AN ULTRA-LOW POWER COMMUNICATION PROTOCOL FOR A SELF-POWERED WIRELESS SENSOR BASED ANIMAL MONITORING SYSTEM

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AN ULTRA-LOW POWER COMMUNICATION PROTOCOL FOR A SELF-POWERED WIRELESS SENSOR BASED ANIMAL MONITORING SYSTEM

by

Tao Ma

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AN ULTRA-LOW POWER COMMUNICATION PROTOCOL FOR A SELF-
POWERED WIRELESS SENSOR BASED ANIMAL MONITORING SYSTEM

Tao Ma, Ph.D.

University of Nebraska, 2012

Adviser: Hamid Sharif

To prevent and control the outbreak of contagious animal disease, many countries have developed animal identification and tracking systems. However, the current animal identification and tracking system, which is based on passive RFID technology, has many limitations such as the short communication range and incapability of automatically monitoring the animal. To overcome these limitations, our Advanced Telecommunications Engineering Laboratory (TEL) in Department of Computer and Electronics Engineering (CEEN), University of Nebraska-Lincoln took the mission of developing a more advanced monitoring system for animal identification and tracking. This dissertation work as a part of this mission was focusing on developing an ultra-low power communication protocol for our animal monitoring system. Our animal monitoring system utilizes the energy harvesting wireless sensor technology, aiming to offer a solar energy powered ad hoc network where all tags are actively collecting all the concerning information of livestock, and automatically passing the information through multi-hop to the hub. To meet the requirements of such an animal monitoring system, this dissertation had carefully designed and thoroughly implemented an ultra-low power communication protocol, which is able to provide multi-hop routing capability with an overall duty cycle level as low as 0.1%. Both lab tests and field tests were also conducted to verify the
developed communication protocol. Furthermore, the two essential elements of this communication protocol: the synchronization error and the throughput, were analytically formulated and analyzed. The validity of these formulations was verified by the lab tests. Currently, the developed ultra-low power communication protocol has been successfully used in our energy harvesting wireless sensor based animal monitoring system.
ACKNOWLEDGEMENT

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Table of Contents

Chapter 1 Introduction ........................................................................................................... 1
Chapter 2 Background ........................................................................................................... 6
2.1 Passive RFID .................................................................................................................. 6
  2.1.1 Near-Field Passive RFID ....................................................................................... 7
  2.1.2 Far-Field Passive RFID ...................................................................................... 8
2.2 Active RFID .................................................................................................................. 9
2.3 Wireless Sensor Network ............................................................................................. 10
2.4 Energy Harvesting Technologies .................................................................................. 12
2.5 Summary ..................................................................................................................... 14
Chapter 3 Problem Statement ............................................................................................ 16
  3.1 Low Power Consumption Challenge ........................................................................ 16
  3.2 Multi-Hop Challenge ................................................................................................ 20
  3.3 Summary ................................................................................................................... 22
Chapter 4 Goals and Motivations ..................................................................................... 23
  4.1 Designing The Communication Protocol .................................................................. 24
  4.2 Implementing The Communication Protocol .......................................................... 28
  4.3 Mathematical Evaluating Of The Communication Protocol ................................... 29
  4.4 Summary ................................................................................................................... 31
Chapter 5 Design Of The Proposed Ultra-Low Power Communication Protocol ............ 32
  5.1 The Adaptive Synchronization Method ..................................................................... 32
    5.1.1 Cycle Detection Phase ....................................................................................... 33
    5.1.2 Synchronization Maintenance Phase ............................................................... 36
  5.2 Separated Sending and Receiving Time Schedule .................................................. 38
  5.3 Data Acquisition Routing Protocol ........................................................................... 40
  5.4 Summary ................................................................................................................... 43
Chapter 6 Implementation Of The Ultra-Low Power Communication Protocol ............... 44
  6.1 Hardware Selection .................................................................................................... 44
    6.1.1 MSP430F2274 .................................................................................................... 45
    6.1.2 CC2500 Radio .................................................................................................... 46
  6.2 Software Implementation ............................................................................................ 47
    6.2.1 Tag Program ....................................................................................................... 48
      6.2.1.1 Voltage detection state ............................................................................. 50
      6.2.1.2 Synchronizing state .................................................................................... 50
      6.2.1.3 Synchronization maintenance state ......................................................... 52
      6.2.1.4 Separated sending and receiving time schedule ..................................... 54
    6.2.2 Hub Program and Packet Definition .................................................................... 58
  6.3 Summary .................................................................................................................... 60
Chapter 7 Mathematical Formulation Of The Ultra-Low Power Communication Protocol .................................................. 61
  7.1 Mathematical Formulation Of The Synchronous Performance .................................. 61
7.2 Mathematical Formulation Of The Throughput Performance ..................................... 69
  7.2.1 Nodes Attempting To Send With The Poisson Distribution .................................. 70
  7.2.2 Nodes Attempting To Send With The Equal Probability ........................................ 71
  7.3 Summary .................................................................................................................. 73
Chapter 8 Results ............................................................................................................. 74
  8.1 Field Test Results ....................................................................................................... 74
  8.2 Validation Of The Mathematical Formulation Of The Synchronization Error .......... 80
  8.3 Validation Of The Mathematical Formulation Of The Throughput ............................ 83
  8.4 Summary .................................................................................................................. 87
Chapter 9 Conclusions and Future Work ....................................................................... 88
  9.1 Conclusions .............................................................................................................. 88
  9.2 Future Work ............................................................................................................... 90
References ......................................................................................................................... 92
List of Tables

Table 2.1 Power density comparison of various energy harvesting sources .................. 14
Table 3.1 Power consumption in wireless sensor nodes............................................. 17
Table 3.2 Energy harvesting rate comparison............................................................ 17
List of Figures

Figure 2.1 Energy harvesting techniques................................................................. 13
Figure 3.1 Instability of harvested energy ............................................................... 21
Figure 5.1 Cycle detection phase A ........................................................................ 34
Figure 5.2 Cycle detection phase B ........................................................................ 36
Figure 5.3 Synchronization maintenance phase ....................................................... 36
Figure 5.4 Flowchart of synchronization maintenance ............................................. 37
Figure 5.5 The separated sending and receiving time schedule ............................... 38
Figure 5.6 Slotted ALOHA MAC ............................................................................ 39
Figure 5.7 Data acquisition routing protocol .......................................................... 40
Figure 5.8 The changed topology ........................................................................... 42
Figure 6.1 TI eZ430RF platform ............................................................................ 44
Figure 6.2 Functional block diagram of MSP430F2274 .......................................... 45
Figure 6.3 State diagram of CC2500 radio .............................................................. 46
Figure 6.4 Relationship between SimpliciTi network protocol and ultra-low power
communication protocol ......................................................................................... 47
Figure 6.5 SimpliciTi packet format ........................................................................ 47
Figure 6.6 State diagram of the main thread ............................................................ 49
Figure 6.7 System clock implementation .................................................................. 50
Figure 6.8 Flowchart of synchronization .................................................................. 51
Figure 6.9 Flowchart of synchronization maintenance ........................................... 53
Figure 6.10 Separated sending and receiving time schedule ...................................... 55
Figure 6.11 Alignment issues between the tag and its upstream tag .......................... 55
Figure 6.12 Effect of the adjustment method ............................................................ 56
Figure 6.13 Random sending process of the slotted ALOHA MAC .......................... 57
Figure 6.14 Implementation of the random sending process of the slotted ALOHA MAC ............................................................................................................ 58
Figure 6.15 Flowchart of hub program ...................................................................... 59
Figure 6.16 Packets definition .................................................................................. 59
Figure 7.1 Adaptive synchronous method .............................................................. 64
Figure 7.2 Clock difference issue ........................................................................... 65
Figure 7.3 Proposed slotted ALOHA MAC .............................................................. 70
Figure 8.1 Energy harvesting wireless sensor based animal monitoring node ............ 74
Figure 8.2 Chain topology ...................................................................................... 75
Figure 8.3 Packets collected at the hub in the chain topology .................................... 75
Figure 8.4 Star topology .......................................................................................... 76
Figure 8.5 Packets collected at the hub in the star topology ....................................... 77
Figure 8.6 Solar test topology .................................................................................. 78
Figure 8.7 Results of packets delivery in the solar test ............................................. 78
Figure 8.8 Results of harvested energy measured in voltage in the solar test ............. 79
Figure 8.9 Clock difference calculating method ....................................................... 80
Figure 8.10 Comparison of the variances of the synchronization errors between the tested
results and theoretical results ............................................................................... 82
Figure 8.11 Comparison of the means of the synchronization errors between the tested
results and the theoretical results ........................................................................ 83
Figure 8.12 Occurrences of no collision when two packets from different nodes are sent in the same slot

Figure 8.13 Throughput test scenario

Figure 8.14 Comparison between the testing throughput and the theoretical throughput
Chapter 1

Introduction

The worldwide outbreak of contagious animal diseases such as classical swine fever, Foot and Mouth Disease (FMD), and Bovine Spongiform Encephalopathy (BSE, or mad cow disease), have led to the needless slaughter of millions of livestock, resulting in economic losses in the billions of dollars. In 1997, the Taiwanese FMD outbreak caused a slaughter of 3.8 million hogs and about 7 billion in economic losses [1]. In 2001 FMD resurfaced, leading to the slaughter of 10 million cattle, hogs, and sheep costing the United Kingdom around 16 billion dollars. As a result of the damage caused by the outbreak of contagious animal diseases, many countries have established strict border protection laws to try to limit their spread. In December of 2003, Japan halted US beef imports after it discovered the first case of mad cow disease in the US. Over sixty-five other nations also implemented full or partial restrictions on importing U.S. beef products due to concerns that testing in the US lacked sufficient rigor. As a result, the export of US beef dropped from 1,300,000 tons in 2003 to 322,000 tons in 2004. However, the most serious contagious disease is probably Avian Influenza (usually called bird flu influenza), since it not only infects poultry but can be passed onto humans. In 2003, two cases of the Highly Pathogenic Avian Influenza (HPAI) virus were reported by members of a Hong Kong family that had traveled to Mainland China. While one family member eventually recovered from the disease, the other died according to a U.S. report from the U.S. Center for Disease Control and Prevention [2]. Severe Acute Respiratory Syndrome (SARS), is
another contagious disease that led to a massive outbreak in China in 2003. It was originally believed to have jumped directly from an animal host to a human being. During the time between 2002 and 2003, an outbreak of SARS in Hong Kong rose to nearly pandemic levels, causing 8,422 cases and 916 deaths worldwide according to the World Health Organization (WHO) [3]. Within weeks, SARS spread across country borders infecting individuals in 37 countries by early 2003. Overall, the direct economic loss of the crisis was estimated at 2% of the East Asian GDP according to a 2005 World Bank report [3].

These incidents have pushed many countries to develop and implement animal identification (ID) and traceability systems that can control and prevent the outbreak of such devastating diseases. The United States Department of Agriculture’s Animal and Plant Health Inspection Service (APHIS) directs several programs for animal disease eradication and control that include animal identification components [4].

The National Animal Identification System (NAIS) program [5] was first proposed in 2002 to protect commercial interests involved in the U.S. agriculture industry from the potential harm associated with the outbreak of an animal disease. The long-term goal of the system was to be able to identify and trace animals of interest within 48 hours. If an outbreak occurred, the animal tracing database could provide timely, accurate reports that detailed where potentially exposed animals had been and what other animals had come into contact with those potentially diseased animals. The establishment of NAIS led to a variety of positive outcomes:

First, NAIS was able to help identify the source of the disease, animal populations that were exposed to the disease, and contain those diseases and animals via
compartmentalization at an early phase of the outbreak. The U.S Department of Agriculture claims that disease testing costs for animal producers would likely be reduced by NAIS via controlling and eradicating animal diseases on both a regional and national scale [5].

Second, economic damages can be greatly minimized by NAIS. Once the contagious animal disease outbreak occurred, a rapid compartmentalization or regionalization would be executed in a specific zone, leaving the remaining area outside of that zone free of the particular disease. Therefore, the spread of commercially harmful diseases could be minimized, and the number of animals that would otherwise have to be killed or removed from marketing channels saved. The NAIS system also facilitates the re-establishment of access to the international market and the reopening of lost export markets. Thus, economic losses that result from animal disease outbreaks are greatly reduced.

Third, NAIS provides tools for farmers and ranchers to keep track of how an individual animal is being raised so that they can identify and explore desirable production characteristics (such as for providing organic, grass-fed and hormone free products) that satisfy their clients and increase their market share. Furthermore, the NAIS system also increases the transparency of the supply chain as it moves from producers to consumers, reducing the risk of unfounded liability claims against livestock producers.

Fourth, food supply related safety issues can be effectively addressed through the use of the national animal identification system. When food borne illnesses from bacteria occur, local health officials will be able to link the illness to a particular product and then trace that product back to the farm or ranch. Such information would be difficult to ascertain without the use of the NAIS system.
For these reasons, the national animal identification system has been an indispensable tool for facilitating current and future livestock production activities. Passive RFID is the technology that currently supports the national animal identification system [6-12]. The passive RFID system consists of a passive RFID tag and tag reader. The passive RFID tag is a passive electronic identification transponder consisting of an electric resonance circuit that acts as a receiving or transmitting antenna. When this transponder is in an electromagnetic field of sufficient field strength generated by the tag reader, the induced voltage in the resonance circuit powers the whole chip, sending its stored information back to the reader.

However, applying the passive RFID technologies to animal identification and tracking has its disadvantages. First, the communicatory range is limited by two factors: 1) The need for very strong signals to be received to power the tag (thus limiting the reader to the tag range), and 2) the limited amount of power available for a tag to respond to the reader (thus limiting the tag to the range of the reader). These factors typically constrain the operating range of passive RFID to 3 meters in length or fewer depending on the power capacity of the tag reader and the frequency with which it is used. Second, characteristics of the animal such as its temperature, rumen pH, and pulse oximetry must be continuously recorded in order to provide timely and accurate health information for animal tracking and monitoring. However, passive RFID tags are only powered while in proximity to a reader. These tags are unable to monitor the status of a sensor continuously and are thus unable to fulfill the requirement. Third, and as a direct result of the limited communicatory range of passive RFID tags, collecting information on multiple animals outdoors by an automatic operation is unachievable. Collecting data from multiple tags
typically entails a multi-step process in which the reader communicates individually with each tag. Each interaction takes time, and the time spent interfering increases with the number of tags needed and thus the overall duration of the operation.

Because of the lacking of the effective tool for animal identification and tracking for NAIS, to develop a new and effective tool based on the state of the art technology became necessary. Under a grant from Nebraska Research Initiative and support from the Advanced Telecommunication Engineering Laboratory (TEL) [13] in Computer and Electronics Engineering Department of University of Nebraska-Lincoln with collaboration with Animal Sciences Department of University of Nebraska-Lincoln, this project was initiated to design and develop the state of the art technology for animal identification and tracking system. This dissertation work is a part of this mission by developing the state of the art communication protocol to support our animal identification and tracking system.
Chapter 2

Background

There are currently four major state-of-the-art technologies able to support the National Animal Identification System (NAIS) in facilitating its task of monitoring and tracking the livestock supply chain: passive and active RFID, the wireless sensor network, and energy harvesting.

2.1 Passive RFID

A passive RFID system consists of a tag reader and passive tags. A passive tag consists of an antenna and a semi-conductor chip encapsulated in some form of protective unit. When equipped with a power supply, a tag reader powers and initiates communication with the tag. Researchers are interested in exploring future opportunities for utilizing passive RFID because such tags operate without the need for batteries or maintenance procedures. Passive tags are also small enough to fit into a practical adhesive label and able to remain in operation over a long period of time [14].

There are two types of design approaches for passive RFID: Near-field passive RFID [15] and far-field passive RFID [16]. The two approaches take advantage of electromagnetic properties in order to transmit energy of a magnitude of 1mW to 1W from a reader to a tag sans physical contact.
2.1.1 Near-Field Passive RFID

According to the paper[17], Near-Field Passive RFID is based on Faraday’s Law of magnetic induction. A reader generates an alternating magnetic field in its proximity by passing a large alternating current through its coil. A tag located in the vicinity of this magnetic field collects an alternative voltage in its own coil. The generated voltage is then rectified and coupled to a capacitor, wherein a reservoir of charge accumulates and supplies power to the tags circuit. The load change of a smaller coil in the tag leads to a change in its own small magnetic field. This change opposes the readers magnetic field, causing the current passing through the coil of the reader to change. Theoretically, the tag readers changing current should be proportional to the load applied to the tags coil. The near-field passive RFID system takes advantage of this phenomenon to communicate. Once it is powered by the reader, a tag can then encode its ID and other data in the changes of the coil load. The reader can then recover this signal by monitoring the change of current through its coil. The operational distance of the near-field coupling approach is limited. The reading distance $D$ is well within the radian sphere, which reversely proportional to the wavelength and the magnetic field strength that the tag coil can capture[18],

$$D \propto \frac{\lambda \cdot E}{2\pi}$$ (2.1)

Thus, as the frequency of operation increases or the magnetic field strength deceases, the distance over which near-field coupling can operate decreases. The magnetic field drops off at a factor of $\frac{1}{r^3}$, where $r$ is the distance between the tag and the reader. Thus, Equation 2.1 can be rewritten as
The typical operational distance of a near-field RFID system is about 10 to 20 cm. The frequency is constrained at a low level, typically between 120 kHz to 13 MHz in magnitude. This thus translates into a low data transmission rate.

2.1.2 Far-Field Passive RFID

In a far-field passive RFID system, the dipole antenna of a tag is able to capture the electromagnetic wave generated by a reader as an alternating potential difference that appears across it [17].

A tag that uses far-field passive RFID sends its data back to the reader in a way that differs from a tag that uses near-field passive RFID. The mismatch between the tag’s antenna and the load circuit causes the reflection from the tag to the reader[after 16-3]. A reader with a highly sensitive radio receiver can detect these reflected waves. Most commercial far-field RFID systems utilize this principle.

The range of the far-field RFID system is constrained by the amount of energy the tag can capture and the sensitivity of the tag reader’s radio receiver. The return signal is small because of the two attenuations of the electromagnetic wave—one that occurs as it travels from a reader to a tag, and the other that results from the reflection back from the tag to the reader. The amount of electromagnetic energy the reader’s radio captures is a factor of $1/r^4$, where $r$ is the distance between the reader and the tag.

Far-field RFID has a longer communication range than the near-field RFID. It can reach 5-20 m [19].
In conclusion, it is evident that both the near-field and far-field RFID approaches are limited to a short range of communication. And because of the unavoidable collision problem, they are unable to support the automatic multiple tag reading function [20]. These limitations ultimately limit their effectiveness and the applicability of their use in the NAIS.

2.2 Active RFID

In contrast to the passive RFID system, active tags have both a radio transceiver and button cell batteries [21]. The tags are able to report the data initiative and periodically back to the reader over a long distance. For example, the spider system manufactured by RF code [22] has a reading range of 150 feet and extended range of 1000 feet with the addition of a special antenna.

The active RFID system has a variety of advantages over the passive RFID system. First, using active RFID it is not necessary to power the reader in order to transmit its data by its own wireless transceiver, thus greatly increasing the communicatory distance. Second, using an on-board battery the active RFID can continuously monitor the environmental conditions and health of the livestock and store the collected information in the on-board memory. In the case of an emergency, the information can be initiative reported back to a reader. Thus, in comparison to the passive system, the active RFID system has the ability to provide timelier monitoring to the NAIS. Third, active RFID is able to automatically read multiple tags over a short period of time. The multi tags and reader in the active RFID system form a centralized network, whereby all tags report data back to a reader initiative using a collision-avoid mechanism (such as carrier sense multiple access (CSMA)). Passive RFID does not have this capability.
However, the active RFID has its disadvantages as well. Active RFID tags require a cumbersome power source (since they are connected to either a powered infrastructure or to an integrated battery). As a result, a tag’s lifetime is limited by the stored energy, which also limits the number of readings the device is able to perform. Furthermore, the active RFID system only supports centralized single-hop network communications, limiting its tracking coverage to within the range of such a network.

2.3 Wireless Sensor Network

A wireless sensor network [23-28] is a collection of distributed sensors that monitor environmental conditions and cooperatively pass their data wirelessly to a central hub.

Wireless sensor networks are advantageous over RFID technologies in many ways. First, the cooperative multi-hop transmission characteristic of a wireless sensor network enables long range communication over multi-hop networks, scattering the communicatory energy consumption among the tags and avoiding the highly energy-consuming long-range single-hop communication network. Second, wireless sensor networks offer more flexible coverage than RFID technologies. Utilizing its ad-hoc networking function, a wireless sensor network can be deployed in a desired topology and offer better coverage than that of a centralized single-hop RFID.

Therefore, wireless sensor networks offer many capabilities that RFID technologies simply cannot. These can be employed to better support the national animal identification system (NAIS) in the monitoring and tracking of animals.

There are a number of existing approaches for animal monitoring using wireless sensor networks. They can be divided into two categories: The stationary wireless sensor network approach and the mobile wireless sensor network approach.
The stationary wireless sensor network approach involves the deployment of a number of wireless sensors in a fixed geographic topology. These wireless sensors are powered by a battery and pass their sensed data through pre-determined routes to a powerful server. At the server, the monitoring data is processed. The Great Duck Island [29] project serves as one example where this approach was taken. 32 wireless nodes were deployed on a small island off the coast of Maine in a fixed topology. Through streaming live data on the web, researchers were able to monitor the behavior of seabirds inhabiting the island. Yet another example where this has been employed is in botanical research. Scholars at the University of Hawaii monitored rare and endangered plant species by setting up a wireless sensor network in the Hawaii Volcano National Park [30]. The camouflaged wireless nodes were deployed in fixed places, relaying sensor data via a wireless link that connected back to the Internet. The major limitation of the stationary wireless sensor network approach in these kinds of research projects is the difficulty of finding a place that the monitored animals can visit on a regular basis.

In the mobile wireless sensor network approach, wireless sensors are attached directly to the animals. All measured data is transferred to nearby fixed infrastructure, which then relays the data back to the base station. The ZebraNet [31] project is an example of how this approach was adopted to track and monitor zebras in Kenya. In this study, GPS-enabled sensor nodes were incorporated into the animal collars, and data marking the geographic location of the animals was passed to a base station. Another example is the Wired Pigs Project [32]. In this project, the health of pigs were monitored through the use of environmental sensors. The sensors collected humidity and temperature information and wirelessly passed the data to a base station. This mobile
wireless sensor networking approach is still in its early stages. It currently still relies heavily on infrastructure to provide the wireless connection in the single hop range. In the future, however, hopefully it will use a more reliable multi-hop network that has an arbitrary topology communication capability.

To sum up, the capabilities of wireless sensor network technologies are promising for achieving the goals of animal monitoring: The multi-hop communication capability enlarges the coverage of the monitoring area; and potential self-organized ad-hoc networks can effectively provide mobile target monitoring. The only major limitation of using a wireless sensor network is that each wireless node requires its own power supply making the implantation procedure quite inconvenient.

2.4 Energy Harvesting Technologies

Energy harvesting is a technique that captures unused ambient solar, wind, thermal, and vibrational energy and converts it into usable electrical energy that sensors can use to perform sensing or actuation functions.

There is currently a lot of academic research that details how to harvest small-scale environmental energy for low-powered electronic devices. There are three categories of energy harvesting techniques: Radiant energy harvesting, thermal energy harvesting, and mechanical energy harvesting, as illustrated in Figure 2.1.
Raghunathan et al. [33] proposed a prototype of a solar energy harvesting system for small scale electronic devices. There is also a significant amount of research that has been carried out to develop schemes to power sensors using wind energy. Tan et al. [34-35] proposed a circuit that is able to harness wind energy and convert it to electrical energy for the board. Weimer et al [36] propose an anemometer based wind harvesting solution. The literature also includes several scholars interested in the small-scale energy harvesting of vibrational energy (see Roundy et al. [37], Schenck et al. [38], Emdison et al. [39], and Glynne et al. [40]. As part of their efforts to harvest thermal energy, Lawrence et al. [41] designed a thermoelectric conversion system that exploits the natural temperature difference between the ground and the air. In Leonov et al. ‘s work [42], a thermal energy harvesting scheme is proposed in which energy is harvested using the temperature difference between the body and the air. The amount of energy that can be harnessed from these ambient environments based on the previously mentioned studies is summarized in Table 2.1.
Table 2.1 Power density comparison of various energy harvesting sources

<table>
<thead>
<tr>
<th>Energy Sources</th>
<th>Power Density</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solar (direct sunlight)</td>
<td>100 mW/cm$^3$</td>
</tr>
<tr>
<td>Solar (illuminant office)</td>
<td>100 $\mu$W/cm$^3$</td>
</tr>
<tr>
<td>Thermoelectric</td>
<td>135 $\mu$W/cm$^3$ at 10 °C gradient</td>
</tr>
<tr>
<td>Blood Pressure</td>
<td>0.93W at 100mmHg</td>
</tr>
<tr>
<td>Vibration Micro-Generators</td>
<td>4$\mu$W/cm3human motion, 800$\mu$W/cm3machine motion</td>
</tr>
<tr>
<td>Piezoelectric Push Buttons</td>
<td>50μJ/N</td>
</tr>
</tbody>
</table>

From Table 2.1 [43], we can clearly see that solar energy is able to provide 100 mW/cm$^3$ of power density during the daytime, performing the best of the mentioned sources.

When the solar panel is brought into indoor conditions such as in an illuminated office environment, the light intensity is reduced tremendously, and the power density of the solar energy drops to almost 100$\mu$W/cm$^3$. This shows that the solar power available indoors is drastically lower than that available outdoors.

In conclusion, there is a significant amount of research available on the topic of energy harvesting. Outdoor solar energy harvesting provides the most abundant source of useful energy, producing about 1000 times more than any other energy harvesting technique.

2.5 Summary

Considering the pros and cons of all the available technologies, the best solution for supporting the NAIS in tracking and monitoring animals is to combine the strengths of the wireless sensor networks and energy harvesting technologies in the design of a new
integrated system that can form a self-organized autonomous multi-hop Ad hoc network able to self-power using energy harvesting technologies. This integrated system will have the most potential for fulfilling all the requirements for supporting the NAIS system and serve to guide the creation of future animal tracking and monitoring systems. Therefore, our TEL lab strives to study, design, develop, and analyze a prototype of this integrated system, aiming to offer the best technology for NAIS. The work of this dissertation is under this direction, focusing on the ultra-low energy communication protocol design, implementation, test and modeling with a purpose of help to fulfill the prototype of the new integrated system.
Chapter 3

Problem Statement

The energy harvesting wireless sensor network approach for national animal identification system (NAIS) is very promising technology. However, a complete and an in-depth study is needed to design and develop a practical communication protocol for an integrated system that is able to provide a multi-hop self-routing ad hoc network only powered by harvested energy from the ambient environment faces many challenges. This need was the main motivation for this research work. It is clear that the findings from this research work can contribute significantly to similar wireless sensor network communication protocols for different applications.

3.1 Low Power Consumption Challenge

This thesis looks at finding a way to reduce the energy consumption of a wireless sensor to a level at which harvested energy from the ambient environment is sufficient to enable it to perform its necessary functions.

Using the technology available today, a typical wireless node consumes from 50mW to 90mW of power when both the radio and the microcontroller are in the active mode. Table 3.1 shows the power consumption information for two popular wireless sensor nodes [44-46]. The radio of a MICAz consumes as much as 59.1 mW of power in the RX mode. The microcontroller consumes as much as 24 mW in the active mode, or about 40% of the total energy consumed by a radio. The total power consumption is about 83.1
mW. The radio of the EZ430-RF2500 wireless node consumes about 56.4mW in the RX mode, and the microcontroller consumes about 0.81 mW in the active mode (together totaling 57.21 mW of consumed power).

Table 3.1 Power consumption in wireless sensor nodes

<table>
<thead>
<tr>
<th>Power consumption sources</th>
<th>MICAz current</th>
<th>MICAz power</th>
<th>eZ430-RF2500 current</th>
<th>eZ430-RF2500 power</th>
</tr>
</thead>
<tbody>
<tr>
<td>Radio (RX mode)</td>
<td>19.7mA</td>
<td>59.1mW</td>
<td>18.8 mA</td>
<td>56.4 mW</td>
</tr>
<tr>
<td>Radio (TX mode)</td>
<td>17.4mA</td>
<td>52.2mW</td>
<td>21.2 mA</td>
<td>63.6 mW</td>
</tr>
<tr>
<td>Radio (sleep mode)</td>
<td>1µA</td>
<td>3µW</td>
<td>400nA</td>
<td>1.2µW</td>
</tr>
<tr>
<td>Processor (active mode)</td>
<td>8 mA</td>
<td>24mW</td>
<td>270µA</td>
<td>0.81mW</td>
</tr>
<tr>
<td>Processor (sleep mode)</td>
<td>&lt;15µA</td>
<td>&lt;45µW</td>
<td>0.1µA</td>
<td>0.3µW</td>
</tr>
</tbody>
</table>

On the other hand, the harvested power rate from the ambient environment is very limited. According to some research [47-49], the rate of energy harvested by a 10 cm² harvesting material can be summarized as Table 3.2.

Table 3.2 Energy harvesting rate comparison

<table>
<thead>
<tr>
<th>Harvesting sources</th>
<th>Energy harvesting rate</th>
<th>Account for how much of MICAz power consumption</th>
<th>Account for how much of eZ430-RF2500 power consumption</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vibration-electromagnetic</td>
<td>0.04mW</td>
<td>0.048%</td>
<td>0.069%</td>
</tr>
<tr>
<td>Vibration-piezoelectric</td>
<td>5 mW</td>
<td>6%</td>
<td>8.7%</td>
</tr>
<tr>
<td>Thermoelectric</td>
<td>0.6 mW</td>
<td>0.7%</td>
<td>1%</td>
</tr>
<tr>
<td>Solar-direct sunlight</td>
<td>37 mW</td>
<td>44.5%</td>
<td>64.6%</td>
</tr>
<tr>
<td>Solar- indoor</td>
<td>0.032 mW</td>
<td>0.038%</td>
<td>0.059%</td>
</tr>
</tbody>
</table>
As can be seen in the Figure, the energy source that offers the best potential for harvesting is direct outdoor sunlight (at a rate of 37mW). However, this rate is still well below the wireless sensor nodes’ full operational power requirements (83.1mW and 57.21mW in MICAz and eZ430-2500RF, respectively).

Thus there is not enough harvested energy to power the wireless sensor node in full operation. In order to reduce the energy consumption of the wireless sensor node to a level at which it can operate solely using harvested energy, a practical, ultra-low duty cycle communication protocol is required.

According to Table 2.2, if outdoor solar energy is used to power the eZ430-RF2500 node, an operational protocol with an average duty cycle of at least 64.6% is needed. However, at night the solar energy drops dramatically, requiring the system to operate at a duty cycle as low as 0.059%. If a wireless node is powered only by thermoelectric energy, the average duty cycle would become at most 0.7% (MICAz), and 1% (eZ430-RF2500). If the energy is harvested using only vibration-piezoelectric energy, the average duty cycle of the operational system will be no more than 6% (MICAz), and 8.7% (eZ430-RF2500). This estimate is based on the assumption that the energy sources are continuously available and energy is not consumed while the radio and microcontrollers are in the sleep mode. In real world applications, of course, the previously mentioned factors must be taken into account. Thus, the required operational duty cycle will be even lower than that presented in the estimates. In order to make a practical wireless sensor node powered only by the harvested energy operate smoothly, the communication protocol must have an ultra-low duty cycle of as low as 0.1%-0.01%. A lot of previous research has focused on energy efficient communication protocols that have a low duty
cycle capability. However, to the best of the author’s knowledge, there is currently no practical communication protocol that has a duty cycle as low as 0.1%-0.01%.

There are two dominant approaches for energy efficient MAC protocol in the literature, common active period protocols [50-61] and preamble sampling protocols [62-71]. S-MAC [57] is a seminal work on common active period protocol design. In S-MAC, nodes turn off the radio during the sleep mode and transmit packets during their wake-up time. Nodes synchronize with each other by exchanging SYNC packets periodically. This simple synchronization method only addresses the offset of the clock differences between two nodes, but does not estimate the clock drift differences. Therefore, the maximum length of the network cycle is limited to tens of seconds, resulting in a minimum duty cycle of 1%.

The other energy efficient communication protocol approach is the preamble sample protocol. The basic concept behind preamble sample protocols [62-71] is to let nodes choose their wake-up schedule independently of other nodes around them. In preamble sampling protocols, a node spends the majority of time in sleep mode; it wakes up only for a short duration to check whether there is a transmission on the channel. To avoid missing the receiving time, each sending frame is preceded by a preamble long enough to make sure that all potential receivers can detect the preamble and obtain the data frame. The drawback to using this approach is the heavy overhead of each transmission, which inhibits the duty cycle from being lower than 1%. Lowering the duty cycle increases the transmission cost of the transmitter. In the scenario in which the ultra-low duty cycle is 0.1%, one packet transmission may deplete all the harvested energy,
leading to a transmission failure. Typically, the optimal duty cycle for preamble sampling protocols is around 1% or higher [70].

Due to the lack of a feasible ultra-low duty cycle communication protocol in the prior literature, a practical communication protocol with a duty cycle as low as 0.1% or less must be developed for the proposed integrated system that is able to provide a multi-hop self-routing ad hoc network powered only by energy harvested from the ambient environment.

3.2 Multi-Hop Challenge

Another important design requirement for energy harvesting wireless sensor networks used in animal monitoring and tracking is to deliver reliable data through multi-hop networks. However, energy consumed as a result of the delivery of data over a multi-hop network is usually costly for the sensor network. Providing a multi-hop routing function in such an ultra-low power consuming communication protocol with an average duty cycle of 0.1% is an extremely challenging task.

There are several network protocols that have been proposed for multi-hop data delivery in the energy harvesting wireless sensor network. However, none of these protocols provide the multi-hop data delivery functionality at the low expense of energy consumption. A modified directed diffusion routing protocol [72] was proposed in the prior art that incorporates the solar power information into its route selecting process to boost the performance of the original directed diffusion [73] in the energy harvesting wireless sensor network. The route discovery of directed diffusion uses a flood method that can devour all energy of a sensor network, causing a network collapse before data transmission can occur. Another routing method proposed for harvesting wireless sensor
networks involves integrating a solar-cell energy model into a geographic routing protocol. By taking into account the environmental conditions, the throughput can be maximized [74-75]. The energy consumption of these routing protocols is also too heavy for the proposed integrated system. Other researchers [76-80] look into how to optimize the routes under specific environmental constraints. Nodes with higher energy harvesting rates are more preferable for relaying packets to the base station than those with lower rates. These routing methods assume the ideal MAC protocol that their works were based on. As a result, only incremental energy can be saved. This is are also not suitable for the task proposed in this thesis.

Finding a way to provide the multi-hop data delivery function using the least possible energy (and thus reducing costs) is a challenging new research area. This dissertation explores a means to deliver data via the communication protocol that consumes minimal energy.

![Graph of harvested energy instability](image)

**Figure 3.1 Instability of harvested energy [81]**
Besides the minimum energy consumption demand for the multi-hop delivery functionality, the instability of harvested energy poses yet another design challenge.

Compared to battery energy, harvested energy storage is very limited and fluctuations are expected over time. The instability of harvested energy adds more dynamic to the sensor network. Thus, this dynamic hardware problem must be taken into consideration when designing and developing the routing functionality.

3.3 Summary

In summary, the design and development of the communication protocol for our energy harvested sensor network based animal monitoring system requires two challenging tasks.

- **The energy consumption of the communication protocol is demanded to have a duty cycle of 0.1% or less.**
- **A dynamic multi-hop routing functionality is required.**

It is a challenge to address these two problems simultaneously. In this dissertation, we strive to design and develop a communication protocol that is able to fulfill the above two challenging requirements simultaneously as a part of the TEL lab’s overall solution for the energy harvested sensor based animal tag system for NAIS.
Chapter 4

Goals and Motivations

As the previous chapter stated, a new communication protocol was needed to address the two challenging problems to develop:

1) A dynamic multi-hop routing functionality.

2) The duty cycle of the communication protocol with as low as 0.1% or less.

In this dissertation, we studied the state of the art communication protocol in the literature, strive to design, implement and mathematically evaluate this required new communication protocol that provides the above two requirements. This communication protocol is needed to be practical in any hardware and software platform, and easy to be replicated for a large volume of wireless nodes. In addition, the new communication protocol had to be mathematically evaluated and be able to easily compared with other existing communication protocols reported in the literature. Bearing these requirements in mind, we break down this task into three objectives:

1) Designing the communication protocol that supports multi-hop routing functionality with an ultra-low power consumption capability.

2) Implementing the designed communication protocol in a hardware and software platform to verify its practical applicability and its easy replication capability.

3) Analytically evaluating the designed communication protocol to give the direct insight of its performance.
4.1 Designing The Communication Protocol

The main task of our communication protocol is to transfer data reliably and accurately with minimum overhead. To be specific, wireless nodes need to sense the concerned animal information, and pass them through multi-hop paths to the hub. In the literature, there are two approaches to achieve data acquisition and transmission functionality energy efficiently. One approach is to independently design an energy efficient MAC protocol and an energy efficient routing protocol and then combine them together with an interface between them. This results in a two-layer communication protocol. Another approach is to design an integrated communication protocol that includes the MAC functionality and routing functionality in a single un-separated layer.

To the best of the author’s knowledge, most of the existing literature focuses on the first approach, that is, separating the task into completely independent layers (MAC and routing). In order to design an energy-efficient MAC protocol [82-90], there are basically two dominant approaches in the literature: The common active period approach, and the preamble sampling approach.

In the common active period approach, all nodes in the network are synchronized to wake up at the same time in order to communicate as well as to sleep at the same time to save energy consumption. This approach has two challenges. The first is the synchronization problem. In a distributed network every wireless node has a different clock. Starting the synchronization of every node in the network and maintaining the synchronization over time means that there will be a heavy overhead to operate the network. In the current literature, the synchronization problem has not been effectively addressed at all. A few of the seminal works on common active period approaches such
as the S-MAC and T-MAC propose a simple synchronization method. This method uses a dedicated period to send a SYNC packet to their neighbors to maintain the synchronization. This method is very inaccurate in terms of timing the network cycle, limiting the duty cycle of the MAC protocol to within an order of 1%-10%. An effective synchronization method able to provide a duty cycle of 0.1% or less is still lacking in the literature. The second problem with using the common active period MAC approach is the collision problem. Since all node traffic is condensed into a small time slot called the wake-up time, the possibility that a collision may occur increases. As is typically the case: The lower the duty cycle, the more severe the collision problem.

In the preamble sampling approach, nodes wake up periodically according to their independent schedule. A sender precedes its data with a long preamble to ensure that its intended receiving node can wake up to obtain the data. The major advantage of this approach is that it is completely free of the burden of synchronization. However, there are drawbacks to the preamble sampling approach. First, a long preamble significantly increases the overhead on transmitters. Such costs prevent the MAC from running at duty cycles less than 1% since such an expensive sending cost becomes prohibitive at an ultra-low duty cycle level. Second, while preamble sampling can be optimized for known periodic traffic, its performance may significantly degrade in bursty transmission and at varying traffic loads.

There are several energy efficient routing protocols proposed in the literature [97-104]. Sensor Protocols For Information via negotiation (SPIN) [105] protocol was one of the earliest works to improve energy efficiency by addressing implosion and overlapping problems in the flooding. The SPIN protocols are resource aware and resource adaptive.
The sensors running the SPIN protocols are able to compute the energy consumption required to compute, send, and receive data over the network. Thus, they can make informed decisions regarding the efficient use of their own resources. The SPIN protocols are based on three key mechanisms: These are namely negotiation, meta data description, and resource adaptation. The negotiation process that precedes the actual data transmission gets rid of the implosion issue because it eliminates transmission of a repeated data message. The use of meta-data descriptors eliminates the possibility of overlap because it allows nodes to name the portion of the data they are interested. Being aware of local energy resources allows sensors to stop the activities when the energy stored is not enough to carry out packet sending. Another energy efficient routing protocol is directed diffusion [73]. This routing protocol starts with a low data rate flood from the source to the sink. When the sink receives data of the source from multiple paths, it reinforces the arrival of the first path by sending an event to all nodes on that path. These energy efficient routing protocols do not consider the MAC protocol that they are based on assuming neighbor nodes are able to hear each other all the time. As a matter of fact, communication among neighbors’ is quite expensive in the ultra-low duty cycle MAC, even when the rate of data transmission is low. In essence, these routing protocols do not decrease by much the number of packet transmissions in their routing discovery. Instead, they only decrease the number of high-data-rate transmissions. Therefore, the total transmission number is still the same as the flooding algorithm, which is an overwhelming energy consumer.

By observing the existing MAC and routing protocols, it can be concluded that the first approach to combining the MAC protocol and routing independently with an
interface between the two of them is infeasible due to the overwhelming amount of energy consumed by the routing protocol.

The second approach for the data acquisition communication protocol is the integrated communication protocol that includes the MAC and routing functionality in a single layer. This is a relatively new approach in the literature. Dozer [106] gives one example where this approach is utilized. The method integrates the MAC protocol and routing protocol to reduce the energy consumption that results from the communication. The routing protocol is based on a formation of the tree structure network, where the sink is the root of the tree and all other nodes are leaves of the tree. Data exchange between parent and child nodes is conducted via a loose TDMA protocol. This communication protocol is able to operate at a duty cycle of 0.2%. However, the synchronization method used by Dozer is very simple. Actually, how a child node initially synchronizes to a parent at the beginning is not addressed in Dozer, which would result in significant energy consumption if the duty cycle is very low. In addition, Dozer’s synchronization maintenance method only calculates for the offset between the parent node and child node, neglecting the difference in drift rates between the parent and child nodes. Therefore, the duty cycle is unable to be less than the 0.2% that they have claimed. DISSense [107] provides an improved version of Dozer’s method. Modifications were made to Dozer in terms of its synchronization method. It replaced the sleeping period in Dozer’s method by using an ultra-low power state called the Low Power Listening (LPL) mode with a 0.1% duty cycle to decrease the synchronization establishing time. DISSense added a guard time interval and resynchronization interval to improve the synchronization robustness of Dozer. However, DISSense’s method does not estimate the
drift rate difference between the parent’s clock and the child’s clock. As a result, the
duty cycle cannot increase by more than 0.1%.

The design objective of the communication protocol proposed herein is a protocol
that has both MAC and routing functionalities in a single layer. The design
communication protocol also has an effective synchronization method that can allow its
duty cycle to reach a level of between 0.01% to 0.1%. This new communication
protocol can outperform the existing data acquisition communication protocol discussed
above in terms of energy consumption level, as well as completely fulfill communication
objectives of the energy harvesting wireless sensor based animal monitor system.

4.2 Implementing The Communication Protocol

Another important goal of this dissertation is to implement the designed communication
protocol in a real hardware platform to ensure that the communication protocol is
applicable, meaning it can be replicated in a large volume of nodes effectively with the
same satisfied performance.

First, through this implementation, we aim to deliver a software package that has
two interfaces: user interface that provides parameter settings for customers, and
hardware interface that provides easy reuse of the software in different hardware. The
main parameters that the user interface provides are the cycle time, duty cycle, and
maximum throughput. The hardware interface provides the transparency to both radio
and a microcontroller, meaning radio driver and microcontroller mode configuration are
separated from the communication protocol code.

Second, the needed debug and testing interfaces are provided since there are many
potential unknown problems that would be occurring while we are implementing it.
Additionally, the synchronization method that we designed is directly influenced by the clock differences of the microcontrollers that we choose. How adaptive the synchronization method is and how low the duty cycle could be reached are needed to be tested based on the chosen hardware. Therefore, the convenient and effective debug and testing interface is necessary to be a part of our implementation task.

Third, the implementation needs to provide strong robustness over the clock differences between nodes with the same and different hardware. There are many factors that determine the clocks of the microcontrollers. Some of these factors include, for example, information related to the voltage, temperature, manufacturer, and age. These factors cannot be predetermined for each operation. The implementation should be transparent to the changes of these factors, meaning that they can operate without problems should these factors change.

Therefore, as a part of this dissertation, we planned to implement the designed communication protocol to meet the above three goals. We believe the protocol implementation is a major factor to verify the applicability of the designed communication protocol in a very tangible way, and also a delivery approach for the performance evaluations of our communication protocol, which can be a reliable reference for our mathematical analysis discussed in the next step.

4.3 Mathematical Evaluating Of The Communication Protocol

The third goal of this dissertation is to deduce the mathematical expression of the performance of our communication protocol. Here, we formulate and present the two most important elements of our communication protocol: the synchronization error and the throughput.
The synchronization capability is the essential contribution of the communication protocol. The synchronization accuracy directly determines how low the duty cycle of the communication protocol can be. The synchronization robustness determines how reliably the communication protocol is able to operate. Therefore, it is a core element of the communication protocol. The performance evaluation of the synchronization capability is able to reveal the limiting boundaries of the energy consumption of the communication protocol, which is the key element of concern in the design of the communication protocol in the first place.

Two factors for synchronization are needed to be formulated, the mean of synchronization error over multi-hop, the variance of synchronization error over multi-hop. The mean of synchronization error give us how accurate of our synchronization method is. The variance of synchronization error show us how robust of our synchronization method is. We believe these two factors would be able to answer how well our synchronization method is able to operate. Furthermore, the formulation of these two factors should be validated by the real test results.

Throughput is the second element that this thesis aims to formulate. The goal of the proposed communication protocol is to deliver all the sensed data from the distributed sensors to a central hub. The reliability of the data delivery of the designed communication protocol is also an important consideration. Formulation of the throughput of the communication protocol gives the packet loss rate which is indicative of the reliability of the proposed communication protocol. Therefore, the throughput must be mathematically modeled and formulated.
Throughput should be formulated as a function of traffic load. By using this mathematical formulation, the maximum throughput and the corresponding packet loss rate could be able to be calculated. Additionally, we planned to validate our theoretical formulation through lab testing.

To sum up, we aim to analytically formulate two important elements: the synchronization error and the throughput in our communication protocol. Mathematical evaluation of synchronization error provides the info on how low the energy consumption of our communication protocol can be theoretically. Mathematical formulation of throughput shows theoretically how reliable the data delivery of our communication protocol is. We believe these two important elements could be able to give the answer to the question: how well is our communication protocol perform theoretically?

4.4 Summary

In this chapter, we break down our goal into three specific objectives: 1) designing the communication protocol, 2) implementation of the communication protocol, 3) mathematically formulation of the communication protocol. We believe we will fulfill these three objectives by completing a step by step design of multi-hop communication protocol with ultra-low duty cycle communication with effective energy harvesting wireless sensor in an animal monitoring system.
Chapter 5

Design Of The Proposed Ultra-Low Power Communication Protocol

The proposed protocol was designed as a communication protocol for a self-powered sensor based smart wireless identification and tracking tag, which provides the multi-hop capability and ultra-low communication power consumption. The design objectives are 1) provide a duty cycle as low as 0.1% to enable the entire network to rely completely upon the harvested energy, 2) support multi-hop communication and automatic route detection capabilities, and 3) provide the capacity to support a network with a large number of nodes in an area so that it operates reliably and with minimal interference with each other.

To achieve these objectives, a communication protocol was designed using three components: An adaptive synchronization method, the slotted ALOHA MAC with a separate sending and receiving time schedule, and the data acquisition routing protocol.

5.1 The Adaptive Synchronization Method

There are two different key state-of-the-art design approaches that can be employed to design communication protocols in wireless sensor networks: The Synchronous approach and the asynchronous approach. The synchronous approach allows wireless nodes to communicate with each other by scheduling all nodes to wake up and sleep at the same time. The asynchronous approach utilizes the preamble of the sending node to ensure the receiving node can receive the data. The synchronous approach offers a wide range of
duty cycle capabilities, and how low the duty cycle is depends completely on the accuracy of the synchronization method. On the other hand, the asynchronous approach trades off the receiving energy consumption for the sending energy consumption. In the ultra-low duty cycle scenario, the expense of sending data can be overwhelming for the energy harvested wireless node. Based on these considerations, the synchronous approach is adopted in our communication protocol, and a highly accurate synchronization method is designed to achieve the ultra-low duty cycle requirements.

In order to design a highly accurate synchronization method, we must first consider the fact that nodes hardly operate at the exact same clock rate in real-world WSNs, and thus their clocks tend to drift at different rates due to frequent inaccuracy and differences in age, temperatures, and voltages. According to our tests, of these factors, the voltage difference is one of the most significant contributors to clock differences. For example, a MSP430 node is programmed to transmit packets periodically over a fixed interval of 250 clock units. Another node and a computer recorded the arriving time of the packets of this transmitting node. The measured interval ranged from 261s at 3.0 volts to 249s at 3.6 volts, suggesting that significant clock rate differences exist.

To overcome the significant clock rate differences among nodes, an novel adaptive synchronization method was designed for our communication protocol. This method consists of two phases: The cycle detection phase and the synchronization maintenance phase.

5.1.1 Cycle Detection Phase

Nodes that have joined a network are called synchronized nodes, while nodes that intend to join a network are called unsynchronized nodes. The synchronized node broadcasts its
beacon at every cycle while the unsynchronized node goes through the procedure to join the synchronized node by detecting the beacons of the synchronized node. This process is called cycle detection.

![Figure 5.1 Cycle detection phase A](image)

As Figure 5.1 shows, the unsynchronized node periodically wakes up to detect the beacons of a synchronized node. Each synchronized node transmits a sequence of beacons separated by a short period of time $\Delta T$. The unsynchronized nodes attempt to detect one of these beacons and then use them to synchronize their activities so that they occur approximately at the time of the center beacon transmission.

The wake-up window size $\Delta t$ is slightly wider than the interval $\Delta T$ between the beacons of the synchronized node. The interval $T_i$ between two consecutive wake-up windows is slightly less than the length of the entire beacon frame of the synchronized node. The unsynchronized node periodically wakes up every $T_i$ interval with a wake up window size of $\Delta t$ until it detects the beacon of the synchronized node. When the first
beacon from a synchronized node is detected, the unsynchronized node records this beacon arrival time $T_1$, the beacon number $N_1$, and the detected synchronized node identification number (ID). Then this unsynchronized node goes to sleep for a period of time $T_d$. This time period is slightly shorter than the cycle time $T_c$ of the synchronized node to ensure that it wakes up in time to observe the next beacon frame transmitted by the same synchronized node. When it receives the second beacon of the synchronized node with the same node ID as the first one, it records the beacon arrival time $T_2$ and the beacon number $N_2$. Note that $T_1$ and $T_2$ are based on the clock of the unsynchronized node and are independent of the clock of the synchronized node.

After that, it is able to calculate its schedule according to its own clock via the following equation.

$$T = (T_2 - T_1) - (N_2 - N_1) \times \Delta T$$  \hspace{1cm} (5.1)$$

where $\Delta T$ is the interval between two consecutive beacons (shown in Figure 5.1). By using this calculated cycle $T$, the unsynchronized node is able to predict the time of the center beacon in the third beacon frame transmitted by the synchronized node using the same ID via the following equation,

$$T_p = T + (\frac{N-1}{2} - N_2) \cdot \Delta T$$  \hspace{1cm} (5.2)$$

where $N$ is the number of beacons in one beacon frame in the synchronized node. In the example shown in Fig. 5.2 this number is 6.

This proposed synchronization method does not expect that the same clock rate exists among differing nodes. Unsynchronized nodes detect the cycles based on their own
clocks using the above mechanism. They use this as the reference for their own cycle. According to our tests, this method works very effectively and reliably.

![Figure 5.2 Cycle detection phase B](image)

**Figure 5.2 Cycle detection phase B**

### 5.1.2 Synchronization Maintenance Phase

Through the synchronization detection process described above, the unsynchronized node is able to synchronize with the synchronized node and proceeds with the periodic synchronization maintenance.

![Figure 5.3 Synchronization maintenance phase](image)

**Figure 5.3 Synchronization maintenance phase**
Since in practice the cycle of the synchronized node changes over time, the unsynchronized node wakes up approximately at the center time of the beacon frame of the synchronized node so that it can capture the beacon for the cycle recalculation. Therefore, every cycle a new calculated cycle is obtained so that the unsynchronized node is able to keep up with the changes of the cycle of the synchronized node (Figure 5.3). This process can be formulated as a pseudo iteration code as follows:

\[ T = (T_{current} - T_{last}) - (N_{current} - N_{last}) \cdot \Delta T \]

\[ T_{pred} = T + \left( \frac{N - 1}{2} - N_{current} \right) \cdot \Delta T \]

\[ T_{last} = T_{current} \]

\[ N_{last} = N_{current} \]

**Figure 5.4 Flowchart of synchronization maintenance**

\( T_{current} \) is the current beacon arrival time. \( T_{last} \) is the last beacon arrival time. \( N_{current} \) is the current beacon number. \( N_{last} \) is the last beacon number. Using this auto-updating method, the unsynchronized node is able to keep up with the cycle drift of the synchronization node.
5.2 Separated Sending and Receiving Time Schedule

Another important component of our proposed communication protocol is the separated receiving and sending time schedule.

Many synchronized approach communication protocols for wireless sensor networks such as the S-MAC [57], T-MAC [62] adopt a common time schedule for both sending and receiving. The problem with the common time schedule approach is that all network traffic is condensed in this small wake-up window, causing collisions by neighbors, especially for ultra-low duty cycle scenarios where the common time window is extremely small. To avoid this issue, a scheme was designed that provides separated receiving and sending time schedules. This scheme is shown in Figure 5.5.

![Figure 5.5 The separated sending and receiving time schedule](image)

In Figure 5.5, Node 2 synchronizes with Node 1 and Node 3 synchronizes with Node 2. The receiving time window of each node is scheduled right after the end of the beacon frame. Node 2 synchronized with Node 1 wakes up every cycle around the
middle beacon of the beacon frame of Node 1 to synchronize with Node 1. When there is a packet that needs to be sent out, Node 2 utilizes the beacon arrival time $T_r$ and the beacon number $N_b$ to predict the starting point of the receiving window of Node 1. $T_s$ can be found using the following equation:

$$T_s = T_r + (N - N_b) \cdot \Delta T$$  \hspace{1cm} (5.3)

In practice, the predication of the starting point of the receiving window of the synchronized node inevitably has some small error due to differences in the $\Delta T$ s among the nodes. To solve this problem in practice, the scheduled unsynchronized node is scheduled to wake ahead of $\Delta t_a$ to sense the wireless channel until it receives the last beacon of the synchronized node. Triggered by the event of receiving the last beacon of the upstream synchronized node, the unsynchronized nodes transmit their data at the same time.

After nodes are synchronized, they start to broadcast their own beacons and establish the receiving window right after the last beacon for data from their down-stream nodes.

![Figure 5.6 Slotted ALOHA MAC](image)
The separated receiving and sending time window approach scatters the traffic over the entire cycle time, thus greatly reducing the collision problem that exists in the common sending and receiving schedule.

As Figure 5.6 shows, the receiving time is divided into many time slots. The sender will randomly select some of the time slots to send its data the upstream node after receiving the last beacons of upstream node. In our application, all the data are small packets, which are less than 1ms with the data rate of 250kps. In the small packet application case, slotted ALOHA MAC is effective and energy efficient.

5.3 Data Acquisition Routing Protocol

One of the most important requirements of our communication protocol is that the data from the wireless nodes has to be delivered back to the network hub through multi-hop communication.

![Figure 5.7 Data acquisition routing protocol](image-url)
Considering the need for energy efficiency and this particular requirement, the following data acquisition routing protocol was designed and tightly integrated with the link management approach described earlier.

In this approach, the hub works as a network coordinator. It initializes the entire network by broadcasting the beacons periodically to start the entire network independently. Other nodes join the network by sensing the beacons either from the hub or from other already synchronized nodes. While all network nodes establish synchronization, the network automatically forms a tree structure where the root is the hub. Figure 5.7 is an example. At the beginning, the hub starts to broadcast the beacon frames periodically. Node 1 and Node 2 are located near the hub, hear the beacons, and synchronize with the hub according to the adaptive synchronization method discussed previously. They then start sending their own beacon frames. Nodes 3 and Node 4 sense the beacons of Node 1 and synchronize with Node 1. Node 6 near the Node 2 senses the beacons of Node 2, and then synchronizes with Node 2. Finally, Node 5 and Node 7 receive the beacon from Node 3 and Node 6, respectively. After that, they then join the synchronization as well. After this process, all nodes in the network automatically form the tree route structure as shown in Figure 5.7, which provides the route for all the nodes to send their data to the hub.

The proposed routing protocol utilizes these routes, which are formed from the synchronization process, to send their data back to the hub. In uplink, each node detects the schedule of its parent, and sends its data and the data its child sent to it to its parent. In downlink, the hub embeds the data in its beacons to its children which also broadcast to its children in the same way.
The proposed data acquisition routing protocol also takes into account changes in the topology. For example, the topology in Figure 5.7 changes to the topology in Figure 5.8. Node 5 is then unable to sense the beacon from Node 3. After two consecutive cycles of unsuccessfully detecting any beacon from Node 3, Node 5 starts to look for other nearby nodes in the network. It goes back to the cycle detection phase again to sense the beacons in the wireless channel. Node 5 would be able to detect the beacon of nearby Node 4 and rejoins the network by synchronizing Node 4. Node 4 then joins the network again and starts sending its own beacons. The route of the entire network then is automatically repaired.

Figure 5.8 The changed topology

This approach essentially embeds our data acquisition routing protocol in the synchronization process. The advantage of this protocol is that it does not incur any extra energy consumption for its routing functionality. This is a very desirable quality for ultra-low duty cycle applications.
5.4 Summary

In this chapter the design of this ultra-low power consumption communication protocol is described. This communication protocol consists of three parts: The adaptive synchronization method, slotted ALOHA MAC with separated sending and receiving schedule, and the data acquisition routing protocol. The adaptive synchronization method enables the communication protocol to operate in a duty cycle of 0.1% or less. Slotted ALOHA MAC with separated sending and receiving schedule provides energy efficient short packets transmission mechanism. The data acquisition routing protocol offers the data delivery capability for the dynamic topology environment with no extra energy consumption overhead. Based on these three components, it is evident that the proposed communication protocol is able to fulfill the task of providing a self-organized multi-hop network powered only by energy harvested from the ambient environment.
Chapter 6

Implementation Of The Ultra-Low Power Communication Protocol

In this section the ultra-low energy consumption communication protocol proposed in the previous section is implemented in the actual hardware. Chapter 6 focuses on hardware selection, software design, and implementation.

6.1 Hardware Selection

The best hardware for implementing the proposed communication protocol is hardware with: 1) a low-power CPU and low-power radio, 2) programmable radio and CPU in terms of their power mode, and 3) an open interface for easily expanding the functionality. Based on these considerations, the TI ez430RF platform, consisting of MSP430F2274 CPU, and CC2500 radio was selected.

Figure 6.1 TI eZ430RF platform
6.1.1 MSP430F2274

MSP430F2274 is an ultra-low-power microcontroller that offers five low-power modes for energy efficient usage. Its digitally controlled oscillator enables it to wake-up from a low-power mode and switch into the active mode in less than 1µs. The microcontroller also has two built-in 16bit timers which can be used as the system clock for the proposed communication protocol. It also has a set of peripheral interfaces to include the universal Asynchronous Receiver/Transmitter (UART), 32 I/O pins and 10-bit A/D converter with integrated reference and data transfer controller that supports the interface to enable energy harvesting circuits and data sensing possibilities. A functional block diagram of MSP430F2274 is illustrated below.

Figure 6.2 Functional block diagram of MSP430F2274
6.1.2 CC2500 Radio

The CC2500 is a low power 2.4GHz transceiver compatible with the Zigbee standard. The current consumption of CC2500 is 13.3mA in RX mode and 400 nA in SLEEP mode. The transfer time from SLEEP mode to RX or TX mode is as fast as 240 µs. It also has an excellent high receiving sensitivity of -104 dBm. The CC2500 is able to be configured through the SPI interface to change its state. The software program operates the radio in an energy efficient way by changing the states. Figure 6.3 illustrates the state diagram along with the corresponding current consumption that can be configured.

Figure 6.3 State diagram of CC2500 radio
6.2 Software Implementation

The software implementation of the proposed ultra-low communication protocol is based on the SimpliciTi network protocol provided by Texas Instruments. The SimpliciTi network protocol provides basic radio operation APIs that are easily implementable by the programmer. Figure 6.4 gives the relationship between the ultra-low power communication protocol and the SimpliciTi network protocol.

![Figure 6.4 Relationship between SimpliciTi network protocol and ultra-low power communication protocol](image)

<table>
<thead>
<tr>
<th>PREAMBLE</th>
<th>SYNC</th>
<th>LENGTH</th>
<th>MISC</th>
<th>DSTADDR</th>
<th>SRCADDR</th>
<th>PORT</th>
<th>DEVICE INFO</th>
<th>TRACTID</th>
<th>APP Payload</th>
<th>FCS</th>
</tr>
</thead>
<tbody>
<tr>
<td>RD*</td>
<td>RD*</td>
<td>1</td>
<td>RO*</td>
<td>4</td>
<td>4</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>n</td>
<td>RD*</td>
</tr>
</tbody>
</table>

*RD: Radio-dependent populated by MRFI or handled by the radio itself

![Figure 6.5 SimpliciTi packet format](image)
By using configuration APIs of the SimpliciTi, the wireless node’s topology (either the star topology or the peer-peer topology) and its radio’s frequency, modulation, data rate, etc. can be configured. Furthermore, by using the Send and Receive APIs, a data packet is able to be sent into the air and the data packets that sensed by radio is able to be retrieved. The specific packet format for the SimpliciTi is illustrated in Figure 6.5.

The packets of the communication protocol are within the App Payload with the port Number 20, which identify the ultra-low energy consumption communication protocol.

The proposed communication protocol is a self-organized network with multiple tags and a hub. Tags automatically form a multi-hop network, cooperatively passing their data periodically to the hub where it is collected and processed. The software of this communication protocol consists of a tag and hub program, described separately in the following sections.

6.2.1 Tag Program

SimpliciTi provides no operating system. The entire program is based on only one thread, thereby free of synchronization issues. It also does not offer the heap functionality. Thus, the variables are unable to be allocated dynamically during the running time. In other words, all the variables have to be pre-defined in advance. The program provides a stack data structure for creating functions.

Based on the above software platform, we implemented the proposed ultra-low energy consumption protocol was implemented as shown in the state diagram in Figure 6.6.

First, an initialization is conducted to set up the board, sensors, timers, and some variables. Then, the voltage of the board read through a 10 bit ADC indicates the level of
the energy reservoir of the system. If the energy accumulated by the energy harvesting circuit reaches a predefined threshold that is regarded as an able-to-function turning point, the program will convert to the synchronization state and start the network cycle detection. If the tag successfully synchronizes the network, it goes to the synchronization maintenance state where the network cycle is being monitored. At the same time, its own data and the data from the downstream tags are sent out to the network following the slotted ALOHA MAC protocol. A data receiving frame follows to offer a slotted ALOHA MAC receiving opportunity for the downstream tags. It does not go back to the voltage detection state from the synchronization maintenance state until the synchronization fails.

Figure 6.6 State diagram of the main thread

In parallel with the main thread discussed above, an independent clock is created by a timer interrupt. As it is shown in Figure 6.7, a long integer variable called the system clock is defined as the timing tick for the system. It records the time of the tag with an exacting precision of around 50milliseconds.
6.2.1.1 Voltage detection state

In this state, the radio is completely turned off. The CPU wakes up every 2 seconds from low power mode 3 to detect the voltage level of the board. In the low power mode 3 (LPM3), CPU, MCLK, SMCLK as well as DCO dc-generator are all disabled, leaving only the ACLK active for the system clock. A Tag in LPM3 consumes as little as around 1µA of current. This enables the tag to accumulate energy from the energy harvesting circuit. As long as there is enough energy to satisfy a predefined level, the tag proceeds to the synchronization state, starting its function.

6.2.1.2 Synchronizing state

After accumulating enough energy in the voltage detection state, the tag enters the synchronizing state, where a passive beacon detection process is conducted. Figure 6.8 illustrates the process.

Certain parameters must be defined before describing the synchronization process. Let \( N \) be the predefined total number of beacons in one frame, \( CN \) be the scanning time during a wake-up period, \( T \) be the duration of the wake-up period; B.N the received
beacon number variable, Detection.ID be the variable that records how many beacons from the same node have been detected, and cycle_t be the predefined cycle period having the same number in each tag.

![Figure 6.8 Flowchart of synchronization](image)

In the beginning, the Detection.ID is assigned a 0 since no beacon has been detected. Afterward, the radio is turned on, and a passive wireless channel scan is conducted. The tag checks the receiving FIFO of the radio continuously until a beacon is retrieved or the
checking time exceeds the CN. If it is the first time that a tag detects the beacon, the arriving time $T_1$ and the corresponding beacon number $N_1$ are recorded. Then the radio would immediately be shut down. The entire tag goes to the low power mode 3 (LPM3) for a period of $4/5$ of the predefined $\text{cycle}_t$, which is approximately the network cycle. After that, the tag starts a new round scanning with a $T \cdot N$ period between each wake-up time. If it is the second time that the tag detected a beacon from the same node, the tag also records the arriving time $T_2$ and the corresponding beacon number $N_2$. Then the network cycle is calculated according to Equation 5.1 in Section 5.1. In practice, there is a possibility that beacons of the same node are missed the second time, resulting in a multiple network cycle calculation instead of one network cycle. To rule out this possibility, the calculated network cycle is compared with $3/2 \text{cycle}_t$. If it is smaller than $3/2 \text{cycle}_t$, the calculated network cycle is single-cycle; otherwise it is multiple-cycle. If it is single-cycle, a tag will go to the synchronization maintenance state. If it is multiple-cycle, a tag will go to the voltage detection state to start it over.

### 6.2.1.3 Synchronization maintenance state

After successfully detecting the network cycle by its own system time tick, the tag enters into the synchronization maintenance state where it wakes up at the upstream tag’s beacon frame, updating the network cycle.

First, let $\text{SF}$ be the synchronization failing sign which records the number of times the beacon of the upstream node is unsuccessfully detected consecutively. Let the index denote if the beacon of the upstream node is received or not in the current cycle. 1 means success. 0 means failure. Let last_index denote if the beacon of the upstream node is received or not in the last cycle.
Figure 6.9 Flowchart of synchronization maintenance

At the beginning, it calculates the supposed wake-up time $T_p$ using Equation 5.2 in Chapter 5, and goes to LPM3 until the $T_p$. Right on the $T_p$, the tag starts to detect the
beacon of its upstream tag. If the beacon is detected, the arriving time \( T_2 \) and \( N_2 \) is recorded, and the detection success indicator would be set to 1 as a sign of success. A new cycle would then be calculated if the last_index were also 1. Afterward, the next wake-up \( T_p \) is updated. There is a possibility that the beacon of the upstream node is not detected successfully for various reasons. In this implementation, a tag loses its synchronization when SF equals 2; meaning the beacons from two consecutive frames of the upstream node have been lost. The process is illustrated in Figure 6.9.

6.2.1.4 Separated sending and receiving time schedule

In the synchronization maintenance state, a tag periodically detects the start time of the receiving window of the upstream node to send out its data packets as well as the packets it has received from its downstream tag to the upstream node according to the slotted ALOHA MAC. Afterwards, its own beacon frame is broadcast. A flowchart that illustrates this process is given in Figure 6.10.

At the beginning of the process, a random generator is created to serve as a tool for sending random packets. Upon detecting a beacon from the upstream tag, which is described in the previous section, the arrival time of the last beacon of the upstream frame is calculated according to Equation 5.3 in Chapter 5. The tag wakes up at a time that is slightly earlier than this calculated time in order to capture the last beacon of the upstream frame. The event of capturing this last beacon triggers a slotted ALOHA transmission from the tag to its upstream tag. Because of the clock differences between the tag and its upstream tag, the tag’s slots do not align exactly with the upstream tag. This phenomenon is illustrated in Figure 6.11.
Figure 6.10 Separated sending and receiving time schedule

Figure 6.11 Alignment issues between the tag and its upstream tag

In order to overcome this issue in the entire network, the tag’s slot duration was adjusted by a ratio which is defined as Equation 6.1.

\[ r = \frac{T}{T_c} \]  

(6.1)
where $T$ is the detected cycle measured by the tag’s own clock, $T_c$ is the hub’s cycle which is predefined as the same for all the tags and the hub.

(a) The receiving widow durations comparison without the adjustment

(b) The receiving widow durations comparison with the adjustment

Figure 6.12 Effect of the adjustment method
By multiplying this ratio to all the slots of the tag, the alignment issue is greatly relieved. Figure 6.12 shows the outcome of the proposed solution. The receiving window duration varies between the different tags due to clock differences, which are clearly illustrated in Figure 6.12 (a). By using this method, the window duration differences are reduced. The effectiveness of this is shown in Figure 6.12 (b).

After the sending out its own packets and relaying packets to the upstream tag, its beacon frame with a receiving window follows for its downstream tags.

A random generator is designed and implemented for a random sending process in the slotted ALOHA MAC function. The random sending process is illustrated in Figure 6.13.

There are several methods to design a random generator. Considering the limited storage capacity of the chosen hardware, an array data structure instead of a queue data structure was used to store the random numbers. The implementation is illustrated in Figure 6.14.
Let $N$ be the total number of slots in the receiving window, and $M$ be the maximum number of packets a tag can send out. The process illustrated in Figure 6.14 is executed over every network cycle. First a fisher-Yates shuffle is applied to the array of numbers, resulting in $N$ random numbers. Second, the first of $M$ numbers of the previous array is selected to be sorted and differentiated. The resulting array of numbers is used as the delays for $M$ packets sending.

In addition, a circular queue data structure was implemented as storage for the packets received from the downstream tags.

**6.2.2 Hub Program and Packet Definition**

A hub is a coordinator of the entire network. It initializes the entire network by broadcasting its beacon frame. A flowchart depicting the process of the hub program is illustrated in Figure 6.15.
At the beginning, an initialization step is taken to set up the board, sensors, timers, radio, etc, which is same as that of the tag. After that a periodic process is started in which the tag first goes to low power mode 3 (LPM3) for a predefined time called the network cycle, after which it wakes up to broadcast its beacons and receive and process the data packets.

In the proposed ultra-low power communication protocol, there are two types of packets: A beacon packet and a data packet. These are defined in Figure 6.16.

**Figure 6.15 Flowchart of hub program**

**Figure 6.16 Packets definition.**
The beacon packet consists of two parts: The identification (ID) and beacon number. The beacon number is used for synchronization calculations. The data packet includes the ID, sequence number, hop counts, and payload. The sequence number and hop counts are for the basic routing information. The payload is for the sensor data such as the temperature and pH value, etc.

6.3 Summary

This chapter explained how the proposed ultra-low power communication protocol was implemented. First, the selected hardware and software platforms were described. Then, the relation between the communication software and the SimpliciTi APIs was illustrated. Finally, the implementation of the tag and hub programs as well as the packet format definition was detailed in the form of flowcharts, state diagrams, figures, and in-text explanations.
Chapter 7

Mathematical Formulation Of The Ultra-Low Power Communication Protocol

In order to better understand and evaluate the performance of the proposed ultra-low power communication protocol, the key elements of the protocol are mathematically analyzed and modeled. These key elements are the synchronous performance and the throughput performance.

7.1 Mathematical Formulation Of The Synchronous Performance

The low-complexity, effective synchronization method has always been a key component of the wireless sensor communication protocol. In the prior literature, many synchronous methods for sensor networks have been proposed. S-MAC, T-MAC and SCP-MAC [71] all transmit a SYNC packet to notify their neighbors of their schedule in order to synchronize the clocks of all the nodes in the network. This synchronization method only compensates for the clock offset and does not consider the clock drift. Dozer is an ultra-low duty cycle MAC protocol. It transmits a beacon to the receiving nodes. The receive nodes must wake up in advance of the beacon to obtain the beacon and use it to adjust local times. DISSense, another ultra-low duty cycle MAC protocol, piggybacks the timestamp on the data packet in order to keep the receiving node synchronized. It also adds a guarding time slot in front of the frame to alleviate the clock
estimation error. All synchronous methods discussed above can be characterized as one-way methods. According to [108], the estimated cycles in one-way methods are inevitably overstretched by a positive offset due to the propagation delay. In Reference-Broadcast synchronization [109], the sender broadcasts a reference message to the receivers. Upon receiving the message, the receivers record the arrival time of the message by their own clocks, and exchange this information among each other to compensate the clock offset between them. The advantage of this method is that it eliminates the clock estimation offset caused by coding and propagation delays. The disadvantage, however, is that it does not take into account the clock drifting effect. It also carries the overhead of third party involvement. Ganeriwal et al. propose a time-sync protocol for sensor networks (TPSN) [110]. Their protocol has two phases: level discovery and synchronization. In the level discovery phase, all nodes in the network form a hierarchical topology in which all nodes synchronize with the root node. In the synchronization phase, a two-way message is exchanged between each pair of nodes. The clock offset and the propagation errors are then calculated at the child node. This method resolves the propagation delay error but does not consider the clock drifting issues either. Miklos et al. propose a flooding time synchronization protocol (FTSN) in [111], whereby they studied the uncertainties in radio message delivery. They argued that there are many factors that are non-deterministic. For example, the sending and receiving time is dependent on the processor load. The radio access time is dependent on the channel contention and propagation distance. This can be regarded as an additional virtual offset of the clocks, which can be modeled as a random variable with small variance. In their design, the sender transmits several probe messages periodically to the receiver. The
receiver uses a collection of the received messages to calculate the offset (including the virtual offsets and clock drifts) by linear regression. This synchronous method resolves both the offset and drifting issues, and is thus more accurate than previous methods. However, the method is complicated and involves the consumption of much more energy than other methods. In their research, P. Yadav et al. [112] applied FTSN in a cluster-based sensor network. Instead of flooding the synchronization message to neighboring nodes, the root node multicast the SYNC message to selected cluster-heads. This method decreases the number of flooding processes. Nevertheless, it still does not resolve difficulties related to the multiple-transmission overhead of FTSN.

In this dissertation, a low-complexity and effective synchronous method is proposed as part of the proposed ultra-low duty cycle communication protocols. All the previously discussed methods try to modify the offset (including the virtual offset) and the drift of all network clocks so that they match the global clock. Unlike those approaches, our proposed synchronous protocol does not modify the clocks in the network at all. Instead, they are synchronized with their own clock. The periodic broadcast event in the network is the same for all detected clocks. Therefore, although they have different measurement results for this period by their own clock unit independently, they are still able to interact with each other at the same physical time. The following section presents a theoretical analysis of the synchronous method and defines the mathematical expression for the error limits of this method for both the one-hop and multi-hop networks.

Before getting into the details on the analysis and evaluation of this synchronous time synchronization method, the method proposed in the paper will be briefly reviewed once more:
In Figure 7.1, the unsynchronized node periodically wakes up to detect the beacons of the synchronized node. The wake-up window size is slightly wider than the interval between the consecutive beacons in the same frame. The interval time between each wake-up is slightly less than the entire beacon frame of the synchronized node. Therefore the unsynchronized node is able to detect the beacon when it arrives. When the first beacon from the synchronized node is detected, it records the time stamp $T_i$ as the arrival time of the beacon, as well as the associated beacon number $N_i$, contained in the beacon message. It then goes to sleep for a period of time shorter than the cycle $T$ (approximately 5 minutes in our example application). It continues to wake up periodically until it detects the second beacon. When it receives the second beacon in the second frame, it records the arrival time $T_c$ of the beacon and the corresponding beacon.
number $N_c$. After that, it calculates its predicted cycle using its own clock via Equation 7.1.

$$\Delta T = (T_c - T_l) - (N_c - N_l) \times \Delta t$$

(7.1)

where $\Delta t$ is the interval between two consecutive beacons in the same frame.

Assuming the number of beacons for the synchronized node is $N$, then the synchronized node is going to wake up at the time $T_b$ in the next cycle.

$$T_b = (\Delta T + \left(\frac{N-1}{2} - N_2\right) \cdot \Delta t)$$

(7.2)

The cycle detection method does not rely on the assumption that the same clock exists in different nodes. An unsynchronized node detects the cycles by its own clock, and uses this as the reference for its own cycle, instead.

![Figure 7.2 Clock difference issue](image)

Figure 7.2 Clock difference issue
Next, the clock measurements of the wireless sensor nodes are modeled. Assuming that several clocks are used in the sensor node to measure the same length of time, then the amount of time measured by each node can be described as follows,

\[ T_i = \text{clk}_i + \delta_i \]  \hspace{1cm} (7.3)

The measured numbers are different from each node due to the different clock \( \text{clk}_i \) and measurement noise \( \delta_i \). Tests were performed using Texas Instruments’ eZ430-RF2500 platform which demonstrated the validity of this model.

In our tests, a hub node broadcasts its beacons every 80 seconds. Four nodes record the arrival time of the beacons from the hub using their own clock. The timing resolution of these four nodes was set at about 50ms per unit. As Figure 7.2 shows, the period of the beacon broadcasted by the hub was interpreted differently by these four nodes in terms of the mean and variance. As shown in Equation 7.3, the mean of the interpreted measurement of node \( i \) is presented as \( \text{clk}_i \), and the corresponding jitter is assumed as a Gaussian random variable \( \delta_i \) with a zero mean. The jitter is due to measurement precision errors.

Next, the mathematical expression is deduced for the behavior of the receiving beacon numbers of the synchronized nodes. As Figure 5.25 shows, Node 1 keeps pace with Node 0. Node 1 predicts the sending time of the middle Beacon 3 in the next frame, \( T_{b1} \), which, according to Equation 7.2 is

\[ T_{b1} = \Delta T_1 + \left( \frac{N-1}{2} - N_{c1} \right) \cdot \Delta t_1 \]  \hspace{1cm} (7.4)

Combining Equation 7.4 with Equation 7.1, then
\[ T_{b1} = (T_{c1} - T_{l1}) + (N_{c1} - N_{l1}) \cdot \Delta t_1 + \left( \frac{N-1}{2} - N_{c1} \right) \cdot \Delta t_1 \]
\[ = (T_{c1} - T_{l1}) + \left( N_{l1} - 2N_{c1} + \frac{N}{2} \right) \cdot \Delta t_1 \]  
\( (7.5) \)

The actual sending time of the middle beacon in the next frame of Node 0 is
\[ T_{b0} = \Delta T_0 + \left( \frac{N-1}{2} - N_{cl} \right) \cdot \Delta t_0 \]  
\( (7.6) \)

Combining Equation 7.6 with Equation 7.1, then
\[ T_{b0} = (T_{c0} - T_{l0}) + (N_{l1} - N_{c1}) \cdot \Delta t_0 + \left( \frac{N-1}{2} - N_{c1} \right) \cdot \Delta t_0 \]
\[ = (T_{c0} - T_{l0}) + \left( N_{l1} - 2N_{c1} + \frac{N}{2} \right) \cdot \Delta t_0 \]  
\( (7.7) \)

The receiving beacon number for the one-hop is then
\[ N_{b1} = \frac{N}{2} + \text{round} \left[ \frac{D_{1-0}(T_{b1}) - T_{b0}}{\Delta t_0} \right] + \text{round} \left[ (\delta_0 + \delta_1) \cdot \frac{1}{\Delta t_0} \right] \]  
\( (7.8) \)

Node 0 and Node 1 have different clocks so they need to be translated into the same clock. Operator symbol \( D_{1-0} \) is used to denote a translation function, which converts the clock in Node 1 to the clock in Node 0. In addition, \( \delta_0 \) and \( \delta_1 \) account for the cycle measurement noise for clocks in Node 0 and Node 1, respectively.

Assume that the propagation latency and the coding latency for the beacon transmission between two consecutive frames are the same. Combining Equation 7.7 with Equation 7.5, we obtain
\[ N_{b1} = \frac{N}{2} + \text{round} \left[ \left( N_{l1} - 2N_{c1} + \frac{N-1}{2} \right) \cdot \frac{D_{1-0}(\Delta t_1) - \Delta t_0}{\Delta t_0} \right] + \text{round} \left[ (\delta_0 + \delta_1) \cdot \frac{1}{\Delta t_0} \right] \]
\[ = \frac{N}{2} + \text{round} \left[ \left( N_{l1} - 2N_{c1} + \frac{N-1}{2} \right) \cdot \frac{\rho_{1-0} \cdot \Delta t_1 - \Delta t_0}{\Delta t_0} \right] + \text{round} \left[ (\delta_0 + \delta_1) \cdot \frac{1}{\Delta t_0} \right] \]
\[ = \frac{N}{2} + \text{round} \left[ \left( N_{l1} - 2N_{c1} + \frac{N-1}{2} \right) \cdot (\rho_{1-0} - 1) \right] + \text{round} \left[ (\delta_0 + \delta_1) \cdot \frac{2}{\Delta t_0} \right] \]  
\( (7.9) \)

where \( \rho_{1-0} \) is the clock difference ratio between the clock in Node 0 and the clock in Node 1. Assume the beacon number is a static random process. Thus \( N_{b1}, N_{l1} \) and \( N_{c1} \) have the same mean and the same variance. According to our tests, \( \rho_{1-0} - 1 \) is in the order of...
Thus the second part of Equation 7.9 is in the order of $1/100$ to the left side of the equation. To simplify Equation 7.9, we can ignore the second term. $N_{b1}$ is further deduced as follows

$$N_{b1} \approx \frac{N}{2} + \text{round}[\delta_0/\Delta t + \delta_1/\Delta t]$$  \hspace{1cm} (7.10)

Furthermore, beacon sequences in the multi-hops case can be formulated as

$$N_{bn} \approx \frac{N}{2} + \text{round} \left[ \sum_{i=0}^{n} \frac{\delta_i}{\Delta t} \right]$$  \hspace{1cm} (7.11)

Assume $\delta_0 = \delta_1 = \delta_2 = \cdots = \delta_n = \delta$. Then Equation 7.11 can be simplified as follows.

$$N_{bn} \approx \frac{N}{2} + \text{round} \left[ \frac{n\delta}{\Delta t} \right]$$  \hspace{1cm} (7.12)

Next the cycle detection errors can be deduced for the synchronous method. In the one-hop scenario, the error comes from two parts. The first part of the error is caused by the beacon offset and clock differences. The second part of the error derives from the beacon detection noise. The one-hop cycle detection error can thus be formulated using the following equation.

$$\hat{e}_1 = (N_{t0} - N_{c0}) \cdot (D_{1\rightarrow0}(\Delta t_1) - \Delta t_0) + \delta_0 + \delta_1$$  \hspace{1cm} (7.13)

According to Equation 7.11, the beacon number in the static stage is the rounded sum of Gaussian noises. Therefore, Equation 7.13 can be further derived as

$$\hat{e}_1 \approx \left( \text{round} \left[ 2 \cdot (\delta_0 + \delta_1) \frac{1}{\Delta t} \right] \right) \cdot (D_{1\rightarrow0}(\Delta t_1) - \Delta t_0) + \delta_0 + \delta_1$$  \hspace{1cm} (7.14)
In the multi-hop case, the cycle detection error is simply the sum of the cycle detection errors over all hops. In order to add up all the single-hop errors, the clock interval should be translated into a unified clock before addition. All of the clocks’ measurements can be translated into the clock of Node 0. Then, the total cycle detection error on all hops is

\[ \hat{e}_n = \sum_{i=1}^{n} \left( \text{round} \left( \frac{2}{\Delta t} \sum_{j=0}^{i} \delta_i \right) \right) \cdot (D_{i\rightarrow0}(\Delta t) - D_{(i-1)\rightarrow0}(\Delta t)) + \sum_{i=0}^{n} \delta_i \]

\[ = \sum_{i=1}^{n} \left( \text{round} \left( \frac{2}{\Delta t} \sum_{j=0}^{i} \delta_i \right) \right) \cdot \Delta t \cdot (\rho_{i\rightarrow0} - \rho_{(i-1)\rightarrow0}) + \sum_{i=0}^{n} \delta_i \quad (7.15) \]

where \( \rho_{i\rightarrow0} \) is the ratio between Clock i and Clock 0.

To further simplify Equation 7.15, assume \( \delta_0 = \delta_1 = \delta_2 = \cdots = \delta_n = \delta \), then

\[ \hat{e}_n = \sum_{i=1}^{n} \left( \text{round} \left( \frac{2}{\Delta t} \cdot (i + 1) \cdot \delta \right) \right) \cdot \Delta t \cdot (\rho_{i\rightarrow0} - \rho_{(i-1)\rightarrow0}) + (n + 1) \cdot \delta \quad (7.16) \]

As can be clearly seen from the error of synchronization expressed above, the synchronous method has a zero mean no matter how many hops are between the two nodes, and an accumulated variance as the number of hops increases.

### 7.2 Mathematical Formulation Of The Throughput Performance

In the proposed communication protocol, a slotted ALOHA MAC protocol was adopted. The slotted ALOHA MAC protocol is commonly used in low data rate communication applications such as satellite communications. It is an energy efficient MAC protocol of use in animal monitoring and tracking applications.

The entire network of the proposed communication protocol is structured as a tree topology. The child nodes communicate to a parent according to the slotted ALOHA MAC protocol, which is illustrated in the Figure 7.3.
Children nodes synchronize in the receiving window of the parent by receiving the last beacon of a parent’s beacon frame. Then they randomly select slots and send their packets accordingly. In the following section, a mathematical expression of the throughput of the implemented Slotted ALOHA MAC protocol is formulated for different assumptions.

![Diagram showing slotted ALOHA MAC protocol](image)

**Figure 7.3 Proposed slotted ALOHA MAC**

**7.2.1 Nodes Attempting To Send With The Poisson Distribution**

First, let $N$ be the total number of slots, $M$ be the number of children, and $q$ be the possibility of sending a packet in one slot by a child. If the population of children attempts to send packet according to Poisson distribution, the probability of there being $k$ transmission-attempts in one slot is

$$p(k) = \frac{e^{-\lambda} \lambda^k}{k!}$$

(7.17)
where $G$ is the average number of transmission-attempts per slot, which is

$$G = Mq$$  \tag{7.18}

In practice, it is very hard to make sure the packets sent in the same slot 100% collide. So let $\mu$ be the chance that two packets sent in the same slot do not collide. The throughput of the proposed slotted ALOHA MAC protocol during one slot is

$$S = G(P(0) + \mu P(1)) = G(e^{-G} + \mu Ge^{-G}) = Mq(e^{-Mq} + \mu Mq e^{-Mq})$$  \tag{7.19}

### 7.2.2 Nodes Attempting To Send With The Equal Probability

First, formulate for the throughput of two children. Let $N$ be the number of total slots and $L$ be the number of packets that send in one entire receiving window.

In this two children case, the probability of there being $i$ transmission collisions in one receiving window is

$$p(i) = \binom{L}{i} \left( \frac{N-L}{N} \right)^{i} \left( \frac{L}{N} \right)^{N-i}$$  \tag{7.20}

Defining vector $P$ as a collection of all the transmission collision cases according to the collision number so that

$$P = [p(1) \ p(2) \ \cdots \ p(L)]$$  \tag{7.21}

Let $V$ be the vector as follows

$$V = [1 \ 2 \ \cdots \ L]$$  \tag{7.22}

Then the throughput of two children case is

$$S = 2N - (1 - \mu) \ <V, P>$$  \tag{7.23}

where $\mu$ is the chance that two packets sent in the same slot do not collide.
Then the throughput in the $M$ children case can be derived. The probability of sending a packet in one slot by a child $q$ is

$$q = \frac{L}{N} \quad (7.24)$$

The probability of a child sending a packet successfully in one slot is

$$p_1 = (1 - q)^{M-1} \quad (7.25)$$

The throughput of a child in one slot is

$$S_1 = q \cdot p_1 = q(1 - q)^{M-1} \quad (7.26)$$

The throughput of $M$ children in one slot is

$$S_{M1} = MS_1 = M \cdot q(1 - q)^{M-1} \quad (7.27)$$

Next, derive one collision case. The probability of a child sending a packet with one collision is

$$p_2 = (M - 1)q(1 - q)^{M-2} \quad (7.28)$$

The amount of data that a child sends with one collision is

$$S_2 = q \cdot p_2 = q \cdot (M - 1)q(1 - q)^{M-2} \quad (7.29)$$

The amount of data that $M$ children send with one collision is

$$S_{M2} = MS_2 = Mq \cdot (M - 1)q(1 - q)^{M-2} \quad (7.30)$$

Therefore the total throughput in the time slot is

$$S = S_{M1} + (1 - \mu)S_{M2} = M \cdot q(1 - q)^{M-1} + \mu M(M - 1)q^2(1 - q)^{M-2} \quad (7.31)$$
If $M$ goes to a large number, and $q$ goes to a small number, and the above equation can be rewritten as follows

$$\lim_{M \to \infty, q \to 0} S_M = M \cdot q \cdot \lim_{M \to \infty, q \to 0} (1-q)^{M-1} + \mu M (M-1) q^2 \lim_{M \to \infty, q \to 0} (1-q)^{M-2}$$

$$= \lim_{M \to \infty, q \to 0} M \cdot q \cdot e^{-q(M-1)} + \mu M (M-1) q^2 e^{-q(M-2)}$$

$$= M \cdot q \cdot e^{-qM} + \mu M^2 q^2 e^{-qM} \quad (7.32)$$

this is the same as the throughput result using the Poisson distribution assumption formulated before.

### 7.3 Summary

In this section, the two key components of the proposed ultra-low communication protocol are formulated: The synchronization and the throughput performance. The proposed synchronous method is very energy efficient and is also highly accurate. Mathematically, the error variance is accumulated over hops, but the error mean is always zero over hops. The proposed implemented slotted ALOHA MAC provides an energy efficient data delivery capability. In practice, there is a possibility that two packets sending in the same slot do not collide. By taking this issue into account, the throughput of the slotted ALOHA for the two different assumptions can be formulated with many children sending packets according to the Poisson distribution in one slot and every child sending a packet with an equal probability in one slot.
Chapter 8

Results

In this chapter, the proposed communication protocol is evaluated in a real field test, and the mathematical formulation derived in the previous chapter is validated through experimental results.

8.1 Field Test Results

In this work, the proposed communication protocol is implemented in the eZ430-RF2500 platform (the red board) connected with the proposed energy harvesting circuit (the green board), shown in Figure 8.1.

Figure 8.1 Energy harvesting wireless sensor based animal monitoring node

Batteries were first used to power the wireless nodes. Two tests were conducted to evaluate the performance of the new communication protocol. In the first test, 8 nodes were arranged in a chain topology as shown in Figure 8.2. Node 1 was one hop away from the hub directly synchronizing with it. Node 2 established a connection to the hub
through node 1 after observing Node 1’s beacons. The same procedure occurred for the rest of the nodes in this test. After all nodes established their synchronization, they formed an 8-hop network. In this test, the cycle duration of the nodes is 1 minutes and 20 seconds. The receiving window size of each node is about 700ms. The beacon detection wake-up time is about 100ms. In terms of testing, each node generates a data packet every 3 cycles. Therefore, the packet arrival interval is approximately 4 minutes in length.

Figure 8.2 Chain topology

Figure 8.3 Packets collected at the hub in the chain topology
The test duration lasted about 4 and a half hours (3:30 am to 8 am). The results are shown in Figure 8.3. A red dot indicated a successfully received packet in the hub. It can be seen that all 8 nodes had stable connections to the hub with an over 97% packet success rate. There were no synchronization failures among the nodes during the entire test time. Some packet-losses were observed at the farther nodes due to an error-prone wireless channel.

In a second test, the network nodes were deployed in a star topology, shown in Figure 8.4.

![Figure 8.4 Star topology](image)

In the star topology all the nodes synchronized directly with the hub. The cycle duration is once again about 1 minute 20 seconds. All the nodes sent a data packet every three cycles. The receiving window size of the hub is about 700 ms. In this test, all nodes essentially compete to send data by the slotted ALOHA mechanism stated in the previous chapter. The test time duration lasted about 4 and a half hours, starting from 2:25 pm to 7 pm. The experimental results are shown in Figure 8.5. There were just a small number of packet losses during the entire test, each of which can be explained by bit errors at the
receiver. No synchronization failure happened among the nodes. The connections were very stable with a 99% packet success rate.

![Figure 8.5 Packets collected at the hub in the star topology](image)

Then, the wireless nodes were connected to solar strips and placed on the roof of the building of the Peter Kiewit Institute as Figure 8.6 shows.

All nodes were placed from 10am to 11pm. The cycle of the node was 4 minutes. The receiving window size was 240ms. It consisted of 8 slots, each of which is 30ms. The duty cycle of the communication protocol in this test is 0.1%. According to the proposed communication protocol, all nodes automatically formed a tree network whose root is the hub. All the packets from the nodes were delivered through this multi-hop network to the
hub. The hub was connected to a computer so that the packet information could be automatically logged in a file. The test results are shown Figure 8.7 and Figure 8.8.

Figure 8.6 Solar test topology

Figure 8.7 Results of packets delivery in the solar test
As the test results show, the multi-hop network was successfully established. Through the multi-hop network, the packets of all the Nodes were delivered to the hub successfully. As can be seen from Figure 8.7, Node 1 to Node 5 was able to deliver their packets to the hub with a reliable communication connection. Node 6, which is the farthest node, sometimes lost packets due to its multi-hop connection and isolated location. Figure 8.8 shows the harvested energy measured by the voltage between the ends of the super capacitors. It can be seen that in the beginning the charging rates of all the nodes were very steep, indicating that the communication protocol consumes a very small amount of energy. By the end of the day, the solar strip lost this power source. The communication protocol operated on the residual energy stored in the super capacitors. It
can be seen from Figure 8.8 that the charge was depleting at a slow pace, thus indicating that the communication protocol is very energy efficient.

8.2 Validation Of The Mathematical Formulation Of The Synchronization Error

In the previous chapter, the mathematical formulation for the error of the synchronization over the multi-hop network was derived. In order to verify the accuracy of this mathematical formula, experiments were conducted using the devices shown in Figure 8.1. The tested synchronization error was compared with the mathematically calculated synchronization error.

First, experiments were conducted and designed by the researchers to collect the tested synchronization error over multi-hops.

![Figure 8.9 Clock difference calculating method](image)

In the experimental tests, the timer of each node was programmed as the local clock with a precision of about 50 milliseconds. In other words, the clock unit of a node is...
50ms. The proposed synchronous protocol was then implemented in each node. The nodes were synchronized one after another, forming a chain topology as shown in Figure 8.2.

Clock differences were collected automatically using the following method: Consider the example presented in Figure 8.9. Node 0 broadcasted its beacon periodically once every 100 clock units with a local Clock 0. The sending times of the beacons from Node 0 were recorded as $s_{00}$, $s_{10}$, $s_{20}$. Node 1 synchronized with Node 0, recording the receiving times of the beacons sent by Node 0 as $r_{01}$, $r_{11}$ and $r_{21}$. Node 1 also sent its own beacons with a constant delay to receiving time of Node 0’s beacons, and recorded the sending time $s_{01}$, $s_{11}$ and $s_{21}$. Similarly, Node 2 recorded the times of received beacons from Node 1 as $r_{02}$, $r_{12}$ and $r_{22}$. Using this method the clock differences between adjacent nodes at each cycle time can be collected automatically. The clock differences ratio between Node 0 and Node 1 in Cycle $i$ can be calculated by the following equation.

$$\rho_{1\rightarrow 0}(i) = \frac{s_{i0} - s_{(i-1)0}}{r_{i1} - r_{(i-1)1}}$$ \tag{8.1}$$

Similarly, the clock difference between Node 1 and Node 2 in Cycle $i$ can be calculated through Equation 8.2,

$$\rho_{2\rightarrow 1}(i) = \frac{s_{i1} - s_{(i-1)1}}{r_{i2} - r_{(i-1)2}}$$ \tag{8.2}$$

Combining Equation 8.1 and Equation 8.2, the clock difference ratio between Node 0 and Node 2 can be given by the following equation,

$$\rho_{2\rightarrow 0}(i) = \frac{s_{i0} - s_{(i-1)0}}{r_{i1} - r_{(i-1)1}} \cdot \frac{s_{i1} - s_{(i-1)1}}{r_{i2} - r_{(i-1)2}}$$ \tag{8.3}$$
This method was adopted for the clock difference collection in experiments performed by the research team.

In the synchronous method, each node predicted the next cycle by employing Equation 7.1 (see Chapter 7). Therefore, the actual cycle error is

\[ \varepsilon_n = \rho_{n \rightarrow 0} \cdot \Delta T_n - \Delta T_0 \]  

where \( \rho_{n \rightarrow 0} \) is the ratio of Clock N to Clock 0, and \( \Delta T_n \) is Node N’s estimated cycle time using the synchronous method.

The theoretical cycle estimation error (Equation 7.16 in Chapter 7) was compared with the actual cycle estimation error (Equation 8.4) in terms of the variance and the mean in different hops as shown in Figure 8.10 and Figure 8.11, respectively.

![Figure 8.10 Comparison of the variances of the synchronization errors between the tested results and theoretical results](image-url)
As can be seen in the Figure, both the mean and the variance of the synchronization error over hops closely match the tested and theoretical results. All the results demonstrate that the proposed synchronization method has a zero-mean cycle estimation error no matter how many hops it has. The variance of the cycle estimation error was limited within 12 clock unit in the eight-hop case, showing the robustness of proposed synchronization method.

![Graph showing the comparison of the means of the synchronization errors between the tested results and the theoretical results](image)

**Figure 8.11** Comparison of the means of the synchronization errors between the tested results and the theoretical results

### 8.3 Validation Of The Mathematical Formulation Of The Throughput

In this section, an experiment was conducted to verify the throughput formulation of the proposed low power communication protocol.
In the proposed communication protocol, the slotted ALOHA MAC was adopted to avoid the occurrence of transmission collision. In this MAC protocol, all the children nodes randomly pick up the slots and transmit their packet at these picked up slots. Due to clock differences, the transmission of the packets from different nodes can still be different even if they occur in the same slot, enabling the possibility of successfully receiving two or more packets in the same slot. Thanks to the clock translation method described in the previous chapter, the clock difference issues have been greatly minimized in the proposed communication protocol. Unfortunately, however, this
problem cannot be completely eliminated. Figure 8.12 shows this phenomenon in a graphical form.

Two independent experiments were conducted. In the first experiment, Node 42 transmitted 6 packets every cycle in 6 pseudo randomly selected slots. In the second experiment, Node 52 also transmitted 6 packets every cycle in the same 6 pseudo randomly selected slots. The upper plot in Figure 8.12 shows the duration in time between the receiving time of the first packet of Node 42 and the receiving time of the sixth packet of Node 42, (marked in a red circle), and the duration of time between the receiving time of the first packet of Node 52 and the receiving time of the sixth packet of Node 52, marked in blue triangle. The lower plot in Figure 8.12 shows slot numbers of the first packet and the last packet of both Node 42 and Node 52. In every cycle, the packets from Node 42 and Node 52 are supposed to collide at the same time since their slot numbers are the same. Therefore, the duration between the first packet of Node 42 and the last packet of Node 42 is supposed to be the same as the duration between the first packet of Node 52 and the last packet of Node 52. However, as shown in Figure 8.12, their actual durations differ from each other by a slight degree.

In practice, this phenomenon cannot be completely eliminated. This is why a throughput formulation for this communication protocol is derived in the previous chapter. Then a test was conducted which is given in Figure 8.13.

![Figure 8.13 Throughput test scenario](image)
In the test, two nodes are implemented with the proposed communication protocol, sending packets at every cycle to the hub. The number of packets sent by each node every cycle increase by 2 every 20 cycles. The average number of packets received by the hub is calculated and compared with the theoretical results. Figure 8.14 shows the comparison.

![Throughput Comparison](image)

**Figure 8.14 Comparison between the testing throughput and the theoretical throughput**

As can be seen in Figure 8.14, the test results match well with the theoretical results, thus validating the throughput formulation.
8.4 Summary

This chapter described the results of a series of tests conducted to verify the proposed communication protocol. The performance of the communication protocol was tested using both battery power and solar power. The test results reveal that the multi-hop functionality was effective and the communication function was reliable. The solar test proved that the proposed communication protocol work effectively when powered by only solar energy. It also accomplished the objectives set in the beginning. Furthermore, the theoretical formula for the synchronization error and throughput derived in the previous chapter were also evaluated through experimental results. The derived mathematical formula closely matched the test results and the results calculated by the derived mathematical formula.
Chapter 9 Conclusions and Future Work

9.1 Conclusions

The National Animal Identification System (NAIS) program was proposed to protect the commercial interests involved in U.S. agriculture from the potential harm associated with the outbreak of an animal disease. However, the current animal identification system, which is based on passive RFID technology, has many limitations such as the short range of information retrieval and incapability of actively monitoring the animal. In order to provide a better technology for NAIS, Advanced Telecommunication Engineering Laboratory (TEL) at the department of Computer and Electronics Engineering (CEEN) in University of Nebraska-Lincoln proposed and developed an innovative self-powered smart wireless Identification and tracking tag system, which enables all tags to form an autonomous multi-hop network, continuously monitoring the health conditions of livestock. The work of this dissertation is a part of this mission, focusing on designing and developing a new communication protocol for our animal monitoring system.

The proposed animal monitoring system is based on self-powered energy harvesting wireless sensor network technology, which has the potential to provide many promising monitoring advantages over the passive RFID technology. For this dissertation, a practical communication protocol was designed and developed to provide a monitoring system capable of supporting a self-routing ad hoc network that is only powered by harvested energy from the ambient environment. We faced with two great challenges of: 1) The duty cycle of the wireless communication had to be no more than 0.1% to meet the low power consumption demand, and. 2) A dynamic multi-hop routing functionality
is required.

To meet the two major challenges above, this dissertation have carefully designed an ultra-low power multi-hop communication protocol, which has the following favorable attributes,

1. A robust synchronization method, which has the potential to reach a duty cycle of 0.1% to 0.01%, was designed.
2. A slotted ALOHA and separated sending and receiving MAC protocol was designed, which provides energy-efficient data convey solution among tags with a collision-reduction effect.
3. A data acquisition routing protocol was designed. it naturally is embedded in the synchronization process, bringing no additional energy consumption cost.

Furthermore, the designed ultra-low duty cycle, multi-hop communication protocol was thoroughly implemented in eZ430-RF2500 module with our energy harvesting circuit. Both laboratory tests and field tests were conducted as to verify the proposed communication protocol. These test results showed our designed communication protocol was able to robustly operate in duty cycle of 0.1% with reliable communication capability. In addition, multiple tags are able to form an automatic ad hoc network that is able to route all data from tags through multi-hop to the hub.

Last, the two elements of the designed ultra-low duty cycle multi-hop communication protocol were mathematically established: 1) the formulation of synchronization error 2) and the formulation of throughput. Both of them were validated by the test results. They were able to serve as tools to evaluate and predicate the performance of the designed protocol.
Through all three works above, a novel low power multi-hop communication protocol has been successfully designed and utilized in our energy harvesting wireless sensor based animal monitoring system, enabling entire network reliably collecting all sensed information from tags to the hub through multi-hops only with the solar power. We believe our ultra-low power multi-hop communication protocol meets the two challenges that we stated in Chapter 3, and is an innovative technology for this mission.

9.2 Future Work

Some open questions are left for future research work. These include; first, the mobility issue on this communication protocol has not been investigated. Animals attached with our monitoring tags could be moving around, forming a dynamic topology. How fast our communication protocol is able to react and recover is very important factor to our monitoring service. In the current work, the minimum time of a broken link got recovered is 3 network cycles. Can this reacting time be improved without consuming additional energy? How to improve it?

Second, the synchronization establishment process has a duty cycle of 1/10, consuming as 100 times power as the communication after synchronization. If the time of synchronization establishment process is a very short period time in the whole network lifetime, the issue with the current synchronization establishment process would be of no significance. However, if the topology changes frequently over time, causing the ratio of the time of synchronization establishment process to the network lifetime to increase to a significant level, the entire power of the communication protocol could significantly rise, resulting in fast depletion of the harvested energy. How to address this issue is a challenging problem and remains open.
Third, the proposed communication protocol is limited within the small packets transmission applications. How to deliver large information such as images through multi-hops to the hub is still open question.
References


