (MIB 510) as for the Crossbow Mica devices. Temperature and light sensors have been included on the node and extra ports have been provided to interface additional sensors if required.

On the software front, a MAC layer protocol inspired from S-MAC has been implemented with some unique implementation procedures not mentioned in literature. LEACH and TEEN have been used as references to devise a routing protocol that serves the purpose of data routing as well as keeps the power consumption in check. An interactive network monitoring application has been created to observe the network conditions and to record the data for future usage. A network deployment application has been completed that estimates the approximate network size based on the environment and the target area. The complete system has been tested with 25 nodes with several clusters at different levels from the sink node. The network performed well and remained stable throughout the experiment.

1.10 Thesis Organization

This thesis is organized as follows. Chapter 2 has the hardware design and node creation process for KFUPM nodes. Chapter 3 focusses on the software interface development for the KFUPM platform. Chapter 4 presents the implementation details of the MAC and the routing layer protocols. The simulation results of the designed protocols are presented in Chapter 5. The radio measurements and design of the network design application are explained in Chapter 6. The thesis concludes with a summary of achievements and an overview of future work provided in Chapter 7.

CHAPTER 2

HARDWARE DESIGN AND IMPLEMENTATION

Wireless sensor nodes require hardware implementation and programming so that it can communicate with other nodes in the network [46]. Figure 2.1 shows the logical block diagram of a typical wireless sensor node. It consists of the following parts:

- Processor Subsystem (typically consisting of a microcontroller)
- RF Subsystem (typically consisting of a radio transceiver)
- Sensor Subsystem (includes sensors for temperature, humidity, light, gas, dust etc).
- Power supply and batteries

This chapter presents the hardware level design details for our hardware platforms. Section 2.1 sheds light on the design details of the KFUPM wireless sensor node node. The

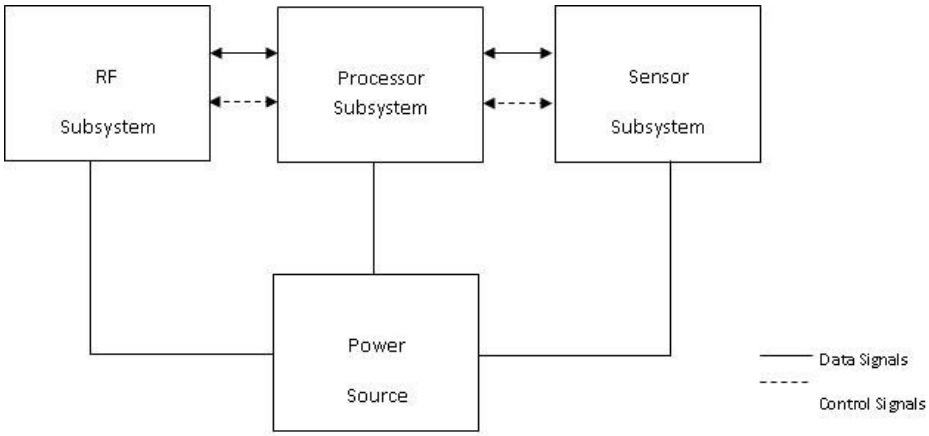


Figure 2.1: Block diagram of a wireless sensor node.

power consumption theoretical and experimental analysis are given in Section 2.2 and Section 2.3 respectively. An energy model based on the analysis is derived in Section 2.4. Finally the chapter concludes with a comparison of the experimental and the theoretical calculations presented in Section 2.5.

2.1 KFUPM Wireless Sensor Node

The main reason for designing an in-house wireless sensor node was to enable easy interfacing of commonly used sensors. In addition, to conserve power at the application level, it was decided to employ the highly power-efficient TinyOS operating system for application design. TinyOS is considered as the default platform for almost all wireless sensor nodes available in the market [47, 48, 49, 50, 51]. Unfortunately all the MCUs available in the market do not support TinyOS structure, therefore, we decided to use

the higher model of the microcontroller (ATmega128) supporting TinyOS. Some of the features of the KFUPM node are given in the following text.

2.1.1 Atmel ATmega128 Microcontroller

The ATmega128 is a low-power, high-performance 8-bit microcontroller offering 128KB of in-system self-programmable flash program memory, 4KB EEPROM, and 4KB internal SRAM. It allows executing powerful instructions in a single clock cycle, achieving throughput approaching 1 million instructions per second (MIPS) allowing the system designer to optimize power consumption versus processing speed. It comes in surface-mount compact form factor thus achieving smaller sized circuit designs. The pin configuration of the ATmega128 is shown in Figure 2.2.

Recall that a mandatory requirement of the WSN design is to conserve the power in the sensor nodes. Hence, this microcontroller has support for different power save modes. Sleep modes enable the application to shut down unused modules of the MCU, thereby saving power. The ATmega128 provides six different power-save modes as explained below:

- **Idle Mode:**

  In this mode the CPU stops but the SPI, analog comparator, ADC, two-wire interface, timers/counters, watchdog and the interrupt system continue to operate normally. This mode also enables the MCU to wake-up from an external trigger.

- **ADC Noise Reduction Mode:**

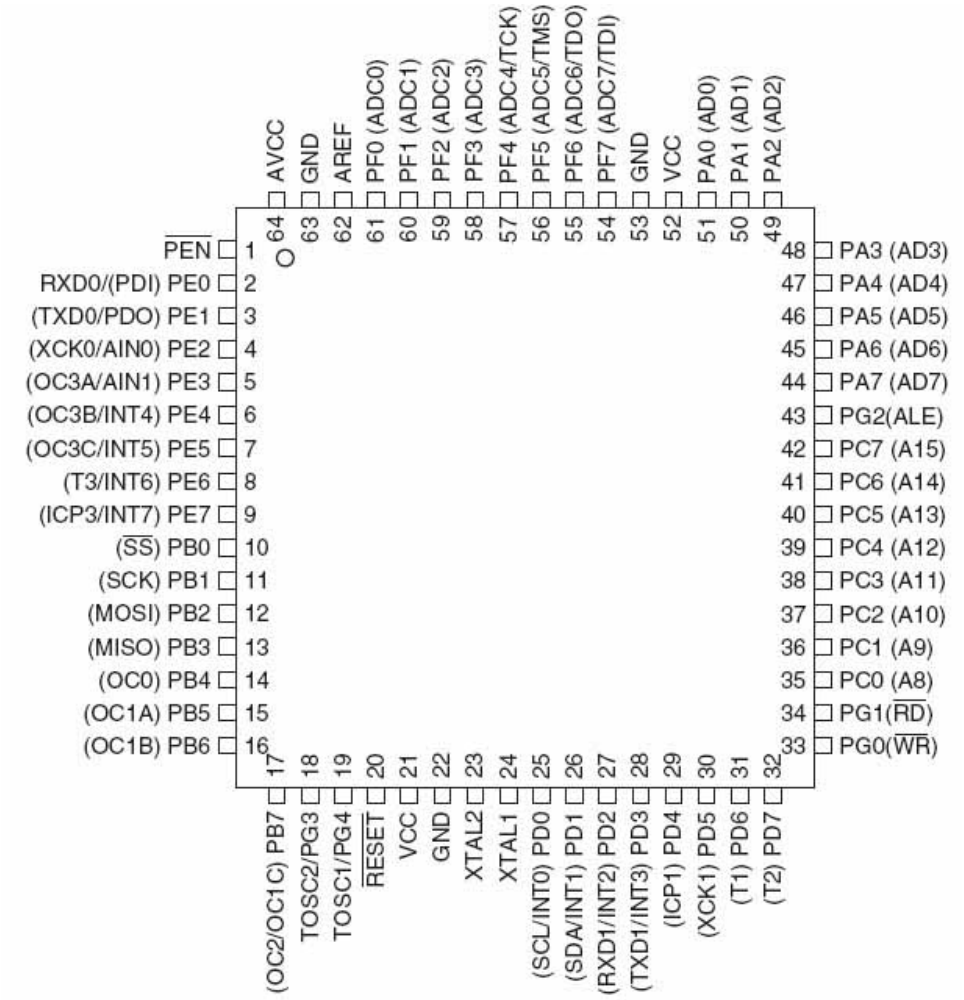


Figure 2.2: Pin configuration of ATmega128.

This mode turns off the CPU but keeps the ADC, two-wire interface, interrupt counter and timer/counter0 keep operating. This mode reduces the noise during ADC operation and also enables higher resolution measurements.

- **Power-down Mode:**

  This mode turns off the CPU and the external oscillator while keeps the two-wire

interface, external interrupts and the watchdog counter keep operating. This mode educes the noise during ADC operation and also enables higher resolution measurements. The MCU can wake-up from this mode only from external interrupts.

- **Power-save Mode:**

  This mode is the same as compared to power-down mode except that all the timers ar also enabled. This enables the MCU to wake-up when timers/counters overflow.

- **Standby Mode:**

  The only difference between this mode and the power-down mode is that the oscillator continues to run. This feature can be used when the oscillator is being used time external circuitry attached to the MCU.

- **Extended Standby Mode:**

  This mode is similar to the power-save mode with the exception that the oscillator keeps operational.

Our nodes required several buffers and keeping track of different timing events and desirably ATmeg128 offers 32 general-purpose working registers, real-time counter (RTC), four flexible timers/counters with compare modes. It has 10-bit ADC with optional differential input stage with programmable gain that were required for the sensors.

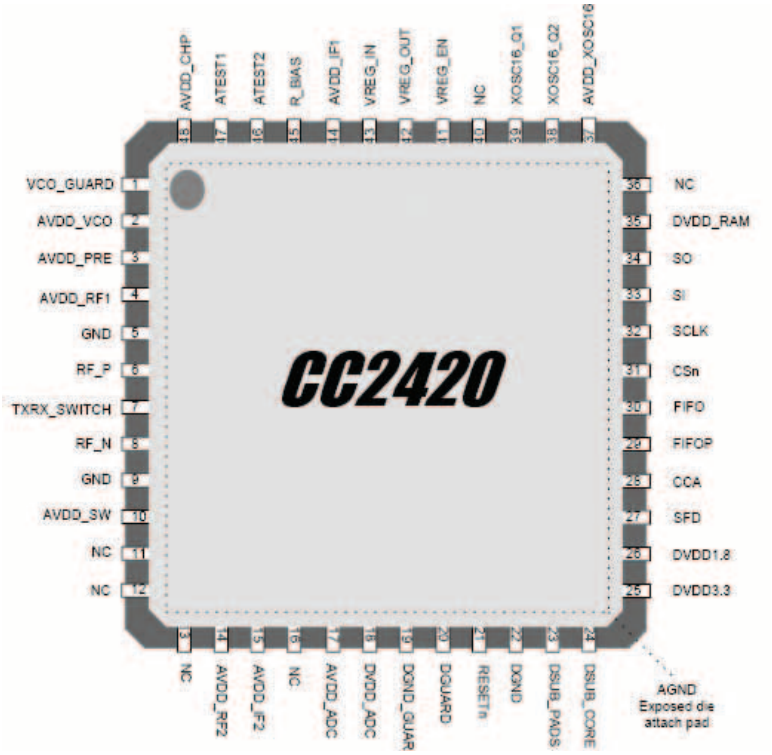


Figure 2.3: Pin configuration of CC2420.

2.1.2 RF Subsystem - CC2420 Transceiver

For RF subsystem, CC2420 transceiver module was selected (Figure 2.3). The component CC2420 is a 2.4 GHz radio frequency (RF) transceiver chip for low-voltage, low-power wireless applications, which is used to interface low-cost microcontrollers and has very useful features such as the compact size as well as data buffering, encryption and authentication. It provides the capability of controlling the transmission power levels so as to meet the requirements of different scenarios of the WSN applications.

In addition, CC2420 provides burst transmissions, channel assessment, link quality indi-

cation and packet timing information. These features reduce the load in any host microcontroller. The CC2420 as shown uses serial peripheral interface (SPI) to communicate with the microcontroller (4-wires serial). Also there are 4 extra lines out of the CC2420 to assist the microcontroller in monitoring the status of the wireless communication. It has 256 Bytes buffer for transmitting and receiving data. The CC2420 supports ZigBee with direct sequence spread spectrum (DSSS) transmission at 2 Mchips/sec and provides an effective data rate of 250 kbps [57]. Moreover, CC2420 has the ability to adjust the transmission power levels as indicated in Table 2.1.

Table 2.1: Transmission power levels of CC2420.

Power Level	Transmitted Power in dBm
31	0
27	-1
23	-3
19	-5
15	-7
11	-10
7	-15
3	-25

We used the daughter board module CC2420EM. It is a Zigbee enabled RF transceiver

Figure 2.4: CC2420EM transceiver module.

with TinyOS support produced by Chipcon. This board has the CC2420 module with its configurations parts and circuits ready and soldered on a PCB with a 40-pins socket along with its antenna as shown in Figure 2.4.

2.1.3 New Circuit Design

For the circuitry design all efforts have been made to reduce the size and weight of the sensor nodes by designing more efficient PCBs and using smaller components with better surface-space utilization e.g. double-sided PCBs. We also searched for smaller sized antenna to be replaced on the RF transceiver.

At this stage, we also decided to equip the wireless nodes initially with two types of sensors for environmental monitoring e.g. light and temperature. The light sensor was installed on-board and the temperature sensor was interfaced with the node via the expansion ports. Nodes sense the raw data and provide the corresponding analog voltage to the microcontroller that is converted to digital format by the internal ADC of the

microcontroller for the processing and later transmission by the RF transceiver to the neighboring nodes. Some of the features of KFUPM node are:

Small Size

The KFUPM node has a reduced area with double-sided PCB design structure. The overall design was also improved so that the dimensions were reduced to a 6.09cm×4.19cm. A smaller, more compact antenna was used to reduce the effective height of the platform. In addition, the optimization in physical area was achieved by relocating some components and using comparatively compact passive components e.g. by using small size 1/8 Watt resistors instead of the standard 1/4 Watt. The crystal oscillators have also been used in a way so as to conserve the space.

Use of LEDs

The LEDs used in the new design are surface mount type and have smaller physical dimensions thus freeing up crucial space and saving the area of the node. The actual area of the ultimate functional node can be even smaller when the LEDs and their peripheral circuitry are removed as they are used in the prototype only for the debugging purposes to let us know the different states of the node during its operation. The current assignments of the LEDs are as follows:

```
All OFF:  Node in Sleep Mode

Green ON:  Member Node awake

Blue ON:  Node sending data

Red ON:  Head node awake
```

Power Source

The KFUPM node is a totally self-powered unit and has an onboard battery pack as the power source. All the wireless nodes in our prototype network are identical in every aspect except the sink/base node and they are powered using batteries. Only the sink node is powered by the commercial power via the USB port of the Network Monitoring Server. Moreover, an ON-OFF switch was also embedded into the design to enable resetting the devices and to avoid the wastage of energy during testing. The wireless nodes are powered by 3 AAA sized (1.5VDC) batteries providing a total supply of 4.5V.

Extension Ports

The designed node has a set of extension ports that provide us the capability to add external sensors. Currently, the node houses on-board light sensor and has provision of installing temperature and humidity sensors on board using those extension ports. We also have the option to add an extra analog sensor and a digital sensor with a 4.5V power port also available for powering the sensors.

Before producing larger numbers of wireless nodes for our network programming, the design was extensively tested for one-to-one communication and then the testing scenarios were extended to more nodes.

2.1.4 Sink Node

In addition to the wireless sensor nodes, one sink node was also required to receive the data from the wireless network. This sink node has one of the purposes of collecting the

data from the sensor nodes in the wireless network and forwarding it to a server so that proper analysis and actions of the data can be performed. Generally, it is assumed that the sink node has unlimited reserves of energy as it is connected to the commercial power supply. Moreover, the sink node is also used to synchronize all the nodes in the network by sending a beacon signal at regular intervals.

The sink node connects serially to a PC USB port using a serial-to-USB connection type converter. Connecting via serial port requires the conversion of the local circuit voltages (know as TTL level) to higher levels (RS-232) so that serial ports can understand the data being received. MAX232CPE by MAXIM Corporation is an example of a voltage level converter. This IC when connected along with peripheral circuitry converts the circuit level voltages (=5V) to serial level (=15V) and vice versa. This enables us to connect the base station with the PC through the serial port. Once the connection is made, the serial port is read through software to view the incoming packets.

2.1.5 Improvement of KFUPM Sensor Node

The KFUPM node was further optimized by redesigning the PCB to reduce the physical dimensions of the wireless node. A comparison of the physical dimensions of original and the optimized model is given in the Figure 2.5. As can be seen, the new version is approximately 20% smaller in area than initial design. The top and bottom layers of the optimized version are shown in Figure 2.6 along with the finished product in Figure. 2.7. In summary, the KFUPM node has been locally designed, developed and optimized for

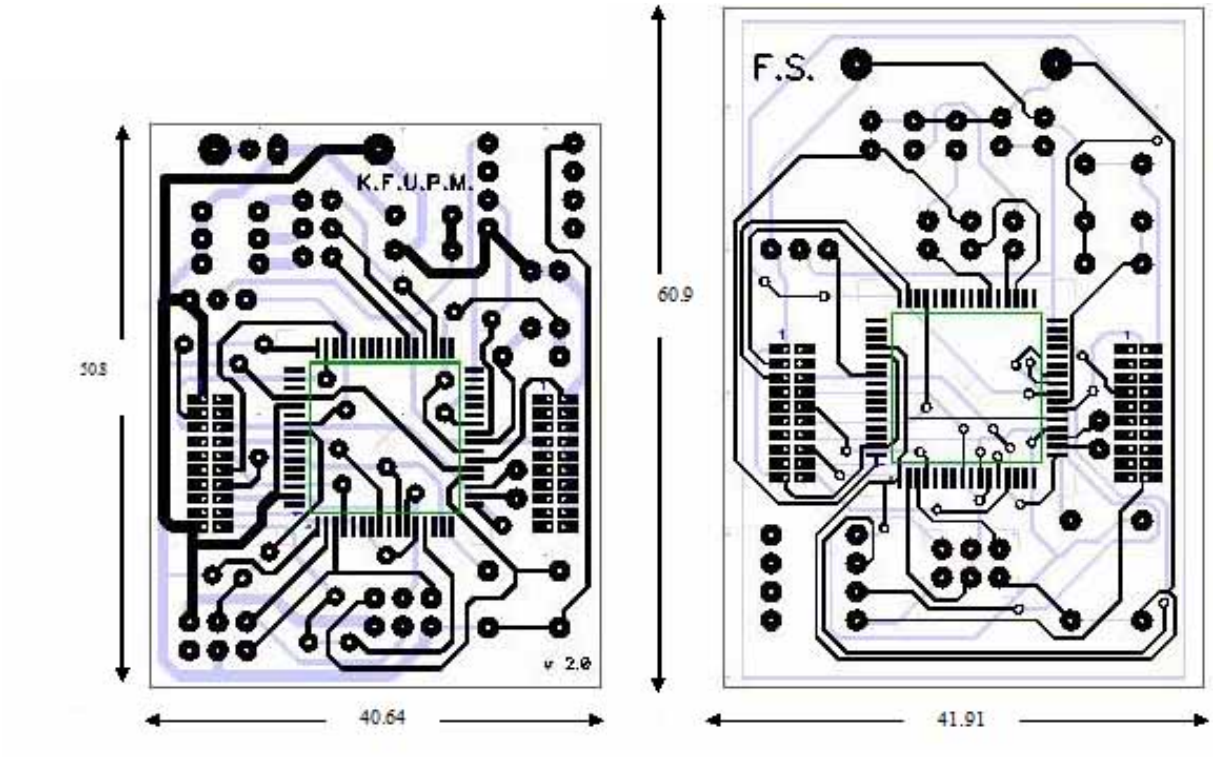
efficient performance. A list of key features of the KFUPM wireless sensor node are given below:

- Atmel ATmega1281 micro controller.
- CC2420 Radio transceiver module.
- On-board sensors (light).
- External sensor interfaced with the expansion port (temperature).
- Power source (on-board power supply and batteries).
- Some peripheral circuitry (e.g. biasing circuits, LEDs, etc).
- A serial programming circuit to burn the code on the device using USB.

2.2 Power Consumption - Theoretical Model

2.2.1 Literature Survey

Literature survey was done for calculating the battery life of the nodes using the transceiver CC2420 and ATmega128 microcontroller but none of the work found was of similar nature. In [52] a new radio battery consumption model is presented to select the most suitable topology and design an energy efficient communication protocol for WSN employing the older, CC1000 radio unit. In [53], a theoretical energy model based on simple finite automata is presented. This model can be used for online accounting, simulation

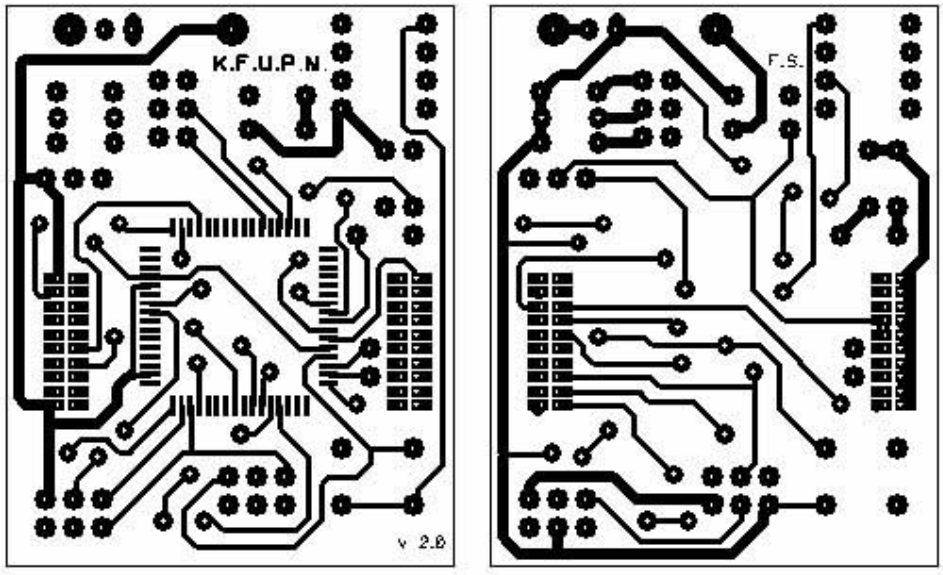


(a) (b)

Figure 2.5: PCB size comparison (in mm) of KFUPM sensor node (a)optimized (b)initial design.

and generation of a-priori knowledge. In [54], an energy isolation mechanism, called the virtual battery was proposed which logically divides energy among applications to provide each its private energy reserve. The work in [55] compared and evaluated wake up solutions for wireless sensor applications.

In our WSN, each node plays two roles, as a member (of the cluster) node and as a head (of the cluster) node. To save the power of the battery both these types of nodes do not sense and transmit the data continuously, instead wake up for a small period of time and



(a) (b)

Figure 2.6: PCB design of KFUPM final version (a)Top (b) bottom.

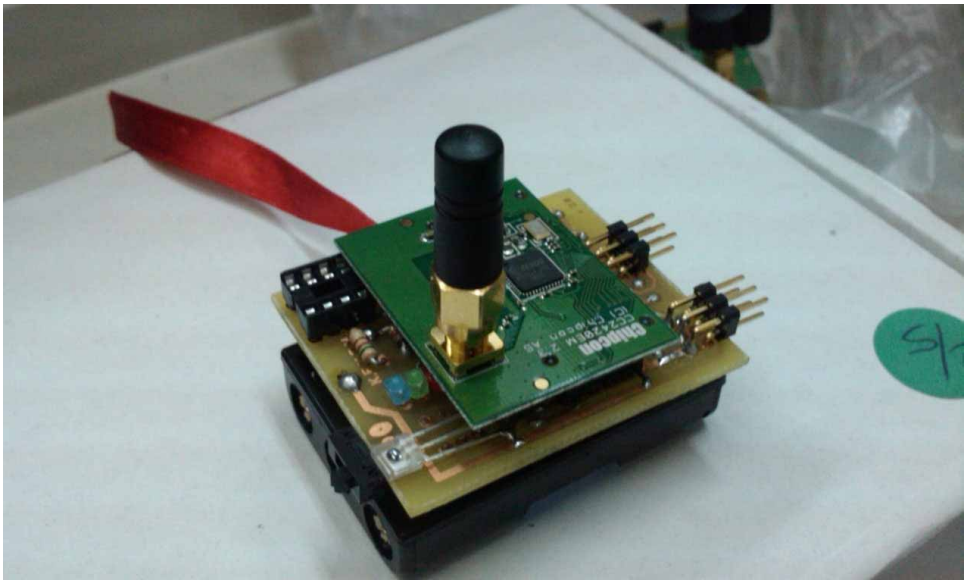


Figure 2.7: KFUPM sensor node in final shape.

then sleep. Head nodes wake up for a little more time as compared to member node. Head nodes also receive data from member nodes and then transmit towards the sink node, whereas member nodes wake up for lesser time and do not receive data from other nodes except CTS byte from the heed node and transmit data to the head node. So the nodes in head-node mode consume more power than the member-node mode. In order to consume the same average power in all the nodes, each node in the same cluster will become a head node at its own turn.

2.2.2 Calculation Methodology

To calculate the current consumption of the node, we will be referring to the default consumption figures given in the data sheets for the various components. For calculating the current consumed as per the duty cycles proposed in the previous sections, we will consider the total fraction of time a node is awake, sleep or in any other modes. By considering proportions of time in particular power modes, the significance of the time duration of operation of a network vanishes; enabling all the calculations to provide average consumption figures [56]. By multiplying the fraction of time a node is in a given power mode with the current consumption of that mode, we get the current consumption when the particular duty cycle is used. Figure 2.8 shows one complete frame employed in S-MAC protocol. This figure will be used extensively in the proceeding calculations, so some terms must be explained as below:

T_f: The total frame duration.

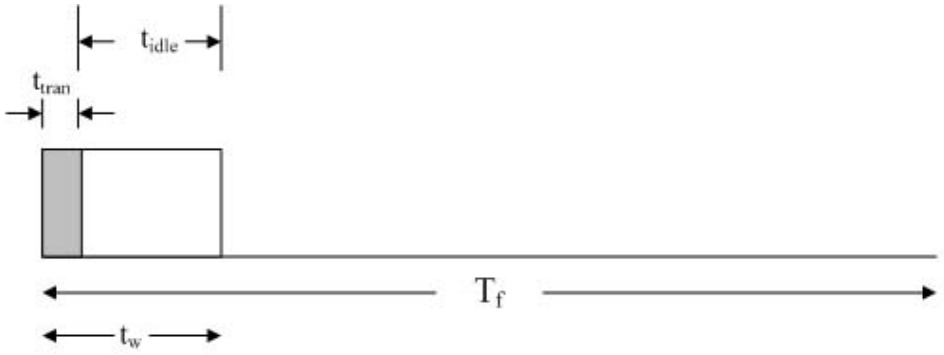


Figure 2.8: Complete S-MAC cycle.

t_w: Wake duration of the node.

t_{tran}: Time during the wake interval spent in sending messages.

t_{idle}: Time during wake interval spent in idle mode.

2.2.3 Power Calculations for Member Nodes

The full cycle of wake and sleep for a member node spans 4 seconds, in which it wakes up for 150ms (t_w) and sleeps for 3850ms. Let p_a indicate the fraction of time a member node is awake and p_s indicate the fraction of time the node is asleep. Observing Figure 2.8 we can calculate the values of p_a and p_s as follows:

$$p_a = \frac{t_w}{T_f} = \frac{150}{4000} = 0.0375. \tag{2.1}$$

$$p_s = 1 - p_a = 1 - 0.0375 = 0.9625. \tag{2.2}$$

Transceiver Current Calculations

a. Wake-up Mode

The transmit power level used by member nodes is 1 for which the current consumption is 6mA (I_t) [57]. Referring to the data sheet [57] we know that,

maximum data rate supported by the transceiver CC2420, R = 250 Kbps.

From the design of our packets, we know that

length of data packets is L_D = 31 bytes = 248 bits,

whereas

length of control (keep-alive) packets is L_C = 17 bytes = 136 bits (keep-alive, RTS, CTS).

Using R, L_D and L_C specified above, we can calculate the time required to transmit a data and a control packet respectively as given below

$$t_D = \frac{L_D}{R} = \frac{248}{250000} = 9.92 \times 10^{-4} s. \tag{2.3}$$

$$t_C = \frac{L_C}{R} = \frac{136}{250000} = 5.44 \times 10^{-4} s. \tag{2.4}$$

Each member node will transmit a keep-alive packet and an RTS, once a CTS is received only then will the data packet be sent. Considering the case of a successful reception of CTS, a member node will transmit 2 control packets (keep-alive and RTS) and one data packet. So the duration for successful transmission is given by

$$t_{tran} = 2t_C + t_D = 2(5.44 \times 10^{-4}) + 9.92 \times 10^{-4} = 20.8 \times 10^{-4} s. \tag{2.5}$$

From (2.5), we deduce that the member node will transmit only a fraction of the total

wake period ($p_{a,t}$) calculated as follows:

$$p_{a,t} = \frac{t_{tran}}{t_w} = \frac{20.8 \times 10^{-4}}{150 \times 10^{-3}} = 0.0139. \tag{2.6}$$

Using $p_{a,t}$, I_t and p_a form Equations (2.1) and (2.6) we calculate the current consumed during transmission, $I_{t,a}$ as below

$$\begin{aligned} I_{t,a} &= p_{a,t} \times I_t \times p_a \\ &= 0.0139 \times 6mA \times 0.0375 \\ &= 0.0031mA. \end{aligned} \tag{2.7}$$

The member node does not sense and transmit every cycle, instead it does so every third cycle, hence the overall current consumption must be decreased by a factor of 3 resulting in $I_{t,a} = \frac{1}{3} \times 0.0031mA = \mathbf{0.0010mA}$.

b. Listening Mode

This mode corresponds to the time during the wake interval when the node is not sending but waiting for packets to arrive from other nodes indicated by t_{idle} in Figure 2.8. In this mode, the node is just sitting idle and waiting for any packets that are intended for it. So, the transceiver is in idle mode and only the microcontroller is operating in full power mode. The current consumed by transceiver CC2420 during this time is 426μA (I_{idle}) [57]. Since the fraction of wake period spent during listening is given by

$$p_{a,l} = 1 - p_{a,t} = 1 - 0.0139 = 0.9861, \tag{2.8}$$

then, current consumed by transceiver CC2420 during listening only can be computed as

$$\begin{aligned} \mathrm{I}_{t,l} &= \mathrm{p}_{a,l} \times \mathrm{I}_{idle} \times \frac{1}{3} \\ &= 0.9861 \times 0.426mA \times 0.0375 \times \frac{1}{3} \\ &= \mathbf{0.0052mA}. \end{aligned} \tag{2.9}$$

c. Sleep Mode

The current consumption of transceiver CC2420 during power down mode is 0.02 μA (I_s) [57]. Hence

$$\mathrm{I}_{t,s} = \mathrm{I}_s \times \mathrm{p}_s = 0.2 \times 10^{-4} \times 0.9625 = \mathbf{1.9250 \times 10^{-5}mA}. \tag{2.10}$$

d. Idle Mode

As the member node transmits data every 3rd wake time, it will be transmitting just the keep-alive packets in the two cycles in-between. Let p_{ctrl} be the fraction of time spent in transmitting keep-alive packets and p_i be the fraction of time spent being idle, then

$$\mathrm{p}_{ctrl} = \frac{t_c}{t_w} = \frac{5.44 \times 10^{-4}}{150 \times 10^{-3}} = 0.0022. \tag{2.11}$$

$$\mathrm{p}_i = 1 - \mathrm{p}_{ctrl} = 0.9978. \tag{2.12}$$

Since this scenario occurs two-third of the time, the current consumed during the idle mode $\mathrm{I}_{i,tx}$ can be given by

$$\begin{aligned} \mathrm{I}_{i,tx} &= \mathrm{p}_{ctrl} \times \mathrm{I}_t \times \mathrm{p}_a \times \frac{2}{3} \\ &= 0.0022 \times 6mA \times 0.0375 \times \frac{2}{3} \\ &= \mathbf{3.3 \times 10^{-4}mA}. \end{aligned} \tag{2.13}$$

Similarly, current consumed during idling, $I_{i,l}$

$$\begin{aligned} I_{i,l} &= p_i \times I_{idle} \times p_a \times \frac{2}{3} \\ &= 0.9978 \times 0.426mA \times 0.0375 \times \frac{2}{3} \\ &= \mathbf{0.0106mA}. \end{aligned} \tag{2.14}$$

e. Receive Mode

Member nodes will receive CTS byte from the CH node. During the receiving of a packet, the transceiver consumes 18.8 mA (I_r) [57]. The time available for receiving a CTS is indicated by t_{idle} in Figure 2.8. Using (2.3) and (2.4), t_{idle} can be calculated as,

$$t_{idle} = t_w - t_{tran} = 150 \times 10^{-3} - 20.8 \times 10^{-4} = 0.148s. \tag{2.15}$$

Hence the fraction of time spent receiving is given by,

$$p_{rx} = \frac{t_c}{t_{idle}} = \frac{5.44 \times 10^{-4}}{0.148} = 0.0037s. \tag{2.16}$$

and the current consumed during receiving is given by,

$$\begin{aligned} I_{rx} &= p_a \times I_r \times p_{rx} \times \frac{1}{3} \\ &= 0.0375 \times 18.8mA \times 0.0037 \times \frac{1}{3} \\ &= \mathbf{8.6 \times 10^{-4}mA}. \end{aligned} \tag{2.17}$$

Memory (flash) Logger Current Calculations

In our node design memory logger is never used during run-time. So, it will consume current as in sleep mode which is 2 μA as mentioned in the manufacturer's data sheet

[58]. Hence, the current consumption of memory logger is as follows

$$\mathrm{I}_{ml} = 0.002mA \times 1 = \mathbf{0.002mA}. \tag{2.18}$$

Microcontroller Current Calculations

The ATmega128 microcontroller (with internal RC oscillator, 4 MHz) has been used. Its consumption as illustrated in the manufacturer's data sheet [58] is the following. The current consumption during wake-up time $I_{MCU,w} = 9mA$, whereas the current consumption during sleep time is, $I_{MCU,s} = 17\mu A$. Hence current consumption during wake-up time is given by,

$$\begin{aligned} \mathrm{I}_{M,w} &= \mathrm{I}_{MCU,w} \times \mathrm{p}_a \\ &= 9 \times 0.0375 \\ &= 0.3375mA, \end{aligned} \tag{2.19}$$

and the current consumption during sleep time is as follows,

$$\begin{aligned} \mathrm{I}_{M,s} &= \mathrm{I}_{MCU,s} \times \mathrm{p}_s \\ &= 17 \times 10^{-3} \times 0.9625 \\ &= 0.0164mA. \end{aligned} \tag{2.20}$$

Combining (2.19) and (2.20) we get the total current consumption of MCU as follows,

$$\begin{aligned} \mathrm{I}_{M,T} &= \mathrm{I}_{M,w} + \mathrm{I}_{M,s} \\ &= 0.3375 + 0.0164 \\ &= \mathbf{0.3539mA}. \end{aligned} \tag{2.21}$$

Total Current Consumption

Adding the current consumptions of the transceiver, MCU and the memory logger (Bold figures),we get the total current consumption as,

$$\begin{aligned} \mathrm{I}_T &= \mathrm{I}_{t,a} + \mathrm{I}_{t,l} + \mathrm{I}_{t,s} + \mathrm{I}_{i,tx} + \mathrm{I}_{i,l} + \mathrm{I}_{rx} + \mathrm{I}_{ml} + \mathrm{I}_{M,T} \\ &= 0.001 + 0.0052 + 1.925 \times 10^{-5} + 3.3 \times 10^{-4} \\ &+ 0.0106 + 8.6 \times 10^{-4} + 0.002 + 0.3539 \\ &= \mathbf{0.3739mA}. \end{aligned} \tag{2.22}$$

Battery Life

The best battery available at the time of these calculations had a rating of 1175mAh. Hence the battery life time of a member node is given by,

$$\begin{aligned} \mathrm{L}_{MN} &= \frac{1175mAh}{0.3739mA} \\ &\approx 3143 \text{ hours} \\ &\approx \mathbf{130 \text{ Days}}. \end{aligned} \tag{2.23}$$

2.2.4 Power Calculations for Cluster Head Node

The cycle of wake and sleep for a head node spans 4 seconds in which it wakes up for 300ms and sleeps for 3700ms. Following a similar procedure to the that followed for the calculation of the member node we can calculate the values of p_a and p_s as follows:

$$\mathrm{p}_a = \frac{t_w}{T_f} = \frac{300}{4000} = 0.0750. \tag{2.24}$$

$$\mathrm{p}_s = 1 - p_a = 1 - 0.0750 = 0.9250. \tag{2.25}$$

Transceiver Current Calculations

a. Wake-up Mode

The transmit power level used by cluster head nodes is 3 for which the current consumption is 8.5mA (I_t) [57]. Referring to the calculations in Section 2.2.3 the fraction of wake period spent during transmission is as follows,

$$\mathrm{p}_{a,t} = \frac{t_{tran}}{t_w} = \frac{20.8 \times 10^{-4}}{300 \times 10^{-3}} = 0.0069. \tag{2.26}$$

Using (2.24) and (2.26) we calculate the current consumed during transmission (Tx) as,

$$\begin{aligned} \mathrm{I}_{t,a} &= \mathrm{p}_{a,t} \times \mathrm{I}_t \times \mathrm{p}_a \\ &= 0.0069 \times 8.5mA \times 0.075 \\ &= 0.0044mA. \end{aligned} \tag{2.27}$$

As the head node transmits CTS every third cycle so ,$\mathrm{I}_{t,a}$ becomes,

$\mathrm{I}_{t,a} = \frac{1}{3} \times 0.0044mA = \mathbf{0.0015mA}$.

b. Listening Mode

In this mode, it is assumed that the head node will receive one packet from the member nodes on average and after that it will transmit it towards the sink node. So, the total time for listening can be calculated as follows,

$$\mathrm{t}_l = \mathrm{t}_w - \mathrm{t}_{trans} = 300ms - 20.8 \times 10^{-4}s = 0.2979s. \tag{2.28}$$

Hence, the fraction of time to receive,

$$\mathrm{p}_{rx} = \frac{t_C}{t_l} = \frac{5.44 \times 10^{-4}}{0.2979} = 0.0018. \tag{2.29}$$

So, the current consumed by transceiver CC2420 during receiving the CTS is given as,

$$\begin{aligned} \mathrm{I}_{CTS,rx} &= \mathrm{p}_a \times \mathrm{I}_r \times \mathrm{p}_{rt} \times \frac{1}{3} \\ &= 0.075 \times 18.8mA \times 0.0018 \times \frac{1}{3} \\ &= \mathbf{8.37 \times 10^{-4} mA}. \end{aligned} \tag{2.30}$$

c. Sleep Mode

Current consumption of transceiver CC2420 during power down mode is 0.02 μA [57]. Hence, the current consumed during sleep is

$$\mathrm{I}_{t,s} = \mathrm{I}_s \times \mathrm{p}_s = 0.2 \times 10^{-4} \times 0.9250 = \mathbf{1.85 \times 10^{-5} mA}. \tag{2.31}$$

d. Idle Mode

As the cluster head transmits every 3rd wake time, so it will be idle during other two-thirds of the wake times except it receives control (keep-alive) packet only from member nodes. Assuming two packets are received as an average from member nodes. Fraction of wake period spent on reception of control packet can be calculated as,

$$\mathrm{p}_{ctrl} = \frac{t_c}{t_w} = \frac{5.44 \times 10^{-4}}{300 \times 10^{-3}} = 0.0018. \tag{2.32}$$

Whereas, the fraction of wake period spent during idling is given as,

$$\mathrm{p}_i = 1 - \mathrm{p}_{ctrl} = 1 - 0.0018 = 0.9982. \tag{2.33}$$

Hence, the current consumed during receiving in the idle mode is as follows,

$$\begin{aligned} \mathrm{I}_{i,tx} &= \mathrm{p}_{ctrl} \times \mathrm{I}_t \times \mathrm{p}_a \times \frac{2}{3} \\ &= 0.0018 \times 18.8mA \times 0.0750 \times \frac{2}{3} \\ &= \mathbf{0.0017 mA} \end{aligned} \tag{2.34}$$

and current consumed in idling is,

$$\begin{aligned} \mathrm{I}_{i,l} &= \mathrm{p}_i \times \mathrm{I}_{idle} \times \mathrm{p}_a \times \frac{2}{3} \\ &= 0.9982 \times 0.426mA \times 0.0750 \times \frac{2}{3} \\ &= \mathbf{0.0213mA}. \end{aligned} \tag{2.35}$$

e. Receive Mode

After the cluster head replies to the member node with a CTS, the member node sends the data packet to the cluster head. So, fraction of time spent receiving data packet is,

$$\mathrm{p}_{r,d} = \frac{t_D}{t_l} = \frac{9.92 \times 10^{-4}}{0.2979} = 0.0033. \tag{2.36}$$

and current consumed during receiving can be calculated as follows,

$$\begin{aligned} \mathrm{I}_{rx} &= \mathrm{p}_{ai} \times \mathrm{I}_r \times \mathrm{p}_{r,d} \times \frac{1}{3} \\ &= 0.0750 \times 18.8mA \times 0.0033 \times \frac{1}{3} \\ &= \mathbf{0.00155mA}. \end{aligned} \tag{2.37}$$

Memory (flash) Logger Current Calculations

In our design memory logger is never used during run-time. So it will consume power as in sleep mode which is 2 μA as mentioned in the manufacturer's data sheet. So, current consumption of memory logger is as follows,

$$\mathrm{I}_{ml} = 0.002mA \times 1 = \mathbf{0.002mA}. \tag{2.38}$$

Microcontroller Current Calculations

The ATmega128 microcontroller (with internal RC oscillator, 4 MHz) is used. Current

consumed during wake-up is given as,

$$\begin{aligned} \mathrm{I}_{M,w} &= \mathrm{I}_{MCU,w} \times \mathrm{p}_a \\ &= 9 \times 0.075 = 0.675mA. \end{aligned} \tag{2.39}$$

and current consumed during sleep is,

$$\begin{aligned} \mathrm{I}_{M,s} &= \mathrm{I}_{MCU,s} \times \mathrm{p}_s \\ &= 17 \times 10^{-3} \times 0.9250 = 0.0157mA. \end{aligned} \tag{2.40}$$

Hence, the total current consumption of the MCU is,

$$\begin{aligned} \mathrm{I}_{M,T} &= \mathrm{I}_{M,w} + \mathrm{I}_{M,s} \\ &= 0.675 + 0.0157 \\ &= \mathbf{0.6907mA}. \end{aligned} \tag{2.41}$$

Total Current Consumption

Adding the current consumptions of the transceiver, MCU and the memory logger (bold figures)we get, the total current consumption as follows,

$$\begin{aligned} \mathrm{I}_T &= \mathrm{I}_{t,a} + \mathrm{I}_{CTS,rx} + \mathrm{I}_{t,s} + \mathrm{I}_{i,tx} + \mathrm{I}_{i,l} + \mathrm{I}_{rx} + \mathrm{I}_{ml} + \mathrm{I}_{M,T} \\ &= 0.0015 + 8.37 \times 10^{-4} + 1.85 \times 10^{-5} + 0.0017 \\ &+ 0.0213 + 0.00155 + 0.002 + 0.6907 \\ &= \mathbf{0.7196mA}. \end{aligned} \tag{2.42}$$

Battery Life

The best battery available at the time of these calculations had a rating of 1175mAh. So,

the battery life of a member node is given by,

$$\begin{aligned} \mathrm{L}_{CH} &= \frac{1175mAh}{0.7196mA} \\ &\approx 1632 \text{ hours} \\ &\approx \textbf{68 Days}. \end{aligned} \tag{2.43}$$

2.2.5 Average Battery Life for Each Node

As mentioned above, in order to consume power averagely in all the nodes, each node in the same cluster will become head node at its own turn. It is assumed that at a minimum there will be at least two nodes in each cluster, one will be the head and other will be the member node. These two nodes will change the role alternately after a fixed interval of time (40 seconds). The power consumption/battery life will be the average of above two calculations. So, battery life time of each node

$$\frac{130 + 68}{2} = 99 \text{ days}. \tag{2.44}$$

The assumption of at least 2 nodes in a cluster is based on the fact that if there are more than 2 nodes in a cluster then each node will play the role of head node for a lesser time. When the node will be head for a smaller fraction of time then obviously it will consume shorter power.So if there are three nodes in a cluster the battery life will be

$$\frac{130 + 130 + 68}{3} = 109 \text{ days}. \tag{2.45}$$

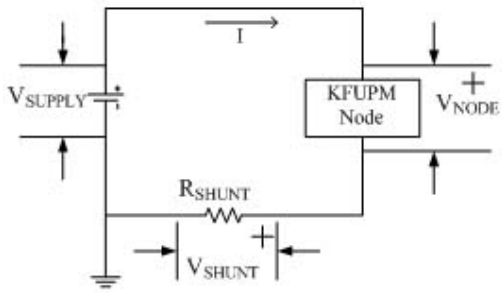


Figure 2.9: Shunt resistor power measurement circuit.

2.3 Power Consumption - Experimental Analysis

Section 2.2 presented a theoretical approach to estimating the network life. To measure the power consumption of the designed node, TinyOS applications were used to operate the node in different modes. In order to measure the actual power consumed by the node, the shunt resistor [59] approach has been adopted. Fig. 2.9 shows the complete circuit setup for the experiment. The main idea here is to use a small ($R_{SHUNT} = 10\ \Omega$) shunt resistor to measure the current in the loop (I). Once the current is measured, the power can be calculated by the relation in 2.46.

$$P_{NODE} = (V_{SUPPLY} - V_{SHUNT}) \times \frac{V_{SHUNT}}{R_{SHUNT}} \tag{2.46}$$

where P_{NODE} is the power consumed by the node, V_{SUPPLY} is the supply voltage (4.5V), V_{SHUNT} is the voltage drop across the shunt resistor, R_{SHUNT} is the shunt resistor and $\frac{V_{SHUNT}}{R_{SHUNT}}$ is the current, I, flowing in the loop (Fig. 2.9).

2.3.1 Power Measurements for MCU in Different States

The ATmega128L MCU can be clocked by either using the on-chip oscillator or by using an external crystal. The wireless node has an external 8 MHz crystal oscillator to provide highly accurate clock pulses for the MCU and the radio. The on-chip oscillator option provides clock pulses with minimum delay but is fairly inaccurate. On the contrary, by using an external oscillator, highly accurate pulses can be produced but some amount of delay is introduced due to the finite amount of time taken by the external oscillator to initialize. The power consumption of the node under the different modes of internal and external oscillators has been analyzed and the results have been provided in Tables 2.2, 2.3, 2.4 and 2.5. A simple application in TinyOS, *TestApp* was written that periodically broadcast packets every 2 seconds with 50% duty cycle. Fig. 2.10 shows a view of the V_{SHUNT} for the complete duty cycle. From Tables 2.2, 2.3, 2.4 and 2.5 it is obvious that the internal oscillator modes consume less power. However, for the external oscillator, when operating at less than the oscillator frequency (0.9 - 3MHz) some frequency limiting circuitry functions consuming more power as compared to the high frequency range (3 - 8MHz) as indicated in Tables 2.4 and 2.5.

2.3.2 Transmission Power Measurements

To measure transmission energy, a TinyOS application called the *SendingMote* was programmed onto one of the wireless nodes. This application turns the node on and keeps

Table 2.2: Internal Oscillator 4 MHz.

Configuration	V_{MAX}(mV)	V_{MIN}(mV)	V_{AVG}(mV)	P_{AVG}(W)
MCU(ON), Radio(ON)	372	352	361	0.149
MCU(ON), Radio(OFF)	56	40	48	0.021

Table 2.3: Internal Oscillator 8 MHz.

Configuration	V_{MAX}(mV)	V_{MIN}(mV)	V_{AVG}(mV)	P_{AVG}(W)
MCU(ON), Radio(ON)	440	380	391	0.160
MCU(ON), Radio(OFF)	56	40	48	0.021

Table 2.4: External oscillator - medium frequency (0.9 - 3MHZ).

Configuration	V_{MAX}(mV)	V_{MIN}(mV)	V_{AVG}(mV)	P_{AVG}(W)
MCU(ON), Radio(ON)	432	376	402	0.164
MCU(ON), Radio(OFF)	248	48	76.1	0.033

transmitting packets of 28 byte payloads every second. The transmission power of the radio was changed between 0, -5, -10, -15 and -28 dBm and the resulting P_{NODE} was calculated using 2.46, where V_{SHUNT} was measured from the circuit of Fig. 2.9. Some of

Table 2.5: External oscillator - high frequency (3 - 8MHZ).

Configuration	V_{MAX}(mV)	V_{MIN}(mV)	V_{AVG}(mV)	P_{AVG}(W)
MCU(ON), Radio(ON)	424	368	407	0.167
MCU(ON), Radio(OFF)	124	48	65.4	0.029

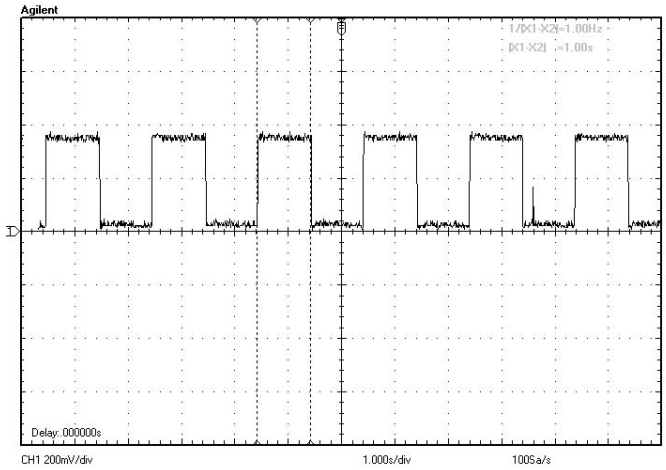
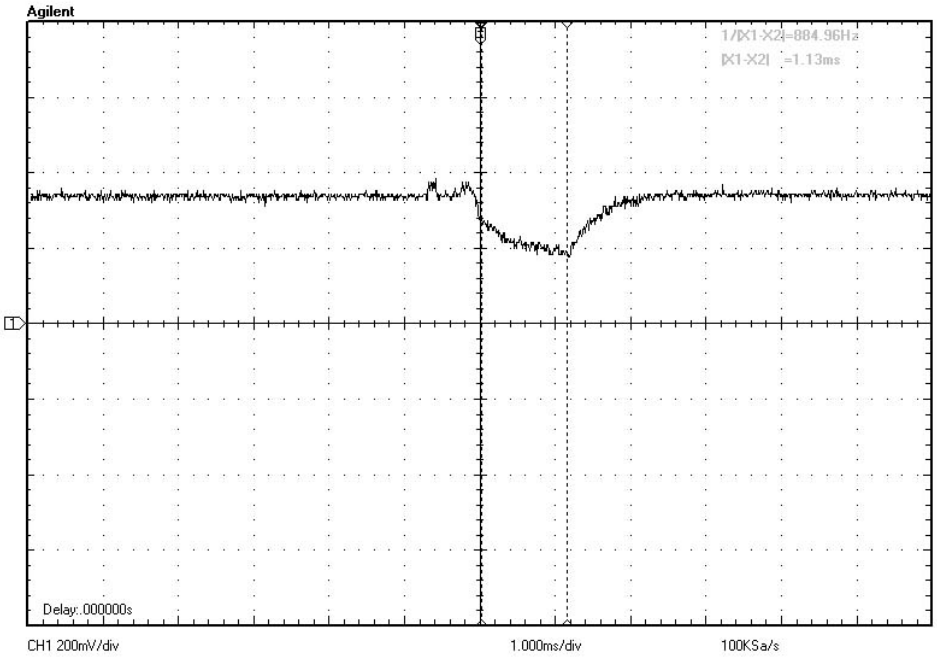
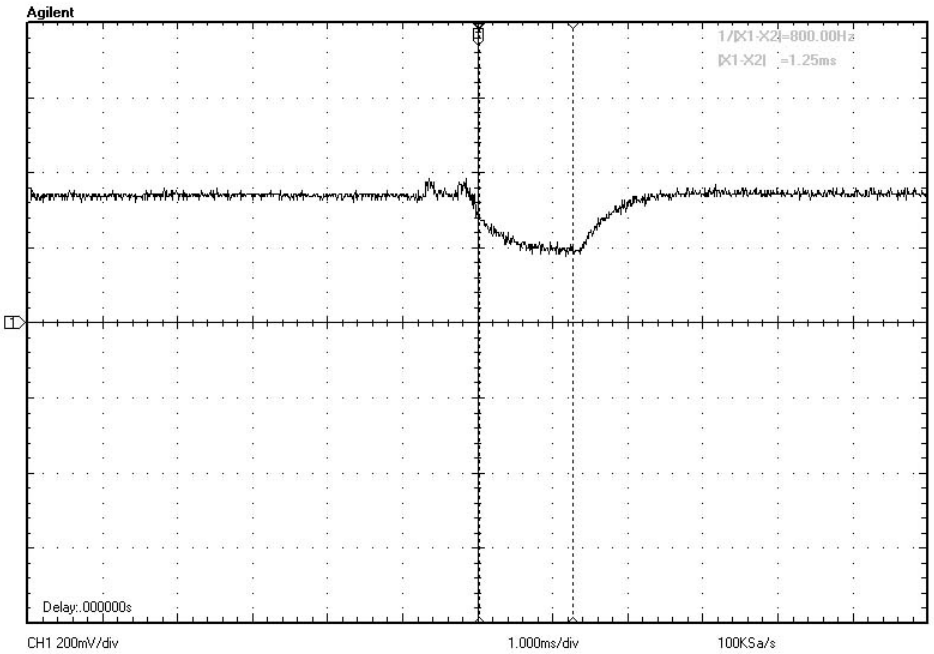


Figure 2.10: V_{SHUNT} measurement for 50 % duty cycle (mV).

the results for V_{SHUNT} at transmission power of -25 dBm and 0 dBm are shown in Fig. 2.11 and Fig. 2.12 respectively. It is observed that V_{SHUNT} is, on average, 191 mV for -25 dBm transmissions and 320 mV for 0 dBm as indicated by Fig. 2.11 and Fig. 2.12. Once the packet has been transmitted, the radio returns to the listen state where it consumes an almost constant current of 35mA (V_{SHUNT} = 350 mV).

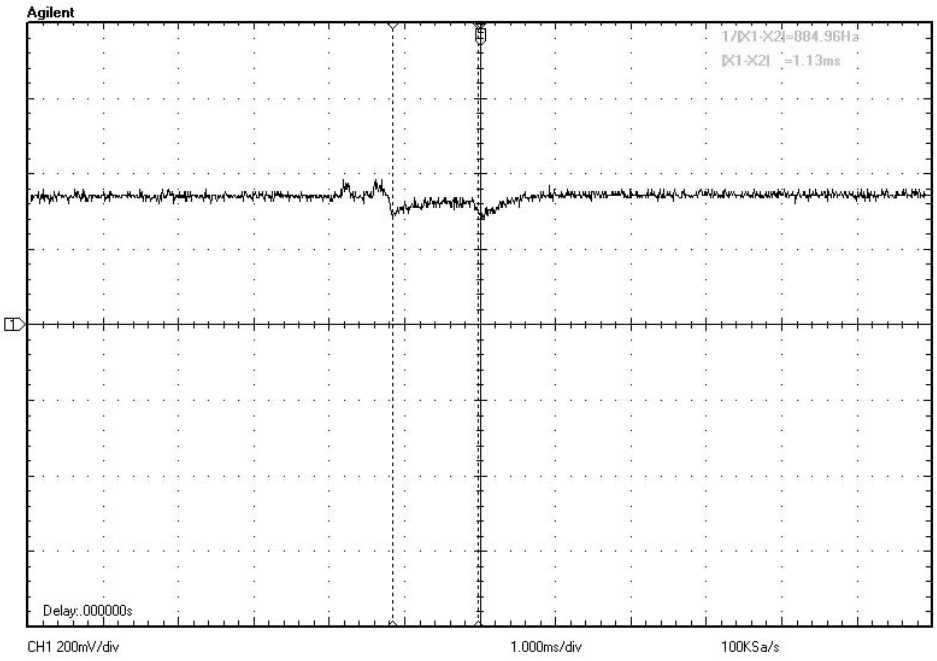


(a)

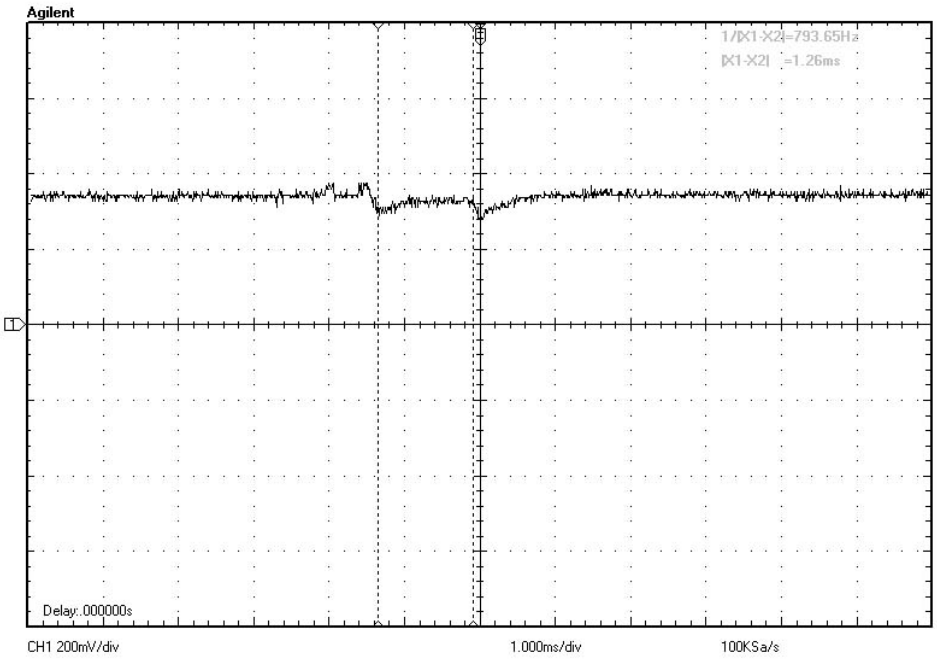


(b)

Figure 2.11: Measurement of V_{SHUNT} (mV) for transmission at -25 dBm with payload size of (a) 16 Bytes (b) 22 Bytes.



(a)



(b)

Figure 2.12: Measurement of V_{SHUNT} (mV) for transmission at 0 dBm with payload size of (a) 16 Bytes (b) 22 Bytes.

2.3.3 Transmission Power Measurements at Varying Payload Sizes

The amount of data to be transmitted has a direct impact on the energy consumption. As the payload size increases, the radio needs to be turned on for a longer time, thus consuming more power. Since TinyOS allows a maximum default payload size of 28 bytes, in order to quantify the energy consumption of the node at different payload sizes, the *SendingMote* application has been employed and for each of the five transmission powers mentioned in Section IV-B, the payload sizes are varied as 10, 16, 22 and 28 bytes. Observing the results of V_{SHUNT} for two different payloads in Fig. 2.11 and Fig. 2.12, the voltage remains the same, however, the duration of the transmission increases with payload size (Fig. 2.11b and Fig. 2.12b). From Fig. 2.11 and Fig. 2.12 it is observed that it requires 1.13 ms to transmit 16 bytes as compared to 1.25 ms for 22 bytes payload regardless of the transmit power.

2.3.4 Sleep State Power Measurements

To monitor the energy consumption pattern during the sleep state, the *TestApp* application was used. This application operated the node in a cycle of 2s with 50% duty cycle, i.e., the radio is ON for 1s and OFF for 1s. The results shown in Fig. 2.10 indicate a current consumption of 35mA (V_{SHUNT} = 350 mV) during the active state and 3mA (V_{SHUNT} = 30 mV) during the sleep state.

2.4 Node Energy Model

The relationship between power and energy is characterized as

$$\mathrm{E}_{NODE} = \mathrm{P}_{NODE} \times \mathrm{t}_{MODE} \tag{2.47}$$

where E_{NODE} is the energy consumed by the nodes, P_{NODE} is the power consumed by the node (from Eq. 2.46) and t_{MODE} is the time spent by the node in a given operating mode.

As observed from Fig. 2.11 and Fig. 2.12, V_{SHUNT} does not remain constant over the entire interval. Therefore, the average value of V_{SHUNT} has been considered in the calculation to provide a much stable result.

2.4.1 Transmission Energy Model

A node was programmed with the *SendingMote* application and each time the transmission power was changed between 0, -5, -10, -15 and -25 dBm. Table 2.6 contains the results of the energy consumption relative to the payload size.

Table 2.6: Energy consumption in μJ for different transmit powers with varying payload sizes.

Transmit Power in dBm	10 Bytes	16 Bytes	22 Bytes	28 Bytes
0	126	151	168.46	192.53
-5	99.9	119.7	133.56	152.64
-10	90.47	108.48	120.96	138.24
-15	83.88	100.57	112.14	128.16
-25	77.94	93.45	104.20	119.08

By using the curve fitting toolbox in MATLAB, we find that the energy consumption changes as a linear function of payload size. Fig.2.13 shows the measured data and the fitted curves for the corresponding data set. The fitting toolbox gives us a linear approximation of our measured data, the coefficients for the different power levels are given in Table 2.7.

Table 2.7: Transmission energy model equations.

Transmit Power in dBm	p_1	p_2	$p_1x + p_2$
0	3.617×10^{-6}	9.077×10^{-5}	$3.617\times10^{-6}x + 9.077\times10^{-5}$
-5	2.868×10^{-6}	7.196×10^{-5}	$2.868\times10^{-6}x + 7.196\times10^{-5}$
-10	2.596×10^{-6}	6.520×10^{-5}	$2.596\times10^{-6}x + 6.520\times10^{-5}$
-15	2.407×10^{-6}	6.046×10^{-5}	$2.407\times10^{-6}x + 6.046\times10^{-5}$
-25	2.236×10^{-6}	5.618×10^{-5}	$2.236\times10^{-6}x + 5.618\times10^{-5}$

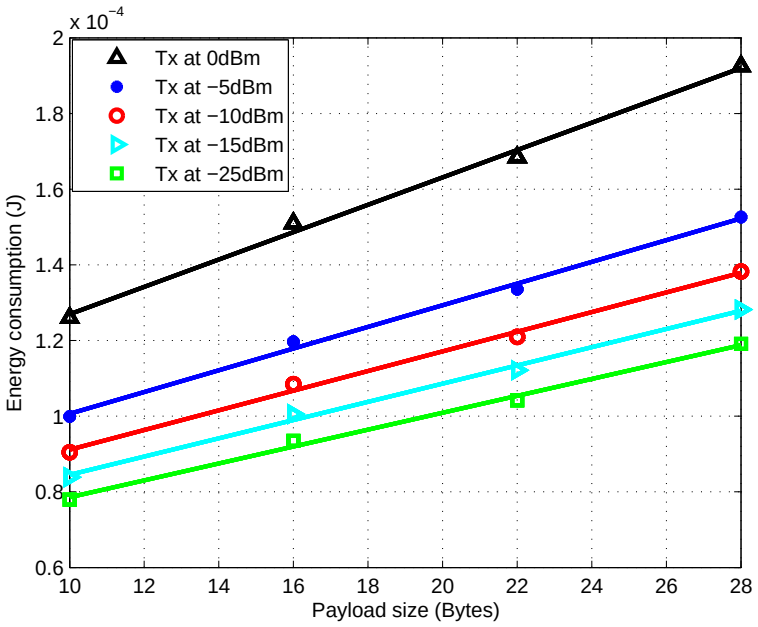


Figure 2.13: Node transmission energy model.

2.4.2 Receiving Energy Model

Unlike the transmission process, the reception of a packet is independent of the payload size. Considering the node listens for 1s the energy consumed is:

$$\begin{aligned} \mathrm{P}_{NODE} &= \mathrm{V} \times \mathrm{I} \\ &= 4.5V \times 35mA = 157.5mW. \end{aligned} \tag{2.48}$$

$$\begin{aligned} \mathrm{E}_{NODE} &= \mathrm{P}_{NODE} \times \mathrm{t}_{MODE} \\ &= 157.5mW \times 1s = 157.5mJ. \end{aligned} \tag{2.49}$$

2.4.3 Sleep Mode Energy Model

Similar to the receiving mode, the sleep mode consumption is also constant as observed from Fig. 4. Assuming the node stays asleep for 1s, the energy consumption is:

$$\begin{aligned} \mathrm{E}_{NODE} &= \mathrm{P}_{NODE} \times \mathrm{t}_{MODE} \\ &= \mathrm{V} \times \mathrm{I} \times \mathrm{t}_{MODE} \\ &= 4.5V \times 3mA \times 1s \\ &= 157.5mJ. \end{aligned} \tag{2.50}$$

2.5 Experimental and Theoretical Lifetime Comparisons

2.5.1 Power Calculations for Member Nodes

Referring to Section 2.2.3, the only factors that have changes in the measurements have been the current values in different modes. The power measurements in Section 2.4 has been used to provide a much accurate power consumption statistics. The currents consumed in the different modes are:

$$\mathrm{I}_t = 19.2mA. \tag{2.51}$$

$$\mathrm{I}_{idle} = 1mA. \tag{2.52}$$

$$\mathrm{I}_s = 0.2mA. \tag{2.53}$$

By using the methodology mentioned in Section 2.4, the total current consumed by the member node in the different states can be derived from Equations 2.7, 2.9, 2.10, 2.14 and 2.17 as

$$\mathrm{I}_{t,a} = 0.0033mA. \tag{2.54}$$

$$\mathrm{I}_{t,l} = 0.0123mA. \tag{2.55}$$

$$\mathrm{I}_s = 1.925 \times 10^{-5}mA. \tag{2.56}$$

The calculations for the memory logger and the MCU remain the same, summing all the

current consumed in different modes, we get,

$$\mathrm{I}_T = 0.4940mA. \tag{2.57}$$

Battery Life

Taking the battery with a rating of 1175 mAh, the life time of a member node is

$$\mathrm{L}_{MN} = \frac{1175mAh}{0.4940mA} \approx 100Days. \tag{2.58}$$

2.5.2 Power Calculations for Cluster Head Nodes

Referring to Section 2.2.3, the only factors that have changes in the measurements have been the current values in different modes. The power measurements in Section 2.4 has been used to provide a much accurate power consumption statistics. The currents consumed in the different modes are:

$$\mathrm{I}_t = 22mA. \tag{2.59}$$

$$\mathrm{I}_{idle} = 1mA. \tag{2.60}$$

$$\mathrm{I}_s = 0.2mA. \tag{2.61}$$

By using the methodology mentioned in Section 2.4, the total current consumed by the cluster head node in the different states can be derived as

$$\mathrm{I}_{t,a} = 0.0038mA. \tag{2.62}$$

$$\mathrm{I}_{t,tx} = 0.002mA. \tag{2.63}$$

$$\mathrm{I}_{t,l} = 0.0499mA. \tag{2.64}$$

$$\mathrm{I}_{rx} = 0.0016mA. \tag{2.65}$$

The calculations for the memory logger, the MCU and the other states remain the same, summing all the current consumed in different modes, we get,

$$\mathrm{I}_{T} = 0.7509mA. \tag{2.66}$$

Battery Life

Taking the battery with a rating of 1175 mAh, the life time of a cluster head node is

$$\mathrm{L}_{MN} = \frac{1175mAh}{0.7509mA} \approx 63Days. \tag{2.67}$$

Comparing the network lifetime figures in Section 2.4 with ones calculated above, it is clear that, the current consumed by the radio during transmission, sleep and idle is different than the figures provided in the datasheet. This difference results in a decrease in the lifetime of the network based on actual measurements.

2.6 Conclusions

A detailed description of the design and optimization process of KFUPM hardware nodes was presented in this chapter. The details of the individual components as well as the design comparison was made. The optimized version was considered as the final version owing to its smaller size as compared to earlier designs. This chapter also provided an

insight into the energy consumption and the life time estimation of the KFUPM node. By using the actual power consumption measurement figures, a linear relationship between payload size and the consumed energy has been derived. Moreover, employing the actual power consumption values, it is concluded that the network life is less due to a difference in the actual measured current and the ones provided in the datasheets.

CHAPTER 3

SENSOR NODE SOFTWARE DEVELOPMENT

Programming is an important part of the wireless sensor node that controls all the functionalities of the node including the sensing, data processing, networking protocols implementation and relaying of data. As discussed in Chapter 1, system programming must be done in such a way that the energy wastage in kept at the least possible value.

Software model development of KFUPM node is explained in Section 3.1. The network monitoring application design details are presented in Section 3.2 with the chapter concluding with a summary in Section 3.3.

3.1 Software for KFUPM Sensor Node

Assembly language is naturally very difficult and time consuming to program as well as to debug. In addition it does not ensure minimum MCU usage to save energy. Because of its associated complexity, Assembly language has its own limitations on the advanced, complex and efficient programming requirements such as in WSNs. Owing to associated severe constraints with Assembly language, a higher level of programming paradigm called TinyOS [51, 60] has been used to create the software interface for the designed node. The system software developed in this work for the implementation of the WSN prototype is hardware platform independent. All the software codes can be compiled for any hardware platform supported by TinyOS.

3.1.1 TinyOS

TinyOS, developed by U.C. Berkeley, is a small, efficient and open-source operating system developed specifically for WSNs [51]. The software itself provides inter-connectable blocks and modules which can be used according to the application requirements. The operating system provides control to handle both sensing as well as device power consumption by varying transmission power levels. Other operating systems like Nano-Qplus [61] do exist for WSN, but the large adaptability and a huge user base has made TinyOS the most widely used platform.

Keeping the limited resource potential of the devices, a new programming language has

been derived from C/C++ called the nesC. To facilitate the programmer, nesC supports component based programming, independent of the hardware platform being used. The components need to be connected according to application and the scheduler inherent to TinyOS controls the operation of the components [62]. Unlike traditional C/C++, TinyOS features event-based scheduler, which releases the resources once they are not being used. This action saves memory and also provides lower power consumption due to less data in the RAM.

TinyOS has mainly been associated with proprietary hardware. Crossbow Technologies is considered as the leader in providing wireless sensor nodes as well as supporting hardware. Mica/MicaZ, Telos/TelosB and Iris motes are examples of some wireless sensor devices from crossbow [47]. The TinyOS package itself comes with complete support for all the above mentioned devices. Since porting TinyOS to KFUPM nodes, a platform had to be defined within TinyOS directories to enable programming. The pin assignment, data flow direction and the handshaking procedures between the onboard devices had to be defined for successful migration to TinyOS. TinyOS enhancement proposals (TEP) are provided by TinyOS and are maintained to provide up-to-date support to the users. TEP 131 [63] is one such document that explains the mandatory conditions for porting TinyOS to custom platforms. By studying the said document, a custom software model for the KFUPM platform was successfully created and was tested by compiling test examples provided in the TinyOS package.

Keeping the changing technology needs in mind, TinyOS has been developed so that newer

hardware devices can be easily accommodated in the already present software structure. This means a flexible hardware abstraction has been adopted in TinyOS [62]. In order to maintain flexibility in the hardware domain, TinyOS hardware structure consists of the following three domains.

1. **Hardware Presentation Layer (HPL):**

   This is the lowest level defined in TinyOS. Individual hardware components i.e., microcontrollers, radio devices and sensors etc. are defined in this layer. Memory mapping of individual devices and the definition of ports of each device is done in this layer.

2. **Hardware Adaptation Layer (HAL):**

   This layer works on top of the interfaces provided by HPL. In other words, the combination of the interfaces of individual components that form a platform is defined in this layer. Definition of ADC channels and interconnection of individual components on the platform are some examples of this layer. HAL is platform dependent.

3. **Hardware Interface Layer (HIL):**

   HIL ports the platform-dependency provided by HAL to a platform-independent interface design. This is the top most level and is independent of the hardware components or the platform being used.

Since the hardware platform being used has been custom built, HAL had to be developed to define the platform (KFUPM). TinyOS already contains HPL support for several components that are available in the market. Therefore, using the HPL support provided by

TinyOS HAL interface for the KFUPM platform has ben defined. The system definition (HIL) was then done independent of the platform specifics according to the demands of TinyOS.

3.1.2 nesC Programming Domain

The network embedded systems C (nesC) is a component-based, event-driven programming language used to build applications for the TinyOS platform. nesC is built as an extension to the C programming language with components "wired" together to run applications on TinyOS. This language enables the release of resources when they are not been used, thus freeing the vital memory caches. In order to make the migration from C/C++ to nesC easier, nesC has a similar syntax as that of the C language. On the contrary, the only thing that distinguishes nesC from C domain is the way the code is organized in nesC. All the applications in nesC are divided into three classes:

1. **Interfaces:**

   Interfaces define the relation between two components [62]. One component *provides* an interface to another component that *uses* it. The providing component must implement some *commands*; which are similar to C/C++ functions. On the other hand, the using interface must signal *events* to mark the completion of commands. To enable concurrency, nesC supports split-phase operations which prevent the usage of a single resource by a particular component for larger amounts of time.

2. **Configurations:**

   Configurations are interconnected components that provide a complete functionality of an application. This interconnection is termed as *wiring* in nesC. While wiring different components, it must be ensured that the commands offered by a component are all implemented in the using component. If any commands are not wired, the program does not compile.

3. **Tasks:**

   Tasks are designed to run long latency operations. Once started, a task runs till completion without any interruptions. nesC handles tasks with the help of a first-in first-out (FIFO) scheduler. All the tasks that are posted in the scheduler are run according to FIFO.

3.1.3 Development of "KFUPM" Software Interface

At the beginning, considerable time was spent exploring the TinyOS application development platform. While studying TinyOS it was realized that a specific software interface had to be developed defining all the details of the hardware architecture of the custom node being developed.

HPL Design

As explained in Chapter 1, TinyOS package has support available for some of the widely used components. Components like the ATmega128, CC2420 radio and the on-board

LEDs had HIL support already available. We had to develop the HIL interpretation for the light sensor (TSL13S) and the temperature sensor (LM-35) for the complete representation. Both the light as well as the temperature sensors are activity-to-voltage devices, i.e., they sense and provide an output voltage that is proportional to the sensed quantity (whether it is the light or the temperature). Since the basic sensing mechanism is the same, only a single interface was required to be created and could be replicated for the second sensor. We implemented a *Read* interface and wired it to the output pin of the sensor. Calling the *Read* interface causes the MCU to sample the voltage at the particular pin to which sensor is connected, thus enabling us to get the digital value of the sensed quantity.

HAL Design

HAL design for the KFUPM node was created by specifying the connections between the different components on the platform. Using the circuit diagram presented in Figure **??** we created a *platform.h* file that included all the components and the location of their HPL files on the disk and defined the KFUPM interface. The next step involved defining the pin connection of the different devices to the MCU. A configuration file was written and the general-purpose I/O pin connections were defined. This marked the completion of the HAL layer and with that KFUPM platform was completely defined.

3.1.4 Installation and Configuration of TinyOS Software Libraries

In order to implement the codes using TinyOS, the first step involved was to install all the binary batches and libraries necessary to build TinyOS applications. This involves libraries such as Avr-gcc compiler, nesC compiler, tinyOS tools repository, avr-libc library, avr-binutils, cygwin, avrDUDE and libusb [64].

3.1.5 Cygwin Environment

TinyOS is best suited and developed to be used with Unix/Linux. However, to use this application in Windows environment, an additional patch called Cygwin is required which basically emulates the Linux environment in windows. Cygwin was successfully installed and configured on the programming PC.

Cygwin is a Unix/Linux-like environment and command-line interface for Microsoft Windows. It is free and open source software, released under the GNU General Public License version 2. It provides native integration of Windows-based applications, data, and other system resources with applications, software tools, and data of the Unix-like environment. Thus it is possible to launch Windows applications from the Cygwin environment, as well as to use Cygwin tools and applications within the Windows operating context. Cygwin consists of two parts: a Dynamic-link library (DLL) as an API compatibility layer providing a substantial part of the POSIX API functionality, and an extensive collection of software tools and applications that provide a Unix-like look and feel.

3.1.6 Compiling Software Code into the Node

To be able to download the codes to the hardware it is important that the PC recognizes the attached custom node. Since there are no drivers available for the custom built node, an application called the AVR Downloader-UploaDEr (AVRDUDE)[64] was utilized for this purpose. This application enables to connect and directly transfer the compiled binary files in either *.hex* or *.srec* format to the attached node via USB interface. AVRDUDE can program the flash and electrically erasable programmable read-only memory (EEPROM), fuse and the lock bits of the AVR microcontroller [64].

In order to download or install the desired files onto the node, the AVRISP MKII programmer has been used. This programmer has the ability to get connected via the USB port. The default hardware drivers that come with this programmer do not work with the AVRDUDE utility. We had to create our own hardware drivers so that AVRDUDE would recognize the port to which the MKII was attached. To do that we used an application called libusb. This utility makes it possible to create dummy drivers so that a particular USB port on the computer can be accessed as if some hardware was attached to it. Once the driver was created we got complete support for out MKII programmer and data download became successful.

3.2 The Network Monitoring Application

The network monitoring application is an important component of any WSN. It is required for the monitoring of the status of the whole network in addition to the network topologies and sensed values over time.

A network monitoring application in the form of front end graphical user interface (GUI) for the monitoring of our developed WSN. This interface provides complete network topology diagram along with a view of the recently received data. The complete route followed by a particular data packet is also shown instantaneously and also offline in this application. We have developed this application for the project not only for the network monitoring purpose but also to help us demonstrate the operation, different functionalities and capabilities of our developed WSN prototype. In addition, the application is linked with a database in which the history of the sensed data and their routes as well as the sensing nodes is kept.

This application will be running at the server computer to which the sink/base node is connected showing different attributes of the network in the form of graphical icons and visual indicators. Several attributes of the network are shown on the front-end application such as

- The newly born nodes.
- Formation of clusters.

- Current head nodes.
- Current sensing member nodes.
- The values of current sensed data such as temperature and light intensity of the area.
- Dead nodes getting out of service in case if not active due to any reason for a specific period of time.
- The route taken by the data from the sensing node up to the sink/base node.
- The nodes and data for the UGN.
- The ability to view the route and data history of any particular sensor node.

3.2.1 Related Work

An extensive literature survey was carried out for the related work but surprisingly not much published work was found in that regard. In [66] Java-based GUI for visualization of wireless data channel communication and the infrastructure backbone activities was developed. It provides a graphical interface for the user to explore the various services offered by the WSN such as temperature and light intensity queries of the building. Secondly, it ensures the validation of the proper operation of the network via augmented visualization of the network topology, the sensor readings, the node health status and the service protocol state.

In [67] a GUI is designed for monitoring current and past measurements for all patients being monitored. All communication between the base station and the PC is done through the universal asynchronous receive and transmit (UART). A separate thread from the main graphical user interface thread is used to maintain constant monitoring of the serial port. Here, the user can add a new patient to the monitoring network at any time by keying in the patient name and the ID of his assigned sensor node. Once entered in the system, all readings received by the PC from the patient's sensor node, will be stored in an object corresponding to the patient. All stored readings can be viewed by selecting the desired patient name in the list.

In [68], the GUI on PDA for patient pulse-rate, and temperature monitoring was presented. It offers four different GUIs. The first is located on the local nurse control station, and it tracks the motion of the resident using motion activations. The second GUI can run on a PDA, permitting a care giver to request real-time environmental conditions of the living space and the vital signs of the resident. It uses a query management system distributed among the PDA, and the sensor devices. The interface graphically presents requested data for clear consumption by the user. Third GUI is an LCD interface board is also designed for the MicaZ for wearable applications. It presents sensor readings, reminders and queries, and can accept rudimentary input from the wearer. The fourth GUI is from a direct medical application based on motion sensors, exists to study the behavioral profile of the user's sleep/wake patterns and life habits, and to detect some pathologies in the early stages.

In [69] the GUI is developed using JAVA to monitor deployment of the sensor network, to initialize the network, and to query the statuses of sensors. In this GUI, the main part is "building plan panel" showing the connection between different sensors located at stairs, exits and emergency exits.

In [70], a graphical user interface (GUI) has been developed in LabVIEW that includes the commands compliant with the IEEE 802.14.51 ZigBee radio sub-specification to send and receive the information in the WSN and shows all active messages in the front panel. This application operates in a PC server and users can control and monitor all parameters.

In [71], the GUI shows the current network topology and serves as a control center from which the user can remotely task the WSN. Moreover, it displays the data collected, which are also persistently stored in a database.

In [72], the GUI platform was developed using Borland C++ Builder programming that is able to interact with the hardware (coordinator) at the base station. Firstly, the user has to discover the surrounding nodes and setting the data polling rate using the buttons provided on the side of the screen. Different colors of the nodes show that the connection between the node and the base station is established or not established. To know the values of the parameters being sensed, the user is able to directly zoom to each sensor node and all the values will be displayed by clicking on the desired node. Here, the actual values of temperature, pH and water turbidity are displayed in real-time. The user can get a one shot display of measurement status at every sensor node by clicking on the coordinator icon. Shown together are the Link Quality Indicator (LQI) values for every

connection between sensor nodes and the coordinator.

All the GUIs discussed above are specific to the application in question. Another problem with the described GUI is that none of them are available for general use. Keeping our network requirements in mind, we decided to create a custom interface that would be easy to implement and simple to operate.

3.2.2 Components Used in Developing

The latest state-of-the-art software tools are used to develop this GUI, e.g.

- Microsoft Visual Studio 2008.
- Microsoft .NET Framework 3.5.
- Visual C 3.5.
- AddFlow 2.0 for .NET.
- Microsoft Access.

The developed NMA can run on Windows XP or Windows Vista/7 platform. The screen resolution should be at least 1024 X 768 for best viewing. Since .Net platform does not natively provide all the required functionalities that were needed to develop the application, we used a software module called AddFlow to help create dynamic icons of nodes, their sensed values and their routes in the form of workflow diagrams. AddFlow is compatible with Visual Studio .NET 2008 so it works under the control of main module programmed in .Net platform for the required graphical functionalities of the application.

Using AddFlow, the drawings can be made and updated dynamically very effectively. Distinct shapes, styles, colors and fonts can be defined on a per item basis (for a node or a link) or as default properties for the display.

3.2.3 The NMA Design

As shown in the Figure 3.1, the main screen of NMA consists of four parts:

Network Viewing Pane

This part of the main window is used to display the network diagram. All the packets received by the sink node are decoded. After extracting the routing information from the received packet, the application draws the route in the network viewing space. In addition, the corresponding values of the sensed parameters (light intensity and temperature) are also displayed along the route. Within the network viewing window, eleven horizontal lines are drawn corresponding to the eleven available power levels. After receiving the packet, the levels of all the nodes throughout the path are determined and the node is drawn in the corresponding space in the network viewing window.

Data Viewing Window

This portion of the NMA is used to display the light and the temperature values of the recently received packet at the sink node along with the ID of the sensing node. Although the sensed parameters are also being displayed along the node on the network, due to the congested space in the network viewing window the font size is relatively small. The

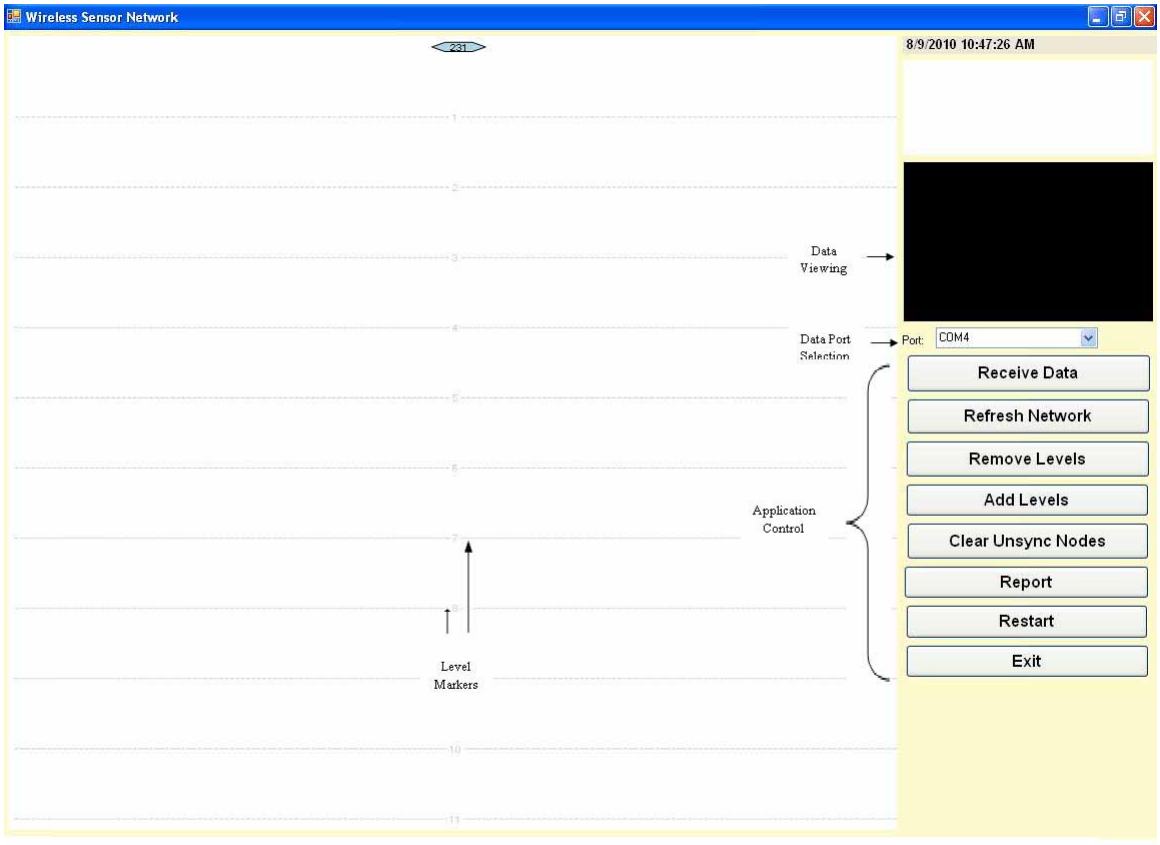


Figure 3.1: NMA main screen shot.

received data is displayed in the data viewing window with a larger font size for ease of monitoring.

Application Control and Options

This part of NMA provides different controls and options available for the operation of the application. the following buttons constitute the application control part.

Data Port Selection: As the server machine may have several USB ports, the port to which the sink node is connected must be selected for the operation of NMA. This

drop-down menu lists all the ports available on the server machine. The administrator has to select the correct port based on the connection of the base node.

Receive Data: This button opens the input/output port for communications. The port that has been selected from the dropdown list must be opened using this button to enable communication with the sink node.

Refresh Network: This button clears or refreshes the network viewing window and the network is drawn again from scratch as packets are received.

Remove/Add Levels: These buttons invert the operation of each other. By default the network viewing window contains the power level lines (Figure 3.1) and the network is drawn around them. If viewing of the network becomes difficult due to increased number of nodes, the level lines can be removed by using remove levels and can be made visible again by add levels.

Clear Unsync Nodes: In case of alarm, unsynchronized nodes from the incident-based portion of the network will start to transmit data. Only five unsynchronized nodes have been programmed to be displayed on the NMA simultaneously. Since there can be only a few unsynchronized nodes (five for this prototype system), once the administrator sees and acknowledges the alarm he can reset or turn it off by the clear Unsync button which removes the unsync node display once the alarm has been acknowledged.

Report: This button opens the report window where the history of the routes for each node can be observed in the report window.

Restart: This button restarts the complete application. The port is closed and needs to

be opened again once the restart is complete.

Exit: This button shuts down and exists the application properly by deleting the unwanted history from the data base and by closing the communications port formally. For error-free exits, the button must be utilized. Fig. 3.2 shows a screen shot of the working instance of NMA.

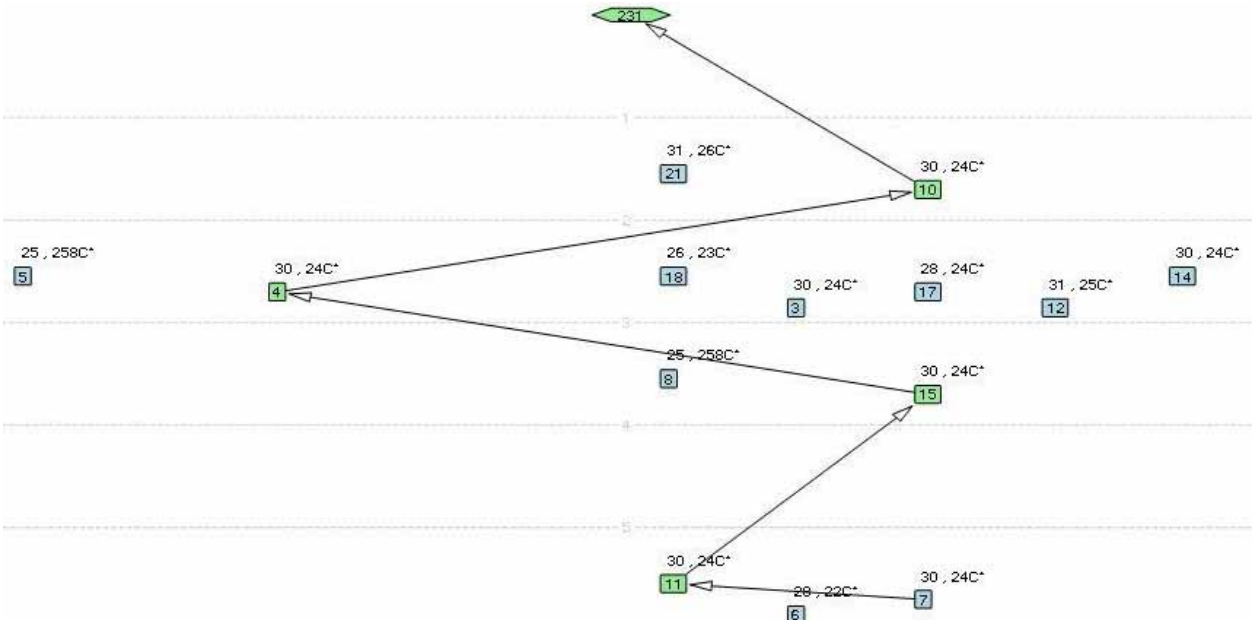


Figure 3.2: Node 7 routes data through CHs 11, 15, 4 and 10

3.3 Conclusions

A detailed explanation of the design and implementation of the software models for the KFUPM node was presented in this chapter. Due to the immense abilities of TinyOS regarding energy conservation, it was employed and was explained in conjunction to

the nesC programming language. All the different patches required for the operation of TinyOS were mentioned in brief detail. The creation of a software interface model in TinyOS for the new KFUPM sensor node has been achieved and subsequent tests have proven its workability. In order to monitor the network, NMA was custom created for this application and has been used extensively for testing.

CHAPTER 4

MAC AND ROUTING PROTOCOL IMPLEMENTATION

In order to set up the WSN, protocols must be implemented both at the MAC as well as on the routing layer to first establish the link level connections up to the sink node and then to route the sensed data reliably. The primary objective in WSNs protocols design is to maximize the node and ultimately the network lifetime. These protocols have to ensure communications network that is robust, reliable, and flexible as well as energy conservative/efficient at the same time. The protocols must also ensure that the topology changes are well covered. The birth or death of a node must not affect the operation of the network and the data acquisition as well as the routing operations should continue in a streamlined manner. For the sink node to receive the data from all the nodes in the network, a routing protocol must be implemented such that the data is reliably

propagated through the network. At the network layer, the main aim is to find ways for energy-efficient route setup and reliable routing of the data from the sensor nodes to the sink node such that the lifetime of the network is maximized.

Section 4.1 provides a brief overview of the work already done at MAC and routing. Basic design considerations are presented in Section 4.2. In Section 4.3, the design assumptions are presented followed by network default settings in Section 4.4. Section 4.5 presents the details of MAC layer protocol implementation. The routing layer protocol implementation is presented in Section 4.6.

4.1 Related Work

A detailed survey of the protocols reported in the literature specifically for the WSNs was made as explained in Chapter 1. The implementation of the MAC layer protocols heavily depend on the nature and type of application in use. Since we had proposed to develop the WSN for environmental monitoring applications (e.g. temperature, humidity and light) we selected the class and type of the protocols to best suit the requirements of these types of applications. These protocols have been selected based on the criteria of simplicity and efficiency and to best suit the environmental monitoring application with the essential requirements of the energy conservation and scalability.

A number of published papers and their corresponding MAC protocols were studied. Two promising protocols were studied in detail; namely the S-MAC [16], and the most recent one SCP-MAC [65].

Routing in WSNs is very different from ordinary networks due to several characteristics that distinguish them from contemporary communication and wireless ad hoc networks, such as:

- In WSN it is not possible to build a global addressing scheme for the deployment of large number of sensor nodes.
- On the contrary to ordinary networks, almost all applications of sensor networks require the flow of sensed data from multiple regions (sources) to a particular sink.
- The most important factor is that sensor nodes are tightly constrained in terms of transmission power, on-board energy, processing capacity and storage and thus require careful resource management.

Due to such differences, many new algorithms have been proposed for the problem of routing data in sensor networks. These routing mechanisms have considered the characteristics of sensor nodes along with the application and architecture requirements.

However, it is important to note that the algorithmic details of S-MAC, SCP-MAC and for the routing layer protocols were not explained in literature of any of the data link layer and networking protocols. Hence we had to create and devise exact and efficient ways to implement the algorithmic details of the protocols by extensive brainstorming, detailed discussions, and hundreds of hours of testing and experimentation to come up with the right approach to achieve the desired goal required from these networking protocols.

4.2 Protocol Design Considerations

4.2.1 MAC

For all shared-medium networks including the WSNs, medium access control (MAC) is an important layer that enables the successful operation of the network. One fundamental task of this layer is to establish links and avoid collisions from interfering nodes. To design a good MAC protocol for the static wireless sensor networks, two important attributes are considered. The very first is the energy efficiency; sensor nodes are to be battery-powered, and it is often very difficult to change or recharge batteries for these nodes. Thus, prolonging the network lifetime for these nodes is a critical issue.

Another important attribute is the scalability and the adaptivity to changes in network size and node density. Some nodes may die over time and some new nodes may join later. A good MAC protocol should gracefully accommodate such network changes. Other typically important attributes like fairness, latency, throughput, and bandwidth utilization may be secondary in sensor networks.

4.2.2 Routing

Design Factors

The following factors play an important role deciding about the class and architecture of network protocols to be used in WSN:

1. Network dynamics: The sensed event can be either dynamic or static depending on the application. Monitoring static events allows the network to work in a reactive mode, simply generating traffic when reporting. Dynamic events in most applications require periodic reporting and consequently generate significant traffic to be routed to the sink. In our case of environmental monitoring, we will assume that we are monitoring static events.

2. Network topology: Another consideration is the topological deployment of the nodes. This is again application dependent and affects the performance of the routing protocol. The deployment is either deterministic or self-organizing. In deterministic situations, the sensor nodes are manually placed. However in self organizing systems, the sensor nodes are scattered randomly creating an infrastructure in an ad hoc manner.

3. Routing mode: Since the transmission power of a wireless radio is proportional to the exponent of the traveled distance squared, multi-hop routing consumes less energy than direct communication with the sink node. However, multi-hop routing introduces significant overhead for topology management and medium access control. Direct routing would perform well enough if all the nodes were very close to the sink. In our case, we intend to use multi-hop routing with clustering in order to optimize the complexity and energy efficiency.

4. Data delivery models: Depending on the application of the sensor network, the data

delivery model to the sink can be continuous, event-driven, query-driven or hybrid. In the continuous delivery model, each sensor sends data periodically. In the event-driven and query-driven models, the transmission of data is triggered when an event occurs or a query is generated by the sink. Some networks apply a hybrid model using a combination of continuous, event-driven and query-driven data delivery. For our application, we plan to use event-driven model as the sensor nodes will be reporting when there is some kind of change in the entity being monitored.

5. Data aggregation/fusion: Since sensor nodes might generate significant redundant data and hence, similar packets from multiple nodes can be aggregated so that the number of transmissions would be reduced. It is well known that energy consumed in processing such redundant packets is much less than energy required for transmission. Therefore, we also plan to make use of data aggregation in order to conserve energy in transmission.

Classification of Routing Protocols for WSNs

Almost all of the routing protocols can be classified as data-centric, hierarchical or location-based.

- Data-centric protocols are query-based and depend on the naming of desired data, which helps in eliminating many redundant transmissions.
- Hierarchical protocols aim at clustering the nodes so that cluster heads can do some aggregation and reduction of data in order to save energy.

- Location-based protocols utilize the position information to relay the data to the desired regions rather than to the whole network.

- There are some protocols that are hybrid and combine the characteristics of the above three categories to achieve their specific application objectives.

Based on the above mentioned considerations and assumptions, a detailed literature survey was made for routing layer protocols and few appropriate hierarchical protocols were studied for potential implementation in our network e.g. low-energy adaptive clustering hierarchy (LEACH) [16], power-efficient gathering in sensor information systems (PEGASIS) protocols [38], threshold sensitive energy efficient sensor network protocol (TEEN) [39], and adaptive threshold sensitive energy efficient sensor network protocol (APTEEN) [40]. The choice to go for hierarchical based protocol was based to simplify the data routing process. If peer based routing was selected, then every sensor node had to know every other sensor node in its surrounding causing memory wastage in updating and maintaining node tables. In hierarchical based protocols, only the head maintains the address tables of its peers, the member nodes do not need to have any tables.

4.3 Implementation Assumptions

During the implementation of the MAC and network protocol, we have made the following assumptions that have to be considered while understanding the operation of our network:

- The network is assumed to be static, i.e. the nodes are stationary and will remain

in the same physical position throughout the lifetime of the network.

- All the nodes have same energy reserves, i.e., they are running on exactly the same type of batteries.
- The nodes are placed/scattered randomly in the field and the nodes form the network and later organize themselves automatically.
- The sink node has unlimited power supply, so power conservation techniques need not apply to the sink.
- The coverage of the sink node is assumed to be all over the network. In other words, all the nodes can hear the packets transmitted by the sink.
- Only the member nodes are responsible for sensing. The CH nodes do not perform sensing and serve for relaying and routing the data packet from sensing nodes towards the sink node.
- The member nodes communicate in Unicast only with their corresponding CHs.
- The keep alive messages are not acknowledged.
- For demonstration purposes and due to the limited number of nodes available, we have assumed that all the nodes will group them in maximum of 10 clusters distributed in 5 levels (although the values of the power levels can be any of the 11 allowed levels).

- We have also assumed that only two clusters can lie at any single power level. However, the implemented networking protocols are totally flexible and can be programmed to support much larger area and number of nodes/clusters, if required.

4.4 System/Network Default Settings

The current settings of the system and network are as follows. These settings can be modified very easily in the system software any time depending upon the particular requirements of the application for which the WSN is being employed:

- All nodes are identical and act both as sensing node and act as CH on their turn.
- The network topology is of cluster based.
- The sink node broadcast the beacon signal at every 4 sec.
- At the startup, every node waits for 5 sec before deciding whether it should declare itself as a new cluster head or to join an existing cluster as a member.
- The received signal strength indicator (RSSI) value threshold is -5 dBm.
- The member nodes send keep-alive messages to their CH once every cycle.
- The duration of the cycle of all the nodes in the network is 4000 ms or 4 sec.
- A cluster head remains ON for 300 ms and sleeps for 3700 ms or 3.7 sec.

- The member nodes are awake for 100 ms and asleep for 3900 ms or 3.90 sec. Thus keeping the same duration of the cycle as that of the cluster heads.
- The responsibility of CH is shifted to other members of the cluster after every 10 cycles or 40 sec.
- The cluster ID is generated by the first CH by padding 0 to its own hard-coded node ID. This cluster ID is maintained by all the nodes throughout the cluster life.
- The communication between the member node and CHs occurs at the lowest transmission power of the transceiver (mode 1) whereas for inter-CHs communications, a higher transmission power level (mode 3) is used.
- If a CH does not receive a keep-alive from a particular node for more than 3 cycles, it is considered dead and is removed from the cluster table.
- After the rotation of the CH, the routing tables are updated within 5 sec.
- The data is relayed from the sensing node to the sink node by multi-hop dynamic routes.
- In the main synchronized network, the environment attributes are being sensed continuously/periodically and being relayed to the sink on a regular basis.
- In the unsynchronized portion of the network, the nodes keep sensing the environment on continuous basis but report the values only in case of a predefined incident.

- Routing tables are updated after every 20 sec.
- The levels once assigned to a node will remain constant during the lifetime of the node.

Figure 4.1 shows the complete timing process graphically. The sink node sends the beacon periodically after every 4 sec. When a node wakes up it listens for 5 seconds, receives the beacon and declares itself head by broadcasting the keep-alive and sleeping after 300ms (Figure 4.1). Similarly a member node on boot-up receives the keep alive of the CH and goes to sleep after 100ms as indicated.

4.5 Implemented Protocol - MAC

As mentioned above also, the MAC protocol that we have actually implemented has many ideas from the S-MAC protocol. Several factors were not mentioned in the literature and have been devised to accomplish the desired tasks.

4.5.1 Packet Format

As suggested in S-MAC protocol, there are two types of packets in our implementation; namely, control packets and data packets. The specific format of these packets has not been defined in S-MAC and therefore we have defined the payload structure of each of these packet types depending on our intended application's need and requirements. The packets are parsed into two sections; namely, the header part and the payload part. The

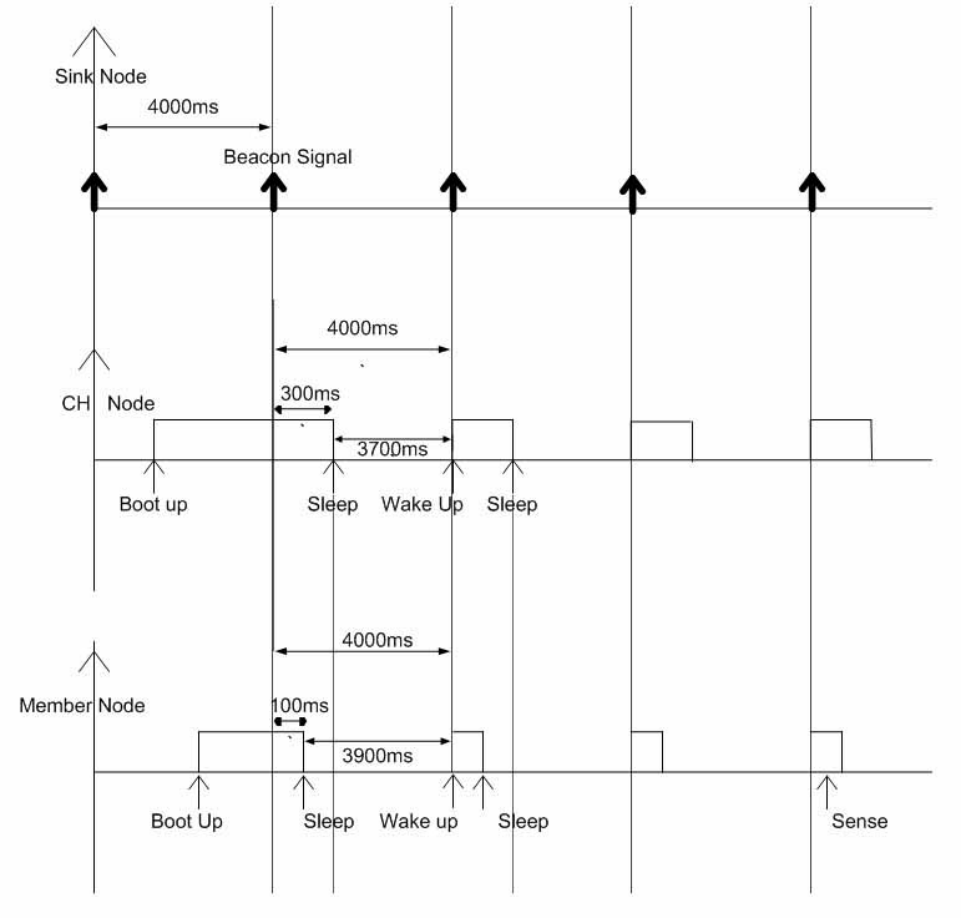


Figure 4.1: Timing diagram of duty cycles of CH and Member Nodes.

header section of the packet is created by the transceiver and we don't have control over it. The payload section of the packet is where we define different fields for different operations both in the control packet and in the data packet.

Control Packets

Control packets are the packets that are responsible for setting up the point-to-point links and clusters, establishing the network topology and ensuring smooth and reliable data

transfer between the nodes. The control packets are obviously overhead for the network operation and ultimately decrease the effective throughput of the system. Therefore, they are desired to be minimally transmitted and only if/when required. Also, since there is no data in these packets, it was a design requirement to make them as small as possible so that least energy is wasted for the transmission of this packet type. The format of the control packets is shown in Table 4.1. It is a 16-bytes packet with the header of 13 bytes long and the remaining 3 bytes are used in different scenarios for different purposes as explained below.

Table 4.1: Control packet definition.

Byte number	Function	Type
1,2	Packet start identifier	Radio header
3	Leading zeros	Radio header
4,5	Destination ID	Radio header
6,7	Source ID	Radio header
8	Payload Length	Radio header
9	Group ID	Radio header
10	Message type	Radio header
11	Cluster ID (CID)	Payload
12	Node level (NL)	Payload
13	Identifier	Payload
14,15	Checksum	Radio header
16	packet end identifier	Radio header

Cluster ID (CID)(1 byte): This field in the packet identifies the cluster ID of the sending node. Each cluster has a unique ID assigned by its first cluster head (CH) at the time of the birth of the new cluster and all the nodes belonging to that cluster are identified by the cluster ID.

Level (L)(1 byte): This field identifies the hierarchical position of the cluster in the routing tree. To enable routing of the packets to the sink node, each cluster assigns itself a power level. This is discussed in more detail in the routing protocol implementation.

Type (T)(1 byte): This field acts as an identifier for the type of the control packet. It distinguishes between the different types of control packets that we have formulated. Table 4.2 gives the details of all the control packet types, their use in the network formation and maintenance and their corresponding values in the T field.

Table 4.2: Type field for control packets.

Type Field Argument	Packet Type	Flow Direction
0x00	Keep alive within a cluster	CH to member nodes.
0x01	Keep alive packet between CHs	CH to other CHs
0x0A	RTS	sending node to receiving node
0x0B	CTS	receiving node to sending node
0x0C	CH control transfer request	Sent from current CH to the new CH
0x0D	CH control transfer response	Sent from the new CH to current CH

Data Packets

The data packet is used to carry the data, from the sensing member node to the corresponding CH, and subsequently from the CH to CH until the data reaches the sink node and ultimately received by the server. The complete length of the data packet is 31 bytes including the header and the payload. The header is 13 bytes long and the remaining portion of the packet is the payload that we have formulated according to our requirements.

We have used the payload part of the data packet not only to carry the sensed data but also to carry the routing information along the route (for the debugging purpose only) as well as to display the routing information on the front-end application (for the demonstration purposes only). In the practical deployment of the network, most part of this routing information is not needed and thus the packet size can be reduced to just 4 bytes required for storing light and temperature data. The format of the data packet is shown in Table 4.3.

The definitions and descriptions of different fields of data packet in the payload part of the data packet are explained below.

Temp and Light (4 bytes): These two fields constitute the data field jointly. The Temp field contains the sensed value of the ambient temperature and the light field contains the sensed reading of light intensity.

Hop Count (HC) (1 byte): This field serves the purpose of indicating the hop count of the packet at a particular intermediate node. The hop count enables to easily and quickly

Table 4.3: Data packet definition payload definition.

Byte number	Function	Type
11,12	Temperature value (Temp)	Payload
13,14	Node level (NL)	Payload
15	Hop count (HC)	Payload
16	Cluster ID (CID)	Payload
17	Sensing node ID (NID)	Payload
18	Intermediate node ID 1 (IID1)	Payload
19	Intermediate node ID 2 (IID2)	Payload
20	Intermediate node ID 3 (IID3)	Payload
21	Intermediate node ID 4 (IID4)	Payload
22	Intermediate node ID 5 (IID5)	Payload
23	Sensing node level (SL)	Payload
24	Intermediate Node Level 1 (IL1)	Payload
25	Intermediate Node Level 2 (IL2)	Payload
26	Intermediate Node Level 3 (IL3)	Payload
27	Intermediate Node Level 4 (IL4)	Payload
28	Intermediate Node Level 5 (IL5)	Payload

fill in the next node ID in the packet without reading the complete packet. For example, if the hop count is 2, this means the packet has already traveled two hops, so the next address is placed at IID-3 without reading the complete address path.

Cluster ID (CID) (1 byte): This field in the packet identifies the cluster ID of the sending node. Each cluster is has a unique ID assigned by its first CH at the time of the birth of the new cluster and all the nodes belonging to that cluster are identified by the cluster ID.

Sensing Node ID (NID) (1 byte): This field carries the ID of the sensing node. This unique ID is assigned to each node at boot-up and is hard-coded inside every node. Each node is given a unique ID that is not repeated in the remainder of the network.

Intermediate Node ID (IID1 - IID5) (5 bytes): These 5 fields are used to convey the complete route information the packet traverses from the sensing node to the sink. In the current implementation, we have programmed the system to operate for a maximum of six hops including the hop from the sensing node to the CH. If the packet reaches the sink with less than six hops, the remaining corresponding fields are set to zero, otherwise, the fields have the node IDs of all the intermediate heads that relay the data packet.

Sensing Node Level (1 byte): This field contains the assigned power level of the sensing node.

Intermediate Node Level 1 (IL1 - IL5) (5 bytes): These fields provide the power levels of the intermediate CHs.

4.5.2 Scheduling Control

Similar to the S-MAC, our implementation also incorporates the coordinated sleeping of the nodes to conserve the power. The sink node serves as the data collection center and also the schedule synchronization source of the network. The sink node is connected via USB port to the Network Monitoring Server for the onward processing of the received data and monitoring of the network status. All the nodes in the network are synchronized with the sink node.

Since the sink node is assumed to have unlimited amount of power, the transmission of the beacon signal is done at the maximum available power level of the radio. The sink node transmits a broadcast beacon signal once every cycle i.e. once in every 4 seconds. This beacon signal prompts all the nodes in the network to sleep after predefined time and at the same time provides a counter value. At the time of startup, all the nodes are randomly placed. When the first node wakes up, it receives the beacon signal from the sink. Upon receiving this packet from the sink, the CHs adjusts their timers such that they go to sleep 300 ms after the reception of the beacon signal while the member nodes sleep after 100 ms of the reception of the beacon signal. This means that the duty cycle for the CHs is 300 / 4000 and the duty cycle for the member nodes is 100 / 4000.

The wake time for the CHs is chosen to be larger than the member nodes because the member nodes simply need to sense the data and pass it on to the corresponding CH. But the CHs not only have to receive data from multiple member nodes, they also have to

take part in the data relaying and routing process also. Therefore, they must keep awake for longer time compared to the member nodes. The beacon signal also has a countdown value that is decremented in each subsequent signal by 4, that indicates the time left until the CH responsibility shifts to another node. Therefore, all the new nodes that boot up later in the network are also tuned to the cluster shifting schedule.

4.5.3 Link Formation

At the time of startup, a node wakes-up and checks for the existence of any neighboring CHs. This node waits for 5 seconds and if it does not receive any signal from any nearby node, it declares itself a CH of a new cluster, otherwise, if the newly wakeup node receives keep alive control signal from an existing cluster head, it measures the signal strength and if the signal strength is below the threshold , it discards the signal from the other cluster head and assumes that it has to make its own cluster by declaring itself the head of that new cluster. This decision is made depending on the threshold value of the RSSI of the received keep alive control packet. More specifically, when any wireless node receives the signal, it measures the power of the received signal by reading RSSI register of the CC2420 Transceiver. CC2420 has this built-in RSSI providing a digital value that can be read by the microcontroller from the 8-bit register. If the RSSI value is less than -5 dBm, it is considered that the new node is physically sufficiently away from the CH that it is better to form a new cluster instead of joining that existing cluster. This means that the new node must form a new cluster and become the CH. The threshold value of -5 dBm

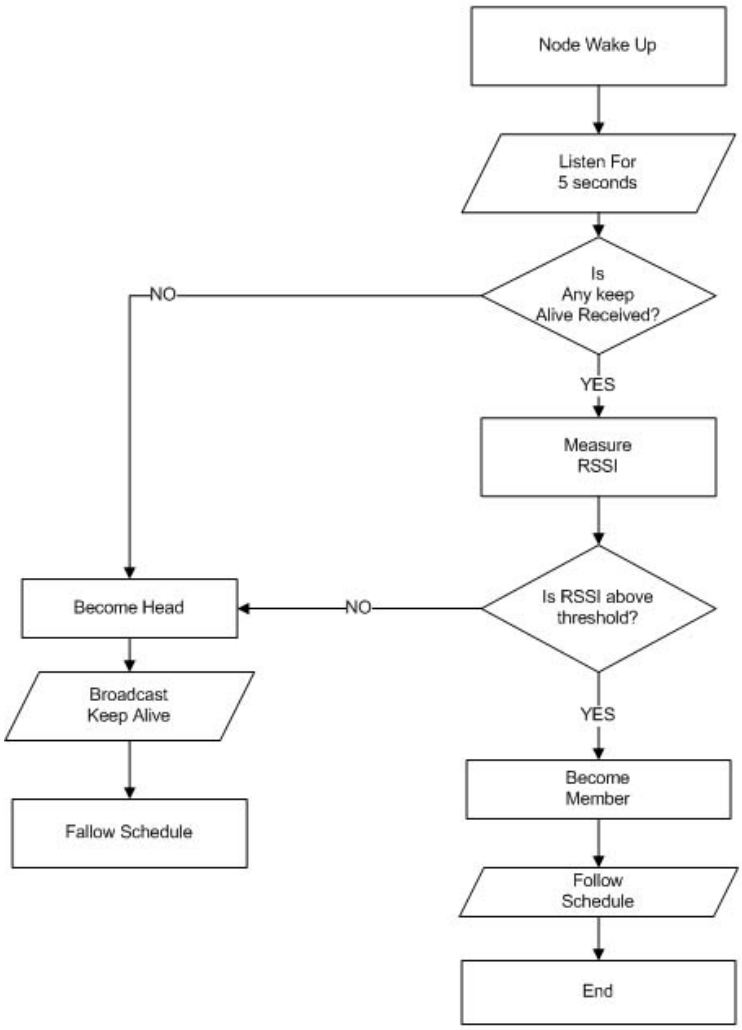


Figure 4.2: Boot-up process of a sensor node.

has been selected after extensive experimentation and has been found to be optimum for a typical indoor environment. This link formation process is represented in flowchart of Figure 4.2.

If the node receives control signal from an existing CH and the signal strength is above the threshold, it joins that cluster as a member and assigns itself the cluster ID of that head. More specifically, if the RSSI of the received keep-alive control packet is greater than -5 dBm, then this new node becomes member of that cluster and adopts the cluster ID that it receives in the the control packet. If a node receives signals from two or more CHs it joins as a member of the cluster whose head is nearer to it by measuring the signal strength of their keep alive signals and comparing their powers.

4.5.4 Formation of Clusters

As other cluster heads wake up, as explained above, they start following the same wake-up schedule which synchronizes them with the timing of the network. With the course of time more clusters can be formed as well as more member nodes can join the clusters and population of the cluster as well as the network grows.

The cluster ID is generated by multiplying the node ID of the first cluster head node with 10. This scheme of generating cluster IDs allows to support a large number of clusters. During the whole operation of the network, all the nodes keep this same cluster ID. Each of the CHs create and maintain a cluster table that has the node IDs of its members. This table is created after receiving the keep-alive packets from the member nodes and is

used to select the next CH in the rotation. The next CH is selected as the node which has the next lower cluster ID than the current CH. In other words CHs are selected based on descending order of node IDs of all the entries of the cluster tables. If a CH does not receive a keep-alive from a particular node for more than 3 cycles, it is considered dead and is removed from the cluster table. New entries are added and old ones are refreshed and updated as the keep-alive messages are received.

The cluster tables are formed and maintained by the CHs only and the member nodes don't need to maintain these tables. When a CH becomes the member node after the cluster rotation, it flushes the clusters table it was keeping and the new CH starts building its own cluster table.

Every CH broadcasts a keep alive packet in each alternate cycle (i.e after every 8s). The purpose of this keep alive is to tell the immediate neighboring CH nodes about the presence of this node and to keep its entry in the routing table entries. As a result, each of the CHs refresh and maintain a routing table to select the proper route, this is discussed in detail in Section 4.6.

4.5.5 Control and Data Packets Transfer

All the member nodes within a cluster regularly (once in three cycles, i.e. every 12 seconds) sense the temperature and light of the environment and send the raw data to their respective CHs soonest as per the multiple access algorithm. In addition to that, the member nodes also send the keep-alive message to their corresponding CHs once every

cycle to help the CH to update its cluster table. It should be noted that the member nodes send data only to their assigned CH (unicast communication) and not to other cluster heads. Once the cluster head gets the data, it routes the data towards the base with the help of the intermediate CHs.

The transmission power of the transceiver CC2420 radio unit can be adjusted at different settings. For the sake of conservation of the energy used in the transmission power, the communications between member nodes and the CHs have been programmed at lowest transmission power (mode 1) of the transceiver so that only the concerned nodes within the cluster get the data with full conservation of power. For inter-cluster head communications, a higher transmission power level (mode 3) is used in order to give heads more coverage as they need to communicate with other clusters heads at further distances.

4.5.6 Channel Contention and Multiple Access Control

In our implementation, the member nodes sample the temperature and light sensors every 12s and send the sensed values to their CHs. But because of the wireless medium and multiple candidates contend for transmission, every node must check whether any signal is present on the wireless channel or not so that collisions can be avoided. This is done both by physical and virtual carrier sense as explained below.

In physical carrier sensing, the node scans the channel physically to check the presence of any signal. If the channel is found to be busy, the node backs off and tries again in the next cycle. On the other hand in virtual carrier sense, the node during its wake time listens

to the transmissions in its vicinity. When it receives a frame destined to another node it extracts the duration field value (containing the remaining time to finish the current transmission) from the frame and put it in the NAV register and starts decrementing it as indicated in Figure 1.3. A member node takes decision to send a (control or data) packet only when the NAV gets zero and at the same time the physical carrier sensing also turns up negative. Similar procedure is followed when the packet is passed from one head node to another head node for relaying the data towards the sink node.

The virtual carrier sensing is performed before the physical carrier sense. Since physical carrier sensing involves powering ON the radio and actually listening to the channel, therefore this step consumes more power as compared to the virtual carrier sensing. Therefore, it has been decided to carry out virtual carrier sensing to decrease the probability of finding the channel busy and only proceed with the physical carrier sensing to ensure that there is no transmission in the neighborhood and the channel is free.

4.5.7 Data Transfer

Once the data is sensed by the sensing node and is available for transmission after making sure the wireless channel is free, the sensing node sends a unicast RTS packet to its CH. When the RTS is received by the CH, depending on whether the CH node is free or not, the CH responds by sending a unicast CTS packet to the corresponding sensing node. Upon receiving the CTS, the node transmits the data packet to the CH. After the successful delivery of the data the CH sends the ACK signal to the member node to confirm that

it has received the data properly. If the intended receiver does not receive the packet for some reason such as collision, the ACK is not received by the member node and the contention process is repeated again. The same procedure is followed for the data transfer from one CH to the another CH. Flowchart in Figure 4.3 shows the implemented MAC protocol.

To ensure that the whole message is transferred during the wake interval of the nodes, a check has been added to ensure that the intended recipient node sends the CTS only if there is sufficient time available in the wake period to complete the transaction. If there is insufficient time to complete the communication, the intended recipient does not send the CTS and the sensing node contends for the channel again in the next wake period.

4.5.8 Head Rotation Operation

As mentioned earlier, in order to balance the power consumption among the nodes in a cluster, the cluster head responsibility is rotated every 10 cycles, i.e., every 40s. This is performed in a descending order of the node IDs of the member nodes in the cluster table. Two special type of control packets called the handshaking packets (Table 4.2) are exchanged between the CH and the member nodes for handshaking of the CH responsibility handover rotation.

Once the switch over of CH takes place, the new CH listens to the keep-alive messages of the neighboring CHs as well as the keep-alive messages of the member nodes to create routing tables and cluster tables, respectively. This process takes time that varies de-

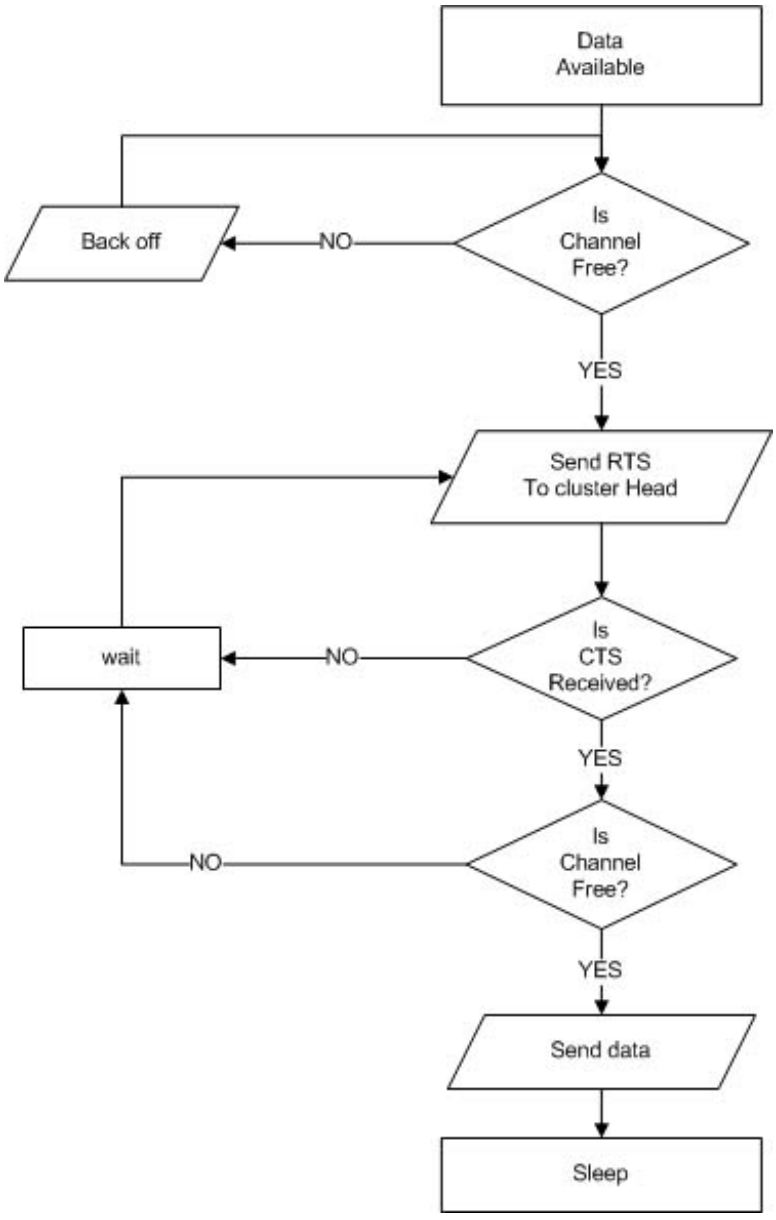


Figure 4.3: Channel contention of member node to send data packet.

pending on the time taken by all the members and neighbor CH to send their keep-alive packets. At the same time, the new CH also transmits its own keep-alive message to alert the neighboring clusters that now it is acting as the head of the cluster and all the routing must be done through it instead of the old CH.

4.5.9 Differences between S-MAC Protocol and Implemented Protocol

As the implementation details were not found during the literature survey, we had to devise unique methods to implement the S-MAC protocol. In the process of doing so, we created a protocol that was different from the S-MAC. Some of the most important differences are listed below.

1. S-MAC is designed for multi-hop networks, and does not require that all nodes are synchronized together. While our implementation enable the nodes to communicate with each others, the sleep times are synchronized, i.e., all the nodes sleep and wake-up at the same time. These schedules are maintained by every node, thus enabling them to know when the neighboring node will be awake so that data can be sent to it. The advantage of our approach is that it reduces the latency of the network as if the different group of nodes follow different schedules, they increase the delay in relaying the data in a multi-hop environment.

2. All nodes are free to choose their own listen/sleep schedules, while in our imple-

mentation the whole network has a single schedule that is controlled by the sink node and followed by all the nodes in the network. This was chosen to simplify the scheduling process as well as to have a single master clock in the network. If there are different groups of nodes trying to schedule the periodic sleeping, it will result in large timing difference among the nodes due to the natural different clock drifts speeds in different nodes processors. Also, in the implementation of S-MAC, they also expect that nodes only rarely see multiple schedules, since each node tries to follow an existing schedule before choosing an independent one. In S-MAC, since neighboring nodes coordinate their sleep schedules the clock drift on each node can cause synchronization errors. Whereas in our techniques the synchronization process remain robust to such errors and simple at the same time. Moreover, all the exchanged timestamps are relative rather than absolute.

3. In S-MAC, the network consists of large numbers of nodes to take advantage of short-range, multi-hop communications to conserve energy. Most communications will occur between nodes as peers, rather than to a single base station. In our case, the infrastructure is cluster-based and the member nodes communicate with their CHs only, and the data is relayed in a multi hop routing manner by cluster heads only.

4. In S-MAC, the nodes do not follow their sleep schedules until they finish the transmission, while in our implementation, the intended recipient node makes sure that there is enough time left in the wake period for receiving the data successfully before

its sleep time and only in that case the CTS signal is sent to the sender. This again simplifies the whole operation as the schedules remain undisturbed.

5. Also, S-MAC protocol does not restrict on using a predefined packet structure and leaves this on the specific implementation. This gives us the flexibility to use custom designed payload structures according to our requirements.

4.6 Implemented Protocol - Routing

The routing layer protocol for our implementation has been mostly inspired by the combination of LEACH and TEEN protocols. However, as mentioned for the MAC protocol implementation also, the algorithmic details of LEACH and TEEN were not explained in literature and we had to invent and devise exact and efficient ways to implement these algorithmic details by extensive brainstorming, detailed discussions, and hundreds of hours of testing and experimentation to come up with the best approach to achieve the desired goal required from these networking protocols.

4.6.1 Network Topology

The sink node has a constant power supply and therefore has no energy constraints. It can transmit with high power to all the nodes. Thus, there is no need for routing mechanism from the sink node to any wireless network node. However, the wireless network nodes are assumed to be far away from the sink node and because of their power constraints it

is not feasible to communicate directly to the sink node.

The network topology that we have implemented is of a clustered type multi-hop routing similar to the LEACH protocol as shown in Figure 4.4. The model consists of clusters (represented by the cloud) each consisting of a number of nodes. In each cluster at any given time, one node acts as a cluster head (CH) (nodes A, B, C, and D etc.), whereas the remaining nodes are the member nodes in that cluster (nodes A-1, A-2, B-1, B-2, etc.). Only the member nodes perform the data sensing and the CHs are responsible for receiving the data from the member node and route it reliably and efficiently to the sink node.

Initially, the CH was fixed and hard-coded in our program but later the CH was successfully programmed to be dynamically rotated based on criteria defined in the Section 4.5.8 and then the head responsibility rotates among the member nodes in order to balance the power consumption load between all member nodes equally.

Network Tree and Routing Tables

During the network setup phase, a logical network tree is created which comprises of all the clusters placed at different power levels. These levels indicate the depth of the tree relative to the sink node. To decide the levels, the sink or base node (S) regularly broadcasts a beacon signal. When any wireless node receives the beacon signal, it measures the power of the received signal by reading RSSI register of the CC2420 Transceiver. CC2420 has this built-in RSSI providing a digital value that can be read by the microcontroller from

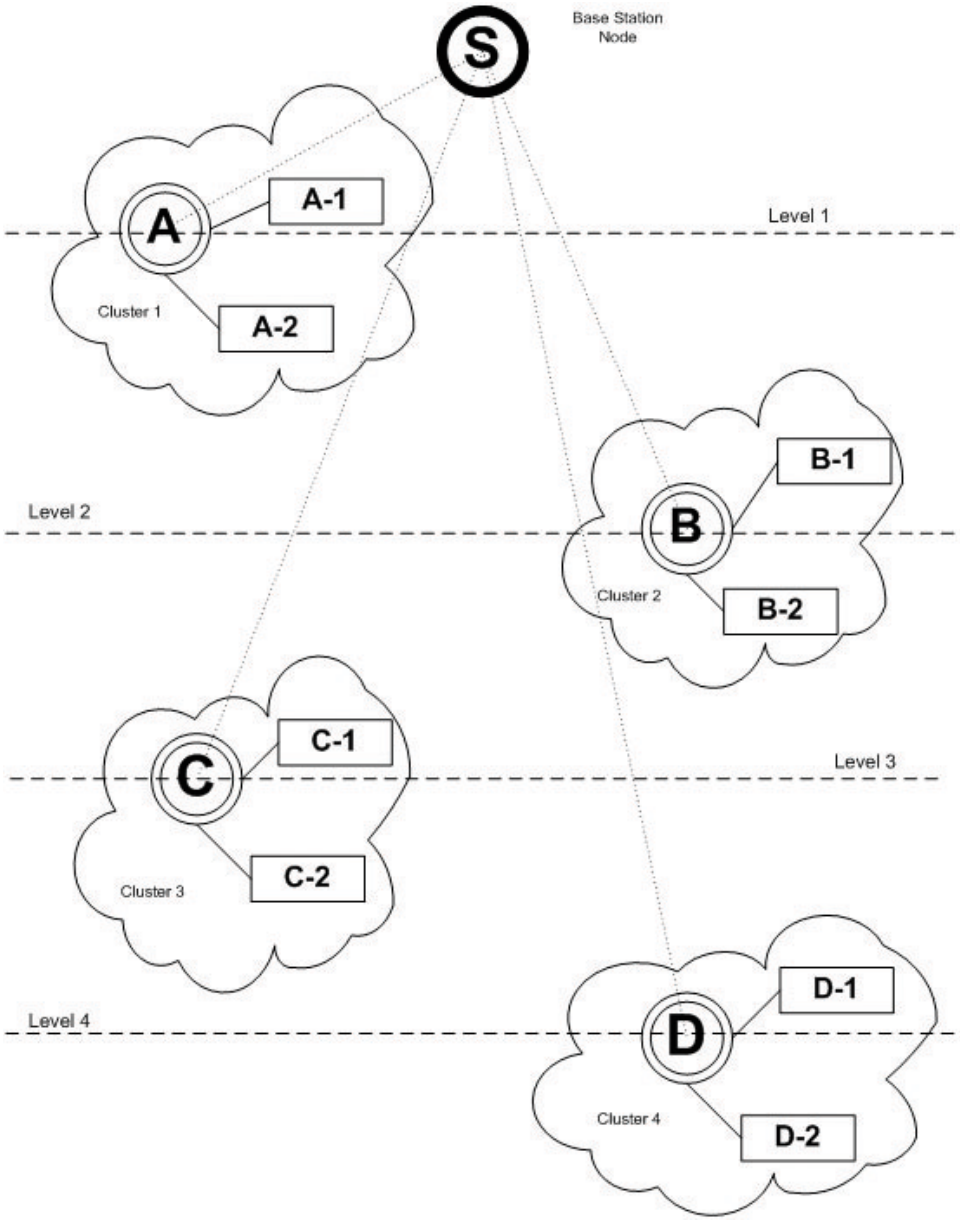


Figure 4.4: An illustration example of a network topology.

the 8 bit register.

Table 4.4: RSSI value resolution and definition of cluster levels.

RSSI Range in dBm	Assigned Level
RSSI $\geq$ 0	1
-10 $<$ RSSI $\leq$ -1	2
-13 $<$ RSSI $\leq$ -10	3
-16 $<$ RSSI $\leq$ -13	4
-19 $<$ RSSI $\leq$ -16	5
-22 $<$ RSSI $\leq$ -19	6
-25 $<$ RSSI $\leq$ -22	7
-28 $<$ RSSI $\leq$ -25	8
-31 $<$ RSSI $\leq$ -28	9
-34 $<$ RSSI $\leq$ -31	10
RSSI $\leq$ -34	11

Depending upon the received value of RSSI, every cluster head node assigns itself a level. To assign the levels to corresponding RSSI values, ranges have been defined so that adequate number of levels is created. The resolutions of the RSSI have been carefully defined after a large number of experimentation and testing and are shown in Table 4.4. It is to be noted here that if levels are assigned over narrow intervals of RSSI, a large number of levels will be created. This can produce situations in which different levels are assigned to nodes that are physically close to each other. On the contrary, if a wide interval

is used, then in situations where the signal strength doesn't vary, majority of the cluster heads will be associated to the same level. We have assigned this interval distribution after rigorous testing of the network and monitoring of the physical separation between the nodes in an indoor environment.

Formation and Updating of Routing Tables

When each of the cluster heads have been assigned a level, a logical tree structure is formed. Each cluster head keeps sending a keep-alive control packet periodically in every cycle to inform the neighboring cluster heads that it is alive. In this packet, the level of the node is also broadcast. The neighboring nodes receive this message and store the node ID and the corresponding level in its routing table. In case, a node dies, and the neighboring nodes don't receive keep-alive message from that node for 3 successive cycles, its neighbors update their routing tables accordingly by assuming it is dead and flushing its entry from their routing tables. In order to accommodate for the topology changes, the routing tables are also updated every head rotation process. This enables the network to include any new CH and to remove the CH that have died.

Routing Operation

When a CH has some data to send to the sink node it consults its routing table and selects the node which is in an upper level (i.e. a level closer to the sink). For example, considering the network of Figure 4.4, the node C would have the address table given in Table 4.2. When node C wants to send data to the sink, it looks through the routing table

and sends the packet to the node that is one level higher in hierarchy or closer (level 2) to the sink. So, node C will send data to node B. Assume that node B dies due to some reason, then the next closer node (node A at level 1) will be the new recipient of data from node C and this process continues. One important rule in this approach is that, data is always sent to the CH that is at a strictly lower level than the current CH. This prevents data from cycling between the nodes.

Table 4.5: Routing table at node C.

Node ID	Level
A	1
B	2
D	4
S	0

A CH forwards the data to the CH higher up in the tree and this continues until the data reaches the sink node (S). If the sending CH has another CH on the same power level as its own, the sending CH will send only to the CH that is strictly higher in the level (lower level number) in the tree. If the sending CH finds two CHs on the same level up in the tree, then it forwards its data to the CH whose entry is the first one found in the routing table.

The protocol that we have implemented takes care of the changes in the topology of the network. For example, if a new node is added anywhere in the network, it either

associates itself with one of the existing clusters or otherwise starts its own cluster. This new node becomes part of the routing mechanism automatically as if it has joined an existing cluster, it takes turn to become CH and ultimately becomes part of a particular routing chain. If that new node has started a new cluster then that cluster will update and may improve the already existing routes depending upon its location and existing power levels in the network.

If a node dies, it is dynamically taken care of by updating the cluster tables that ultimately reflects on the update in the routing tables as well. We also expect that the clusters closer to the sink node will exhaust their energy reserves sooner than the clusters that are relatively further away form the sink node. In that situation or for any other reason, if the whole cluster dies, the routing tables at the remaining clusters adopt this change in the routing information by updating their routing tables insuring that the process of data delivery from the alive network continues.

4.6.2 Data Delivery Models of the Network

There are two formations of network possible: static monitoring and dynamic monitoring. Dynamic events in most applications require periodic reporting and consequently generate regular traffic to be routed to the sink. Monitoring static events allows the network to work in a reactive mode, simply generating traffic and reporting when an incident occurs. We have implemented both approaches in our network.

Monitoring of Dynamic Events: Synchronized Network

Similar to LEACH, our main network acts in a proactive manner and regularly sense and forwards data to the sink node. The implemented network protocol in this part of the network takes care of this job efficiently and very robustly. All the member nodes are periodically sensing during their wake time and are sleep most of their life in order to conserve their energy reserves. The sensing nodes wakes up periodically and send the sensed data to their CH. The purpose of making our network proactive is to enable the regular reporting and monitoring of the elements in the environment.

Incident-based Monitoring: Unsynchronized Group of Nodes (UGN)

At the same time, like TEEN, the network also has the ability to act in a reactive mode. A portion of the network, called the unsynchronized group of nodes (UGN), operate outside the domain of our main network. These nodes remain in the sleep state (transceiver OFF, CPU at low power mode 1) most of the time. At the same time they keep sensing the environment continuously and only wakeup to report an incident if the sensed value crosses a pre-defined threshold. In contrast to the main network, these nodes do not form clusters and don't follow any time schedules. They also don't need to maintain the cluster tables, network topology and routing tables.

Once there is an incident occurrence (threshold crossing of the sensed value) to be reported is ready, the node wakes up and listens for the keep-alive messages from the main network. Due to the criticality of the situation that this node needs to report, this node hands over

the data to the CH of the main network from which it receives the signal first, regardless of its distance and location on the network. The UGN sensing node follows all the MAC protocol procedures as described in Section 4.5 to contend for the channel and to deliver the data reliably to the first CH it hears from. After successful delivery of the incident, this nodes goes to its sleep mode again and the data is relayed to the sink node by the main network CHs according to their routing tables.

4.6.3 Differences between LEACH/TEEN Protocols and Implemented Protocol

LEACH is based on a clustered approach. The nodes group themselves into clusters and decide a cluster head that communicates with its peers to route data. The protocol implemented has some implementation differences with LEACH that are:

1. In LEACH, the cluster heads change randomly over time in order to balance the energy dissipation of nodes whereas in our implementation the CHs are rotated periodically in pre-defined manner.

2. In LEACH, the nodes form clusters dynamically, i.e., with the death of any node the memberships of the clusters are updated and nodes can reorganize themselves in different manner as earlier. In our case the nodes form fixed clusters and they retain their membership till the end. This not only simplifies the implementation, it also results in savings of energy from the overhead of communication required for

making new clusters.

3. LEACH uses single-hop routing where each node can transmit directly to the cluster-head and the sink. Our implementation employs multi-hop dynamic routing thus resulting in savings of transmission power required as multi hop routing is much more energy efficient in terms of transmission power required to communicate between two nodes.

Although TEEN is also based on clusters, but the definition of hard and soft threshold makes to suitable only for incident based reporting. Following are some differences between our protocol and the TEEN protocol.

1. As explained in the TEEN protocol, the nodes group themselves into clusters, and elect a cluster head from amongst them. In our implementation, the CHs are not elected but the responsibility is rotated among all the members evenly and periodically in order the load balances the power consumption within the cluster.

2. The TEEN protocol defines only two levels of clusters, one among the member nodes and the second one among the CH. On contrary, we have defined a total of eleven (11) cluster levels so that our system can support large sizes of networks with small multi-hop routed communications among the CHs thus saving lot of power for transmission.

3. In TEEN, the thresholds are set by the sink node, but in our implementation of the UGN, the thresholds are pre-programmed in the sensing nodes. The UGNs in our

network wake-up only when there is some alarm that must be reported to the sink. By pre-programming the threshold levels, the UGNs do not need to wake-up and listen to the sink node to receive thresholds, thus conserving power.

4.7 Conclusions

This chapter presented a detailed discussion on the S-MAC as well as the TEEN and LEACH protocols and their usage in the WSN domain. All the important design considerations for MAC and routing protocols have been highlighted. At the same time, a complete discussion on the implemented protocols at MAC and routing layers has been provided. A comparison of features of the implemented and the original protocols show that our MAC protocol has a better synchronization and easier implementation capabilities as compared to S-MAC. Similarly the comparison of the existing routing protocols with the implemented protocol reveals that our head rotation policy enables a better energy consumption throughout the cluster as compared to LEACH and TEEN. On the contrary our MAC protocol assumes that all the nodes can receive signals from the sink, which can become difficult in different environments. Also, the pre-programmed thresholds can become difficult to change as priorities for alarms change.

CHAPTER 5

SIMULATION RESULTS

Chapter 4 presented the design details of the MAC and the routing protocols actually implemented on the KFUPM nodes. Although the implementation process had to be devised in a unique manner, the actual design of the protocol has been simulated on the network simulator (ns-2.28). This chapter presents the simulation results of the basic S-MAC, the implemented S-MAC and the routing protocols. Comparisons in the performance of the implemented S-MAC and the basic S-MAC as well as the LEACH and the designed routing protocols have been presented to indicate the energy-efficient behavior of the designed methodology.

The rest of the chapter is organized as follows: Section 5.1 presents the simulation results and commentary on the S-MAC protocols, Section 5.2 has the results for the routing protocol simulations and comparison studies and the chapter concludes with a summary in Section 5.3.

5.1 S-MAC Simulation

S-MAC is one the most basic MAC layer protocol designs to be used in WSN. [73] et al. have simulated the protocol with some duty cycle dynamics based on traffic rates and have provided a comparatively energy efficient model. The basic S-MAC with dynamic sleep schedules was introduced by [16] which provided increased energy efficiency at the cost of higher end-to-end packet latencies.

As mentioned in Section 1.4, S-MAC is based on a fixed duty cycle. All the neighboring nodes follow the same schedules, with some of the nodes following multiple schedules to help relay information from nodes having different sleep schedules. This section presents the simulation parameters and results of the ns-2.28 [74] simulation of the S-MAC protocol.

5.1.1 Simulation Parameters

The following parameters have been fixed for simulation:

1. All the simulations for S-MAC comprise of a network consisting of 30 nodes. The nodes have been arranged such that the data from the first node reaches the sink node over 10 hops.

2. The simulation time for this protocol is 1000 machine seconds. At the end of the simulation the required parameters are examined.

3. Each node has been programmed with energy reserves of 19035 Joules which correspond to 4.5 V DC with the batteries having a rating of 1175 mAh.

4. Each of the 30 nodes generates 31 Byte packets. Among these 31 Bytes 18 Bytes belong to the payload itself, whereas the remaining constitute the MAC headers.

5. The traffic generated is poisson distributed with the different inter-arrival times to observe the effect of varying traffic loads.

6. The S-MAC has been programmed with a 10% duty cycle having a complete cycle period of 4 seconds.

7. In order to test the S-MAC protocol, a simple routing protocol has been used that just passes the packets between immediate neighbors.

8. The results generated by ns-2.28 are written in a text file and include the time when each packet was sent/received. It also indicates that if any packets have been dropped or not. In addition the energy remaining at the end of each packet transfer is also indicated by the result script. Since the major interest in this section is on the MAC layer, only the MAC layer traces have been turned on. The routing and application level traces have been turned off, so that only the packets from the MAC layer can be monitored.

9. A python script has been written to extract data throughput, end-to-end delay and energy consumed by the network.

5.1.2 Energy Analysis

To analyze the energy consumption per delivered packet the CSMA/CA, basic S-MAC and the implemented S-MAC have been simulated with 10% duty cycles for the later two cases. The traffic generation has been varied by changing the inter-arrival time of the packets at the generating nodes. Using a small inter-arrival time means the packets are generated faster and hence imply a congested network. Fig. 5.1 shows the energy consumed per packet delivered with respect to varying traffic generation rate.

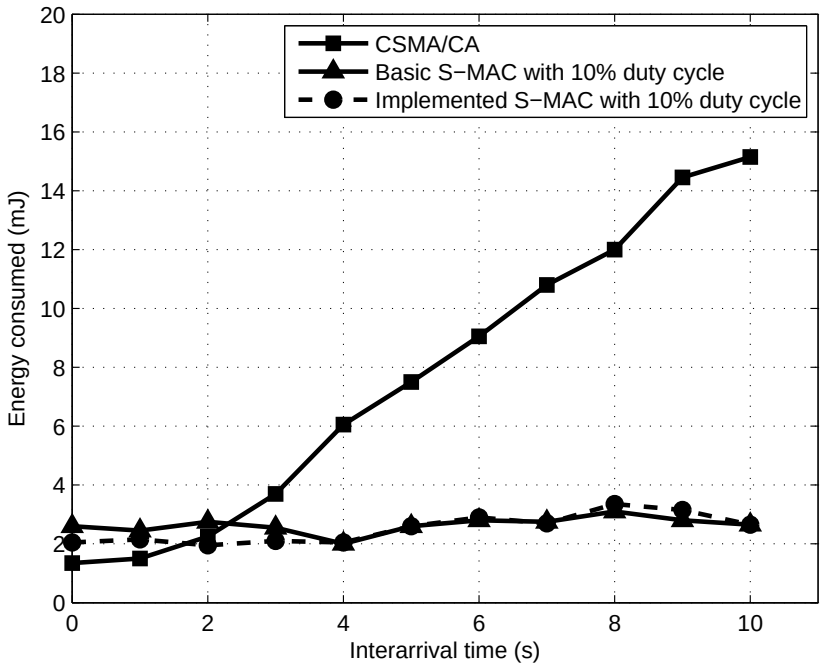


Figure 5.1: Energy consumed per delivered packet with varying packet generation rate.

In Fig. 5.1 S-MAC results have been compared with the case of CSMA/CA and the

implemented S-MAC. It can be observed that when the network is highly congested (inter-arrival 0.001-2s) it is more efficient to not deploy any sleep cycles. By keeping the nodes ON continuously, all the packets can be delivered to the destination successfully with little energy cost per delivered packet. During the same period, a 10% duty cycle basic S-MAC shows an almost constant energy cost since only 10% of the generated packets are sent regardless of the generation rate. The node is OFF for 90% of the time, so the packets generated during that time will either be delayed or dropped because of the limited buffer size. The implemented S-MAC, as explained in Section 4.7.9 employs same sleep schedules for all the nodes in the network as opposed to the basic S-MAC which supports some of the nodes following multiple schedules to overcome the tight synchronization issues. From Fig. 5.1 it is obvious that when the network is highly congested the energy consumed by the nodes per delivered packet is less because the nodes are ON only once in the duty cycle (since a single schedule is being followed). This means that a larger number of packets are either delayed or dropped due to the single schedule in the implemented approach. As the packet generation rate decreases (high inter-arrival times), the results of CSMA/CA indicate an almost linear increase in energy consumption per delivered packet. The reason of this being that the nodes are constantly ON and the packets being generated are less hence increasing the cost. When either of the S-MAC approaches are analyzed, the cost remains approximately constant regardless of the packet generation rate because the node is transmitting only 10% of the time. Fig. 5.1 portrays the superiority of the duty cycle S-MAC in case of varying traffic loads by indicating an almost constant packet cost.

5.1.3 End-to-End Latency Analysis

To analyze the latency, the packet generation rate was fixed at an inter-arrival time of 3s. The simulation was repeated for different hop counts (from 1 to 10) and the end-to-end delay in packet reception was averaged for all the successfully received packets. The result of this simulation is provided in Fig. 5.2.

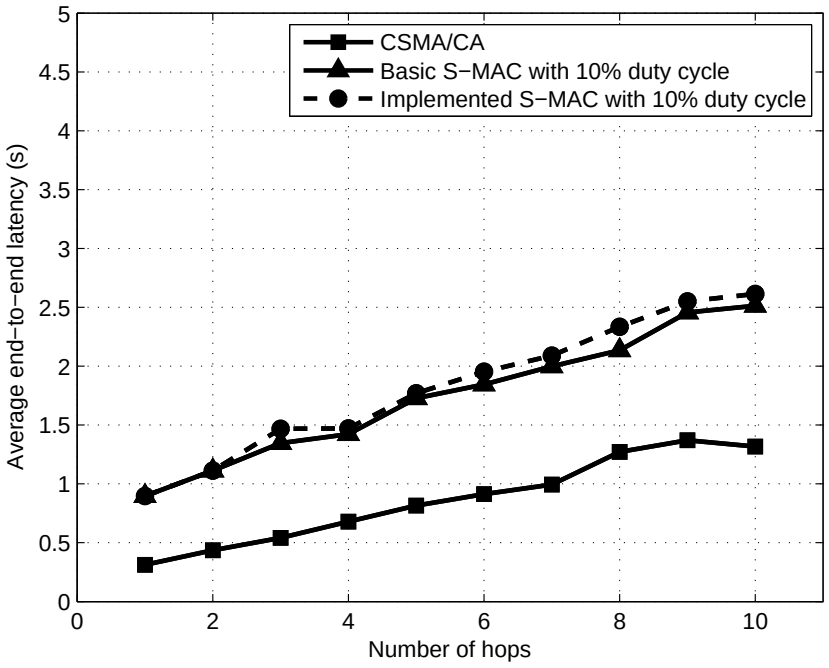


Figure 5.2: Average end-to-end latency over different hops.

Due to the use of a 10% duty cycle basic S-MAC and the implemented S-MAC show an average delay that is much higher as compared to CSMA/CA because at each hop the packet can only be transmitted if the nodes are awake. If an intermediate node receives

a packet and it does not have enough time to forward it, it will delay this process to the next wake cycle, thus introducing delay into the packet. Moreover, it is observed that the end-to-end latency in case of the implemented protocol increases with the number of hops and is higher than the basic S-MAC approach. The reason for this increase is the fact that the basic protocol enables some of the nodes to follow multiple schedules thus enabling them to wake-up more than once in a given cycle. This multiple wake-up enables the basic S-MAC to forward a larger number of packets per cycle and hence the end-to-end delay is decreased. In the case of implemented S-MAC, since each node is ON only once in a cycle, therefore only a limited n=umber of packets can be transmitted thus delaying the packets till the next cycle. For a system with operating with CSMA/CA, this delay is only because of the time taken by the nodes to forward the packets, which as seen in Fig. 5.2 is nearly linear.

5.1.4 Throughput Analysis

Throughput has been defined as the number of bytes of payload that are actually received at the destination without retransmissions. The result of this simulation is provided in Fig. 5.3. To measure this parameter, the simulation was run over the entire 1000s interval and the received bytes were determined to calculate the average throughput. As it was observed in Section 5.1.2, when CSMA/CA is employed, a highly congested network (inter-arrival 0.001-2s) provides the highest data throughput since a huge number of packets are being received at the destination. As the packet generation decreases, the throughput

also starts to decrease, until it becomes almost constant at nearly 4.6 Bytes/sec. Since the packets being generated are less, the throughput is understandably less.

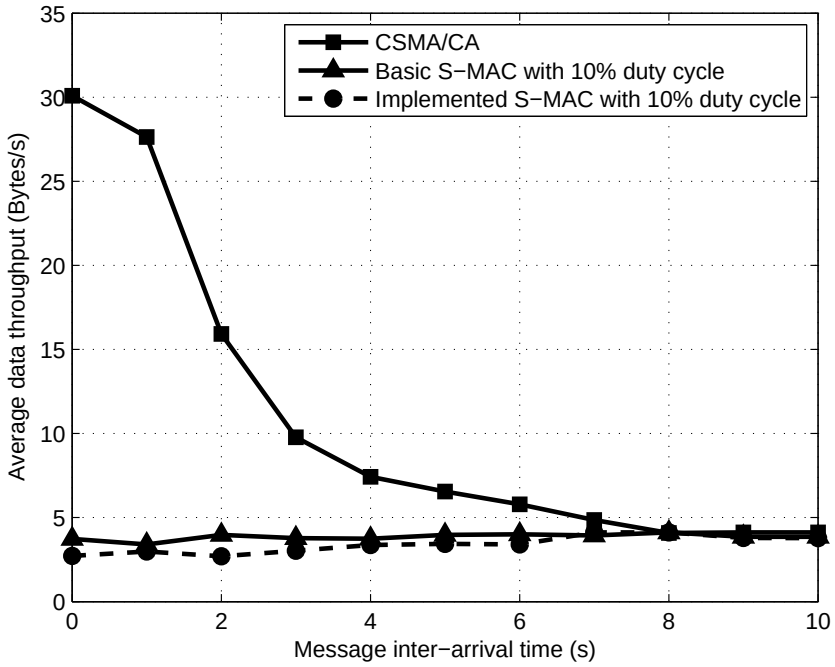


Figure 5.3: Average data throughput at varying traffic rates.

In case of 10% duty cycle basic S-MAC, the throughput remains nearly constant at 4.6 Bytes/sec because of the small duty cycle. Regardless of the number of packets being generated, the transmission takes place only 10% of the time resulting in nearly uniform throughput figures as indicated in Fig. 5.3. The throughput for the implemented protocol is lower than the basic S-MAC because all the nodes in the implemented protocol are ON only once in a cycle as opposed to multiple times in case of the basis S-MAC. However, as the network becomes less congested, the throughput for both the basic and

the implemented protocol converge.

5.2 Routing Protocol Simulation

As described in Section 4.8, the designed protocol has been inspired from the periodic monitoring protocol call LEACH. Therefore, the results of the designed protocol will be compared with simulation results of LEACH and conclusions will be made based on these figures.

5.2.1 Simulation Parameters

In addition to the assumptions mentioned in Section 5.1, following parameters have been fixed for simulation:

1. All the simulations of a network consisting of 51 nodes. 50 nodes form the sensing network, where as the last node acts as the sink (destination) node collecting all the packets.

2. For the designed protocol, the head shifting takes place every 100s.

3. Implemented S-MAC with 10% duty cycle has been selected as the MAC protocol of choice for all the simulations in this section.

5.2.2 Energy Consumption Analysis

Since LEACH and the designed protocol are based on a clustered hierarchical approach, the 50 sensing nodes have been distributed into 10 clusters containing 5 nodes each. In addition, all the 10 clusters generate data and are located at different levels relative to the destination node. So, there are 10 levels with a single cluster at each level. The results of average energy consumed by the complete network with respect to the simulation time is provided in Fig. 5.4.

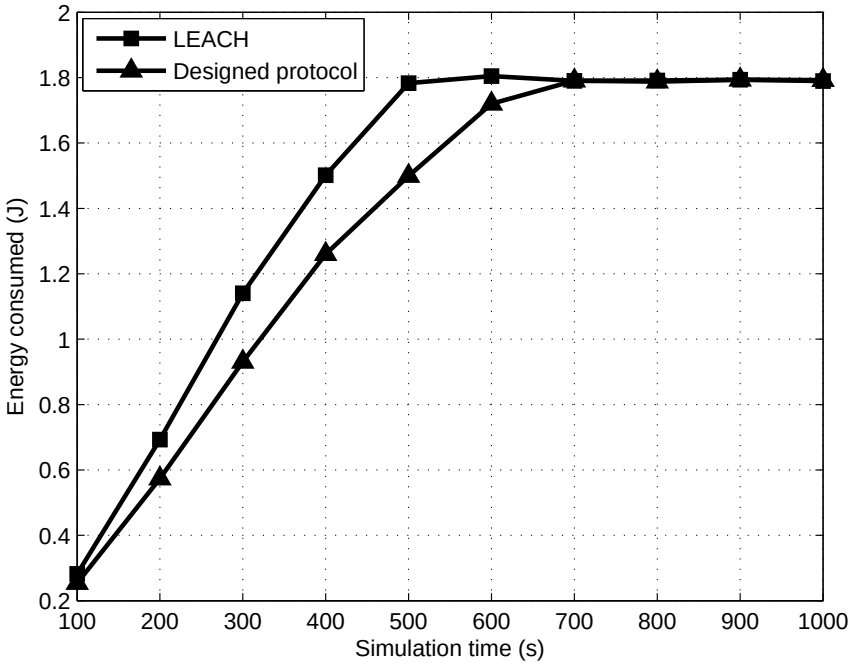


Figure 5.4: Average energy consumed by the network.

From the above figure, it is deduced that when the simulation starts, all nodes have not

woken up. As the simulation time elapses, the nodes start to wake up at random times and start joining the respective clusters, this leads to a gradual increase in the energy consumed (Fig. 5.4) regardless of the protocol adopted. At around 700s the energy consumption for both LEACH and the designed protocol becomes constant since all the 50 sensing nodes have initialized and have joined the clusters.

It is observed from the curve that, although the energy consumption is following the same pattern for both the protocols, the LEACH tends to have a higher average energy consumption due to a fixed cluster head. A look at the curve for the designed protocol indicates that the head shifting process has in fact led to an improvement in energy consumption during the initialization stage of the network. As the network matures, the consumptions of both the protocols become the same.

5.2.3 Network Lifetime Analysis

The network lifetime can be defined with respect to any application; [76] have defined the network life as the time from the start of the network until the first node depletes its energy and dies, on the other hand [77] define thenetwork lifetime interms of the service offered to the end-user. For the proposed setup it has been defined as the time from the start of the network till the failure of the first cluster. Each cluster is deployed in a different physical area sensing the characteristics from that area. If a complete cluster fails, the corresponding area can no longer be sensed and therefore the network breaks.

In case of the LEACH protocol, the cluster head has been fixed. Since the cluster head

is responsible for connecting the cluster with the rest of the network, its death means the death of the cluster. Although the sensing nodes of the corresponding cluster are still sensing, their inability to communicate with the other clusters means their data cannot reach the sink node. For the designed protocol, the cluster head responsibility rotates between all the available cluster members. This process ensures that the energy consumption among all the nodes in the cluster is uniform and the complete cluster dies simultaneously as compared to just the cluster head.

In order to analyze the network lifetime, LEACH and the designed protocol have been simulated with different cluster sizes and the impact of cluster size on the network has been analyzed as shown in Fig. 5.5.

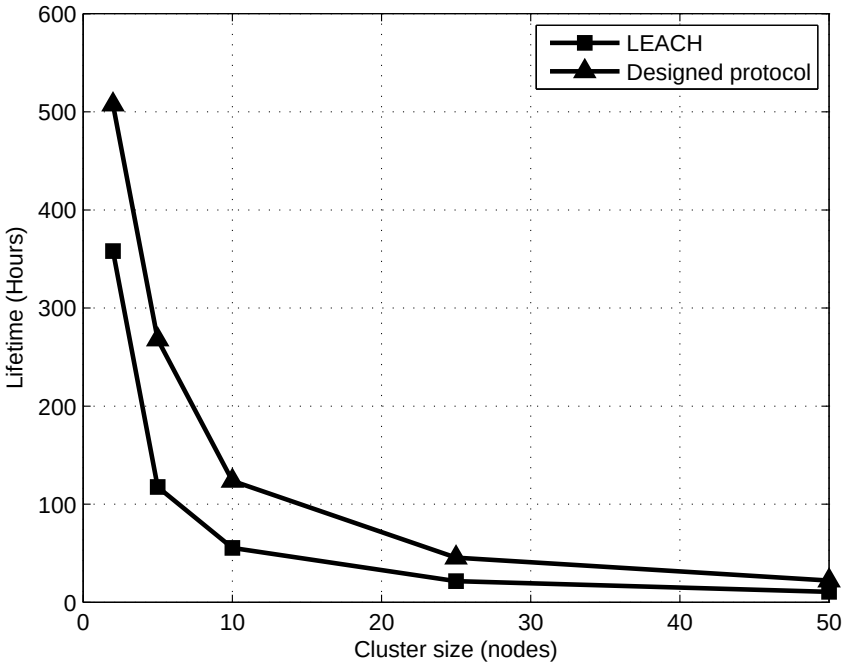


Figure 5.5: Network life vs. varying cluster sizes.

It is observed from both the curves that as the cluster size increases, the lifetime decreases; since the number of nodes in the cluster are increasing. In case of LEACH, an increase in cluster size means that the cluster head has to communicate and relay information from more member nodes which requires more energy and hence the cluster dies earlier. For the designed protocol, since the cluster head responsibility is being rotated among the member nodes, an increase in the cluster size means a decrease in the time each member node has to spend as the cluster head. This leads to lesser energy consumption at individual nodes, but the energy dissipation due to the added communication requirement for the new member nodes is there.

From Fig. 5.4 it is clear that as the cluster size increases both the curves start to converge. When all the 50 nodes form a single cluster the lifetime provided by the designed protocol is marginally better because of head rotation as compared to the LEACH.

5.2.4 Received Packet Analysis

As discussed in previous sections, head rotation mechanism improves the energy consumption figures and adds to the overall network life of the system. However, this comes at the price of reduced packet delivery. When a cluster head transfers its responsibilities to another member, the undelivered packets, if any, at the old cluster head are dropped. In addition, the other member nodes require some time to realize that the cluster head has now changed. All this process leads to a decrease in the PRR at the sink node. A comparison of LEACH and the designed protocol is given in Fig. 5.6. It can be observed

that, as the network populates, the number of generated packets also increases. Some of these packets are dropped due the small duty cycle of S-MAC. However, if the results in Fig. 5.6 are compared for both protocols, it is evident that some of the packets are dropped during the cluster head shifting process for the designed protocol leading to a lower PRR.

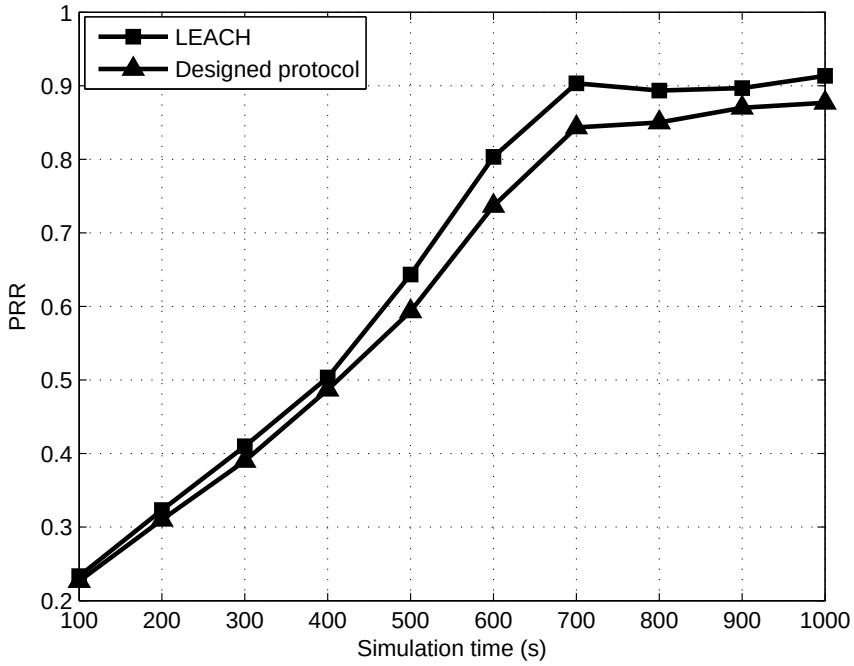


Figure 5.6: Successful packet reception analysis.

5.3 Conclusion

After analyzing the results of S-MAC simulation, it can be concluded that for medium to light congested networks, S-MAC has the lowest energy cost per delivered packet as com-

pared to CSMA/CA. The implemented approach of using strict synchronization throughout the network results is comparatively less energy consumption per delivered packet as compared to the basic S-MAC. The cost for energy-efficiency is paid in terms of higher end-to-end delays over multiple hops and comparatively less data throughput. The chapter also included the analysis of LEACH and the new designed routing protocol. From the simulation results, the designed protocol shows a much better energy utilization as compared to LEACH. At practical cluster sizes (5-10 nodes per cluster) the network life offered by the designed protocol is almost twice as compared to the LEACH protocol. This increase in network life comes at the compromise of the offered PRR.

CHAPTER 6

DESIGN OF SENSOR NETWORK DEPLOYMENT APPLICATION

The deployment of a WSN is highly dependent on the target environment. As with wireless communications, factors like fading and interference vary depending on the environment. Indoor channels are considered worst because of the high level of interference due to reflection from walls and other equipment in the vicinity. In fact, the presence of chairs, tables and even the material of the wall itself affects the signal propagation characteristics. On the contrary, an outdoor or open space has comparatively better signal propagation aspects. As with the indoor environment, the presence of foliage, sand and mud have an affect on the signal propagation in the outdoors. After knowing the type of environment in which the network is to be setup, the question of network size arises; more specifically, what is the least number of nodes that could be used to cover a particular area with some

propagation characteristics. This chapter tries to find the answer for this question by creating a MATLAB application that provides the deployment figures for two different cases. Actual received signal strength measurements have been used to reach a conclusion regarding the number of nodes required to create a network. The KFUPM node has the ability to extract the received signal strength (RSS) from the received packet. This ability was utilized in all of the measurements in this chapter.

Section 6.1 presents the antenna characteristics based on experimental analysis for the two types of antennas used for the measurements. The design methodology of the application is presented in Section 6.2 and application design details along with the analysis of two distinct case studies is presented in Section 6.3. Finally the chapter concludes with Section 6.4 presenting the conclusion.

6.1 Antenna Characteristics

For the KFUPM wireless sensor node, the CC2420EM transceiver unit operates in the industrial, scientific and medical (ISM) band. The unit also comes with an external antenna that could be changed as desired. One of the most important parameters in wireless communications is the radiation pattern of the antenna itself. During the simulations, an omni-directional antenna radiation pattern is assumed to simplify the process, which may not be true in practice. Therefore, a radiation pattern measurement has been performed for two different kinds of antennas to provide an accurate representation of the signal propagation which would be employed in the design of the application.

6.1.1 Antenova Standard Antenna

The CC2420EM unit comes with an Antenova antenna that has a hight of about 3.5 inches as shown in Fig. 6.1. The Antenova antenna is designed to operate at 2.4 GHz with applications in WiFi, Bluetooth and ZigBee. The antenna works with linear polarization providing a peak gain of 2.2 dBi and an 80% operating efficiency [78]. The radiation pattern in the azimuthal range as provided in the datasheet is shown in Fig. 6.2.

Figure 6.1: Antenova antenna.

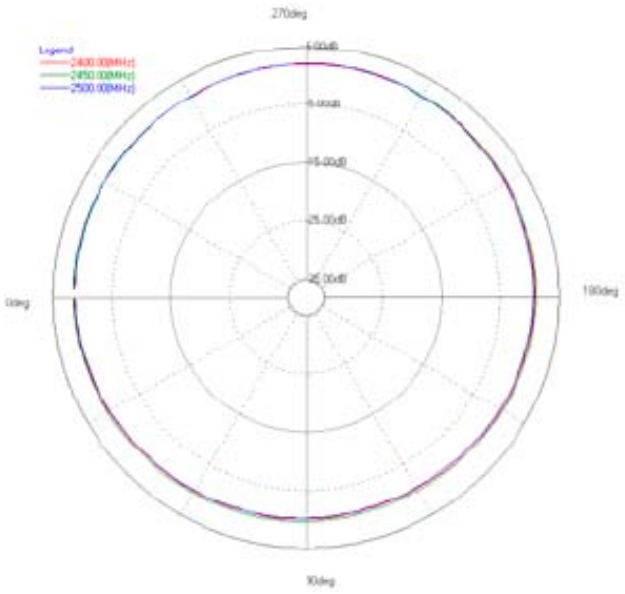


Figure 6.2: Antenova antenna radiation pattern from the datasheet.

In order to measure the radiation pattern of this antenna, two KFUPM nodes have been used. The receiving node was connected to the PC and its location was fixed. The transmitting node was programmed to transmit 4 packets/second at at transmit power of 0 dBm. Each of the transmitted packets contained a sequence number which was used to determine any lost packets at the receiver. All the measurements were performed in an open environment at Building 33 (university stadium).

The distance between the transmitter and the receiver is fixed at 10 cm. In addition the transmitter was rotated 22.5 degrees to get receive power measurement for 16 different angles. The results of this measurement are provided in Fig. 6.3. Comparing the radiation patterns in Fig. 6.2 and Fig. 6.3 it is obvious that the antenna does not display a

completely omni-directional coverage as indicated in the datasheet.

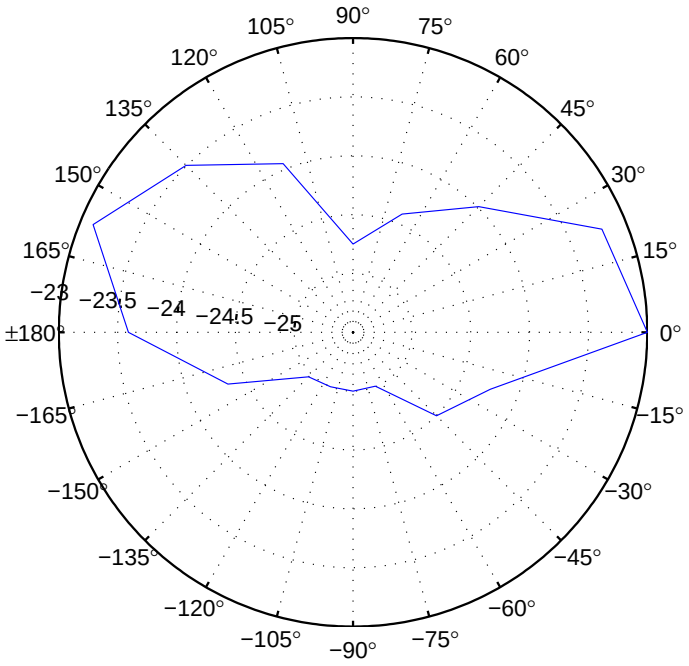


Figure 6.3: Radiation pattern in dBm of the Antennova around the azimuthal axis.

As indicated in Fig. 6.3, the received signal power varies depending on the orientation of the antenna. One important thing that must be analyzed here is the relationship of this variance with the distance from the receiver. For this setup, the received signal power was measured by varying the transmitter-receiver distance between 10 cm, 2 m, 4 m and 8 m. The results of this experiment are provided in Fig. 6.4.

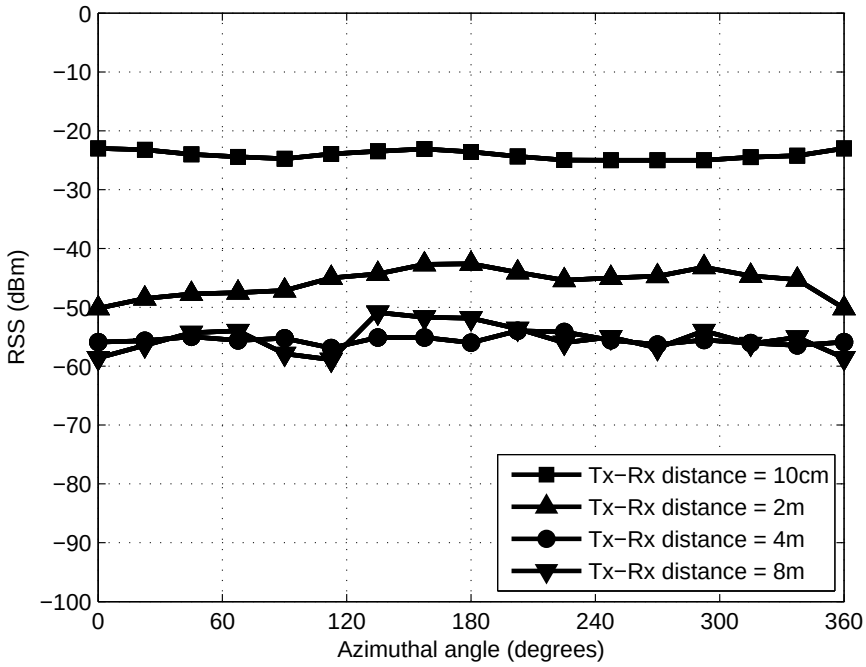


Figure 6.4: Received signal strength with varying azimuthal angle at specific transmitter-receiver separation for Antennova antenna.

As the transmitter moves away from the receiver, we observe that the variations in signal strength with changing azimuthal angle become significant. Comparing the variation at 10 cm and 8 m we see that a maximum variation of 3 dBm occurs when the inter-node distance in 10 cm, whereas upto 10 dBm change is observed when the nodes are 8m apart.

RSS for Indoor Environment

For measurement in an indoor environment, a typical living room was selected with furniture and electronics to model for a common household environment. The distance between

the transmitter and receiver was varied and the received signal strength was recorded as shown in Fig. 6.5. Due to the presence of different objects in the vicinity, the signal strength fluctuates. At 4 m distance it becomes higher as compared to 3m which is due to the reflections caused by the objects. In addition the height of the node relative to the ground was changed to see the effect. It is observed that when the nodes are placed at ground level, the reflections from the ground cause severe attenuation leading to a lower received signal strength as compared to the case when the nodes are elevated at 60 cm.

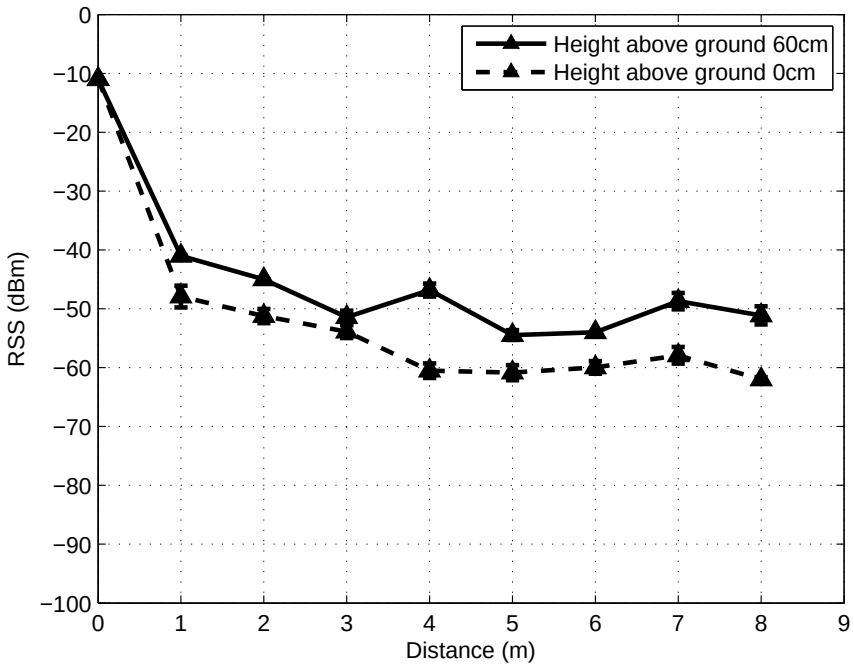


Figure 6.5: Received signal strength with varying distance in an indoor environment for Antennova antenna.

RSS for Outdoor Environment

The outdoor measurements were performed in Building 33 (stadium). Again the distance between the transmitter and the receiver was changed form 10 cm to 60 m and the nodes were placed at a height of 60 cm. The RSS figures were recorded as displayed in Fig. 6.6.

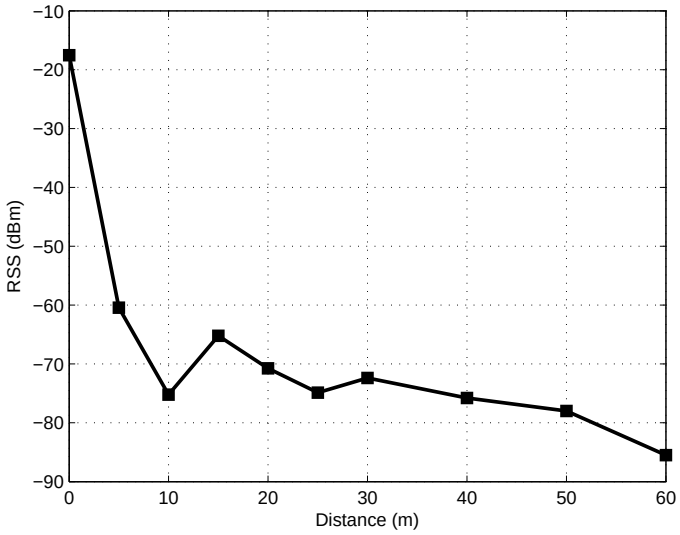


Figure 6.6: Received signal strength with varying distance in an outdoor environment for Antennova antenna.

One important factor in case of WSN is the packet receive ratio (PRR) defined as the fraction of transmitted packets successfully received. As each of the transmitted packets has a sequence number, the receiver extracts this sequence number and determines any missing sequence numbers to calculate the PRR. For the transmission power of 0 dBm even at a distance of 60 m the PRR remains 1, indicating that all the packets are successfully received. However, when the transmit power is decreased to -5, -10, -15 and -25 dBm, the

PRR becomes zero after a given distance. Fig. 6.7 shows the PRR measurements done in an outdoor environment when transmitting at different powers.

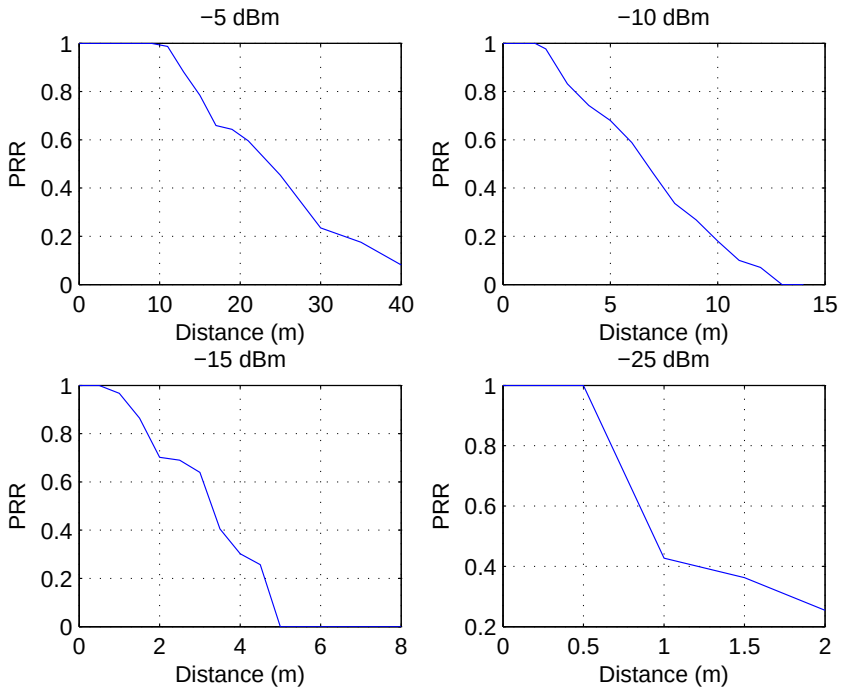


Figure 6.7: PRR measurements for different transmit powers in an outdoor environment.

6.1.2 Stubby Antenna

This antenna has a height of about 1 inch and was originally acquired to decrease the size of the KFUPM node. Like the antennova, the stubby antenna provides linear polarization and an overall gain of 2.2 dBi. The radiation pattern in the azimuthal plane as provided in the datasheet is shown in Fig. 6.8. Since this antenna is being used, therefore its analysis is presented in this section.

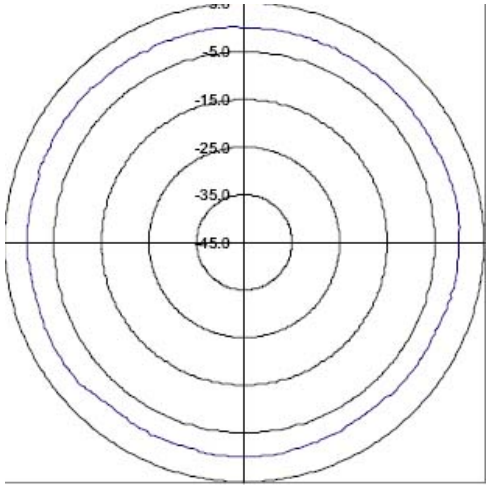


Figure 6.8: Stubby antenna radiation pattern from the data sheet.

The procedure adopted for the Antenova antenna as described in Section 6.1.1 is replicated by changing the transmit antenna to a stubby antenna. The radiation pattern is provided in Fig. 6.9. Comparing the radiation pattern of the two antennas, it is obvious that the stubby antenna provides a much omni-directional coverage as compared to the Antennova. This advantage comes at the cost of the signal strength; as the stubby antenna has an RSS of -25 dBm as compared to -23 dBm for the Antennova. Observing the radiation patterns from Fig. 6.8 and Fig. 6.9 complete omni-directional behavior is confirmed by the measurements.

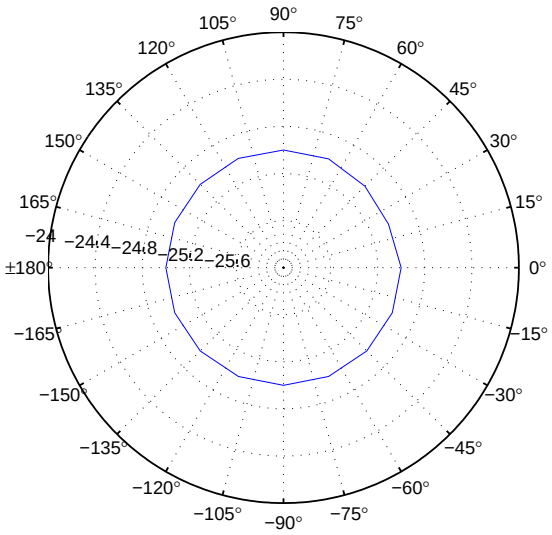


Figure 6.9: Radiation pattern in dBm of the Stubby antenna around the azimuthal axis.

The RSS readings for the stubby antenna with varying azimuthal angle are provided in Fig. 6.10. As it can be observed, the signal strength shows an overall constant behavior over varying azimuthal angle. Comparing with the results in Fig. 6.4 it is concluded that although the Antennova provides better RSS, however, the stubby antenna has superior omni-directional abilities.

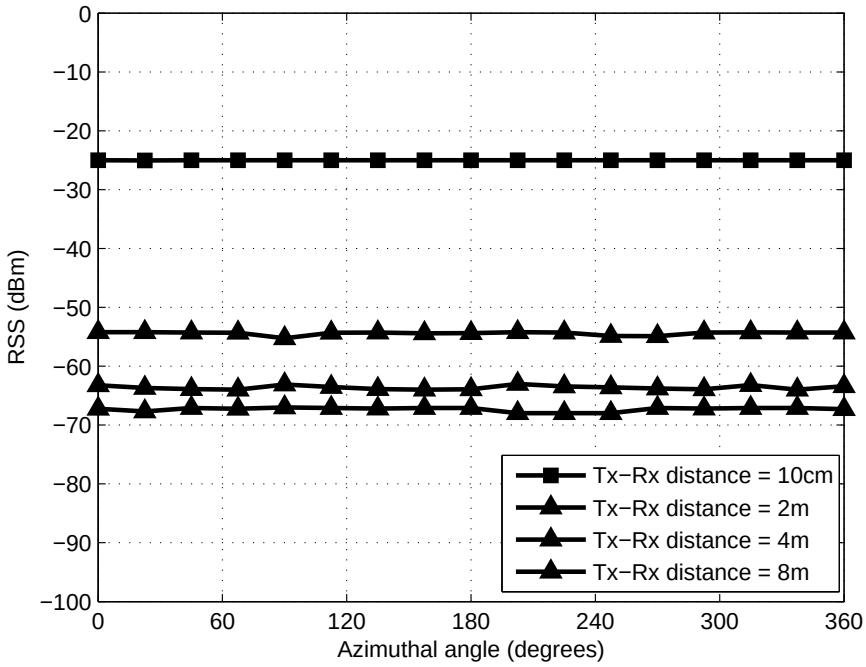


Figure 6.10: Received signal strength with varying azimuthal angle at specific transmitter-receiver separation for Stubby antenna.

The same environment as that for the experiment of Antennova as presented Section 6.1.1 was selected for the stubby antenna as well. The results are shown in Fig. 6.11. A comparison with the results in Fig. 6.5 reveals that the RSS decreases in the case of the stubby antenna. Although the pattern followed is the same, however, the stubby antenna shows an increased signal loss when transmission is done at ground level as compared to the Antennova.

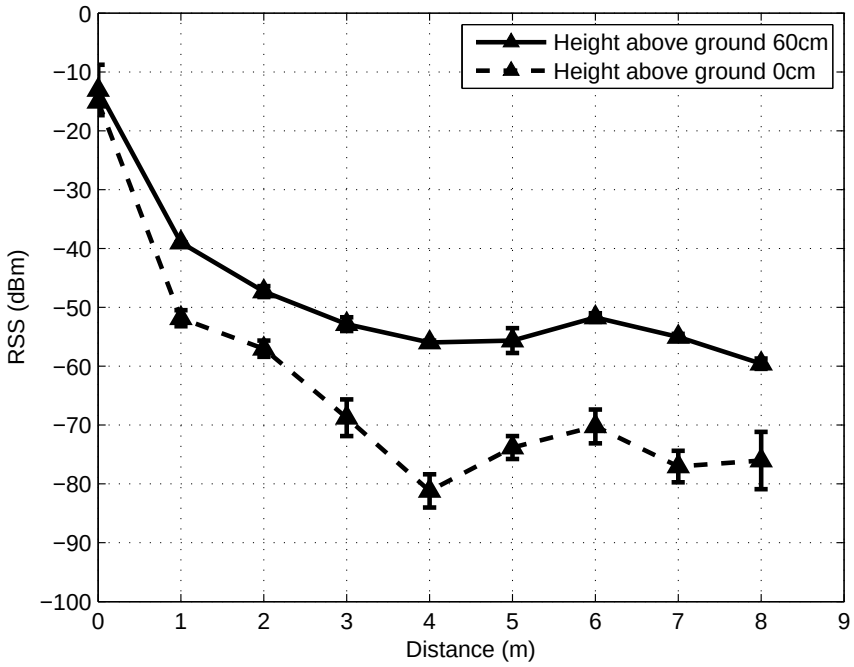


Figure 6.11: Received signal strength with varying distance for Stubby antenna.

6.2 Design Methodology

After doing all the RSS measurements, this data has been put into constructive use for designing the application. By using the data in Fig. 6.6 and Fig. 6.5 it is deduced that the Antenova antenna does not have a completely omnidirectional radiation pattern, the stubby antenna, however, shows a completely omnidirectional pattern and hence can be approximated with a circular radiation characteristic in the azimuthal plane. In simpler terms, given a particular required value of RSS, the corresponding distance provides the maximum separation d_{max} between the transmitter and the receiver to maintain the

required value of RSS.

As the Antennova has an approximately omni-directional radiation pattern, this corresponds to a transmission radius of the node, i.e. $r_{trans} = d_{max}$. It must be noted that each node in a cluster acts as a member nodes as well as a cluster head. Since the cluster head is responsible for communicating with other clusters it transmits at higher power levels when communicating with other cluster heads and uses -25 dBm (the least possible transmit power) when communicating with own cluster members. Consider the scenario presented in Fig. 6.12.

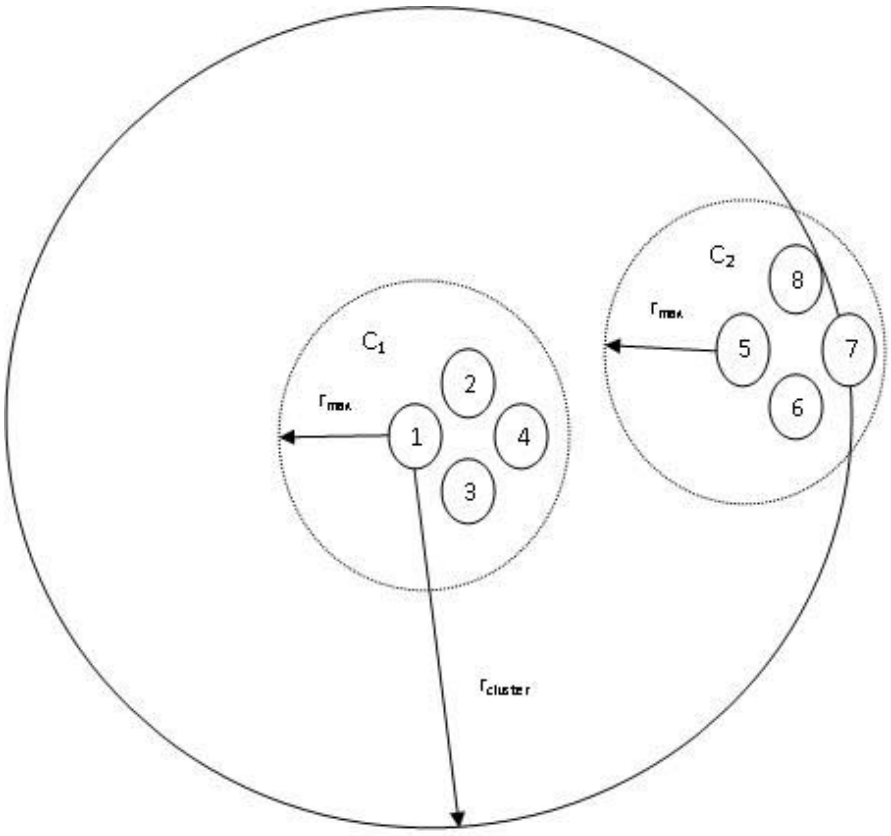


Figure 6.12: Transmission radius at different power levels.

Consider two clusters, C_1 and C_2 comprising of nodes 1,2,3,4 and 5,6,7,8 respectively. The cluster size has been limited to 4 nodes per cluster for simplicity. It is evident from the above figure that node 1 of C_1 is furthest away from nodes 7 and 8 of C_2. In order for both the cluster heads to communicate they must lie within the transmission radii of each other. The worst case condition occurs when node 1 is the cluster head of C_1 and node 7 or 8 is the cluster head of C_2. Let r_{max} represents the maximum transmission radius when transmitting within the cluster (-25 dBm) and $r_{cluster}$ be the maximum transmission radius when transmitting at the higher power level. It is evident from Fig. 6.12 that the $r_{cluster}$ must be large enough so that the next hop cluster node is within its transmission radius.

This imposes a bound on the maximum separation between two closest clusters to be less than or equal to $r_{cluster}$ to ensure that cluster heads which are farthest away from each other do communicate. If the separation is less than $r_{cluster}$, communication is possible at stronger RSS but more nodes are required to cover the region.

6.3 Application Design

The deployment of a WSN requires a trade-off between cost, network life and the end-to-end latency existing in the network. Cost and network life is directly related to the number of nodes and their transmission powers in the network. The end-to-end latency, as seen in from the simulation results of Fig. 5.2 is dependent on the number of hops. This section presents two case studies and provides analysis of the different factors for

network design.

In WSN the PRR plays a much important role as compared to the actual RSS. In the radio measurement results presented in Fig. 6.6, it is observed that packets are received at extremely low RSS (-90 dBm) but are can be used for successful extraction of information. In the following case studies the PRR measurements presented in Fig. 6.7 have been used to determine the inter-node and inter-cluster spacing. In addition, the node power consumption figures presented in Table 2.6 have been utilized to determine the operating life of the network based on actual measurements. The end-to-end latency has been determined from the S-MAC simulation results presented in Fig. 5.2. In short, the practical PRR measurements, the power consumption measurements for the KFUPM node and the simulation results have been combined to generate a model to help in the deployment of a WSN.

6.3.1 Case 1: Fixed Cost and PRR

In this case the cost and the desired PRR are fixed and are provided to the application. The cost is provided as the total number of nodes available to setup the network. Fig. 6.13 provides the results of the simulation for a network comprising of 50 nodes at a PRR of 0.9.

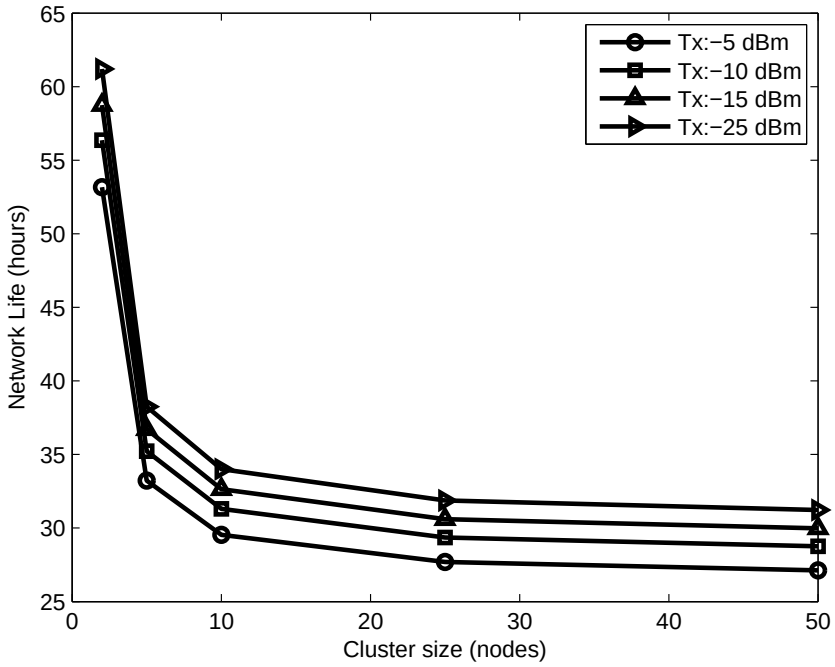


Figure 6.13: Network life (in hours) of a network with 50 nodes at PRR=0.9 for a fixed area.

It can be observed that regardless of the transmit power, when a smaller number of nodes are placed in a cluster, the resulting network topology has a large number of clusters thus increasing the overall network life. As the number of nodes per cluster increases the network life decreases and becomes nearly constant for extremely large network sizes. Table 6.1 shows the complete network life in hours as well as the maximum separation between clusters required to maintain a PRR of 0.9 for the different inter-cluster transmission powers.

Table 6.1: Network life (hours) and corresponding maximum separation between clusters (meters) for a network of 50 nodes at PRR=0.9 for different transmit powers (P_t).

Nodes/cluster	P_t: -5dBm	P_t: -10dBm	P_t: -15dBm	P_t: -25dBm
2	53	56	59	61
5	32	35.13	37.06	38.3
10	30	31.03	33	34
25	28	29	31	32
50	27.01	29	30.02	31
Maximum distance between clusters (m)	12.6	2.5	1.3	0.6

As the transmission power is decreased the network life understandably increases, however the maximum separation required to maintain a PRR of 0.9 also decreases. The end-to-end latency analysis based on the simulation results of S-MAC is presented in 6.14.

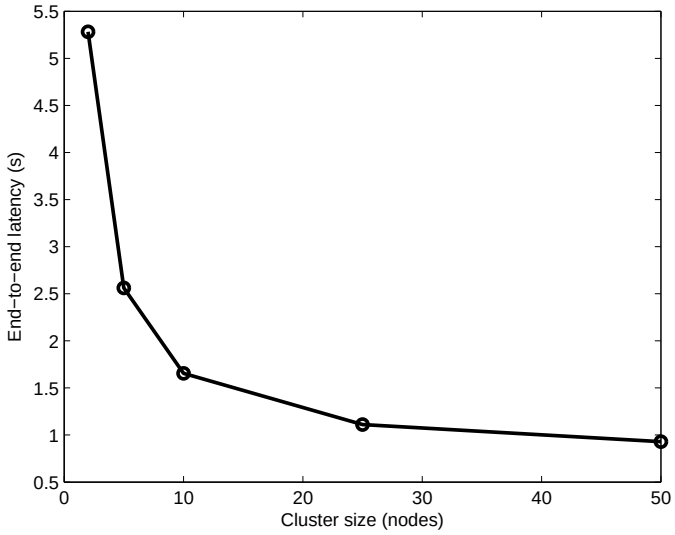


Figure 6.14: End-to-end latency at different cluster sizes for network size of 50 nodes at PRR=0.9.

The end-to-end latency presented in Fig. 6.14 has a higher value when the network has a large number of clusters (small number of nodes/cluster) because of the effect of nodes backing off due to insufficient time to transmit packets to the next hop nodes because of the duty cycle. As the number of hops decreases, the delay also drops.

Fig. 6.15 presents the network life figures for a network with 50 nodes and a required PRR of 0.5. As it can be observed from Fig. 6.13 and Fig. 6.15, the network life is not dependent on the PRR, but on the number of nodes/cluster. PRR just controls the maximum separation between adjacent clusters as indicated in Table 6.1 and Table 6.2.

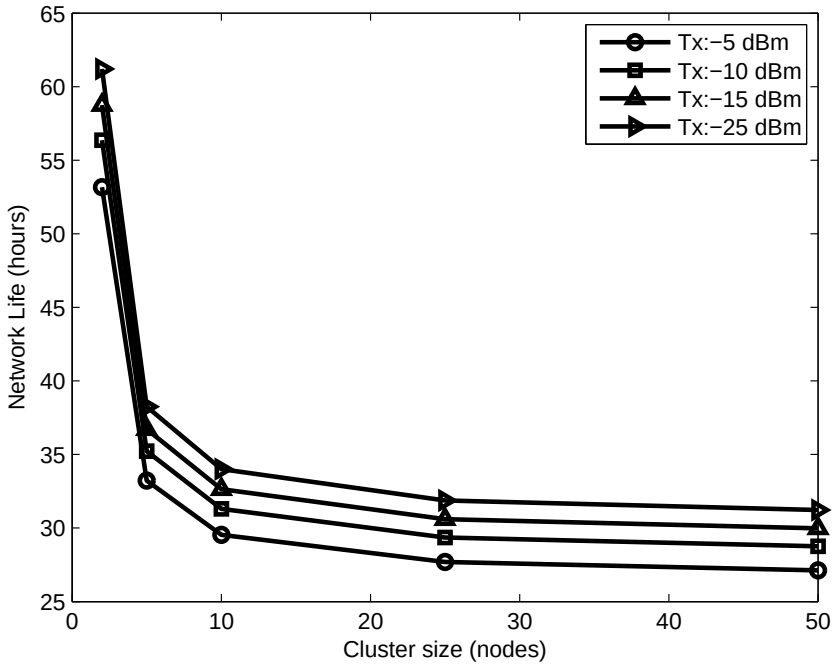


Figure 6.15: Network life (in hours) of a network with 50 nodes at PRR=0.5 for fixed area.

Table 6.2: Network life (in hours) and corresponding maximum separation between clusters (in meters) for a network of 50 nodes at PRR=0.5.

Nodes/cluster	P_t: -5dBm	P_t: -10dBm	P_t: -15dBm	P_t: -25dBm
2	53	56	59	61
5	32	35.13	37.06	38.3
10	30	31.03	33	34
25	28	29	31	32
50	27.01	29	30.02	31
Maximum distance between clusters (m)	23.7	6.7	3.3	0.9

One thing that can be observed from the maximum separation figures given in Table 6.1 and Table 6.2 is that the lower the desired PRR, the higher is the maximum separation; which in turn means a larger physical area can be covered with the same number of nodes at each of the different transmit power ranges.

6.3.2 Case 2: Fixed Deployment Area and PRR

In case 1, the physical dimensions of the target area were not taken into account, instead, the network was designed for a particular deployment cost. In some scenarios, the situation might demand designing the network for a given physical dimension where cost might not be an important factor. Since the cost (number of nodes in the network) is not specified by the user, the design must include an analysis of the number of nodes/cluster

and the total number of nodes required for a given situation.

Consider the target area A_t which needs to be setup with a WSN using the outdoor RSS model. Since the transceiver allows the transmit power to be varied between -25 dBm, -15 dBm, -10 dBm and -5 dBm, the corresponding transmission radius can be determined by using the desired PRR from Fig. 6.7. The total number of clusters in the network ($N_{cluster}$) at a given inter-cluster transmission power (P_c) can be calculated as:

$$N_{cluster} = \frac{A_t}{A_c}. \tag{6.1}$$

where A_c in Equation 6.1 is the transmission area of a cluster head node.

After determining the total number of clusters required in the network, the number of nodes in individual clusters depends on the intra-cluster transmission power (P_{ic})used. By varying the P_{ic} the transmission area of the member nodes (A_m) changes thus changing the number of nodes in the cluster (N_{member}). Mathematically this process can be depicted as:

$$N_{member} = \frac{A_c}{A_m}. \tag{6.2}$$

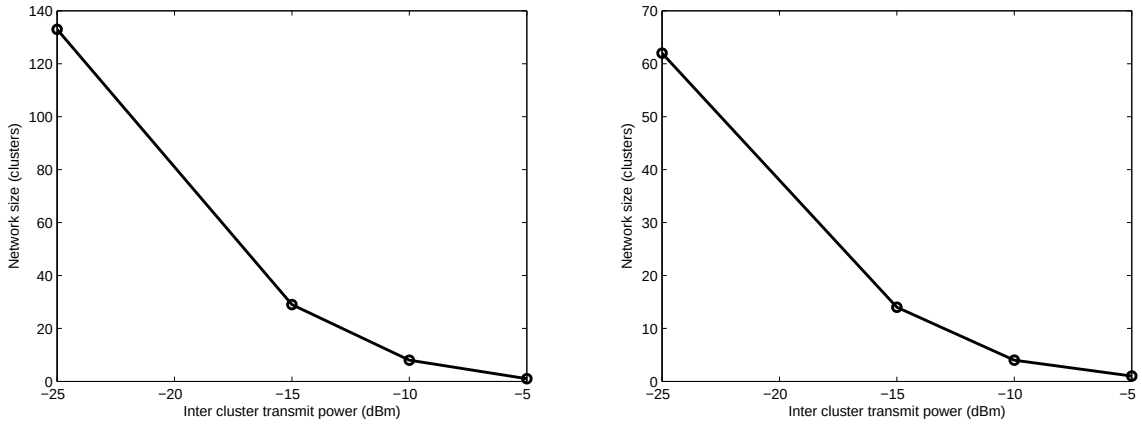
Fig. 6.16 shows the total number of clusters required to effectively cover the given area for two different cases for varying P_c. It can be observed that as the P_c increases, the total number of clusters required to cover the given area decreases. Tables 6.3 and 6.4 show the total number of nodes/cluster under different conditions of P_c and P_{ic}. Its is observed that as the the P_{ic} decreases the number of nodes in the cluster increases. By using the plots in Fig. 6.16 and the data in tables 6.3 and 6.4 the total number of nodes can be determined.

Table 6.3: Total nodes in the network at varying P_c and P_{ic} for 10m×15m with PRR of 0.9.

	P_{ic}: -5dBm	P_{ic}: -10dBm	P_{ic}: -15dBm	P_{ic}: -25dBm
P_c: -5dBm	1	25	94	441
P_c: -10dBm	-	8	32	136
P_c: -15dBm	-	-	29	145
P_c: -25dBm	-	-	-	133

Table 6.4: Total nodes in the network at varying P_c and P_{ic} for 10m×7m with PRR of 0.9.

	P_{ic}: -5dBm	P_{ic}: -10dBm	P_{ic}: -15dBm	P_{ic}: -25dBm
P_c: -5dBm	1	25	94	441
P_c: -10dBm	-	4	16	68
P_c: -15dBm	-	-	14	70
P_c: -25dBm	-	-	-	62



(a) (b)

Figure 6.16: Number of cluster in the network for a PRR of 0.9 and target area of (a) 10m×15m and (b)10m×7m.

6.4 Conclusion

In order to provide accurate network deployment statistics, real life radio measurements are required to ensure the network design operation according to the desired level. The transmission radiation analysis of the stubby antenna proves it to me completely omni-directional in the azimuthal plane whereas the Antenova does not exhibit complete omni-directional characteristics. By using the PRR measurements and analyzing the results of the two cases presented, it is concluded that, for a fixed cost network a decrease in the desired PRR result in an increase in the coverage area of the network where as the end-to-end latency and the lifetime of the network remain independent of the PRR. When a desired physical area is to be deployed with a WSN, it was found that for a given

inter-cluster transmission power, the total number of nodes increase as the intra-cluster transmission power drops, resulting in highly dense clusters.

CHAPTER 7

CONCLUSIONS AND FUTURE RESEARCH

7.1 Contributions and Achievements

As was proposed the following tasks have been successfully completed:

1. **Creation of Wireless Node**: Using off-the-shelf sensors and components, we have successfully created a KFUPM wireless node that can support a maximum of four different sensors (two digital and two analog). The node has a high performance MCU with a double sided design to reduce the size to a minimum. The use of special stub antennas has further decreased the overall height of our node.

2. **MAC Protocol**: A MAC protocol inspired from the famous S-MAC protocol has been implemented on KFUPM nodes. Uniquely devised MAC implementation

scheme as well as special payload formats have been used on the KFUPM devices. The simulation results of the implemented and the basic S-MAC reveal the energy efficiency of the implemented protocol as compared to the basic S-MAC at the cost of higher latency and slightly lower throughput.

3. **Routing Protocol**: Useful features of both TEEN and LEACH have been combined into a new protocol that employs cluster head approach and at the same time is suitable for dynamic environments in addition to the incident based (UGN). Dynamic head shifting has been employed to increase the lifetime of the network. The simulation results prove that the designed protocol promises an almost twice the network life as compared to LEACH with acceptable delay.

4. **Deployment Application Design**: A special application to provide an approximation to the size of a typical network based on real-life measurements has been designed. Based on the presented case studies, network design can be done for either fixed cost of fixed area.

7.2 Future Research

WSN is a diverse field and due to the diverse nature of applications several enhancements to the current work cane be done. Following few ideas can be used to enhance the proposed network.

1. The protocols presented in this report assumed static network, i.e., the nodes are

stationary all the time. The same scheme can be modified to accommodate mobile nodes. As the nodes move, their power levels change relative to a central sink, and the network topology changes constantly.

2. By using multiple sink nodes, the network coverage can be increased. Each of the sink nodes would be connected to a central server which would supervise the data collection from all the sinks. No hand-offs would be required as the member nodes would not be permanently assigned to sink nodes.

3. By using a single sink node, the coverage could be increased by enabling the sensing nodes to relay or regenerate the beacon signal from the sink. This would enable the nodes which could not directly receive the beacon from sink node to get the regenerated beacon signal from the other nodes thus providing synchronization. Although a single synchronization would be achieved, clock drift would need to be countered to ensure tight schedules.

4. Variable transmission power control can be implemented to provide much tighter control on transmission energy consumption. Each node would transmit at the least required transmission power that caused successful packet transmission to the neighboring node. This would prevent unnecessary interference between nodes far away from each other.

5. The present approach assumes eleven fixed power levels to create the routing tree. These levels could be adjusted dynamically depending on the environment in which

the system is operating.

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VITAE

- Farooq Sultan
- Born in Dammam, Saudi Arabia on 30th July, 1986
- Nationality: Pakistani
- Received B.S. Telecommunications Engineering from COMSATS Institute of Information Technology (CIIT) in August 2008
- Worked in Pakistan Telecommunications Corporation Ltd. (PTCL) as a trainee engineer at the international gateway exchange, Rawalpindi
- Joined King Fahd University of Petroleum & Minerals, Dhahran, Saudi Arabia as a Research Assistant in February, 2009
- Completed M.S. in Telecommunications Engineering from King Fahd University of Petroleum & Minerals, Dhahran, Saudi Arabia in January 2011
- E-mail: farooqstn@hotmail.com
- Phone: 0561505634
- Present Address: P.O. Box 1661, King Fahd University of Petroleum & Minerals, Dhahran- 31261, Saudi Arabia
- Permanent Address: H. No. 81, Street 35-A, Sector I-9/4, Islamabad, Pakistan