Ultra Low Energy Communication Protocol for Implantable Wireless Body Sensor Networks

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Abstract

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Medical science will soon start to benefit from wireless communication and implantable sensor technologies being developed for use in the human body. Such technologies have a potential to revolutionize the health-care industry by providing real-time patient monitoring capabilities to the health-care professionals. In this regard, implantable wireless body sensor networks (IWBSNs) have recently emerged as an important and growing area of research. The implantable sensors are required to be reliable and very small so that the body does not reject them. They must stay functional in the human body for years, and most importantly, they must not be a source of discomfort to the potential patients. The life time of their embedded batteries could vary from a few days to a few weeks using current hardware and software technologies. In order to make such devices suitable for implantation an order of magnitude reduction in energy use is required. Our research is motivated by this goal.

In this thesis, we identify and analyze the sources of energy use in typical devices meant for Implantation in a human body. Our detailed mathematical analysis and computer simulations clearly demonstrate that improving the efficiency of communication protocols is the only realistic way of achieving this goal. Unfortunately, none of the existing low range low energy wireless communication protocols can be used in IWBSNs because of the small energy resources available in the implanted sensor nodes. We propose a new energy aware communication protocol which efficiently encodes data in time domain. It ensures accurate transmission of information. The encoding scheme does this by sending only a single signal from the sensor node to the base station. The protocol is called the Time Based Coded Data protocol or TBCD in short. For proper operation of this protocol reliable synchronization is required. Our proposed synchronization algorithm is energy efficient and stable under worst case conditions as compared to existing algorithms. A sensor node using existing state of the art technology that can only last for a few weeks can be made to last for few years using our proposed communication protocol and the synchronization algorithm.

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I would lovely express my warmest appreciations and thankfulness to my supreme God's gift, my family, for whatever I received from them as their love, patience, helps and ..., persuaded me to go on this long way, and I did. I wish them all the bests forever and ever and ever, with my thankful little heart! overloaded from their love, a kind of ultra impressive love that no one could ever have an idea about how I experienced it. My heart! would never be able to express it truly. Just thanks.

Dedication

I would lovely dedicate whatever I have, to my family . . . my dearest, who are all I have.

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List of Acronyms

ADC	Analog to Digital Converter
AIDS	Acquired Immune Deficiency Syndrome
ASK	Amplitude Shift Keying
BBQ	Barbie-Q
BG	Blood Glucose
BS	Base Station
BSN	Body Sensor Network
CB	Cluster Based
CTS	Clear To Send
CVD	Cardiovascular Disease
DAC	Digital to Analog Converter
dBm	deci Bel millwatt
DPM	Dynamic Power Management
ECG/EKG	Electro Cardio Graph
EEG	Electro Encephalograph
EMG	Electromyography
EOG	Electro Oculo-Graph
EDH	Error Detection and Handling
FCC	Federal Communications Commission
FPGA	Field Programmable Technology
FSK	Frequency Shift Keying
GPS	Global Positioning System
HIV	Human Immunodeficiency Virus
HR WPAN	High data Rate Wireless Personal Area Network
IWBSN	Implantable Wireless Body Sensor Network
IMS	Institute for Microelectronic Circuits and Systems
kbps	kilo bit per second
LEACH	Lower Energy Adaptive Clustering Hierarchy
LR WPAN	Low data Rate Wireless Personal Area Network

LUT	Look Up Table
MAC	Medium Access Control
MAN	Metropolitan Area Networks
MIPS	Million Instruction per second
NTP	Network Transfer Protocol
OOK	On Off Keying
PDA	Personal Device Assistant
PEGASIS	Power-Efficient Gathering in Sensor Information Systems
PLL	Phase Locked Loop
PCB	Printed Circuit Board
RFID	Radio Frequency Identification
RSS	Received Signal Strength
RSSI	Received Signal Strength Indicator
RTC	Real Time Clock
RTS	Request To Send
SpO_2	Saturation Percentage of Oxygen
TB	Tree Based
TBCD	Time-Based Coded Data
TDM	Time Division Multiplexing
TG	Task Group
TPSN	Timing-synchronization Protocol for Sensor Networks
TinyDB	Tiny Data Base
WBSN	Wireless Body Sensor Network
WLAN	Wireless Local Area Network
WMAN	Wireless Metropolitan Area Network
WPAN	Wireless Personal Area Network

Introduction

Chapter 1

1. INTRODUCTION

Among patients who had heart attacks worldwide, over 30% of them died even before reaching to the hospital [63]. Cardio Vascular Disease (CVD) is the main cause of death in the world and the main forms of CVD are coronary heart disease and stroke [2]. Each year, about 12 million people die of heart attacks or strokes worldwide, but they can often be prevented. Nearly two-third of people in Europe who are involved in different forms of CVD die before they can reach medical care. In U.K. alone, each year CVD costs the health care system around £1.8 billion [2]. In North America 71 million American adults are involved with 1 or more types of CVD. Over 27 million have hypertension and about 65 million have pre-hypertension. The total annual costs in the US are $63.5 billion.

In the early 20th century the physicians got interested in developing methods to implant smart medical devices inside the human body in order to take better care of the patient's health system. In 1950s, teams of scientists in medical engineering, electronics, chemistry, bio-engineering and physics were able to design and produce Pace-Makers and implanting them in the patient's hearts. Heart attack can suddenly happen usually without prior normal appearances, but cardiac rhythm disturbances happen in the heart which can be detected before appearing the problem, only by appropriate sensor technology [45]. All of this persuaded the researchers to generate and develop a low cost and reliable network system for human health care. Scientists from different disciplines such as computing, electronics, bioengineering and medicine have come together to develop this new emerging technology. Existing Wireless Sensor Network (WSN) hardware platforms were extensively modified for Body Sensor Network (BSN) applications. There is still mush research work and development required for BSN to reach the desired point. However strides in this area are being made. The rapid technological growth in physiological sensors, low power integrated circuits and wireless communication have enabled a new generation of wireless sensor networks. These wireless sensor networks are pretty suitable for applications, such as health monitoring. BSN is an interdisciplinary area which allows inexpensive, continuous and ambulatory health monitoring with real-time updates of medical records via Internet. A number of intelligent physiological sensors are integrated into a wearable wireless body area network, which can be used for computer assisted early detection of medical conditions.

1.1 BSN

Body Sensor Network (BSN) or Body Area Network (BAN) are terms used to describe the application of Implantable/Wearable health monitoring devices as smart sensors (Figure 1.1).

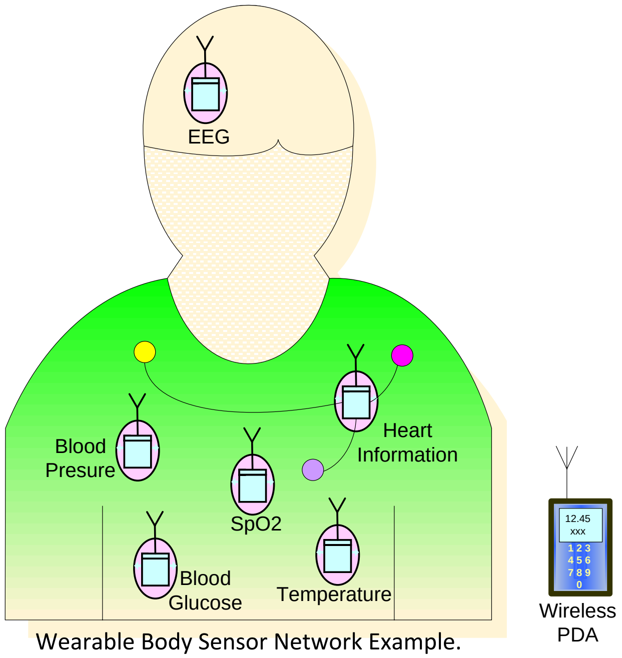

Figure 1.1: Wearable Body Sensor Network Example.

A typical BSN or BAN is made up of:

1- Vital sign monitoring sensors, for example, SpO2, Blood pressure, Blood Glucose and others.

2- Communication, to transmit vital signs to a central Base Station (BS) where medical practitioner or care givers can monitor and analyze the patient's health status.

The technology of the BSN is still being hardly used under wearable equipments on the patients which are not comfortable and efficient. On the other hand, it cannot provide all required medical laboratory tests information from outside the human body. But the clinicians are receiving benefits from such service hopping to achieve a complete and reliable implantable wireless BSN system in the near future. There are other kinds of BSNs like as shown in Figure 1.2 which is internal BSN. The patient can swallow a sensor node which is encapsulated in a small pack. Such sensors contain all internal sections of a complete sensor node. These kinds of sensors can only be used for sampling and transmitting some stomachic and/or intestinal physiological information to a BS.

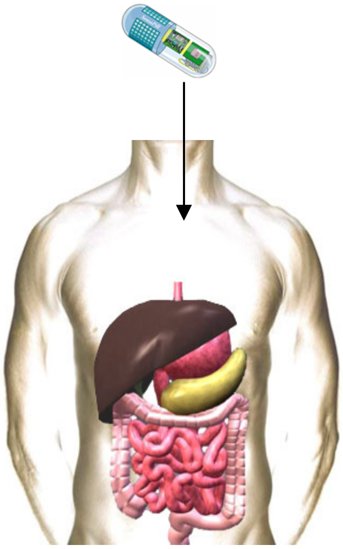

Figure 1.2: Internal Body Sensor system.

Data transfer for an implanted biosensor must use wireless communications as it is impractical to distribute wires throughout the body.

1.2 IWBSN

After all these achievements, scientists and health care professionals started working on a very new area of research related to BSNs or WBSNs at beginning of 21st century. It was mainly started in 2004. Their goal is to develop the WBSN system very efficiently by implanting tiny smart sensors at different locations inside the human/animal body to enable close monitoring of the important physiological changes inside the body, where it is not possible under warble technology from outside the body. This will have a great potential for finding better treatments, efficient drug delivery, better management of chronic illnesses and improving the quality of life for human health care. This is called IWBSN (Implantable Wireless Body Sensor Network). Since then, researchers in all related sciences have been trying to provide feasibility of implanting such small/tiny biosensors inside the human body. The sensors must be very small so that the patients do not feel them and that they do their everyday normal activities comfortably such as; working, walking, running, doing exercise and so on. These implantable sensor nodes should be designed as small as possible (in millimeter range) so that the body accepts them and allows them to stay in the body. They must stay well-functioning inside the body for years, wirelessly connected to a local external PDA (Personal Device Adapter) Base Station (BS) in close proximity of the patient's body. In order to make these sensor nodes bio-compatible, their surface must be covered by special materials consistent with the tissue of the body so that the tissue of the body does not reject them. Materials such as glucose-permeable hydro-gel [66], polyethylene and polyurethane are examples of such coverage materials [17]. A network of biosensors is fundamentally different from other wireless networks. They have a continuous but very small source of power. This energy constraint necessitates using of a highly energy-efficient communication protocol [77]. Advances in semiconductor technology have made it possible to build miniature but reliable biosensors. The implanted sensors in the human body are devices that detect, record, and transmit information regarding physiological changes periodically (e.g., one sample per second or less/more) depending on what physicians need. Teams of physicians, clinicians, health care professionals and technicians must work very closely with the patients to collect information on the patient's health status eventually, both for patient care and research studies purposes. Patients could be located everywhere away from the hospitals and health centers around the world. The information is first processed and wirelessly transmitted to the Base Station (BS) outside but in close proximity to the patient’s body. This definition for the IWBSN allocates that this network system is a star network topology, since there are limited number of sensor nodes around a central node all communicating only with the central node which is called here BS (Base Station). Figure 1.3 shows an example of such network consisted of several sensor nodes connected wirelessly to a BS located outside the human body.

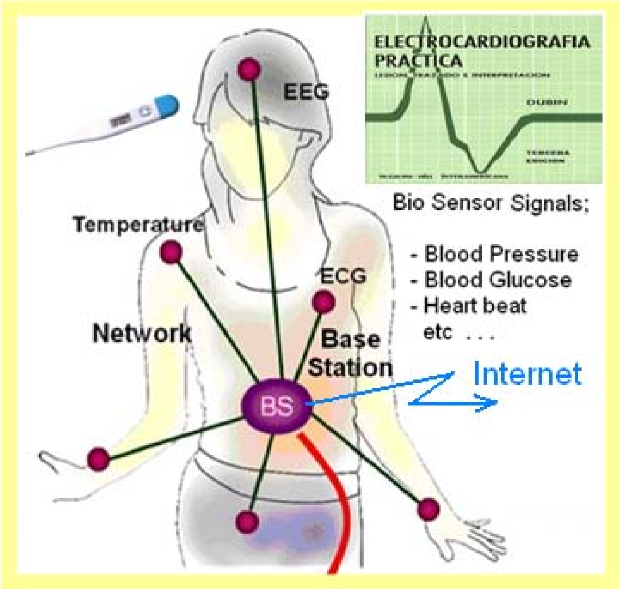

Figure 1.3: Topology of Implanted Sensors in body.

The BS should be able to forward all real time information received from the sensors instantly to the medical team wirelessly using Internet through a Wireless Local Area Network (WLAN) or cellular phones, etc… worldwide. All of these features combined together form a complete system called IWBSN. Once any emergency case is detected by this network service, the physicians/computer-systems will be able to immediately inform the patient by sending appropriate messages or alarms, asking him/her to do corresponding cares. Research in this area is advancing steadily. However, designing small implantable sensors with a long life still remains a challenge to date. Such technologies, when fully deployed, would allow real-time monitoring of patients from anywhere in the world. Frequent surgical replacement of the embedded battery in the sensor node must be prevented to avoid and reduce the risk of infection. Table 1.1 lists some of the many important physiological parameters that can be monitored using implantable sensors.

A general form of the Wireless Body Sensor Network (WBSN) Design Structure is illustrated in Figure 1.4. Each sensor node in WBSN or IWBSN consists of four major components, a battery, a sensor, a controller and a transceiver including a tiny antenna. The main challenges in monitoring the information include biosensor design, miniaturized power source, power scavenging, ultra low power RF data path, multi-sensory data fusion, autonomic sensing, secure and light weight communications protocols [6]. The size of a sensor node and its power consumption are two major challenges in the design of implantable WBSNs. Researchers have shown that one of the main technical challenges in the area of IWBSN is “standard and light-weight communication protocols” [89] and the vital requirement in this regard is reliable Time Synchronization within the entire Network.

Table 1.1: Some examples of Physiological parameters to be monitored by implantable sensors.

Physiological parameters:
Heart Rate
Breath Rate
Body Temperature and Heat Exchange
Heart Status, Electro Cardio Graph (ECG or EKG)
Brain Status, Electro EncephaloGraph (EEG)
Evaluating physiologic properties of muscles, Electromyography (EMG)
Measuring the resting potential of the retina, Electro Oculography (EOG)
Pregnancy Status
Tracking the Cancers
Kidney Status
Spinal Column Status
Blood Oxygen (SpO_2)
Blood Urine
Blood PH
Blood Glucose
Blood Pressure
Blood Culture test
Red Blood Cells Count
White Blood Cells Count
So many other Blood related parameters . . .
etc . . .

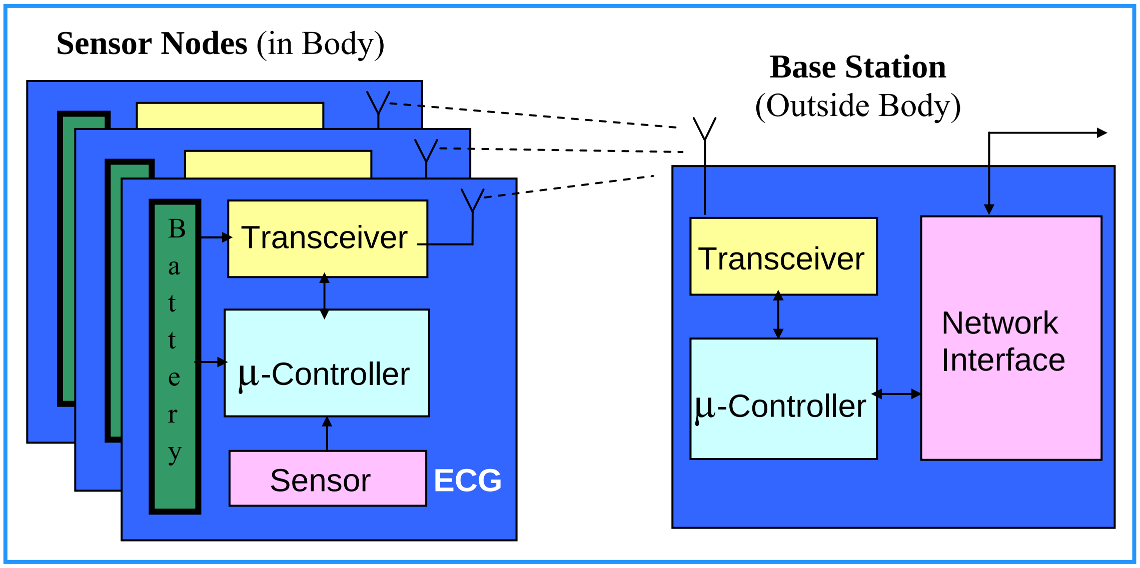

Figure 1.4: Wireless Body Sensor Network (WBSN) Design Structure.

It is almost a consensus among engineering communities that issues such as biocompatibility, context awareness and multi-sensor data fusion, quality of service and security issues would not remain as significant challenges in future, as very good solutions are already available. That's why the type of transmission and the choice of transmission protocol play a major role in the longevity of the sensor's battery. Since radio transmission consumes big amount of energy, the development of new and innovative techniques and protocols is absolutely essential for realizing cost effective WBSNs for both communication and synchronization algorithms.

In this work we employ the advanced technology of the low-range/low-power wireless transceivers and propose efficient techniques to achieve significant throughput in DPM (Dynamic Power Management). DPM is a way to save the energy in the devices by controlling the ON/Off power under operating system [6]. Therefore, the selected analog transceivers in this work are assumed that are properly noise protected with reasonable signal strength and sensitivity with respect to benefit from advanced low-power light weight transceiver technology.

1.2.1 Need of implantable sensors and wireless communication

The demand for long-term vital sign monitoring outside the clinics is considerably increasing. Body Sensor Networks (BSN) technology has internationally become the interest of researchers both in academia and industry in recent years. With the development of innovative wireless wearable/implantable biosensors, the applications for BSNs are extending from *In-Vivo* monitoring and intervention to everyday healthcare, as well as fitness, sports and security. *In-Vivo* research is a form of clinical trial and testing in terms of studying for observing the overall effects of an experiment on a living subject. Considering some examples of medical lab tests in the following descriptions can give us a general idea regarding the importance and highly demanding access to such a reliable implanted wireless sensor network inside the patient’s body.

1.2.2 Blood Tests

Some kinds of such blood tests are pretty known to everybody, but many of them are not. For example; blood culture is a test to detect germs such as different bacteria in the blood. To do the test, the doctor will take a blood sample and send it to a lab for testing. The skin must be wiped with an alcohol pad, and then smeared with a special antibacterial solution before drawing the blood. This carefully sterilizing the skin is very important to prevent contamination of the blood that is being drawn. There are bacteria on the surface of the skin so that they may appear in the blood culture or any other blood test, and interfere with identification of the germ or other parameters causing the infection. Sometimes it seems like a lot of blood is drawn for the test. It is important to draw enough blood for the culture test and as well for other tests to get accurate results. This may be about 10 milliliters or more per test.

1.2.3 Blood Pressure monitoring system

Researchers from Fraunhofer IMS (Institute for Microelectronic Circuits and Systems) in Duisburg, Germany, report of designing a small intravascular arterial pressure monitoring device [56]. Continuous cuff-less blood pressure monitoring will desirably open a new comfortable face for hypertension diagnosis and the treatment. Figure 1.5 shows such an implantable small device. If a person's blood flows through their arteries at too high a pressure, even when they are lying still on the sofa, they could be in danger. High blood pressure causes the heart to constantly pump at full speed, which strains both the heart and vessel walls. Some drugs can temporary help the patient, but in most cases the patient's blood pressure is still difficult to regulate and has to be consistently monitored over a long period of time. This is an exhaustive process for the patients. Patients have to wear a small case containing the blood pressure meter close to their body. There is an inflatable sleeve on their arm to record their blood pressure values. This is too difficult for the patients, especially at night.

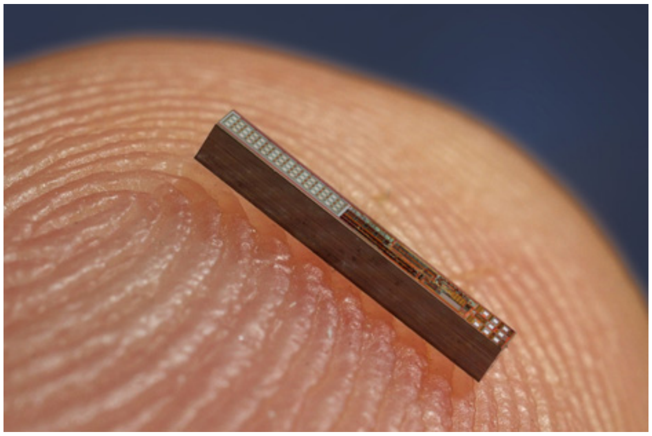

Figure 1.5: Intravascular arterial blood pressure monitoring device.

The new implantable sensor systems could replace all these processes. But still supplying the energy would be a big challenge in such innovations. This could be resolved by either radiating required amount of electromagnetic waves towards the big coil around the sensor inside the human body which benefits from RFID (Radio Frequency Identification) technology, or being supplied by another innovative technique dealing with very small implantable batteries. Employing the RFID technology for the implanted wireless sensors in human body requires the patient's body to be under the risk of large and long term wave radiation. The researchers in department of the Fraunhofer IMS, report of introducing another small pressure sensor to be implanted directly into artery. "The sensor, which has a diameter of about one millimeter including its casing, measures the patient's blood pressure 30 times per second. They are relying on use of special components in CMOS technology which requires little energy only for sampling the data. They again in this case employ the property of the RFID technology which supplies the electricity wirelessly via coils (Figure 1.6), and that's why the sensor size is bigger than the expected small size. But, again the big problem is with the power and communication. It is connected via a flexible micro-cable to a transponder unit, which is likewise implanted in the groin under the skin. This unit digitizes and encodes the data coming from the micro-sensor and transmits them to an external reading device that patients have to wear it on their belt. Then the sampled data will be forwarded to a base station to be analyzed by the doctor. This way they transfer the data through painful and exhaustive cables which is a big burden to the patient's body just for data communication instead of wireless data transmission. That's because the medical system is still suffering from inaccessibility to a reliable and efficient electronic wireless technique in implantable form and size in the body. If such big issue in emerging the process of implanting devices is resolved, there will be extensively use of the technique in many other heath care applications saving the patient's lives. For example; Implantable pressure sensors are also suitable for other applications, such as monitoring patient's status who are suffering from cardiac insufficiency. The researchers are currently performing the first clinical trials.

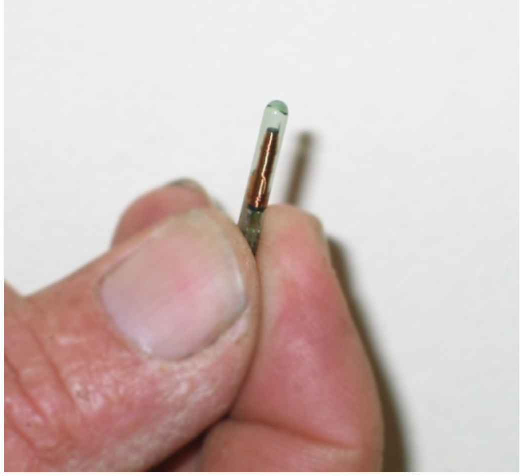

Figure 1.6: The implantable pressure sensor using RFID technique connected to long cables inside the body.

1.2.4 Glucose Monitoring System for Diabetics

Diabetes is a serious disease affecting up to 8% of the world's population in many societies, especially in advanced countries. It is becoming increasingly prevalent worldwide by growing the populations. People are involved in different dietary habits. Today, Diabetes is being controlled by daily insulin injections, drugs or if it is not in dangerous case, by diet. Diabetic patients have to measure their Blood Glucose (BG) several times a day. Using the normal equipments like lancet device which uses a special needle for blood sampling is a painful experience by punching different areas on their body. Each time a certain amount of blood is sampled to measure the blood glucose using a BG meter. Clinical studies have shown that tight procedure of glucose control is significantly important and is strongly recommended to be repeated several times per day. Because of the unpleasant, cumbersome nature of this test procedure (Figure 1.7), patient compliance is very much poor.

Figure 1.7: Cumbersome method of blood glucose measurement.

Too much glucose indicates that more insulin is required, and too little glucose requires immediate action to raise the levels. Exceeding the glucose causes most of the long-term consequences of diabetes, including blindness, nerve degeneration, heart and kidney failure and many other dangers for human's health. However, in the short term the more immediate danger is from lack of glucose below the standard level (sometimes called insulin shock), which can occur at any time of the day or night and can cause the patients to lose their consciousness. For practical reasons, night time blood glucose variations are often neglected, but lack of glucose in blood at night can be a particular worry for parents of young diabetics. The best way to avoid such dangerous consequences is to frequently monitoring the blood glucose levels. The Doctors in this area believe that; if a reliable implantable glucose sensor was available to use as a blood glucose alarm alerting patients when their glucose levels goes up or drops below a threshold value, it would reduce the possibility of diabetics suffering from these adverse and harmful effects. Based on combination of existing technologies in a biocompatible format, totally Implantable with long term functionality is strongly demanded.

Cyber Medical Ltd. in United Kingdom reported about the people with advanced conditions of diabetes, that monitoring the levels of glucose in their blood is very important. This is usually achieved by painful method such as finger pricking (Figure 1.7) which is a multi-billion dollar business in the world, mainly on using numerous disposable strips. Some blood sample is analyzed in a blood glucose meter device. Based on the result, the patients should adjust their insulin dosage to keep their glucose levels as close to "normal" as possible. The state of the art BG controllers like automatic Insulin Pumps (Figure 1.8) [34], are preprogrammed to infuse a fixed amount of insulin and cannot monitor or decide automatically how much insulin to infuse.

Doctors say we have to help them to determine the amount of Insulin each time needed to inject in the body using the extracted blood from the body [35]. A tiny Blood Glucose sensor implanted inside the patient’s body would be a great help by eliminating such important issues, by continues real-time monitoring the measured BG all the time. The obtained information then could directly be used by Insulin Pump devices to make proper and accurate real time decisions. This will help to protect the patient’s body against the risk of the incorrect dose.

Figure 1.8: Installing the Insulin Pump [34].

1.2.5 Benefits of continuous glucose monitoring

Without doubt, there is a clear medical need for a reliable and continuous blood glucose monitoring device. Clinical studies have shown that the blood glucose concentrations must carefully be controlled. In order to achieve such control, it is necessary to monitor blood glucose concentrations frequently to keep the insulin in appropriate level. A vital solution in this regard for frequent glucose testing and insulin administration is an important subject of clinical research. Teams worldwide (like Cyber Medical group, Figure 1.9) are working to provide as small implantable glucose sensors as possible.

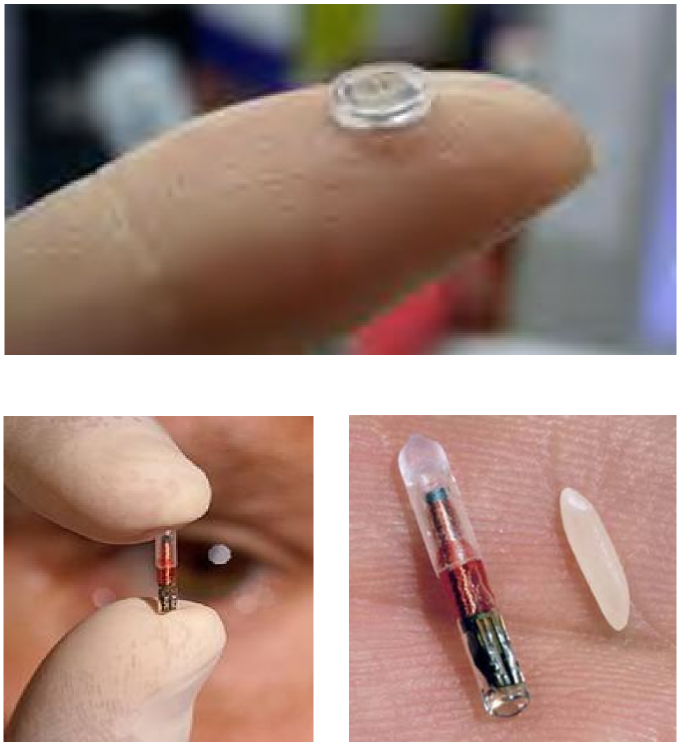

Figure 1.9: Implantable Glucose Cyber Sensor examples from Cyber Medical Ltd., UK.

Two different types of implantable glucose sensors are being developed;

1. Measurement through the skin, which is painful and bothering the patient.
2. In Vivo (deep under the skin) measurement, this needs access to a feasible implantable technique.

Among variety of approaches no reliable system has yet led to long-term automatic measurement.

1.2.6 SpO$_2$ measurement in Blood

SpO$_2$ (Saturation and Percentage of Oxygen) is another parameter which indicates the amount of oxygen attached to the hemoglobin cell in the circulatory system. The value of SpO$_2$ which is normally about 96% goes up and down depending on how well a person is breathing and how well the blood is being pumped around the body. Monitoring such information to the clinicians would be so much valuable especially when patients are in critical status.

1.2.7 Other Blood Parameters for Test

There are numerous other important clinical lab tests on patients in the clinical laboratories specialized to medical fields. As a trivial sample, a series of examples on Blood only in Clinical Laboratory Tests include:

Blood Hemogram: (Hemoglobin (Hb), placket count, Red blood cells (RBC), Red cell distribution width (RDW), White blood cells & differential count (WBC).

Blood Chemical Constituents: (Albumin (serum), Alkaline (serum), Calcium (serum), Ferritin, etc.

Blood Cerebrospinal Fluid: Cell count, Glucose count, Proteins (total) etc.

Blood Urine: Calcium, Chloride, Potassium, etc.

Blood Infection test: Blood Culture, etc.

1.2.8 Cancer detection

Early cancer diagnosis and choosing the right treatment are the most important factors in fighting against cancer. One of the best ways to monitor the cancer is to look for cancer markers and detecting compounds which are produced by cancerous cells. But until now, this has always been done by performing blood tests or biopsies (a medical test involving the removal of cells or tissues for examination). Martin Leach from the

Institute of Cancer Research, London, UK, said 'This would be indeed an interesting advance if one could envisage truly real-time experiments, where it will be possible to observe where and how chemotherapeutics (chemical treatment) work.' And this could perfectly benefit from feasible technological solutions in an efficient form of implanted appropriate small sensors and monitoring their required real-time experiment results wirelessly. Teams continue to work closely with clinicians also in this important field hoping to propose and develop such implantable technology [11].

1.2.9 Targeting HIV Detectors

Researchers in Canada have also achieved an *Electrochemical Sensor* for the HIV virus detection and the key AIDS drugs using a Bio-Organo-Metallic approach [39]. The biosensor passed the tests in the presence of human blood at high concentrations. They hope these results in their approach will be very beneficial from future technology by being adopted with the real implantable wireless body sensors soon.

There are so many other clinical laboratory tests required for human health care for which an implantable sensor would be assigned to.

1.3 Implantable Micro Batteries

Implantable small medical batteries are being under development. For example Figure 1.10 shows a sample made by Eagle Picher Medical group in Vancouver Canada [16]. The battery's size and shape (cylindrical, 0.260" long × 0.090" diameter or 6.6mm × 2.3mm) enables a device so small that it can be deployed via a minimally-invasive procedure rather than traditional implantation surgery. The device is also presently under clinical trials in Europe. The Micro Battery will create new opportunities for device manufacturers in medical implant fields.

Figure 1.10: Implantable medical battery [16].

1.4 Contributions

In this work an efficient ultra light weight and low power consumption as digital processing communication protocol is proposed for the IWBSNs. The transmission method and the transmission protocol between sensor nodes and the BS has the most important impact on the life-time of the tiny sensor's battery and play the major role in the longevity of the sensor node's life. Any of the existing standard communication protocols, such as ZigBee [93] which is one of the best low power communication protocols applicable to low range sensor networks, consumes the largest portion of the sensor's energy. This has been shown in chapter 3 that how the radio transmission energy consumption is relatively very high, and how the definition of new techniques and protocols with energy saving capability has critical impact on the reliability of these WBSNs. Since these devices are required to run with limited resources (energy, processing, and memory), their utility protocols (collecting, processing, and communication) should be designed carefully to work reliably and more importantly, be resource-efficient. Enabling such communication technique introduces a healthcare revolution by long term health monitoring of patients providing real time feedback to the medical experts. This issue has been resolved in this research by proposing a novel communication protocol with consuming least amount of energy, satisfying the energy constraint in tiny resources available in miniature implanted sensor nodes in body. This protocol is named “TBCD” stating Time Based Coded Data in which the Data is coded in time slot domains and then transmitted. The high consuming parts of the system can then be kept in OFF/Sleep mode for long terms enabling the system with a considerable low activity duty cycle. The digital controller in the BSNs also can stay in standby mode keeping its status in low energy consumption for long periods of times.

In chapter 4 by describing the TBCD protocol we realize that such protocol would be necessarily dependant on continuous reliable time synchronization between the BS and all sensor nodes. Current standard algorithms for synchronization have their own disadvantages as same as for the current standard communication protocols. Because they all transfer long message packets between the network nodes which is not consistent with the energy constraint in communication within IWBSN. Therefore, in this research a novel low energy synchronization algorithm has also been proposed to complement this research proposal solution.

In order to fulfill the work completely, the complete transaction procedures among the nodes and the BS have been studied to finalize the solution. This study demonstrates that such ultra low power networks suffer from wireless delay transmission through the analog transceivers. Thus a simple methodology was offered to eliminate the effect of the wireless delay on correctness of data transmission. These are the major contributions in this research work as listed in three different categories in the following list;

1- Proposing Ultra low energy Communication protocol (TBCD) for IWBSNs.

2- Proposing Ultra low energy Time Synchronization algorithm applicable to TBCD Communication protocol.

3- Eliminating the effect of wireless transmission delay.

1.4.1 TBCD Communication Protocol

An ultra-low-energy communication protocol has been defined and enhanced here at a higher level of abstraction for IWBSNs and its correctness has been shown in both theoretical and practical ways. Several enhancements of this protocol which is named "Time-Based Coded Data" (TBCD) are presented in this research, demonstrating its effectiveness and correctness through appropriate simulation environments. This method would then allow saving the very small amount of energy available in the very tiny battery of the sensor node, hence lasting considerably longer period of time in the human body. Provided complete description on TBCD communication protocol in chapter 4 demonstrates how the information read by the sensors in human body are coded in different time domains and how they are wirelessly sent to the BS by only a very short signal instead of long messages encapsulated in large packets by other standard protocols. Figure 1.11 shows a simplified model of an IWBSN.

The IWBSN benefits from the advanced technology in producing very small sensors to be implanted in the human body. One example of these tiny sensors is the sample shown in Figure 1.12 and Figure 1.13 illustrates a model of such tiny sensors implanted in the body to communicate with the BS under TBCD protocol.

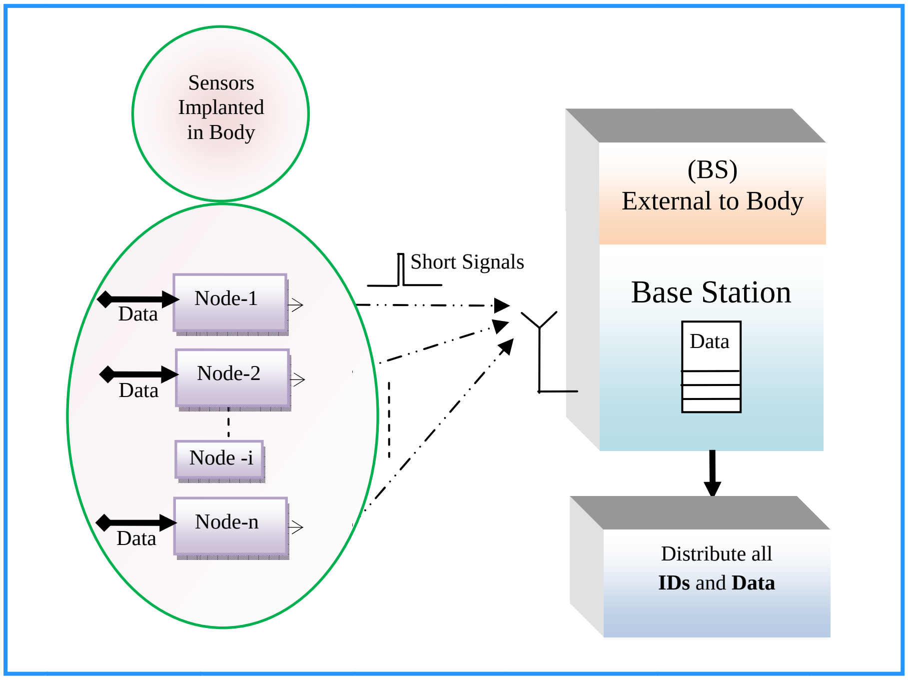

Figure 1.11: Implantable wireless body sensor network model.

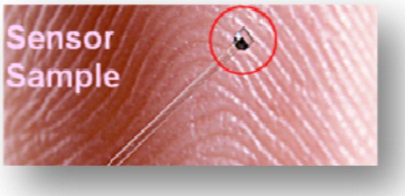

Figure 1.12: An example of a tiny sensor sample.

Our results are compared as well with the other known protocols in this area such as ZigBee [92, 93] and ANT [85, 86], and the results show huge difference with respect to the gain versus these standards. Figure 1.14 shows the general topology of a complete implantable wireless body sensor network.

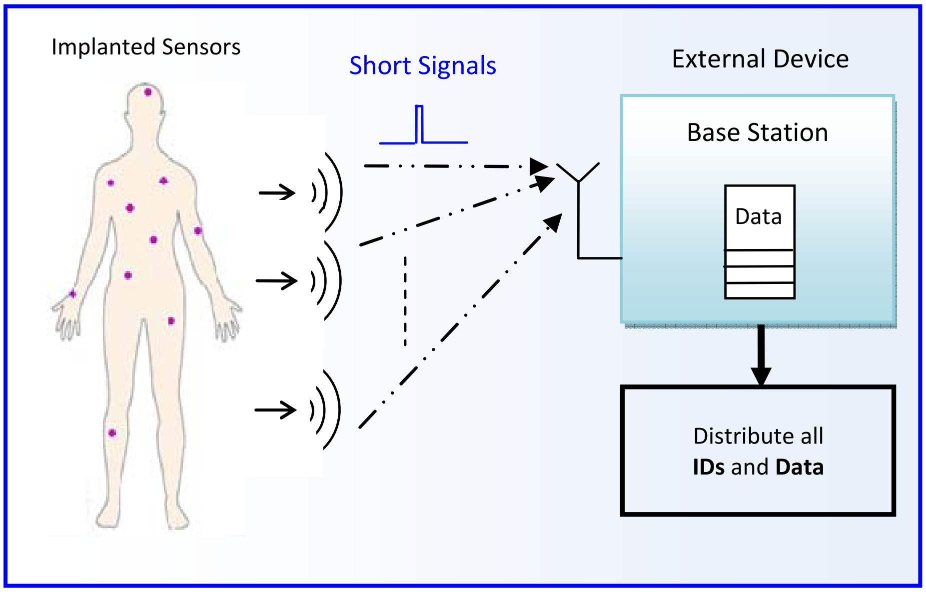

Figure 1.13: Sensors model implanted in body.

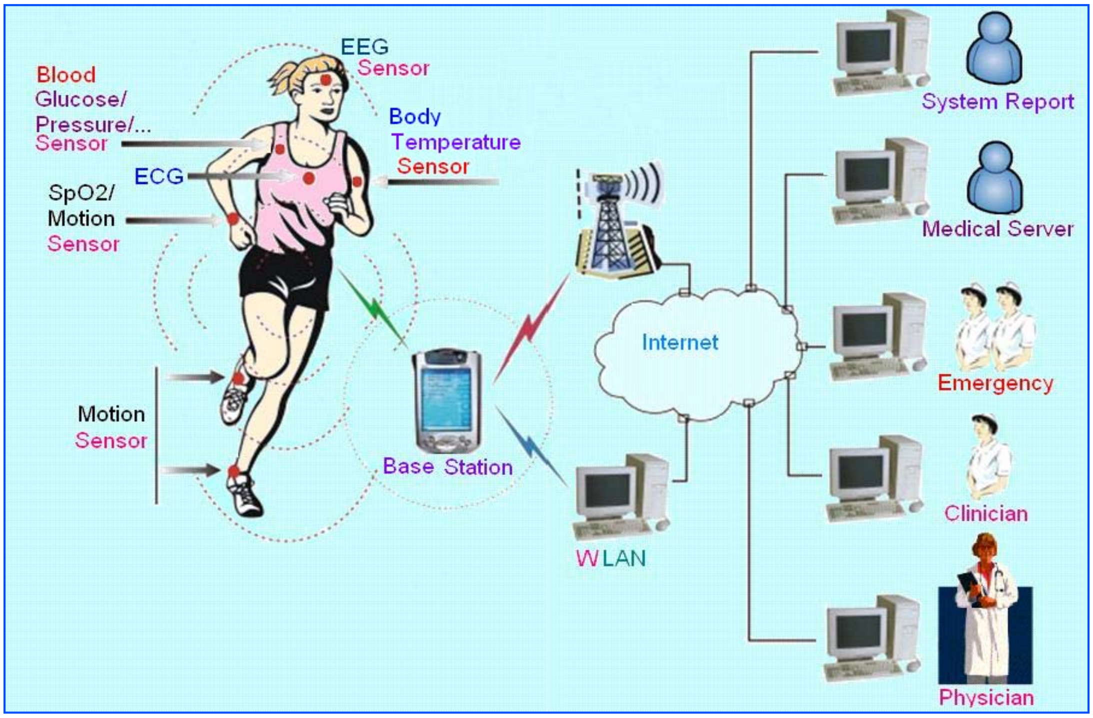

Figure 1.14: General topology of a complete IWBSN system.

The complementary part of this work is a new ultra low power Synchronization algorithm which is given along with the proposed communication protocol and all together have been demonstrated the effectiveness of all proposals through Matlab simulations as well.

1.4.2 Time synchronization

We also introduce our novel low-range low-energy Synchronization algorithm well suited for TBCD communication protocol. The proposed synchronization algorithm works based on a technique similar to the TBCD algorithm. It uses the core aspect of the TBCD communication protocol by transferring its short messages/signals and Time-Stamps within the specific time slots known by all sensor nodes installed in the sensor network system.

1.4.3 Wireless Propagation Delay Elimination

This section in chapter 4 represents the proposed methodology of delay calculation and delay elimination between the BS and all sensor nodes automatically. One serious potential problem related to this protocol is the signal propagation delay between the sensor nodes and the BS. This delay affects the correctness of our protocol since it is directly dependent on a precise and reliable time synchronization constraint between the BS and all nodes. The proposed method calculates this delay and can automatically adjust and eliminate the error derived from wireless transmission process to achieve correct transmitted data under the TBCD communication protocol. In addition, we propose a hardware implementation to test the protocol along with calculating the delay using FPGA and hybrid Transceiver boards.

The rest of the thesis is structured as follows; the preliminary literature review in chapter 2 gives some basic background in this area, and surveys the current works related to IWBSNs. Chapter 3 discusses critical issues and hurdles as bottleneck in achieving feasibility of embedding IWBSN in human body. Contributions in this research are given in chapters 4 and 5. In chapter 4 we find the complete description of the proposed ultra low-energy TBCD communication protocol in details for wireless body sensor networks. Validating the correctness of the proposed solution is also presented in this chapter. We will also find how the impact of the error derived from delay in wireless data transmission will be eliminated and fixed automatically by the given simple technique at the end of the chapter. Next in chapter 5 a complete description of an innovative low energy synchronization algorithm is proposed as complementary part of the TBCD communication protocol along with proof of the concept, and finally chapter 6 concludes the thesis.

1.5 Summary

In this introduction we reviewed basic information about reading/monitoring the patient's health status through different methods. The current state of the art of technology is only able to monitor some results through the systems called wearable wired/wireless body sensor networks. But the medical teams requested for an implantable technique being able to have so many tiny sensors implanted inside the human body, while permanently monitor their information to the medical teams wirelessly through the world wide networks such as internet. Therefore, based on the challenges related to power consumption and energy issues derived from the miniaturization, we introduce our contributions by proposing a very low power communication protocol along with its requirements such as delay control mechanism and ultra low power synchronization technique. In the next chapters we will investigate through the related researches and state of the art to find out how the problem could be solved.

Literature Review and State of the Art

Chapter 2

2. LITERATURE REVIEW AND STATE OF THE ART

2.1 Introduction

In This chapter we study some basic definitions and background information about the area of this research work. In general, wireless communications are categorized in two different types of network topologies; star and peer-to-peer. Star networks are based on a central control node as Base Station (BS) which controls all communications as a master node, and the Peer-to-peer communication is used in ad-hoc networks. In star based networks the BS acts as a master node in the network and all sensor nodes must communicate only with the BS even if the other nodes are within the accessible range. Figure 2.1-a shows a star network topology with a master node, and Figure 2.1-b shows a peer to peer network topology where all nodes can send and receive data to and from each other within their range.

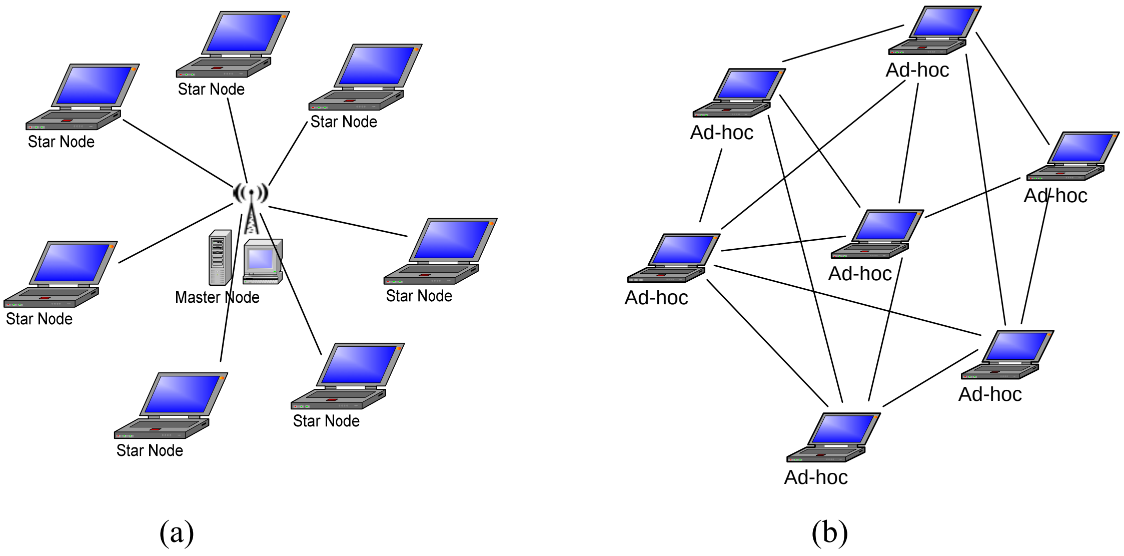

Figure 2.1: (a) Star network topology, (b) Peer to peer network example (ad-hoc).

Any network system like WBSN can connect to other network types through a device which is called a gateway. This device converts appropriate network techniques between two different network types. Table 2.1 compares specifications of some well known network types [4].

Table 2.1: Classification of wireless networks according to their coverage [4].

Network	Coverage	Data rate	Application	Technology
WWAN	> 10 Km	< 10 Mbps	Mobile Internet/Phone	Satellite
WMAN	< 10 Km	< 100 Mbps	Broadband	IEEE 802.16
WLAN	< 1 Km	100(s) Mbps	Ethernet Replacement	IEEE 802.11
WPSN	< 10 m	< 10 Mbps	Data transfer	IEEE 802.15.4 Bluetooth
WBSN	< 2-5 m	< 1Mbps	Health Monitoring	Proprietary

WBSNs are mostly designed based on the star network topology. One important reason is related to low energy resources available in the nodes, and thus the sensor nodes cannot take care of the other node’s information by extra communication with them. However, in the next sections we discuss the drawbacks of the other ad-hoc based methods versus star topology, and then we focus only on the star topology for the IWBSNs. Figure 2.2 shows a WBSN on a human body which is connected to WLAN/WWAN through its Personal Device Assistant (PDA) or the BS, and then through a gateway which is a wireless router.

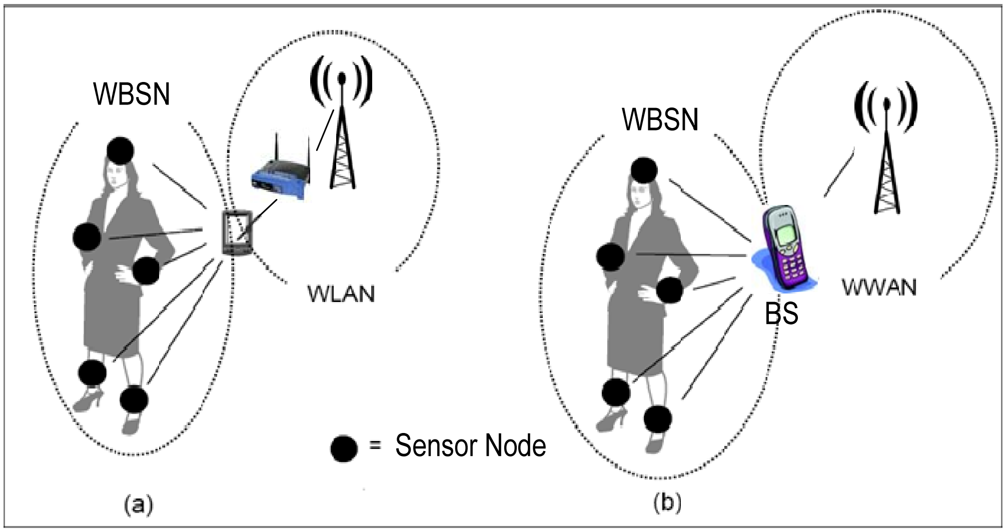

Figure 2.2: (a) WBSN connected to WLAN, (b) WBSN connected to WWAN.

In the next section in this chapter we consider the state of the art and current technologies related to WBSNs in terms of both hardware and communication methodologies. This will cover all sensor nodes components including digital and analog parts, and as well all to date relevant standard communication protocols. As we will clearly see so far, low range/low power sensor networks have always been suffering from energy issues, especially for the body sensors in the field of human health care. This has motivated the engineers to focus their researches more and more on low energy or ultra low power consumption techniques which are totally unaffordable bottleneck for in-body implantable sensor devices.

2.2 Sensor node components

An implantable sensor node in an IWBSN usually consists of four major components as below;

- Battery
- Sensor
- Digital Controller
- Transceiver (including tiny antenna).

Figure 2.3 illustrates the architecture of a sensor node. The sensor reads the data and forwards it to a preamplifire. The amplifired/filterred data is converted to a digital vector through the ADC (Analog to Digital Converter). The Digital Controller section which consists of a tiny low power Micro Controller and digital signal processing circuitry, receives the input data, analyzes it and shifts the result to the transceiver section for transmission towards the BS. Messages received from the BS also can be detected by the transceiver section and forwarded to logic section for corresponding analysis.

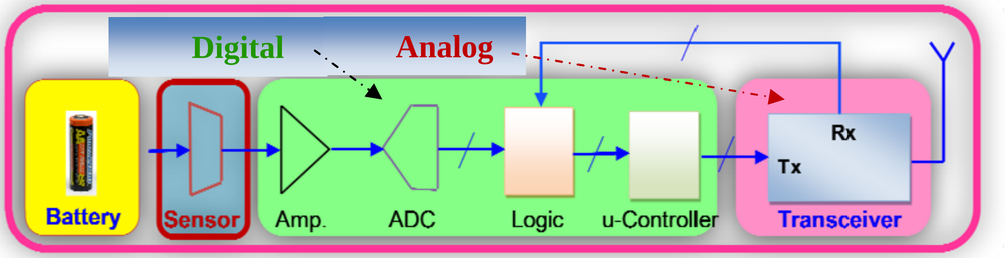

Figure 2.3: Major components in a sensor node.

2.3 Transceivers specifications

Power consumption is always an issue. Transceiver in a sensor node must work while having as least activity as possible. It could be either in OFF-mode, sleep mode, idle mode or active mode. Except in OFF-mode the transceiver consumes energy, especially in active mode with maximum power by sending or receiving data. In idle mode it is waiting for request for required action, and in sleep mode the transceiver is in its least consumption status. But some parts in the transceiver may still need power to keep the system ready for quick and fast re-operation. The most important part is the oscillator which may need to be always running for quick wake up operations. However, it is totally dependent on the technology of the transceivers or just the oscillators used in the sensor nodes. They vary in different types of sleep modes in terms of the power consumption. Obviously, the higher transmission data rate as well helps and keeps the transceiver in active mode for shorter period of time. This is as well related to the communication method which is dependent on how the communication protocol deals with data transmission and how long lasts to let the transceiver go back into sleep mode. Dealing with very small packets (one byte or few) is an overhead in WSNs because of the start-up/wake-up time which has really large impact on the power consumption. For example, the startup time for a transceiver (μAMPS-1) with 1 Mbps transfer rate is about $470\mu s$ [4]. This means $8\mu s$ (plus start-bit and stop-bits) plus $470\mu s$ transmission time per each byte in a sensor network. Therefore, the start-up time, data rate, and the type of sleep mode are important parameters in the design and overall result is that the start-up/wake-up periods have the considerable impact on the design in terms of energy consumption. Usually all transceivers in bi-directional communications execute a mechanism to detect any existing error by applying a Cyclic Redundancy Check (CRC) on each packet transmission which is again energy costly. When an error is detected, three different options are available to choose [4]:

1- Accept the arrived erroneous packet and use it anyway (this often happens in voice applications).

2- Drop the packet and wait for the next transmission.

3- Request for retransmission.

The Medium Access Control (MAC) algorithm decides which node has the right to send data. For low power sensor networks a listening free channel access mechanism is the best. There are three methods applicable for different channel access mechanisms [4]:

1- *Polling*
2- *Strobing*
3- *Cyclic broadcast*

In the *polling* method in the network, the BS (as a master) asks each sensor node (as slave) to send an update of its status. Thus, the Polling technique is involved in incoming and outgoing messages for each sensor node, therefore, the Polling method is the most precise technique in terms of data accuracy because of supporting retransmission. But in terms of time inefficiency it has the largest impact on the network power usage. If the second method (strobing) is applied, the BS (master) periodically sends a request to all sensor nodes for their status updates. The sensor nodes respond in turn, without any individual request from the BS or master. So that first sensor node1 answers by sending its own status, then sensor node2, then 3 and etc. But if Cyclic method is applied, each sensor node must send its information in a specific predefined time slot which could be used in a star topology network system. Then it would be the most efficient technique in terms of energy consumption, since no extra long incoming/outgoing messages are required to transmit in the network. But it is required to have very reliable clock generators at the sensor nodes being synchronized together. Because the clock drift cannot support proper data at right time. This all means that the system in this case requires a reliable time synchronization algorithm available. All these compressions imply that the cyclic technique which reminds a kind of Time Division Multiplexing (TDM) is the most efficient method if a reliable and efficient synchronization algorithm in terms of both precision and energy consumption is available.

Transceivers specifications are important in terms of the size, power and energy consumption. Figure 2.4 shows a typical example of a miniature transceiver for low energy, low range applications [61]. This is not a new product in technology, but the most interesting aspect of this transceiver is its small size and it is not requiring any off-board antenna. The overall size of a sensor node for WBSNs is one of the most important factors especially for implantable sensor node applications. The described features in Table 2.2 show the interesting specifications of this small and miniaturized transceiver in 1mm^3 ($1x2x0.5\ mm^3$) with embedded on chip antenna.

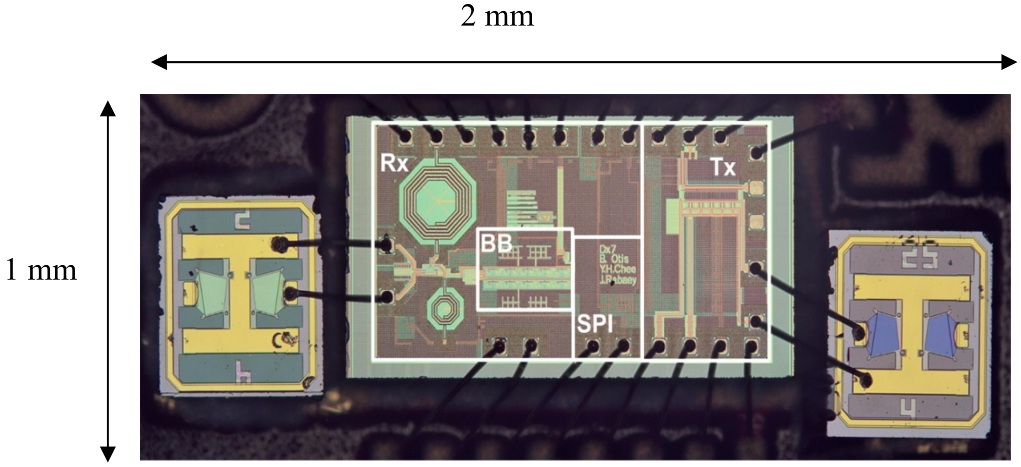

Figure 2.4: A fully integrated miniature transceiver [61].

The antenna occupies a significant area/volume of the node. An efficient antenna requires certain dimensions in range of λ/4 to λ/2, where λ is the operating wavelength. Therefore, there is inherent relation between antenna efficiency, antenna size, power consumption and carrier wave frequency. At the frequency of 2.4 GHz, λ/4 equals about 3cm and hence for tiny sensor nodes embedding such straight on-chip antenna is not possible. But instead it would be possible to benefit from printed antennas on PCB

Table 2.2: A miniaturized transceiver's features [61].

A Fully Integrated Rx/Tx	Specifications	Description
Output Power	0dBm	Tx power: (1mW)
Receiver Sensitivity	-56 dBm	Rx antenna sensitivity
Power	65 µW	Average power
Components	No external Components	(Inductors, Crystals, Capacitors)
Technology	0.13µm	CMOS
Size	1 mm^3	Very small = (1x2x0.5) mm^3

(Printed Circuit Board) to reduce the size and as well the cost [8]. Table 2.3 gives specifications of such small transceiver along with other components in a sensor node.

2.3.1 Power radiation

The minimum power radiation (PTx_{min}) needed for communication between two nodes to meet the receiver's sensitivity is dependent on some factors as given here [69]:

$$\boldsymbol{PTx_{min} = \left(\frac{4\pi f}{C}\right)^2 \times \left(\frac{d^n}{G_t G_r}\right) \times PRx_{sens} \times LF} \qquad (2\text{-}1)$$

Table 2.3: Nominal current consumption of a state-of-the-art sensor node when active [8].

Components	**Current Consumption (mA)**	**Condition**
Transmitter	17.4	0 dBm output power
Receiver	19.7	-94 dBm RX Sensitivity
Microprocessor	0.5	3V supply, 1MHz Clock
Sensor	< 0.03	Normally reading data
Voltage Regulator	0.02	Average

where f is the carrier frequency, d is the distance between the two nodes, Gr and Gt are the antenna gain of the receiver and transmitter's antennas respectively, $\mathrm{P}Rx_{sens}$ is the receiver's sensitivity or remaining power of transmitted wave at the receiver, C is the speed of the light which is the same as speed of the electromagnetic wave being studied here, n is the path loss exponent and LF is the loss factor related to all other losses (matching parts, cable loss, etc.). According to Equation (2.1) the detected signal strength decreases quadratically with the distance between the transmitter and receiver. For WSN applications, a normal antenna with Gr and Gt, = 1 with LF=1 (almost in ideal situation) is desired, and the path loss exponent n is typically between 2 and 4 [5, 69]. For a range of about 10m, a 2.4GHz communication system requires about 0dBm (deci-Bel miliwatt) of transmit power to be detected by a receiver with a sensitivity around -50dBm In theory. This is based on no extra attenuation or hurdles (LF=1) assuming n=3, and it goes to around -80dBm depending on different values for LF and n in reality [67, 48, 5]. Experimental results in a ZigBee based sensor network design in [5] shown in Figure 2.5 also clearly justifies this calculation. Based on the Equation (2-1), measuring the PRx_{sens} or Received Signal Strength (RSS) at the receiver side could be used to estimate the distance between the transmitter and the receiver. The received signal strength is usually converted to a Received Signal Strength Indicator (RSSI) which is defined as ratio of the received power (PRx) to a reference power as P_{Ref}.

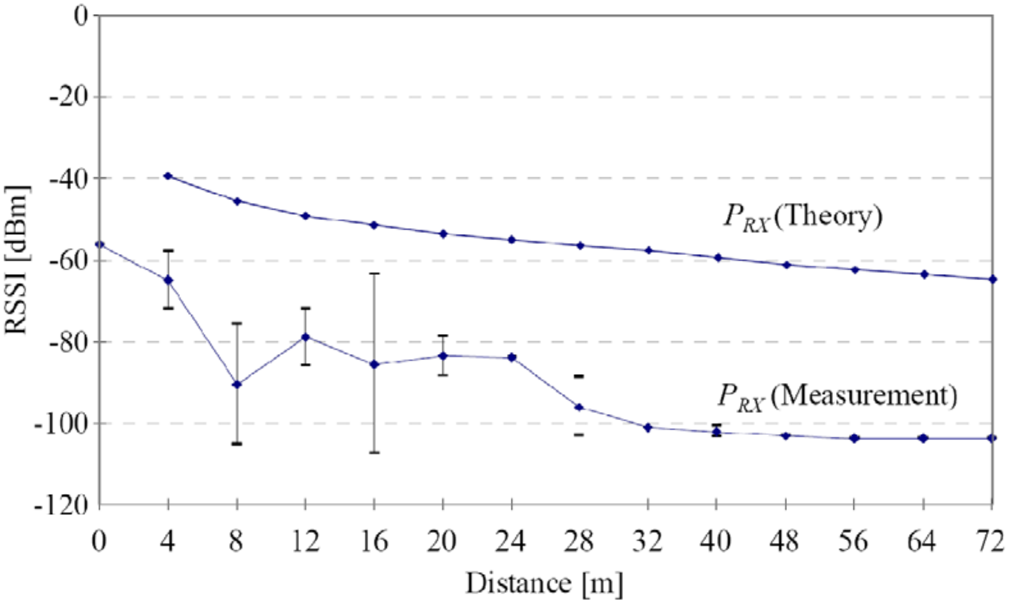

Figure 2.5: RSSI as quality identifier of the received signal power PRx (Theory), and Received Signal Strength measured by a Chipcon CC1010 sensor node (Measurement) [5].

Typically, the reference power is assumed as 1mW and the RSSI is generally introduced by the Equation (2-2) in dBm.

$$\boldsymbol{RSSI = 10 \times log\left(\frac{PRx}{P_{Ref}}\right) \quad dBm} \qquad (2\text{-}2)$$

2.3.2 Oscillator and Start-up Time

Oscillators suffer from long start-up time when switching OFF and ON is essential in low power applications. It is so difficult to reduce the start-up time to be much less than the transmit time. For example, in a network with a data rate of 200kbps it takes only 1 millisecond to transmit a 200 bits data packet. If a maximum of about 10% overhead is accepted, then the wakeup time must be less than 100µs. But normal resonators typically require several 100's microseconds to several milliseconds to reach their nominal oscillation during the start-up time. To overcome this problem in low power WSNs, benefiting from new technology of RF MEMS based oscillators is appreciated for frequency generation, which requires only a few microseconds to reach steady state. FBAR oscillator is one example using MEMS technology. The FBAR has a very small form and occupies only about 100µm × 100µm [71, 8]. The Start-up time for an FBAR Oscillator is shown in Figure 2.6. It consists of three phases [87] described as follows:

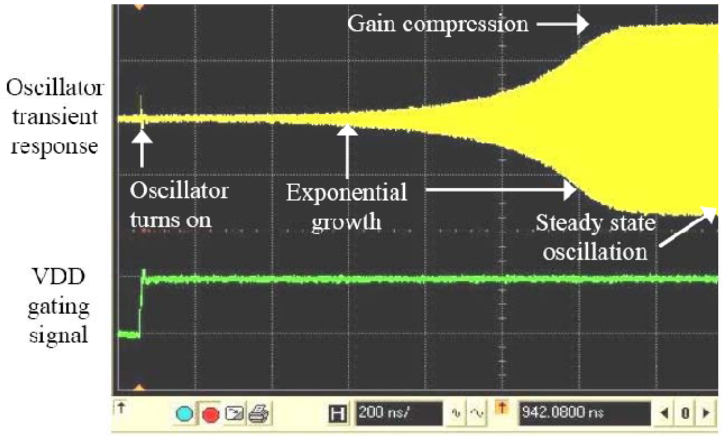

Figure 2.6: Measured start-up transients of an FBAR Oscillator [87].

It has shown in here that the startup time of the FBAR oscillator is about 1.25µs which is a big advancement in reducing the start-up time. If the startup time constitutes 10% of the bit period, the oscillator takes (1.25µs ÷ 10%) or 12.5µs to be able to support data rates of up to 80 kbps with On-Off Keying (OOK) modulation. But, to achieve a higher data rate, the startup current can be increased temporarily. As shown in Figure 2.7 [8], during the oscillator start-up, VC1 can temporarily help to accelerate the start-up time by increasing primary start-up current. By using this technique, the startup time is reduced to 300ns without significant increase in the power. Again if 10% of the data transfer time period is assumed for oscillator start-up time, then it will be capable of supporting a maximum data rate of 330kbps.

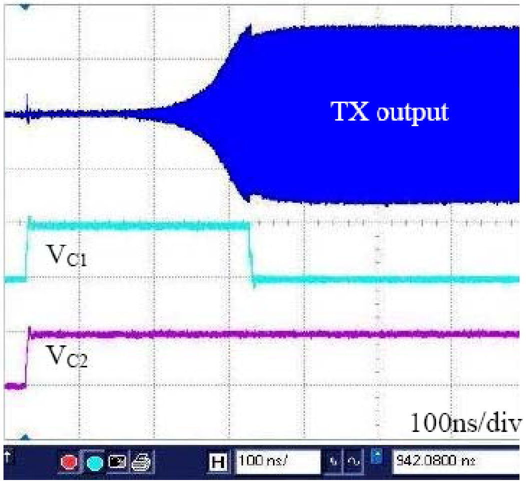

Figure 2.7: Transient waveform of the fast startup oscillator [8].

2.4 Sensor Components Power Consumption

An illustrated sensor node in Figure 2.8 shows its general structure consisted of four different main components such as Battery, Sensor, Digital circuitry and the Analog section.

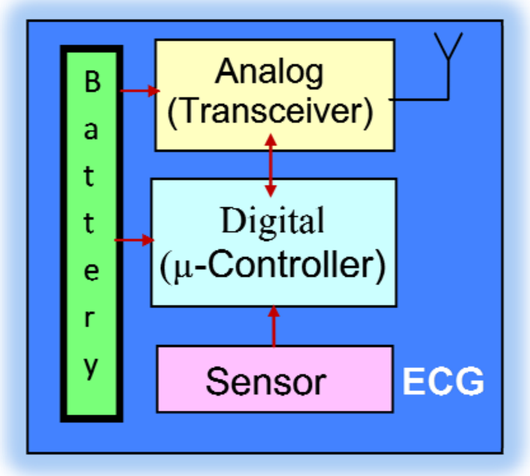

Figure 2.8: Components of a sensor node.

The Analog section comprises the transceiver circuit. But the Digital section is consisted of different parts such as; Pre-Amplifier to receive the sensor data and forwarding it to the ADC (Analog to Digital Converter), then the digitized output of the ADC is forwarded to the digital controller which is finally directed to a Microcontroller for final analysis and making all required decisions and actions.

The total power consumption of such sensor node would be obtained by summation of all average powers by these sections as in Equation (2-3).

$$P_{Total} = P_{Sensor} + P_{Amp} + P_{ADC} + P_{Logic} + P_{uC} + P_{Transceier} \qquad (2\text{-}3)$$

The ADC section in (Figure 2.3) consumes trivial amount of energy, for example like the technique used in [76] with 31 pj/8bit sample @ 1 Volt including the preamplifier which is extremely low. Also another novel 8-bit technology by 25-250 kS/s range for clock sampling frequency in range 200 kHz to 2 MHz with a corresponding power dissipation from 220nW to 560nW using 0.55V power supply [13] applicable to very low power wireless sensor networks. For the logic controller, the available technology of the low power counters and comparators significantly alleviates the power issue of logic parts. For example, a Real Time Clock chip like; "RTC DS-1372" which is a 64-bit counter/Comparator with a power consumption of 400nA @ 3Volts (only 1.2µW) can be used as 16-bit counter even with much less consumption. Counters and comparators are generally the most power consumer components in digital controller circuits because of large number of switching. In the standard structure of a sensor node, a microcontroller exists that can surprisingly benefit from one of the latest technologies like the *ultra low power Phoenix* Processor as a platform for sensing applications with 29.6pW [22] in sleep mode, and 2.8µW @ 1MHz in active mode. This is really low consumption which is embedded in a very small miniature size as in the picture in Figure 2.9 comparing with the size of a penny. Assuming about 10% of the activity time for the processor, it gives an average of around 0.3µW power consumption. These referenced example information related to all digital sections in a sensor node imply reliable ultra low energy components as expected for BIO sensors applications. But in analog view of point things are totally different. For example, current technology of the low-range transmitters like those used in ZigBee transceivers which is a well known applicable to low power sensor networks with 0dBm output power setting, consume about 100nA (0.33µW @3.3 Volts) in sleep mode and about 26mA or 85mW in active mode [7].

These measuring results will be used in chapter 3 to achieve an optimized average power consumption and consequently to obtain a realistic life time for the sensor nodes in body.

Figure 2.9: MSP430 Phoenix Processor on a Penny [22].

2.5 Wireless Communications

Here we consider the general data transaction methodology in standard communication protocols. Figure 2.10 simply illustrates how standard communication protocols accomplish handshaking in general [65]. In this figure, T_on is the required time by the receiver to turn ON or wake up. The transmitter starts the data transaction by sending a Request To Send (RTS) signal to the receiver and waits in listening mode for the ready or Clear To Send (CTS) signal from the receiver side in T_{Listen} seconds. If there is no response after T_on seconds, then this process is repeated until either CTS signal arrives or a time out event occurs. Once the CTS signal is detected, the transmitter can send the data packet and wait for a confirmation. The entire process will be discussed and compared with the proposed communication protocols in the following sections. A number of researchers are studying toward WSNs and many protocols proposed in order to reduce the energy consumption at the nodes. Wireless networking requires larger processing and protocols than wired protocols. Sensor nodes in WSNs carry normal data acquisition and processing phases, and also need appropriate service protocols and packet transfers that the network generates them asynchronously.

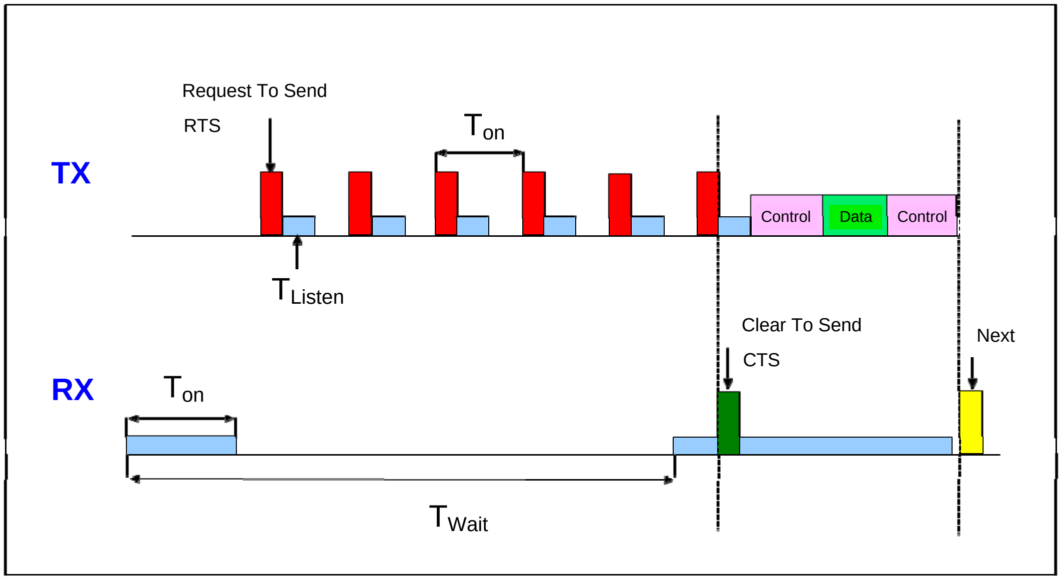

Figure 2.10: general form of the Low Power communication protocol in data transaction.

However, hardware resources remain constrained, especially in terms of memory and power. It introduces a structured event-driven execution model facilitating implementation of sophisticated protocols and algorithms. Many research communities in different fields have investigated in monitoring applications related to Sensor Networks. They all try to reduce the energy consumption in the network especially in the sensor side. There are numerous methodologies proposed and available to the different applications in wireless networks. Now we recall and study many of them by focusing on the core of their concept and their impact on the network systems in terms of efficiency in what they contribute especially in energy savings.

Byers and Nasser in [6] have proposed dividing the sensors into different types to reduce power usage. Some sensors are used for communication and others for the sensor application. In [31] we find a proposed method using clusters of sensors and rotating the cluster head to equalize power usage among sensors and extend sensor life. Improving power efficiency through topology control has also been examined in [32, 68, 82]. HTTP based protocol was proposed by Dokovsky et al as well as a TinyOS based protocol suitable for wearable BSNs [8]. Directed Diffusion [36] is a data-centric protocol for general data collection in sensor networks which focuses on data management to reduce the activity of the sensors. Cougar [91] and TinyDB [54] are database abstraction of sensor networks and provide declarative interfaces. These are based on ACquisitional Query Processing (ACQP) by focusing on both traditional techniques and new query processing techniques in sensor networks. In other words, focusing on the smart sensors which have control on “where, when, and how the data should be sampled and delivered to the query processing. This way they try to reduce the energy compared to traditional systems. Skordylis et al. have made a complete survey in approximate data management for sensor networks [75]. In [10], Chu et al. proposed an approach to compress data using replicated dynamic probabilistic models to guarantee eliminating the error in measurement readings. This is similar to BBQ (A Tiny-Model Query System) approach proposed in [12]. Both of these works establish statistic models of real situation of sensor networks in order to reduce sensing and communication issues. Jain et al. in [37] propose correlation of data sources and also introduce filter architecture to maintain the network bandwidth. The server and the source follow the same copies of the filter and the server tries to predict the data from the source. Then the source updates the corresponding filter on the server if the prediction by the server is not accurate. Lazaridis and Mehrotra in [42] have proposed an approximation method, called Piecewise Constant Approximation (PCA) approach, for data producer to transmit time series to data collector. The approach represents time series with a sequence of segments. Korpip et al. in [41] classify user daily activities based on audio features. Du et al. in [15] decompose the features into global and local classes, and present a network model to recognize interacting activities on data. David Jea et al in [38] propose series of approximate data collection by reducing sensor data resolution. They declare that accurate results are possible even with 50% reduced resolution. All of these works and many more have similarly contributed in data management in order to reduce the activity of the sensor network, and consequently expecting some reduction in sensor energy.

There exist only few protocols which are designed specifically for WBSNs. These protocols usually try to balance the traffic over the network [74] and cannot be considered as a solution to the corresponding power issues. For example, the CICADA-S [74] protocol is the first integrated solution that was not able to solve the issues derived from this mobile medical monitoring scenario properly. Several issues exist in this area of research including low energy consumption, limited computation, continuous operation, robustness, scalability and reliability. TinyOS, as an old protocol is designed specifically good for wearable BSNs, but not for the implantable [44]. Tree-Based (TB) and Cluster-Based (CB) protocols in [83, 77] use only a small number of nodes to transmit data to the external base station. LEACH (Lower Energy Adaptive Clustering Hierarchy) protocol uses techniques that are based on algorithms for distributed cluster formation, adaptive cluster formation, and change of cluster header position [52, 30]. Another proposed protocol in this area is PEGASIS (Power-Efficient Gathering in Sensor Information Systems) [43], which is an improved version of LEACH. In PEGASIS, each node communicates only with a close sensor node and takes turns transmitting to the base station. Based on the simulation results for this method, PEGASIS performs about 100% to 300% better than LEACH when 1%, 20%, 50%, or 100% of nodes die [43].

All of the standard communication protocols are mainly playing with the topology of the network or different compression methods. These communication protocols use also the same standard methods by attaching large control information (100s of bits) to the main data which is of course useful and important for their corresponding applications in different aspects of networking. But it is totally different related to energy constraints in ultra low energy wireless networks. For example, ZigBee, which is one of the best and most commonly used protocols in low power wireless sensor networks, adds up to 27 control bytes to the main data [7]. The IEEE 802.15 TG4 is chartered to investigate a low data rate solution with multi-month to multi-year battery life and very low complexity [46] but may not meet the requirements for using the batteries as small as required to implant in the body. These standards will be discussed in next sections.

2.5.1 IEEE 802 working groups

Now we consider the most commonly used communication protocols to survey on their high energy consumption effects in BSNs. There are large amount of control bytes required to be sent at each time communicating which keep the transceivers in active mode along transmission time. IEEE 802.15 working group is appropriate standard for WPAN applications. It is generally categorized in several different Task Groups for different applications [46, 80]. We will go to discuss them more in next section.

IEEE 802 Wireless Networking Groups:

- 802.11: Wireless Local Area Networks (WLAN)
- 802.15: Wireless Personal Area Networks (WPAN)
- 802.16: Wireless Metropolitan Area Networks (WMAN)

2.5.1.1 IEEE 802.15

IEEE 802.15 working group is introduced as appropriate standard for WPAN which is covering different applications:

IEEE 802.15 Wireless Personal Area Networks (WPAN):

802.15.1: Bluetooth (v1.1 based MAC/PHY)

802.15.2: Unlicensed Band for WPAN

802.15.3: High data Rate (HR) WPAN

802.15.4: Low data Rate (LR) WPAN, (ZigBee MAC/PHY)

IEEE 802.15 working group has a number of different stages of standardization which are being in the process of approving as standards. The first step to generate an IEEE standard task group is to propose a project, and this is called Project Authorization Request (PAR). The appropriate IEEE board must first approve it before the actual standardization process can begin. When a PAR is approved then the new task group will be introduced as a new standard. For the time being there are six approved PARs and consequently six task groups; 802.15.3*c*, 802.15.4*c*, 802.15.4*d*, 802.15.4*e*, 802.15.5, and 802.15.6.

Wireless body sensor network works within the smallest covering area which is only surrounding the area around and in very close proximity to the body of a human and there is no standard proposed and confirmed available for such low power low range wireless sensor networks by the moment yet. In November 2007 IEEE appointed a new task group within the 802.15 working groups and numbered it Task Group-6 [84, 4] in order to work out a new standard for WBANs/WBSNs (Wireless Body Area/Sensor Networks). Following is a list of other IEEE ongoing task groups.

Task Groups ongoing:

TG3c:	**802.15.3c:**	mm-Wave
TG4c,d,e:	**802.15.4c,d,e:**	Alternative PHY (802.15.4c for Japan)
TG5:	**802.15.5:**	Mesh networking
TG6:	**802.15.6:**	Wireless Body Area Networks (WBAN)

And as well for RFID and some others which are categorized in study group;

Study Group:

SG_RFID: Radio Frequency Identification Study Group

SG_VLC: Visible Light Communication Study Group

WBAN IEEE has chartered the newest working group (802.15.6) that is going to bring standard requirements intended for WBANs/WBSNs supporting networks in the close proximity to the human body. Therefore, by IEEE organization there is no efficient and practicable communication protocol yet to be accepted as a good standard for the area of WBAN/WBSN [4].

Potential applications are sensor networks, interactive toys, remote controls and home automation, and it is a commonly used protocol for the BSNs. The LR-WPANs define four frame structures each requiring transmitting a certain number of control bytes [46].

Here is some quick review on the frame structures in IEEE 802.15.4 standard. In this view we will get enough idea about how lengthy beacon frame and attached control bytes are required for a simple data transfer within IEEE task groups for low range WPANs [49] related to low energy wireless networks.

2.5.1.2 IEEE 802.15.4 Data transfer

This is the data transfer mechanism between two nodes in the network, from a coordinator to a device. When the coordinator has a data to transfer to a device in a beacon-enabled network, it informs the network by beacon that a data message is waiting for transfer. The device is usually listening to the network beacon periodically. If the device finds a message is pending, requests for the data by transmitting a Medium Access Control (MAC) command. The coordinator acknowledges the successful reception of the data request by transmitting an acknowledgment frame. Then the pending data frame will be sent. The device acknowledges the successful reception of the data by transmitting an acknowledgment frame and the transaction is then complete. This sequence is summarized in Figure 2.11 [49, 46].

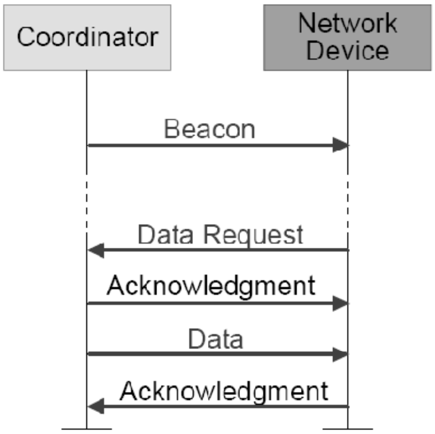

Figure 2.11: Communication between a coordinator and a device in a beacon-enabled network.

If it is a peer-to-peer PAN, then every node can communicate with every other node in its radio availability. Then in order to do this effectively, the nodes will need to synchronize with each other which is so much costly and many other measures need to be taken into the account to achieve synchronization. Now we consider the frame structure to see how large control information is required for data transaction using IEEE 802.15 group.

2.5.1.3 IEEE 802.15.4 Frame structure

The frame structures in IEEE 802 groups have been designed to keep the complexity as minimum as possible, but sufficient and reliable. Headers and footers have been attached to the structure of each successive protocol layer. The LR-WPAN defines four frame structures [49, 46]:

- A beacon frame, used by a coordinator to transmit beacons
- A data frame, used for all transfers of data
- An acknowledgment frame, used for confirming successful frame reception
- A MAC command frame, used for handling all control transfers

The following diagrams in this sub-chapter obtained from [49] illustrate the fields that are added by each layer of the protocol. The packet structure illustrated below the PHY represents number of bytes that are actually transmitted on the physical medium. Based on the illustration in Figure 2.11, these are Beacon Frame, Data frame, Acknowledgment frame and MAC command frame which are all illustrated in Figure 2.12 to 2.15.

Beacon frame:

Figure 2.12 shows the structure of the beacon frame from the MAC sub-layer in a beacon-enabled network. The MAC service Data Unit (MSDU) contains the super-frame information, like pending address specification, address list, beacon payload fields and etc. The MSDU contains a pre-header as a MAC Header (MHR) (2+1+4 or 10 bytes) and appended with a MAC Footer (MFR) (2 bytes). The MHR contains the MAC frame control fields, beacon sequence number (BSN), and addressing information fields. The

MFR contains of 2-bytes Frame Check Sequence (FCS). The MHR, MSDU, and MFR together form the MAC beacon frame, or MAC PHY Data Unit (MPDU) (2+k+m+n bytes). The MPDU is then passed to the PHY as the PHY beacon packet payload which is the PHY Service Data Unit (PSDU). The PSDU contains a pre-header as Synchronization Header (SHR) (4+1 bytes), and a PHY Header (PHR) (1 byte) containing the length of the PSDU in number of bytes. The SHR, PHR, and PSDU together form the PHY beacon packet, (i.e., PPDU).

The idea of considering all these sub-frames in the frame structure is to count number of all control bytes attached to the main data frame and compare or evaluate within the ultra low range and low power wireless network systems.

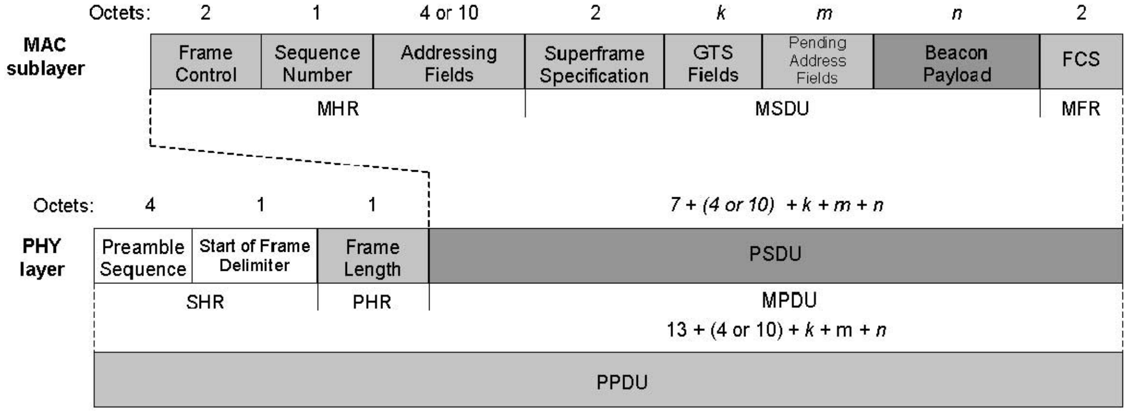

Figure 2.12: View of the beacon frame structure (IEEE Standard 802.15.4).

Therefore, only the length of the beacon frame is as big as:

$$\text{Beacon frame size} = 13 + (4 \text{ or } 10) + k + m + n \qquad (2\text{-}4)$$

where n is data pay load size, k and m are dependent on the fields vary from 8, 10, 12, 18 and up in bytes [49].

Data frame:

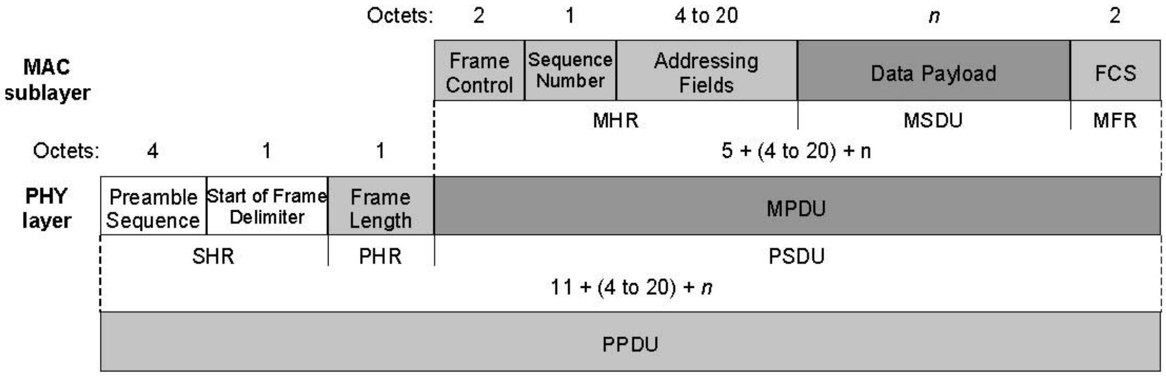

Figure 2.13: Schematic view of the data frame (IEEE Standard 802.15.4).

$$\text{Data frame size} = 11 + (4 \text{ to } 20) + n \qquad (2\text{-}5)$$

Acknowledgment frame:

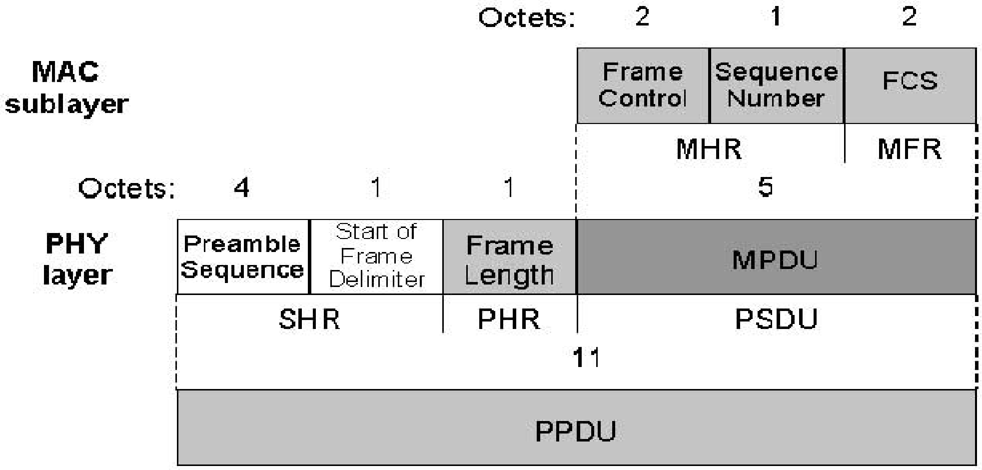

Figure 2.14: Schematic view of the acknowledgment frame (IEEE Standard 802.15.4).

Acknowledgement frame size = 11 (2-6)

MAC command frame:

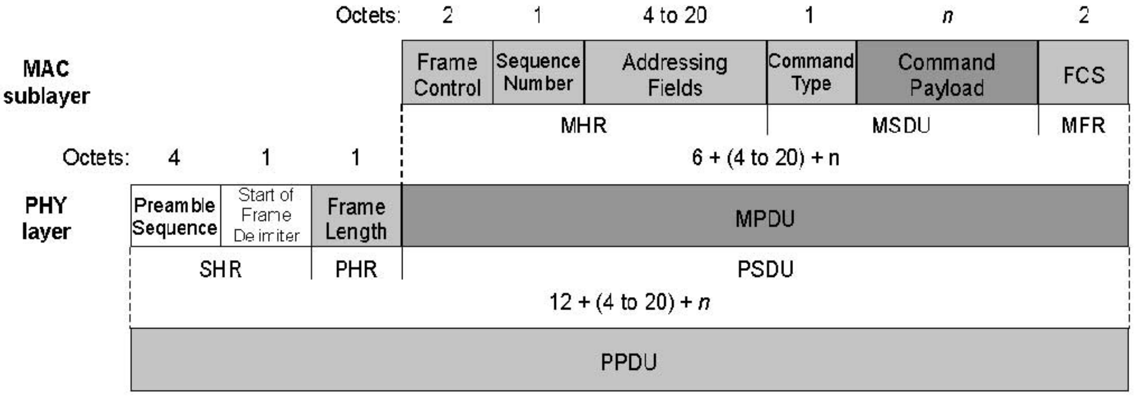

Figure 2.15: Schematic view of the MAC command frame (IEEE Standard 802.15.4).

MAC command frame size = 12 + (4 to 20) + n (2-7)

According to IEEE Standard 802.15.4 in peer to peer data transfer [49], considering only the header and footer control information, the beacon frame needs 17+ bytes, data frame 15 to 31+ bytes based on the addressing mode, acknowledge frame 11 bytes and the MAC command frame needs to send 16 to 32+ bytes plus the length of the main data. Therefore, totally the minimum number of the control bytes in frame structure per each complete successful transaction in the communication using IEEE 802.15.4 technique is as following:

$(\text{IEEE Control bytes})_{\min} = 17 + 15 + 11 + 16 = 59$ bytes (2-8)

2.5.2 ZigBee Protocol

Another new version of the IEEE 802.15.4 standard protocol is introduced as ZigBee in 2006. The ZigBee Alliance is developing very low-cost, very low power and two-way wireless communications standard protocol. The frame structure in ZigBee is much less than the IEEE working group 802.15.4 and contains at least 27 control bytes. In this protocol at the network, the control header comprised at least 12 bytes for request and 15 bytes for confirmation [93, 44].

$$(\text{ZigBee Control bytes})_{\min} = 12 + 15 = 27 \quad \text{bytes} \qquad (2\text{-}9)$$

ZigBee is one of the well known standard communication protocols applicable to low range, low cost and low energy wireless sensor networks. ZigBee Rx current in the receiver @ -50dBm is 18.5mA and @ -100dBm is about 23mA. Typical ZigBee Tx current in the transmitter @ 0dBm output power is 25.8mA [33]. Battery Lifetime based on Free-Scale ZigBee in High-Duty Cycle for 5-Byte data transmission in intervals of 1.28 seconds, assuming 200mAh available battery capacity is given as 33 days [92]. Duty Cycle means the ratio of the active time (T_{Active}) within a specific period of the function, to the total time of the same cycle period (T_{Period}) found in Equation (2-10).

$$DC = \frac{T_{\text{Active}}}{T_{Period}} \qquad (2\text{-}10)$$

Thus:

$$\left(Batt_{Life\_Time}\right)_{1Hz} = \frac{33\ days}{1.28} = 25.78\ days$$

$$I_{Avg} = \frac{200\ mAh}{25.78\ days} = \frac{200\ mAh}{25.78\ \times 24\ hrs} = 323\mu A$$

$$T_{\text{Active}} = \frac{200mAh}{25.8mA} = 7.75\ hr$$

$$DC_{Total\_ZB} = \frac{7.75\ hr}{25.78\ days} = 1.25\% \tag{2-11}$$

where $\left(Batt_{Life\_Time}\right)_{1Hz}$ is the battery life-time in one second intervals (1Hz), I_{Avg} is the ZigBee average current in the transmitter at 0dBm (1mW) output for 1Hz sampling and DC_{Total_ZB} is transmission duty cycle.

2.5.3 ANT Protocol

ANT is another new emerged technique by 2009 which is competing with the ZigBee [85]. ANT also uses its own Hardware and communication protocol and has improved the efficiency on lowering the average power consumption and longevity of the battery operation in the sensor node. The Peak Tx current in ANT is about 15mA and the Peak Rx current at 0dBm is 17mA. The average Tx and Rx currents in ANT for one sample every 2 seconds (0.5Hz) in bit-synchronization are 35uA and 25uA respectively [86] as improved in their new version in (ANT+). We compare all the results in this work based on one second interval which means one sample per second per sensor node. Then the average Tx and Rx currents in ANT along with duty cycle for one second intervals (1Hz) are given below:

$Rx_{Avg\_ANT} = 50 \quad \mu A$

$Tx_{Avg\_ANT} = 70 \quad \mu A$

$I_{Avg\_ANT} = 50 + 70 = 120 \quad \mu A$

$$DC_{Rx\_ANT} = \frac{50\,uA}{17\,mA} = 0.0029 = 0.29\% \tag{2-12}$$

$$DC_{Tx\_ANT} = \frac{70\,uA}{15\,mA} = 0.0046 = 0.46\% \tag{2-13}$$

$$DC_{Total\_ANT} = 0.29\% + 0.46\% = 0.75\% \tag{2-14}$$

2.6 Summary

In this chapter we studied the classification of wireless networks and their coverage range, and the transceiver's specifications. We showed that the kinds of Time Division Multiplexing techniques are the most efficient methods in low power wireless networks if a good synchronization algorithm is supporting the network.

We also analyzed different components in the tiny implantable sensor nodes in terms of the size, performance and as well their power consumptions. The transceiver's specifications guarantee the size constraint for IWBSNs as the advanced technology offers miniaturized transceiver devices. But the energy constraint in low power networks is still a big issue. Especially for the implanted devices in tissues of the body that suffer from large signal attenuation throughout the body. Fast start-up technology of the low power oscillators can also alleviate the energy problem. It was shown that all other components in the sensor node can benefit from miniaturized ultra low power technologies. But the excessive energy consumption by the transceivers cannot be resolved by the current advanced technology of the hardware. Different related standards in communication protocols were also reviewed, compared and measured to find out how the IWBSN can benefit from the most efficient one. The related IEEE working groups, ZigBee as a well known efficient modified version of IEEE, and the ANT+ as the most recently emerged low power protocols were analyzed and compared. In the next chapter the duty cycling results of the transmission under these low power protocols will be analyzed to estimate the energy consumption. Then it will be shown that how a big difference in duty cycle of the power usage is significantly essential in IWBSNs to save the small amount of energy in the tiny batteries in the small wireless nodes.

Energy Issues

Chapter 3

3. ENERGY ISSUES

Generally, energy consumption in any electronic system is a serious challenge today. In analysis of many different approaches in the state of the art in previous chapter we showed that how proposed communication mechanisms have been and are trying to increase their efficiency for low power wireless sensor networks. A Low Power wireless sensor network first of all implies lack of energy availability in a sensor node. Therefore increasing the efficiency in this regard directly implies decreasing the energy consumption of the sensor nodes which are suffering from such power constraint. Since in this research we are targeting the implantable wireless body sensor networks, a sensor node cannot be implanted in human body if the size of the sensor node is unacceptable based on the metabolism of the human body or it will be rejected from the body gradually. Furthermore, an implanted sensor node with large size bothers and harms the patient's body and could hurt the limbs. It could also cause swelling, bruising, bleeding, infection and etc. We are not considering especial big implantable devices such as Pace Makers which have been under studying by the medical researchers since 10s of years ago. A pacemaker is a sophisticated electronic device that analyzes the function of the heart and when necessary, sends precisely-timed electrical signals to the heart to correct abnormalities in the heart's electrical system. Figure 3.1 and Figure 3.2 show samples of such devices while giving an imagination of the size [88]. As shown in the Figure 3.2 the size of these implantable devices is very big nevertheless they have been implanted inside the human's chest successfully. That's because the main device is placed somewhere under the skin in chest, not deeply inside the sensitive spot in the body (Figure 3.3). Fortunately the mechanism of the heart is exceptionally so strong to accept and consistence with such big implantable devices.

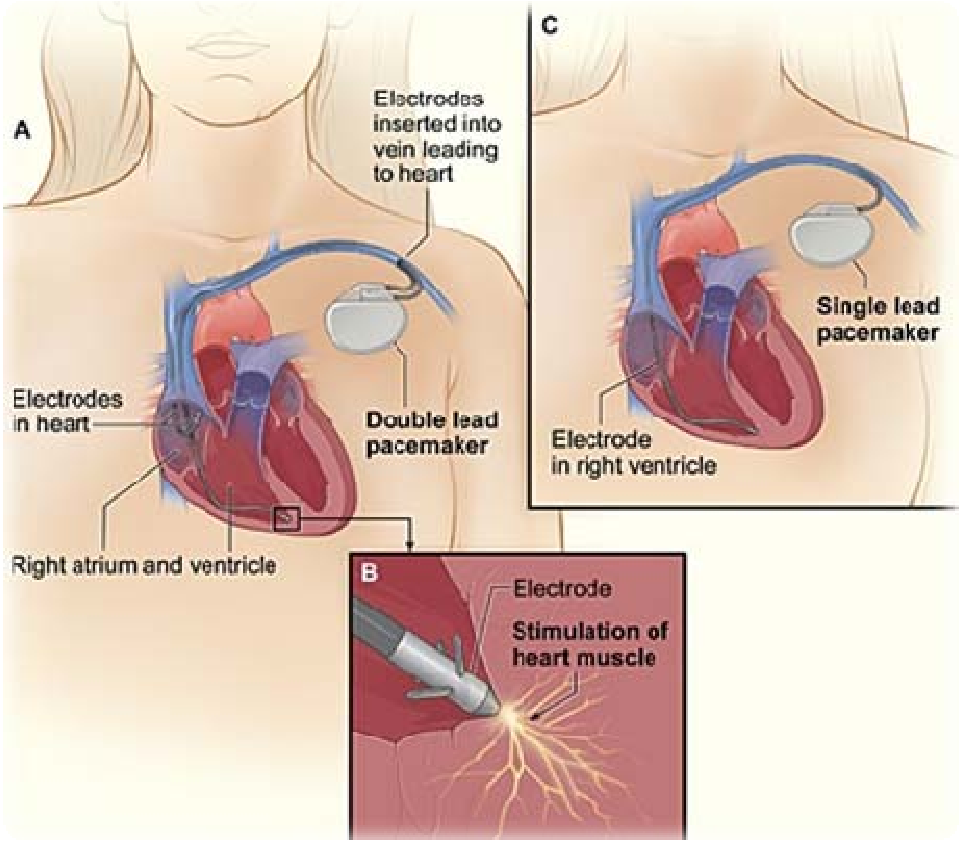

Figure 3.1: Cross-Section of a Chest with a Pacemaker [88].

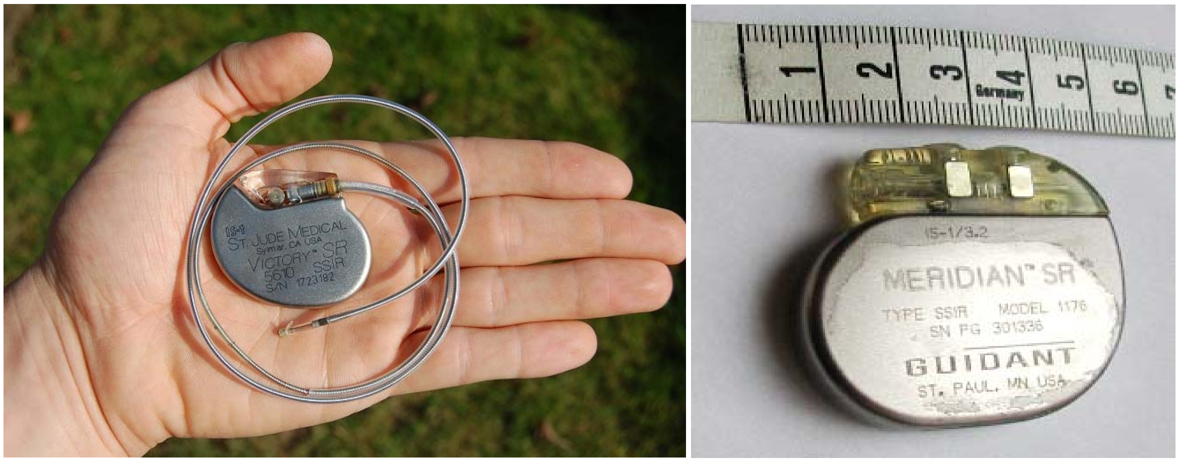

Figure 3.2: Real Pace Makers having big sizes [88].

Figure 3.3: Showing how a Pace Maker is placed under the skin in the chest.

But in this research we are interested in very tiny biomedical sensor nodes implantable everywhere in the human body even in sensitive spots where medical scientists prescribe to implant. There are numerous medical techniques proposed by medical scientists and researchers for monitoring health status of the patients, but these methods are not well suited for sensor implantation due to the inability to miniaturize the associated electronic technologies yet. One of the most important reasons is the need of big batteries associated with the available electronic technology like the small implantable example of such tiny and ultra low capacity battery shown in Figure 3.4 [16]. Consequently, no standardized techniques exist for real-time, continuous monitoring of physiological changes in body yet [23]. Since these implantable sensors must reside in their locations in the body for years, the capacity of their energy suppliers must meet the specifications of the electronic hardware associated with them. They need to transfer their collecting physiological information wirelessly but reliably from inside the body to their central device (BS) external to the body in proximity. Therefore an efficient wireless communication mechanism is critical and essential to satisfy all requirements

Figure 3.4: A tiny implantable battery produced by Eagle pitcher Inc [16].

Many standard communication protocols for WSNs were discussed in chapter 2 describing their methodologies and advantages on how they could meet low-power low-range wireless sensor networks. In this chapter we will show how these classes of the current approaches fail satisfying the energy requirement for implantable wireless sensor networks.

3.1 IWBSN Challenges

The main challenges in monitoring the health status include biosensor design, miniaturized power source, power scavenging, ultra low power RF data path, multi-sensory data fusion, autonomic sensing, secure and light weight communications protocols [44]. The transceiver section in WBSNs usually consumes the largest portion of the small energy in the tiny battery compared to the other components in the sensor node. The size of a sensor node and its power consumption are the two major challenges in the design of implantable WBSNs.

G. Yang and B. Lo in [89] point out the following considerations as the main technical challenges in achieving a successful implantable wireless body area network:

1) Novel multi-domain sensors
2) Implementation considerations
    - Low power RF transceivers
    - Energy scavenging
    - Battery technology
    - Miniaturization
    - System integration
    - Process and cost of manufacturing
3) Biocompatibility and materials
4) Context awareness
5) Multi-sensor data fusion
6) Quality of service
7) Security
8) **Standards and light-weight communication protocols**

In this research, we investigate all of the above persistent and significant issues in details in order to understand and identify the major problems and important bottlenecks related to energy consumption. Following is a brief analysis and discussion on them.

Novel bioelectrical, biochemical, biophysical, and mechanical sensors are already being designed that are small and very sensitive [90] all including a useful text describing many examples given by Gardner in [28]. However, they are all improving the specifications to get better performance, and are no longer considered a big hurdle in achieving our goal of practical and cost effective implantable sensors nodes.

The challenges in the hardware implementation are discussed in different categories:

- The advanced low power RF transceivers continue to benefit from their throughput and efficiently especially the very high sensitivity on signal detection in the new technology of the receivers.

- Energy harvesting or scavenging means collecting any kind of available energy sources around the node, and then converting to electrical energy using appropriate converters. But in terms of consistency with implantable sensors, this technique is not applicable because the converters sizes tend to be much bigger than those sizes suitable for in-body implantation. They are not small enough to be implanted beside the sensor nodes in the body and cannot stay there for long time. Therefore, energy harvesting also is not a feasible solution for IWBSNs.

- The state of the art battery technology is still incapable of producing them in enough small sizes suitable for attachment with the tiny sensors while at the same time having enough energy density to sustain a long sensor life time.

- Other categories such as miniaturization, system integration and the cost of manufacturing are all steadily being improved. In this research work, we believe the incremental gains in performance can only be achieved with the more integration and advancement of existing technologies.

Regarding the other issues, it is almost a consensus among engineering communities that issues such as biocompatibility, context awareness and multi-sensor data fusion, quality of service and security issues would not be big challenges in future since very good solutions are already available for them.

3.2 Energy Harvesting

Energy harvesting which is also known as power harvesting or energy scavenging is the process to capture and store by the energy derived from external sources such as; solar power, thermal energy, wind energy, kinetic energy and etc. Energy harvesters currently cannot produce sufficient energy for high power applications, but can provide very small amount of energy to supply very low-power electronic devices. It is practical in some kinds of WSNs in which their sensor nodes have enough capability to place them in terms of the size and collecting the energies from the environment. But it cannot be used in tiny sensor nodes like in IWBSN nodes, because of the size constraint and lack of energy in environment. Power density of the energy harvesting technology on some environmental sources has been measured in [94]. For example; Acoustic noise with 100dB strength generated 960nW/cm^3, Vibration in a microwave generated 116µW/cm^3 and Thermoelectric with 10^{o}C deviations generated 40µW/cm^3. Therefore such technology with these specifications can never be implanted as part of a sensor node in the human body, since it needs a large volume of space and enough energy around in the environment for scavenging.

3.2.1 RFID Powering

This is a very relevant question that if IWBSN can benefit from RFID technology to overcome all energy problems and powering issues. To answer this question it is very important and vital to consider the human body's resistance versus the amount of the electromagnetic field radiation under the RFID technology. In this regard appropriate standard regulation has been introduced for measuring the amount of electromagnetic fields to be absorbed by body and is called Specific Absorption Rate (SAR). Therefore, before thinking of the RFID in IWBSNs we need to find out about the SAR regulation.

3.3 Specific Absorption Rate

The tissue of the human body is very sensitive to the Radio Frequency (RF) waves. It is seriously dangerous and important the body is exposure to electromagnetic fields regarding how much energy the body absorbs. Radiation in wireless communication is electromagnetic waves and its radiation towards the body will get absorbed by the tissue and generates heat in it depending on the radiation energy. Maximum power of the electromagnetic waves allowed towards the human body must be measured based on the standards, to avoid significant risk of damage in tissue [57]. SAR (Specific Absorption Rate) is a standard measure of the rate at which the energy is absorbed by the body when exposed to an RF (Radio Frequency) electromagnetic field. It is defined as the power absorbed per mass of tissue every second per kilogram, and has units of watts per kilogram [84, 4] as given in Equation (3-1);

$$SAR = \frac{\sigma|E|^2}{\rho} \quad \text{(W/Kg)} \tag{3-1}$$

Where σ is the electrical conductivity of the tissue, E is the RMS electric field and ρ is the density of the tissue. FCC limit for RFID reader systems is at 1W of radiated power. Some adequate experimental studies have been done on the SAR of the human body in an environment with a typical RFID reader system in [1]. Their studies have shown that the RFID reader antennas at the distance of about 10cm from the human body operating normally, will result in SAR of up to 2.02763 W/Kg, which is above the limit for safe exposure of RF radiation as allowed by FCC in US.

RFID technique cannot be a solution for powering the sensor nodes in IWBSNs, because of several reasons. If RFID technique is supposed to be employed in IWBSNs, then the base station in role of the RFID reader must radiate the required amount of the electromagnetic field towards the sensor nodes to read them. Then based on the above experimental results, the BS must be in close proximity to each sensor node as close as less than 10cm. and this is not possible, because plenty number of such sensor nodes are assumed to be implanted everywhere inside the body. If BS can read one of these sensors because of being in proximity with that sensor, then obviously it will be much farther from all other sensors distributed in other spots in the body. Assuming one reader per sensor node also is out of context and infeasible. Moreover, the RFID technology in the transmitter nodes need embedding big coil which is another disadvantage in terms of the size of the sensors that need to be as small as required size.

3.4 Problem investigation

The implantable sensor nodes need either an ultra low energy mechanism or an ultra low duty cycle of power activity especially in components with higher power consumption in the system and the most effective one of them is the transceiver section in the sensor node. The first factor is directly related to efficiency of the hardware technology in terms of the power consumption, and the second factor lies in keeping the activity time of the sensor nodes in the shortest possible time periods. This is inherently dependent on the data transfer or communication protocol techniques. To clearly find out where the major problem is stated as the bottleneck in the system, in the next sections we go throughout all involved factors and their impact on efficiency and feasibility of the system. Obviously if we assume enough energy resource available per each node in the system, there will be no hurdle preventing us to implement and establish such network system. Because then, it would confidently be possible to employ any of those available high performance communication methods, and run the system properly. But in reality this is not the case and such facility does not exist. Since we have to compromise with such bottleneck as lack of the energy, then we investigate on all different effective aspects of energy consumption in the system. To do this we need to focus on one sensor node to see what amount of average energy a sensor node needs to work properly, and how long the life time in average is expected at least. Therefore any effective parameter in life time and as well as in energy consumption should be considered and computed within the following list;

a. Hardware power consumption at each time the system wakes up
    - ADC/Amp
    - Digital controller
    - Micro Controller
    - Transceiver
b. How frequently the sensor node wakes up.
c. Mechanism of the communication protocol used in the network.
d. Activity time per cycle (Duty Cycle)
e. Data transmission speed (data rate).
f. Data packet length amount in each transaction
g. average power consumption
h. Total life time based on the average power consumption

Some of the above factors are not subject to any significant change on them for improvement. For example in b. it is not decidable here, because sampling rate of the sensor data is determined by the application and we cannot limit it. Data transmission rate in e. as well is not subject to change significantly and the network systems can just benefit from the advancements in the digital controllers and analog transceivers in terms of the speed and power consumption where the hardware technology permits. Therefore, we continue investigating the problem by studying on digital and analog components power consumptions, as well as on how and which of the related communication protocols could be well suited to support the tiny sensor nodes live with long term life time in body. First, we analyze the total power consumption in next section which will give us useful results which are required for corresponding calculations in the following section. Then based on the relevant communication protocols well suited for IWBSNs, considering the data rate, energy of the battery, duty cycle and other important factors, we can estimate the sensor node's life time in body. Then we can see if it meets the in-body medical constraints.

3.4.1 Power consumption

To evaluate the power consumption we must take all consumer parts of the sensor node into the account and then use these to calculate the average power consumption. To do this we should find out the active times and the power consumption of each component separately and then find overall consumption to get the total average power consumption for sensor node.

The t_{ON} for the transceiver per each wakeup and complete processing is equal to sum of the transmission time (t_{trans}) and overhead time for start-up and end-up ($\mathrm{T}_{\mathrm{Overhead}}$), where t_{trans} is dependent on the number of bits (N_{bits}), sent at each transmission and the transmission Data Rate ($\mathrm{D}R_{trans}$). Then the resulted t_{ON} is according to Equation (3-2).

$$T_{ON} = t_{Overhead} + \frac{N_{bits}}{DR_{trans}} \tag{3-2}$$

The overhead time is introduced by the startup (t_{Start}) and the turn off time (t_{End}).

$$T_{Overhead} = t_{Start} + t_{End}$$

$$T_{ON} = t_{Start} + \frac{N_{bits}}{DR_{trans}} + t_{End}$$

Integration of the power consumption by all components in the sensor node is simply illustrated in Figure 3.5.

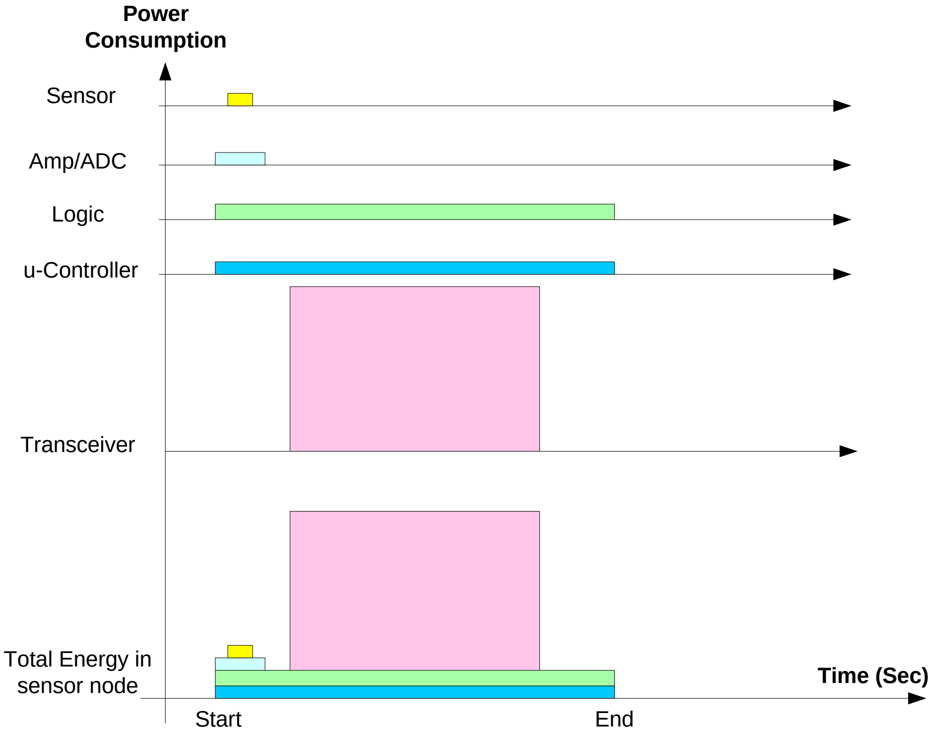

Figure 3.5: Power consumption integration.

Assuming that the total integrated power is represented as a function of the voltage (V) by current consumption over time $I(t)$, the total amount of consumed energy in active node is given by integrating the voltage (V), times current $I(t)$ from t_{start} to t_{End} by Equation (3-3).

$$\boldsymbol{E_{Active} = \int_{t_{Start}}^{t_{End}} V \times I(t)dt = \int_{t_{Start}}^{t_{End}} P(t)dt} \quad (3\text{-}3)$$

Then the power for fixed period of time assuming static current consumption or current consumption signature per specific component, and consequently the time-period would be easily obtained from the following equations:

$$P = \frac{E_{Active}}{t_{period}}$$

$$t_{period} = \frac{E_{Active}}{P}$$

When the life time of the battery should be estimated then energy of the battery is dissipated according to the active power of the device. If the battery energy is given in mWh (milli-Watt-hour), the active power consumption P is in mW, then the battery life time ($t_{\text{life-time}}$) will be calculated in hours as in Equation (3-4), or for example in years by Equation (3-5).

$$\boldsymbol{t_{life\_time} = \frac{E_{batt}}{P_{Active}}} \quad (3\text{-}4)$$

$$\boldsymbol{t_{life\_time} = \frac{E_{batt}}{P_{Active}} \times \frac{1}{365 \times 24}} \quad (3\text{-}5)$$

This way we can calculate the power consumption or the working life time as a coarse grained estimation. Long term life time covering more than few years does not consider the aging of the battery which is totally dependent on the manufacturing technology varying from 1 to 10 years or more.

3.4.2 Signal attenuation

When the signal is transmitted from the transmitter, there will be significant loss of the signal strength by broadcasting it through the air or any other environment. If the distance between the transmitter and the receiver is d, then the transmitted signal strength will be exponentially reduced based on $(d)^2$ and other effective parameters. Hence, there is a relation between the power of the transmitted signal (P_{Tx}) and the minimum signal strength required at the receiver side to be detectable by the receiver antenna (P_{Rx}), based on the distance d. Therefore, the receiver together with the antenna must be enough sensitive on the very low strength arrived signal (P_{Rx}) to overcome such path loss. This is called the sensitivity power in the receiver (P_{Sen}) and obviously as the condition in Equation (3-6) it must be enough sensitive to be able to detect the corresponding arriving signals.

$$P_{Sen} \geqq P_{Rx} \tag{3-6}$$

Experimental results on several precise tests and measurements between pair of the transmitters and receivers with different transmit powers (P_{Tx}) within different short ranges up to 40 (m) has been done by researchers in Berkeley [61]. This way they have obtained the minimum received power required at the receiver antenna (P_{Rx}), which can clearly determine the required sensitivity range for the receivers to detect the signal in reality. This can be obtained from the path-loss transmit-power curves given in Figure 3.6 [61]. They have measured the path loss in the range on three different receivers with the sensitivities of -50dBm, -60dBm and -70dBm which can give reliable estimation on many more sensitive receivers within this range. These tests have been experimented in the air, and the signal attenuation varies in different environments.

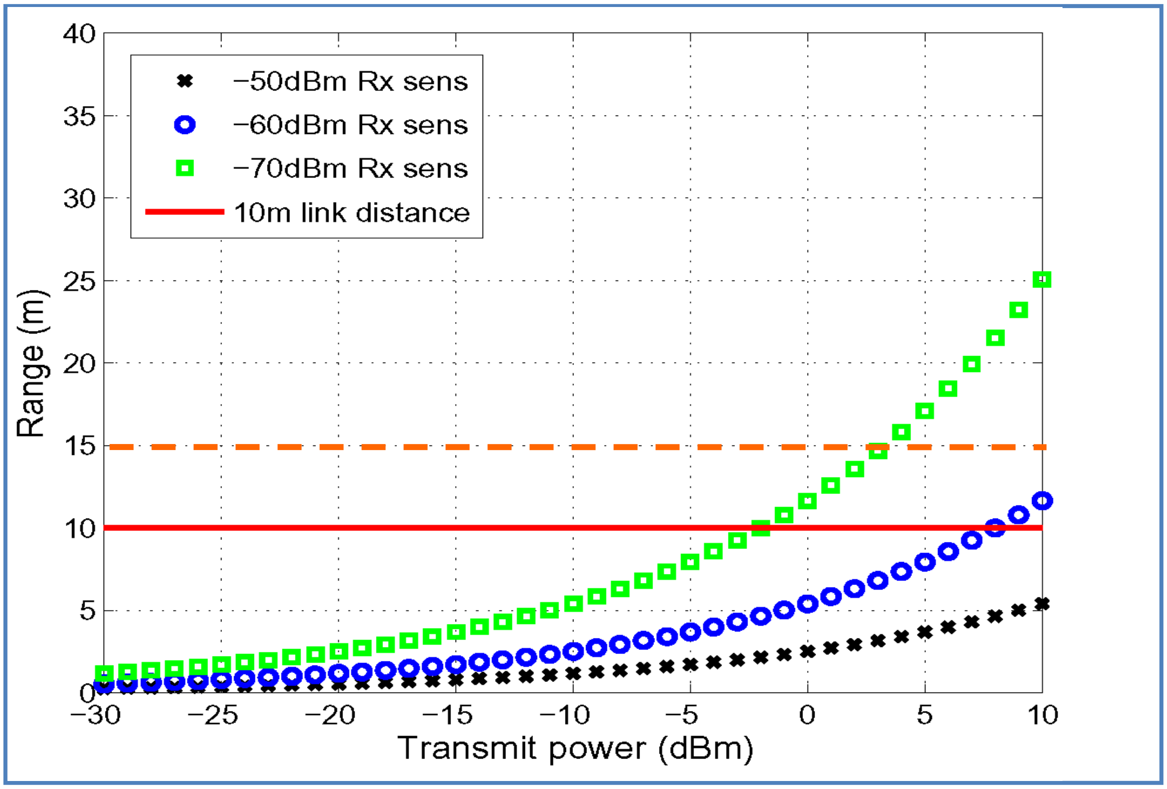

Figure 3.6: Path Loss in short range versus Transmit Power [61].

Signal transmission through tissue of the body has also shown considerable loss in signal strength. In [73] authors examine this effect by placing a transmitter at the center of a human body and measure signal attenuation at 418 MHz and 916 MHz. Their experimental results have shown that the average loss of the signal strength through the body can be between 14.7 to 18 dBm. However, it is totally depended on both the location of the sensor in the body and how the BS is close to the sensor around the body.

The signal attenuation by body has been reported even by 30 to 40dBm. This loss of the signal strength can be compensated by either increasing the transmitter output power or increasing the receiver sensitivity by the same dB loss. State of the art receivers, with sensitivities around as low as -120dBm or even better are now available in the new advanced technology. For example, MAX1470 is a receiver from Maxim [55] with the sensitivity of -115dBm operating at 5.5mA supply current. Such a sensitive receiver can reliably be used to alleviate the signal attenuation even much more than 40dB loss in the body tissue. It provides the possibility of consuming less energy at the transmitter in body to generate even lower detectable signal strength. For example, by using the MAX1470 receiver with -115dBm sensitivity, assuming the maximum of 40dBm loss in the transmitted signal throughout the body, it can act like a receiver with 40dBM lower sensitivity which is around -75dBm. Then, according to the path loss graph in Figure 3.6 for a transmitter with 0dBm output power (1mW), such receiver would be able to detect this signal in a range above the -70dBm curve in the figure which shows a distance around 15m far from the transmitter (dashed line). However, the receiver which is the Base Station in our IWBSN is expected to be always accompanied with the patient, and therefore such results and measurements demonstrate satisfying the required conditions more than what expected.

There are more useful experimental results by authors in [8] in Table 3.1 showing the signal attenuation and the impact on frequency shifting by placing the wireless transmitter node on top of different materials. They observed that low dielectric constant materials such as foam, plastic, books and wood do not cause much attenuation and frequency shifting against the transmitted wave. The worst cases of frequency shifting and signal degradation occurs when the node is placed on top of an Aluminum plate or at front of the human head. These cases result in 8.7 dB attenuation in the signal power and 80kHz shift in the carrier frequency for the Aluminum and 7.2 dB signal attenuation and up to -37 KHz frequency shift by human head.

These factors are all effective on the reliability in the system and their impact on the signal transmission loss from the sensor nodes to BS or vice versa must be taken into the account.

Table 3.1: Wireless transmitter sensor node affected by different materials in environment [8].

Material	Signal Strength Attenuation (dB)	Carrier Frequency Deviation (kHz)
Foam	0.3	< 1 kHz
Book	0.8	< 1 kHz
Wood	0.7	< 1 kHz
Plastic (PVC)	0.8	1
Solar Cell	0.8	10
Human Hand	7.2	37
Metal (Aluminum)	8.7	80

3.4.3 Power Consumption Issues

In section 2.4 and 2.5 we introduced different ultra low power technologies with excellent specifications for IWBSNs. These are all summarized here in Table 3.2 along with their power consumptions calculations in Average, Active or Sleep modes for sensor node components. Two of the most recently and well known technologies (ZigBee and ANT) for low power and low range wireless sensor networks are exampled.

The summarized average power consumptions of the sensor components using the ANT technique from the above table are shown in Table 3.3.

Comparing these results clearly shows the huge difference in power dissipations between the transceiver and other components in a sensor node, and this discrepancy is depicted better in a graph in Figure 3.7. By these results we find out the impact of the energy consumption by the analog transceivers in sensor nodes. That’s while we found the better or even best components for our calculations in terms of the efficiency in power consumption while considering other required performances for a sensor node. The overall power consumption in the sensor node is given in Equation (3-7).

$$P_{Total} = P_{Sensor} + P_{Amp} + P_{ADC} + P_{Logic} + P_{uC} + P_{RTx} \tag{3-7}$$

where P_{uC} is Micro-Controller’s power and P_{RTx} is Transceiver’s power. The sensor power consumption is negligible, since it does not require any especial power source and its data is sensed and read by the ultra sensitive preamplifier which detects samples and forwards the sensor data to ADC.

Next in the final section we try to extract a conceptual relation between such big energy consumption in the transceivers and the mechanism of the data communication between the nodes.

Table 3.2: Power consumption for the sensor node components and two of the most recently and well known technologies (ZigBee and ANT) for low power and low range wireless sensor networks.

Component	Type	Power consumption	Power Unit	Description
ADC/Pre Amp	**[Hindawi]**	**0.3**	**uW**	**Average**
Counter/Comparator	**(RTC DS 1372)**	**1.2**	**uW**	**Logic power**
u-Controller	(MSP430)	30	pW	Sleep
u-Controller	(MSP430)	2.8	uW	Active
u-Controller	**(MSP430)**	**0.3**	**uW**	**Average**
Transceiver	(ZigBee)	0.33	uW	Sleep
Transceiver	(ZigBee/Tx)	25.8×3=77.4	mW	0dBm output @ 3V
Transceiver	(ZigBee/Rx)	23×3=69	mW	@ -100dBm Sensitivity input
Transceiver	(ZigBee/Total)	323×3=969	uW	Average
Transceiver	(ANT/TX)	15×3=45	mW	0dBm output @ 3V
Transceiver	(ANT/RX)	17×3=51	mW	low range erceiption
Transceiver	**(ANT/Total)**	**120×3=360**	**uW**	**Average**

Table 3.3: Power consumption examples of the components in a sensor node.

	ADC/Amp	**Logic**	**uC**	**Transceiver**
Average Power consumption	0.3 uW	1.2 uW	0.3 uW	**360 uW**
Power usage ratio	0.08%	0.33%	0.08%	**99.51%**

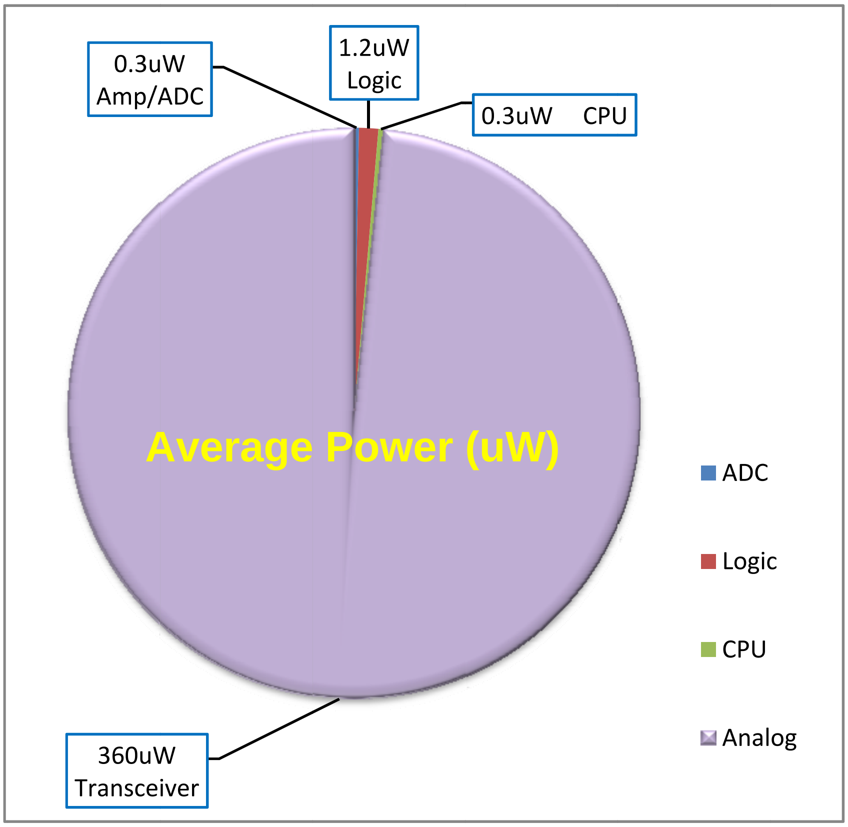

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Figure 3.7: Example of Average Power consumptions for Sensor Components.

3.4.4 Communication protocols issues

In all existing commonly used communication protocols for WBSNs discussed in previous chapter the energy consumption is too high. Large amount of control information attached to the main data to be sent in each transaction within the communication, keeps the transceivers in active mode for long periods of times. To elaborate on this issue, as found in chapter 2 in general, all improvements in these protocols have been related to use of different compression methods, constructing efficient topologies or balancing the traffic over the network [74]. Here we will find out how these protocols even after all these improvements cannot eliminate the significant power issue in the transceivers embedded in the sensor nodes for IWBSNs. In the process of data transmission in the existing standard low power communication protocols hundreds of control bits need to be attached to the data to transmit regardless of the amount of data. This issue will be more highlighted especially for applications where the amount of data to transmit is low such as the wireless body sensor networks, these protocols become very inefficient in terms of energy. The more relevant and well known light weight communication protocols that already were discussed in chapter 2 will be analyzed by studying on their minimum sizes of their frame structures.

The IEEE 802.15 TG4 [46] is a multi month/year battery-life and low power low data rate communication protocol standardized for home automation, sensor networks and BSNs. It needs at least 44 control bytes for each data packet. The best version of the IEEE 802.15.4 standard protocol is also known as ZigBee and was introduced in 2006 [7]. ZigBee standard communication protocol is a low power and low cost solution for low range transmissions. The frame structure in ZigBee protocol contains at least 12 Bytes for request and 15 Bytes for confirmation or response disregarding much other extra control information attached as the header/footer to data packet [93]. This makes a minimum of 27 control bytes plus the main data which is fixed in minimum 5 bytes in ZigBee and must be transmitted in each round of communication. Therefore, using this standard assuming one start bit and two stop bits packing each byte, it would have to transmit a total of up to 308 bits of data to transmit a minimum packet of data. ANT+ has a simplified control procedure since it uses only 10 bytes for both Request and Acknowledge and the size of the main data to transmit is fixed to 8 bytes. Minimum total number of bits in each case is given in Table 4.1 in the next chapter. Table 3.4. shows the minimum frame structures used in the three low power communication protocols as; IEEE 802.15.4, ZigBee, and ANT.

Table 3.4: Comparison between the frame structures of three light weight and low power communication protocols.

	IEEE 802.15.4	**IEEE 802.15.ZigBee**	**ANT+**
Bytes/Req	17+	12	10
Bytes/Ack.	11	15	
Bytes /MAC	16+	0	0
Main Data	1+ (Min)	5+	8
Total Bytes	45+	32+	18
Total bits **(1 start$_{bit}$ + 2 stop$_{bit}$)**	495+	352+	198

For implantable body sensor applications the transceivers must be kept in OFF/sleep mode until there is data for transaction. This keeps the energy wastage to minimum amount. When needed, the transceiver wakes up, sends/receives the data and then goes back to the sleep mode. These active and inactive time periods introduce the activity Duty Cycle of the system. In the next section we will show how the large amount of transceivers power consumptions by these protocols are derived from their excessive activities. Because that's only the communication protocol's mechanism that turn the transceivers ON and keep them working active as long as they need to get their job done.

3.4.5 Battery Life Time

Now we calculate a typical battery life time based on use of the low power protocols by their transceivers. Other component's power consumptions are negligible versus the overall transceiver's power. In order to get some realistic idea we consider a small battery in range of the implantable size and will get a life-time estimation for each case separately. For example, a typical coin cell battery like CR-2450 in Figure 3.8 has a capacity of delivering about 600 mAh at 3V.

CR-2450 Coin Cell Battery: 620 mAh
Voltage: 3V
Diameter: 24mm
Height: 5mm
Volume: 2260 mm^3

Figure 3.8: CR-2450 coin cell battery, as an example cell which is normally used in low power sensor nodes.

Based on the Journal of Power Sources in [14] the energy density of up to 650 mWh/cm^3 for the MDX batteries with an end voltage of 2.5 V have been confirmed for implantable applications. An implantable sensor node can contain a tiny battery in a reasonable size of around 20 to 50mm^3 like an implantable example in [16] which in fact could vary depending on different spots to implant in body. Such tiny batteries can carry capacity of approximately from 10 to 30mWhr energy. For example, we can again refer to the already introduced implantable small medical battery from Eagle Picher group in Figure 3.9 with the size of about 27mm^3. The energy capacity of the batteries in each technology is linearly proportional to the size of the internal materials. The tiny implantable battery from Eagle Pitcher has a capacity of up to 20mWh at 3V.

Eagle Pitcher Cell Battery
E: 20 mWh, @3V
Volume: 27 mm^3

Figure 3.9: An implantable small sample of a medical battery from Eagle Picher group.

Now we refer to average power information of the transceivers that we already obtained in Table 3.2 to calculate the sensor node's life time for the communication protocols using the above implantable battery. Since the ZigBee is a member of IEEE 802.15 Task Group 4, both can use the same hardware transceivers. We do calculate the life time for ZigBee and ANT which are much more efficient than IEEE 802.15.4:

$(P_{Avg})_{ZigBee} = 969$ µW

$(P_{Avg})_{ANT} = 360$ µW

$(E)_{Batt} = 20$ mWh

$(\text{Life-Time})_{ZigBee} = 20\text{mWh}/969\text{uW} = 20.6$ hrs

$(\text{Life-Time})_{ANT} = 20\text{mWh}/360\text{uW} = 55.5$ hrs

The small battery in this example would only be able to supply the transceiver using the ANT protocol for up to 55 hours which is less than 2.5 days. Analysis similar to the one shown above shows that the life time of the same battery powering the ATMEL ATA5749 fractional-N-PLL transmitter IC chip [26], would last about two times longer. This transmitter has an output power of 5dBm at 7.3 mA current and is designed for operation in the 300 to 450 MHz band, which covers the implantable frequency range based on the FCC regulations. Therefore based on its specifications it consumes about (7.3mA × 3V) 22mW. Based on the 15mA transmitter current consumption in ANT, the ATMEL ATA5749 can gain the throughput about over two times better. Then we can say, if ANT might be able to employ such technology and benefit from this gain, then the sensor node life time with the same implantable tiny battery would last up to 5 days long.

ZigBee and ANT+ were know of the most efficient communication protocols for low rang and low power wireless sensor networks especially in terms of the power consumption. But, based on the achieved results it is so clear that neither ZigBee nor ANT+ even by exploiting the most advanced technology of the transceivers can support and drive the implantable wireless sensor networks, since it is not possible to change the batteries in the patient’s bodies every few days through surgery.

3.5 Summary

Overall, considering all the results discussed in this chapter, existing communication protocols have the major impact on the high power consumed in the sensor nodes.

Therefore because of the limited size of the batteries, the type of the transmission and the choice of the transmission protocol play a major role in the longevity of the sensor node's battery. Since the radio transmission is very expensive in terms of energy cost, the development of the new and innovative techniques and protocols is essential for realizing cost effective IWBSNs. This critically implies that the impact of the power usage Duty Cycle in data transmissions is essential. Therefore, the activity time period of the transceivers must be significantly decreased in communication protocols in order to achieve an ultra low power data transmission mechanism to satisfy the IWBSNs persistent constraints. Hence, after considering all these challenges, we highlight the weaknesses and the critical bottleneck in the existing standard communication protocols. From this point on in this research, we will focus on identifying and analyzing the sources and mechanisms that result in wastage of energy during wireless data transmission. In this regard, the work in this research presents new protocols that significantly affect on saving the energy and power consumption in wireless transceivers for low range/low power wireless sensor networks.

Novel Low Energy Communication Protocol

Chapter 4

4. NOVEL LOW ENERGY COMMUNICATION PROTOCOL

4.1 Introduction

The IWBSN is still in its early stages in communication research area while involved in several issues existing in this area including energy consumption, limited computation, continuous operation, miniaturization, robustness, scalability and reliability. Attaching large amount of extra information before and after the data payload in standard data transmissions makes a high duty cycle in transceiver's activities. This has an important impact on energy cost in standard communication protocols, especially for the applications which are dealing with small data payloads. The proposed solution given here will eliminate the most important and critical bottleneck in this area which is highlighted as energy consumption in communication by the transceivers. This is done by proposing a novel technique in data transactions within the nodes in low power wireless sensor networks where the amount of data is not big, like WBSNs. This is a new ultra low energy communication protocol given for IWBSNs, and as well applicable to any other low power low range wireless sensor network. This new communication technique is totally different than all other standard protocols presently available. It is demonstrated that how the new protocol leads to save significant portion of the energy from the power source. This new protocol can reduce both the size and the power consumption of the sensor nodes making it possible to design the sensor nodes as small as required to implant inside the human body. It significantly helps extending the battery lifetime of the tiny sensor nodes in the human body by keeping the transceivers in minimum activities. The proposed technique works based on reliable time synchronization established between all active nodes in the network. It divides the time between all sensor nodes and codes the sensor data in time and then sends a signal based on the coded data in time per each sensor. Hereby, it is named Time Based Coded Data (TBCD) communication protocol. But the synchronization algorithm as an essential requirement for the proposed communication technique is itself another serious issue in this work. That’s because the synchronization algorithms also need to employ an available standard communication protocol to do their transactions with their messages through the network. Then this is not possible to benefit from existing synchronization algorithms in this work, since again the same problem of high power consumption by using the normal communication protocols will come out and kills the small energy sources available in the tiny nodes. In this regard, in order to fulfill this research work a new low power synchronization algorithm is also proposed perfectly match to the proposed protocol while its power consumption is so trivial. The overall results in proposed ultra low light, low energy communication protocol shows very high throughput compared to the other available methods in data transmission for BSNs. Both of these contributions are clearly examined and the results as proof of their concepts have been shown through the appropriate simulation environments.

4.2 Preliminary definitions

There are many standard communication protocols proposed for WBSNs to reduce the energy consumption. The frame structure in all of them is usually big. For example in ZigBee [92, 93] as a very commonly used low power protocol the frame structure is over hundreds of control bits excluding the main data. This will involve the nodes with large and long transactions even when sending only a small amount of data in single or few bytes. This is the critical bottleneck in IWBSNs which keeps the transceivers in sensor nodes in active mode for long time and kills their energy in a few days or weeks. In the example given in section 3.5.5 the life time is even less than one day (20.6 hrs). Generally as described in section 2.3 there are three different methodologies reading the data from the sensor nodes in a Master-Slave wireless network with star topology. These are; Polling, Strobing, and Cyclic Broadcasting, and based on the description, in the Cyclic method each node sends its data in a specific predefined time slot. Thus, it means the sensor nodes need proper time synchronization among all nodes to be able to send their data at right time within a TDM (Time Division Multiplexing) schedule. But this is the most efficient technique in saving the energy, because each sensor knows when to attempt to do the transaction and no excessive request/acknowledge is required then.

The novel communication protocol proposed in this work is offered for the wireless sensor networks with star network topology. In such network system there is a powerful and high performance central node which is rich in amount of energy resource. It can manage all data transactions within the network as a master dealing with all available sensor nodes in the range as slaves. In this work the TDM technique is also employed in the master/slave star network and the core of the communication protocol is designed based on the TDM scheduling. Figure 4.1 simply illustrates an example of a star network topology with 8 sensor nodes as slaves and a base station as the master node in a cyclic method using TDM technique. The time between every two sequential sensor nodes in such networks is called a time slot and is assigned to the sensor node located at the starting time of this slot time. For example the time period between t_i and t_{i+1} in Figure 4.1 is called time slot "T_i" and is assigned to the node(i) so that;

$$T_i \in t \ : \ t_i \leqq t < t_{i+1}$$

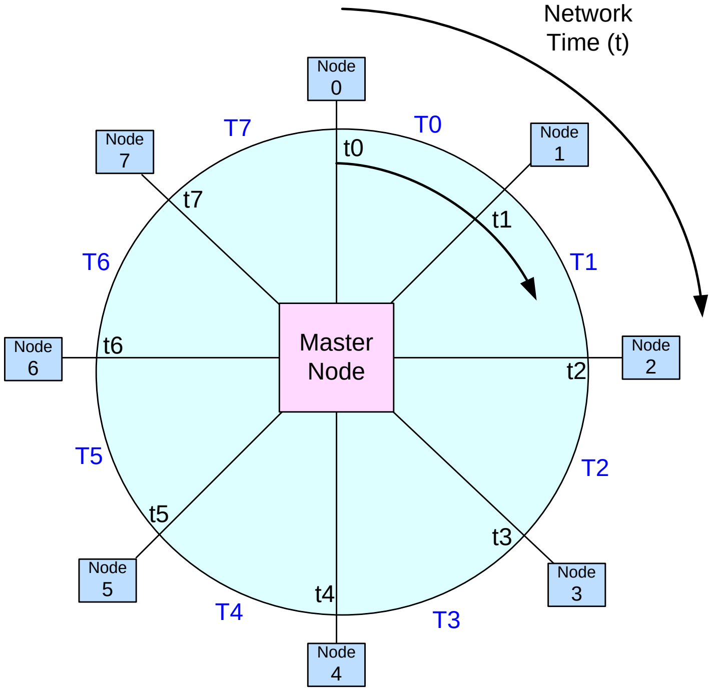


Figure 4.1: A Star Master/Slave Network Topology using TDM scheduler.

The Master node in the star network systems discussed in this research is always called BS (Base Station) and the other slave nodes are called Sensor Nodes. In this new protocol instead of sending the complete data packet including its all control information at the header and footer in each round, first the data will be coded in the time slot domain T_i, then a very small signal will be sent to the BS sharp at a certain calculated moment within T_i time slot wirelessly. This will prolong the battery lifetime of the sensor node in human body significantly. The transceiver in the BS is rich in energy source being able to be always in active listening mode. But the sensor nodes are almost always in sleep mode unless at the calculated and specified moment within their corresponding time slot to send the small signal through the transmitter. This specific moment within the time slot implies the sensor data coded in the time domain. In fact the sensor data which is normally a real number within a limited range will be sampled at the input port of the sensor node and then it will be converted and coded into a moment within the time slot associated with that sensor node. Normal standard communication protocols generally attach too many number of extra control bytes before and after the main data to be sent. These control bytes as described in section 2.5.1.3 are usually carrying a large amount of information about the communication mechanism such as; source address, destination address, length of the packet, error/parity checker info, channel info, request or acknowledgement info, some specifications related to the communication protocol being used, baud rate (data transfer speed) range or reference, and often much more similar information related to the characteristics of the communication mechanism. In the normal standard protocols some of these control information attached to the data are essential and cannot be ignored in their data transmission, but not all of them. The rest of the control information are usually helping to achieve higher reliability or adding some extra features to the technique. The important and essential information attached to the data vary in different standards and different protocols. The general frame structure in IEEE communication protocols as a valid approved standard would be valuable to consider and study on its different control segments. Again by referring to the general format of this frame structure in 2.5.1.3 we will find all the control information in such categories we just described above. For example; Preamble Sequence is used to introduce starting of the main frame, the Start of Frame Delimiter is used to determine the border limit to emphasize on the starting of the frame which is used as frame synchronization factor in the receiver but not an essential factor. Also, the Frame Length which is carrying the size, different Addressing Fields more importantly to address the source and destination, Sequence Number to track the order or number of the frames, and overall some other frame control information gaining the performance and other aspects of the communication protocol. These communication protocols can carry data packets in different sizes in their specific standard range, but whether the size is big or small it does not affect much on the amount of attached information to the data. We can refer to the information in Table 3.2 and their experienced results on small size of data discussed and calculated in section 3.5.5. The proposed method (TBCD) in this report is applied to the IWBSN applications or any other ultra low power low range wireless sensor network carrying small data periodically within the network. The proposed ultra low energy protocol in this work will show that how easy the TBCD technique can eliminate and ignore all essential information by squeezing the necessary control bytes including the small data itself in only one or few single bits as the whole data to be transferred to the BS. Then obviously it will indeed contribute in energy saving surprisingly. This is all explained in detail in the following section.

4.3 TBCD Communication Protocol

There are two special counters in this protocol required in the entire network in each sensor node and the base station. These counters play the main role of the concept in the algorithm. These two counters are called ID-Counter and Data_Counter. The ID_Counter is for identifying the sensor ID, and the Data_Counter is to search for the corresponding data to be sampled by the sensor in the node. These two counters in the design are concatenated to each other so that the lower order is Data_Counter and the higher order is ID_Counter (Figure 4.2). Whenever the unsigned value of the Data_Counter in any sensor node or in the BS overflows (which is supposed to happen for all nodes at the same time because the synchronization has already been established with respect to the wireless delay), then at this moment its associated ID_Counter will increment by one.

Then the Data_Counters will reset and restart counting from zero to sample and update the next sensor data.

In this protocol all counters in all nodes must be initialized to reset at the same time with the BS. All of these special counters in all sensor nodes and in the BS always follow their counting with the same rate by using unique clock generators in all nodes. This means they are all synchronized together based on their internal network time.

ID_Counter	Data_Counter

Figure 4.2: Counters. ID_Counter concatenated with Data_Counter.

Therefore, all Data_Counters in all nodes are counting together with the same initial value and with the same rate, and also it is the same for all ID_Counters in all nodes. Each sensor node has its own ID number as a constant value assigned to it permanently. According to the star topology defined for this work the sensor nodes will be scanned in order based on their ID number in a Cyclic-Broadcasting TDM technique (refer to section-2.3**)** as slaves by the BS as master node. Therefore sensor nodes will be selected for reading their data one at a time based on their ID, and each sensor node can recognize its time slot (T_i) by keeping the track of its ID_Counter to get activated, then reading its sensor data and sending it to BS. The sampling rate will be defined in network configuration as required for the applications. Sensor data in any sensor node is sensed by the sensor and detected by a sensitive low energy preamplifier. Then the sensor data which is an analog value as a real data will be forwarded to an ADC to convert to a binary value in desired number of bits based on the required resolution in the application.

The transceiver in the BS is supposed to be always in active mode, but in the sensor nodes, the most high power components are almost always in sleep mode, especially the transceiver section which is the highest energy consumer.

Assume a sensor node ("i") live in the network is ready to send its sensor data to the BS within its proper time slots. Whenever the ID_Counter in the sensor node hits the ID number of the node ("i") , and at the same time also if the sensor data ("d") which is output of the ADC in the sensor node coincides with the same value in its Data_Counter, then at this particular moment the node will completely wake up. Only the sensor node whose ID number ("i") hits the value in its ID_Counter at this moment, can wake up and sample its sensor data. Then immediately generates a short signal, turns its wireless transmitter ON, sends the short signal wirelessly to the BS and then quickly turns the transceiver OFF and returns back into the sleep mode.

At the same time in the BS the signal will be detected through the air (disregarding the delay for now). Assuming perfect synchronization between all nodes, the values of the Data-Counter and ID_Counters in the BS at this moment are the same as values in the same registers ("d" and "i" respectively) in the sensor node who has sent this signal. Then the real sensor data in its real format-when it was read by the sensor node before converting to the binary value-would be achieved through a corresponding Look Up Table (LUT). The value of the ID_Counter ("i") will be used as the address of the LUT in the LUTs array (in BS) to locate the corresponding LUT, and the Data_Counter value ("d") will be used to pick the real value read by the sensor through this LUT. Therefore, a series of LUTs must be prepared in the BS configuration, so that each LUT is associated with a sensor node addressed by the sensor ID number ("i") and each location of this LUT(i) is a real value ("d") that the ADC in sensor node can convert to the binary values. That means the LUTs are in the form of a two dimensional array as; LUT(i, d).

Then the same real value that was read by that sensor will be extracted from its LUT in the BS. This way every sensor node can recognize its turn to run the transmit process, and the base station can also distinguish if each arrived signal is corresponding to which sensor node. Two important issues are highlighted here; the environment noise and the wireless delay in signal transmission. The noise could be eliminated by expanding the alert signal in few bits instead of a single bit. But here we generally discuss the core of the protocol always in ideal case by assuming one single bit as the short signal to transfer. Based on the time synchronization established between all sensor nodes and the BS, all sensor nodes and the BS are always reading the same value in the counters with respect to the wireless delay. The modulation technique in this protocol and the required hardware and specifications of the wireless receiver/transmitters are discussed later in section 4.8. It is shown that the carrier modulation in this protocol cannot be a type of Frequency Shift Keying (FSK) technique, but a type of Amplitude Shift Keying (ASK) technique does meet the requirements properly.

As an example we consider a sensor node reading the blood glucose in human body. Normally, the body maintains the blood glucose level in a range between 3.6 and 5.8mM (mMol/L, i.e. milliMoles/liter). As simplest case example, we can consider only three sensor nodes all with equal data ranges. For instance, we assume the data resolution in a range of 8 different levels which implies to a 3-bit data resolution.

Then the sensor in such example can read the blood glucose in range [3, 6.5] by tolerance of 0.5mM. Therefore it can read a value out of these eight values; [3, $3._5$, 4, $4._5$ 5, $5._5$, 6, $6._5$]. Then the output of the ADC in the sensor node would be a value in range [0, 7]. Each value in this range is representing a corresponding real value in the range [3, $3._5$, 4, $4._5$ 5, $5._5$, 6, $6._5$]. For example, assume a glucose sensor in body reads some value “d” as “$4._5$” in a sensor node whose ID number “i” hits its ID-Counter. The associated value with this data “d” by the output of the ADC based on the above definition for the glucose range would be “011” in binary in range [000 to 111]. Then the binary value “011” will be compared to the output of the Data_Counter which is a 3-bit counter in this example. Once the counter hits this data (i.e. Data_Counter = “011”), the short signal (in this sensor node only) will be generated and sent to the antenna. The BS (with synchronized ID and Data counters) will receive this signal at the time when its Data_Counter equals the same value “011” and finds the real sensor data as “$4._5$” through the LUT(i, d). Of course the effect of the environment noise is considerable as the case for any other wireless system and the air delay also must be taken into the account. The air delay could be measured by a technique given in this work in section 4.10. The air delay calculation and error compensation will be done in configuration phase. Therefore, once the signal is detected in BS, the BS will report the associated data with its Data_Counter at this moment through the LUT for the corresponding sensor node “i” through simultaneous ID-Counter.

The zero status in all ID_Counters for the entire network is always reserved for initialization, configuration and synchronization phases. TBCD and its effectiveness and correctness are demonstrated through several simulations in normal case and worst cases in section 4.4. The general flows of these ideas are simply illustrated in following flowcharts. Figure 4.3 shows the flow of the procedure for sensor nodes, and Figure 4.4 shows a flow of the procedure for the base station.

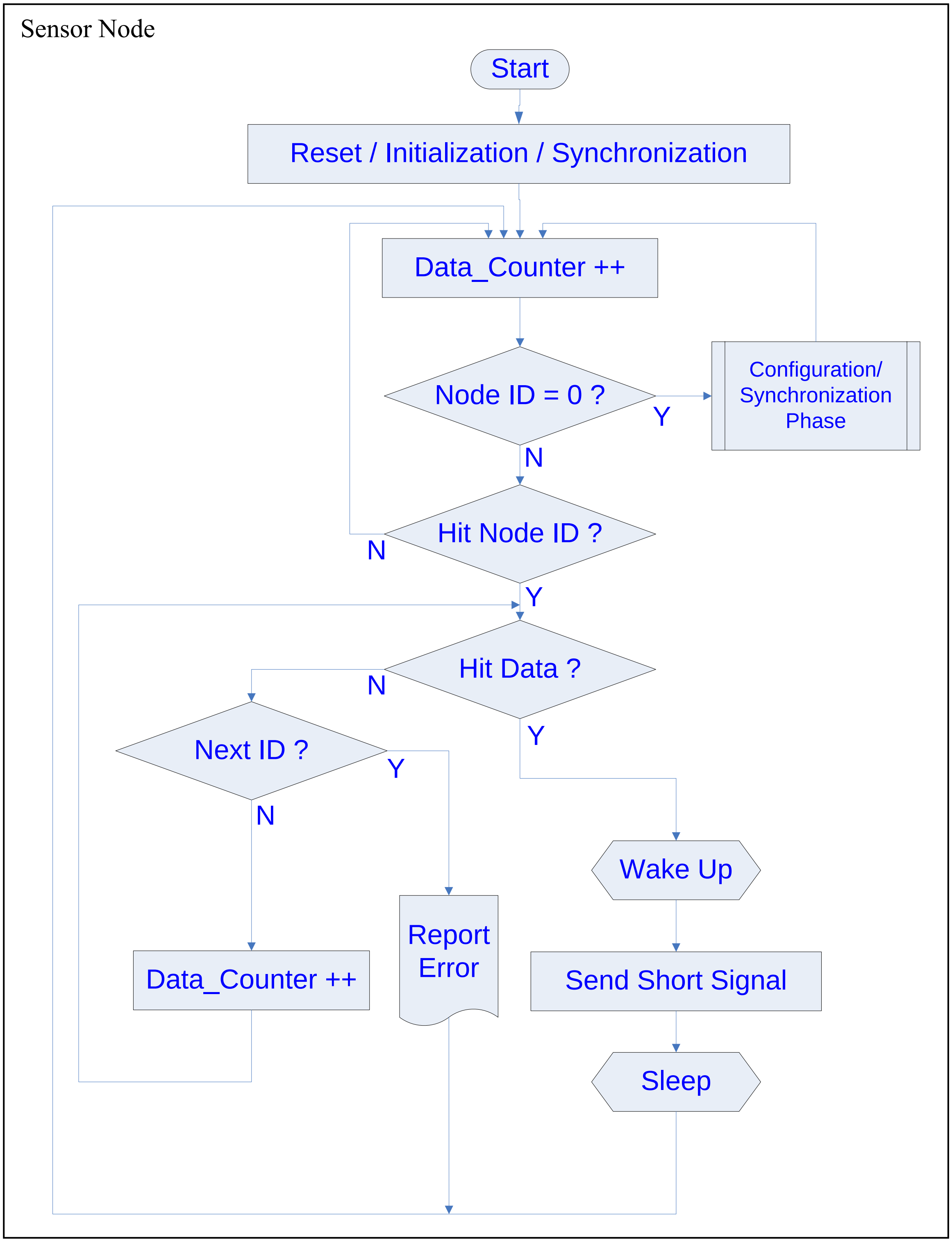


Figure 4.3: Flow Chart of the Procedure for Sensor Nodes.

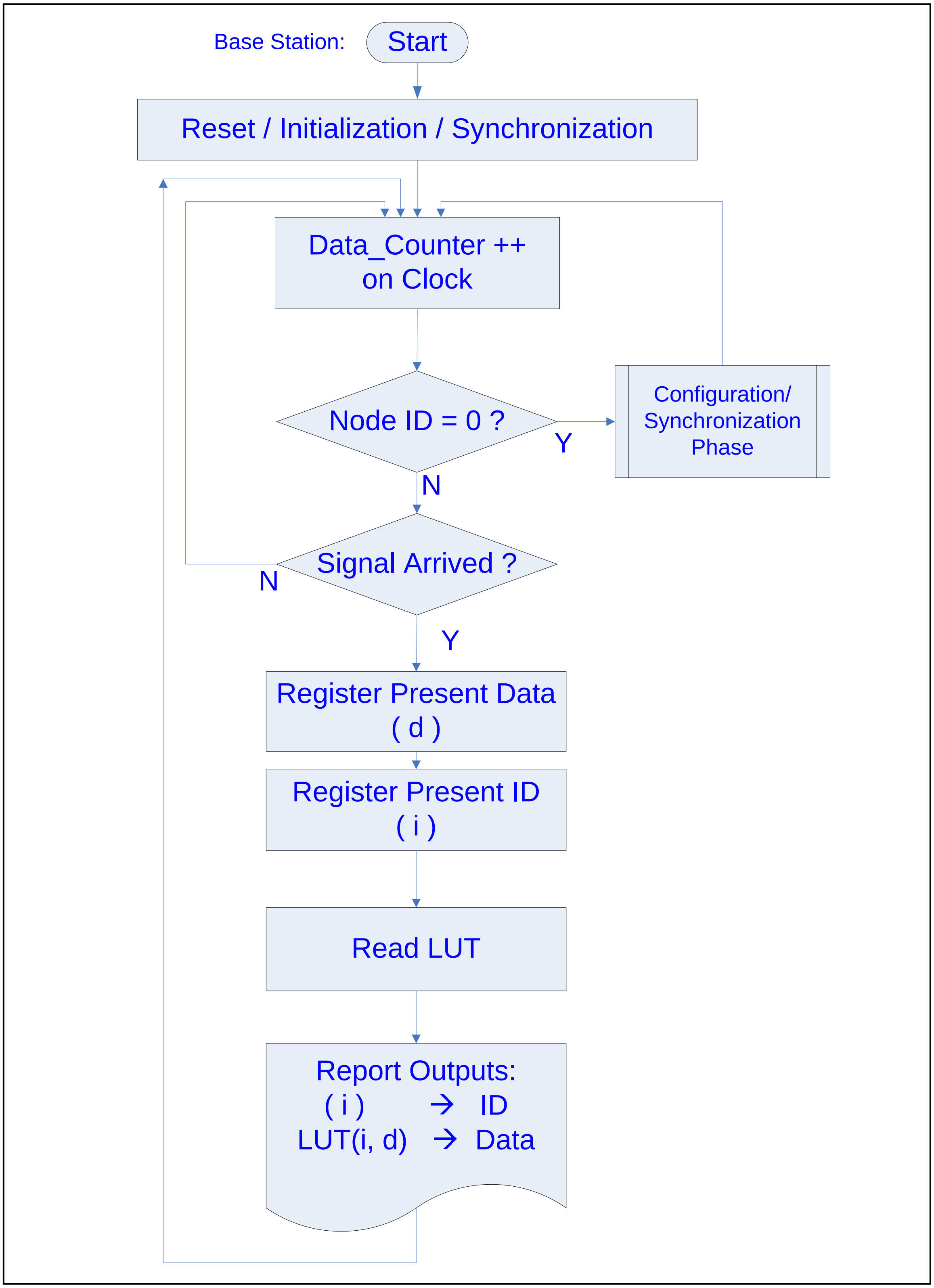


Figure 4.4: Flow Chart of the procedure for Base Station.

4.3.1 TBCD Algorithm

The description of the procedure for both sensor node and the BS are given in the following algorithms.

General Algorithm for Sensor Nodes:

```
         Initialization and synchronization, Assign Node_ID
         Reset counters, Start counting ID & Data counters, (Clk : f KHz)
Start:   if  ID_Counter  = 0      then    do configuration and updates
         else
             wait until ID_Counter = Node_ID  then
             wait until Data_Counter = Sensor_Data  (by ADC) then
             Turn On the Transmitter
             Send Short Signal
             Turn Off the Transmitter
         end if
         loop Start     // repeat for the next round
         end.
```

General Algorithm for Base Station:

```
         Initialization and synchronization, Assign all Node_IDs
         Reset Counters, Start counting ID & Data Counters (Clk: f KHz)
Start:   if  ID_Counter  = 0  then    do configuration and updates
             Wait until arriving the Short Signal          then
             Obtain Sensor_ID     from  ID_Counter
             Obtain Sensor_Data from Data_Counter
         end if
         loop Start     // repeat for next round
         end.
```

Considering three sensor nodes in Figure 4.5 having equal data ranges as a simplified example illustrates how each node transacts with only a short signal per data.

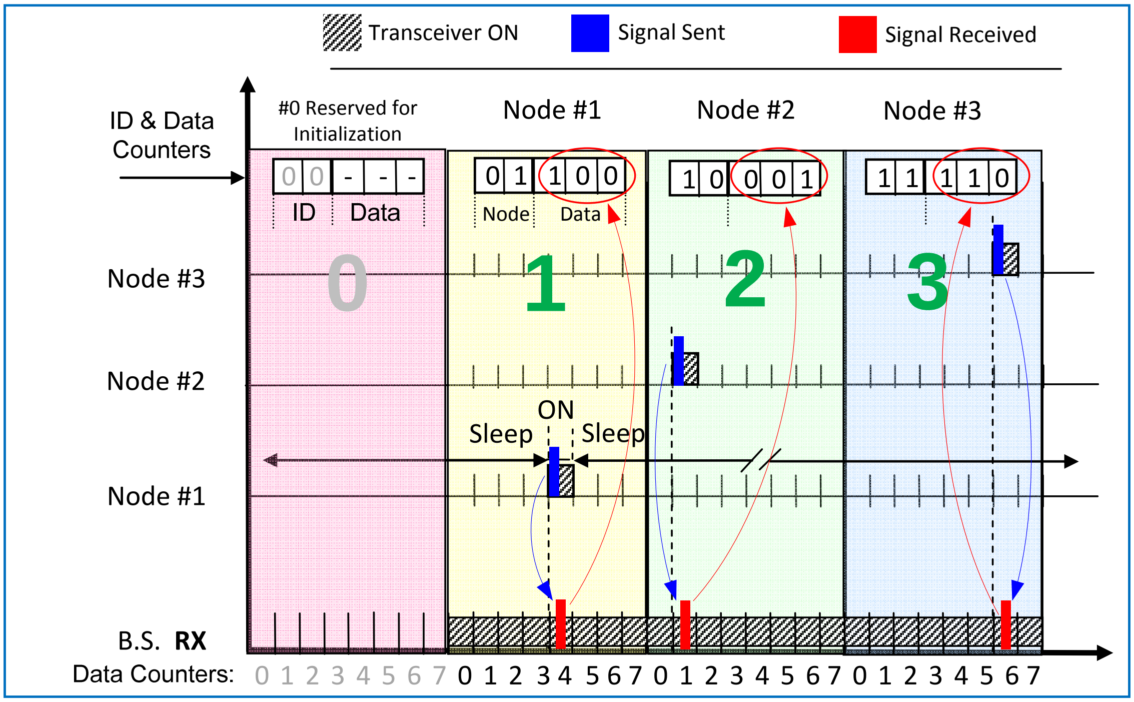


Figure 4.5: A three-sensor example illustrating the TBCD protocol mechanism.

Assuming all sensor nodes are perfectly synchronized with the BS and no delay for instance. Two bits for ID_Counters provides a small network with four time slots from 0 to 3 $(00, 01, 10, 11)_b$ and three bits for Data_Counters in range 0 to 7 provides a data range with 8 steps resolution per each sensor node. Time slot #0 is reserved for initialization, and three sensors are located in other time slots. It show how the data from each node is captured in the BS using the received short signals within each node's time slot. For example, in sensor node-1 the sensor data "4" has generated a short signal in step #4 within the time slot "1" and the BS has received it in the same time slot and converted it to $(100)_b$ in binary and registered it from Data_Counter. This data is also associated with node #1 which is registered from ID_Counter containing $(01)_b$ in binary. The correctness of the data received by BS can be verified simply in synchronization phase. Since in this algorithm no actual data is transferred and it only depends on a signal based on perfect synchronization, thus, the verification of the data is relied only on the synchronization efficiency. Description of the synchronization algorithm in the next chapter demonstrates how it can guarantee such precision.

The model structures of these sensor nodes and the BS are shown in Figure 4.6. The clock frequency depends on several factors including sensor data range, number of sensors and the sensor sampling rate. The complete details about the scalability of the protocol design could be found in section 4.5.

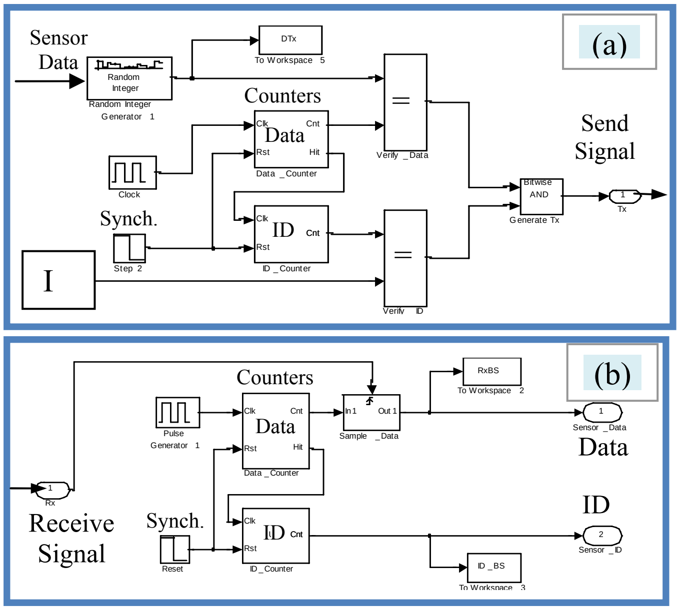


Figure 4.6: (a)- Sensor model, (b)- Base Station model.

4.3.2 Protocol Key Properties

Assuming that the sensor node "i" sends the data "d" to the base station, then the key properties of the protocol are given below:

In Sensor Node:

$\forall\ Node(i)$

$\exists\ R(DATA_{Node}\ , ID_{Node}) \quad AND$

$\exists\ d.(DATA_{Node} = d) \quad AND$

$(ID_{Node} = i) \ \Rightarrow\ [data\_valid(i) = True]$

In Base Station:

$\forall\ (Base\ Station)$

$\exists\ \ i.data\_valid = \ True \quad AND$

$(ID_{BS} = i) \quad \Rightarrow \quad [DATA_{BS} = d]$

where *R* is the relationship between all counters in sensor nodes and the BS and synchronization, *DATA_s* and *ID_s* are counters in sensor nodes, and *DATA_bs* and *ID_bs* are counters in the base station.

4.4 Simulation

The proposed protocol is modeled and simulated in MATLAB_SIMULINK environment. It has been verified in different cases in low and high resolutions. The protocol has been examined under stimulating different kinds of input to the nodes such as asserting sine waves with different frequencies, and also under different random vector sets assigned to all sensor nodes in the following examples. These results are considered as proof of concept in functionality of the protocol. For example, the simulation results in Figure 4.7 show the results obtained from only four sensor nodes each capable of reading the data in 8-step resolution. As example in here these sensor nodes are reading the Blood Glucose in range 3.0 to 6.5 mM (milliMole/gram) by 0.5 milliMoles per each level. First location of the sensor nodes with ID=0 as usual is always reserved for corresponding configuration cases. Three different sine-wave generators with different frequencies are used as input data sources to stimulate the sensor nodes in order to do a complete scan within the data range. The obtained results in the BS for each sensor node are shown by the stepped sine-wave per each corresponding sensor data source. The ID_Counter and Data_Counter are also shown assuming all synchronized with the BS. The magnified portion of the Figure 4.7 in Figure 4.8 is clarifying the results in a more visible resolution. The 2-bit ID_Counter determines which sensor nodes the obtained data belong to. For example, the sensor node #1 in Figure 4.8 has read the blood glucose as 5.0mM in range [$3._0$, $3._5$, $4._0$, $4._5$ $5._0$, $5._5$, $6._0$, $6._5$] which is converted by ADC to a 3-bit binary value as “4” out of range [0...7]. Then the BS has detected it (when ID_counter = 2), at the beginning of stage-4 of Data_Counter. On the other side, the same synchronized counters in the BS produce this value (5.0mM) within the stage-4 of the Data-Counter assigned to ID(2) which is obtained in ID_Counter at the time of detecting the short signal on the RX output of the receiver.

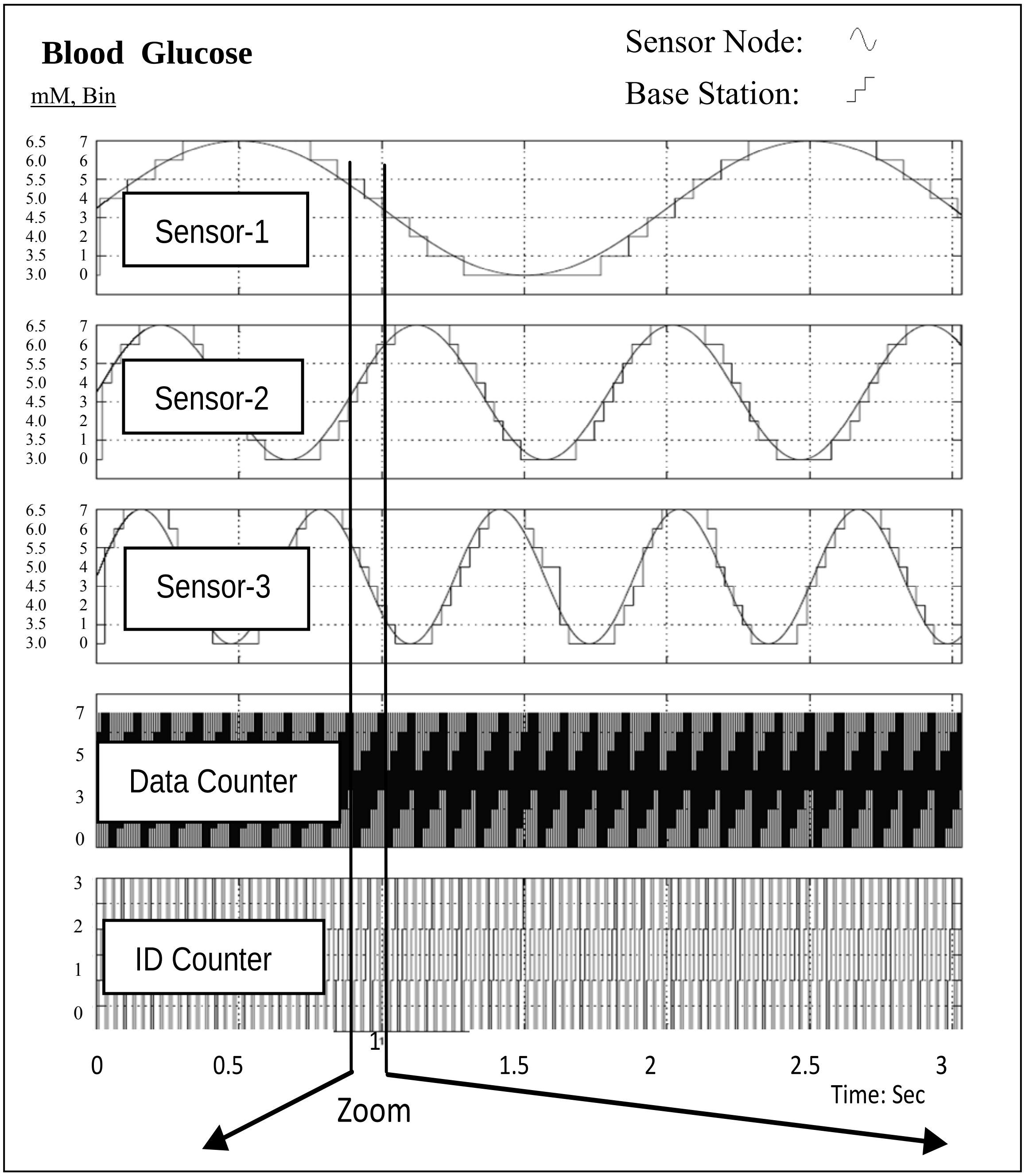


Figure 4.7: Three sensor nodes example Simulation results.

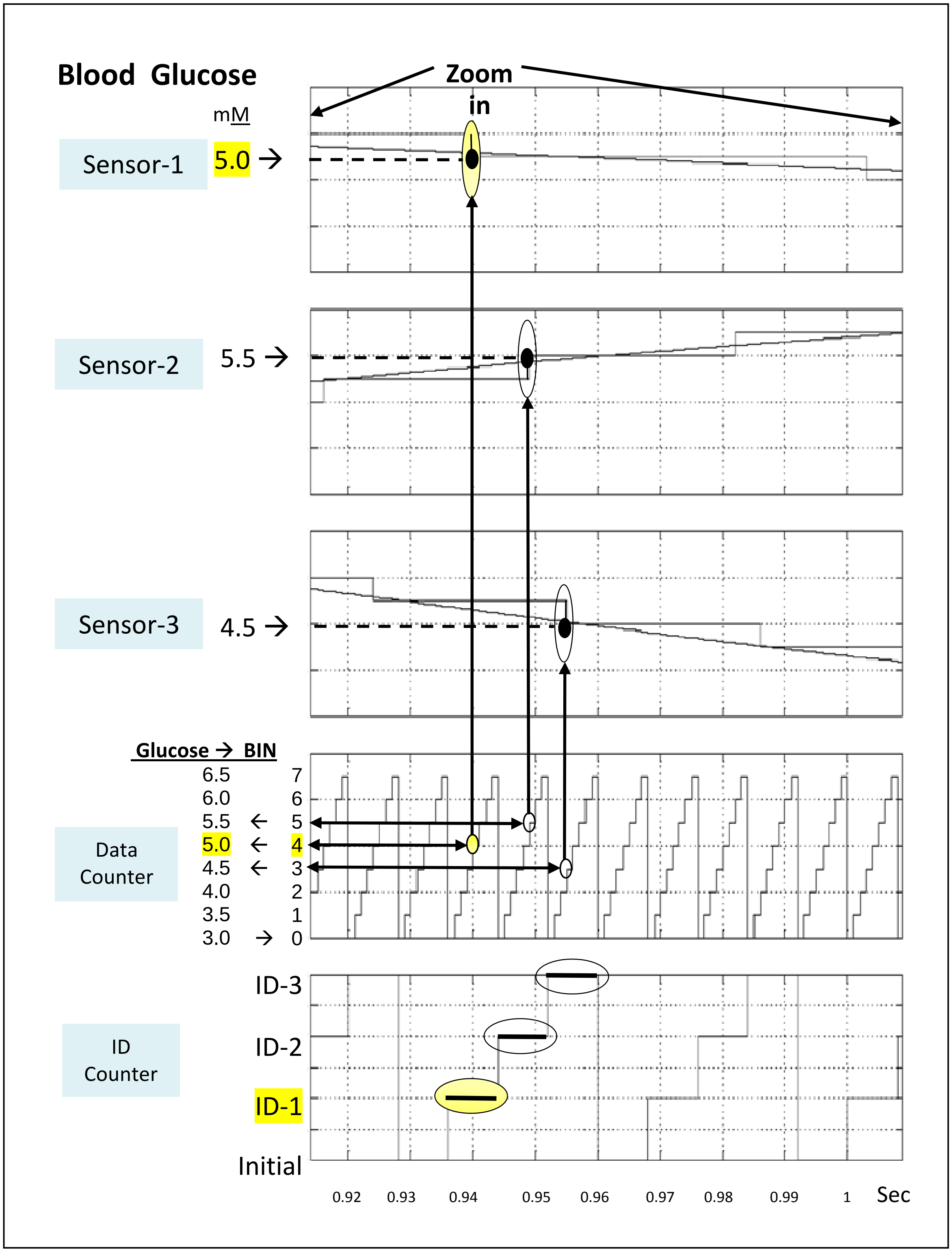


Figure 4.8: Simulation example of three Sensors with 3-bit data.

The simulation has been done in larger scales for example, using 8 bits range for number of sensor nodes, with 10 bits data per each sensor input. This supports up to 256 sensor nodes each in data range [0, 1023]. In Figure 4.9 the simulation done on 16 sensor nodes each reading up to 8-bit of input data has been depicted in order to be able to read and understand the details. The random number generators stimulate random numbers in range [0, 255] as input to all sensor nodes. As shown in this figure, the corresponding data to each sensor node is obtained with slightly corresponding delay derived from the algorithm within the same clock cycle in each step in the BS. As example, a stage in third network cycle in time-slot (ID=2) is highlighted showing the sample input data of (Data=115). This simulation has been done assuming 0 sec delay in wireless transmission for now, and proper synchronization between the BS and the Nodes.

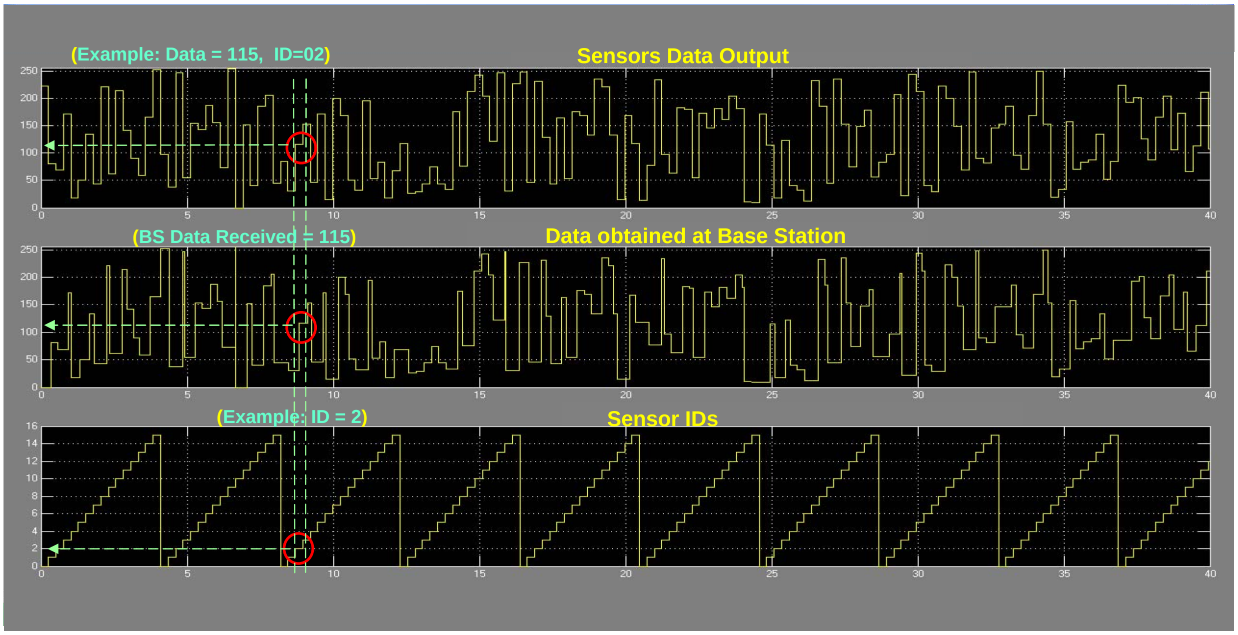


Figure 4.9: (a) Simulation results of a Sensor Network covering 16 Sensor nodes each with 8-bit data resolution in range [0, 255].

4.5 Scalability

We define the term “*Network Cycle*“ as one complete cycle of the network in which the m-bit ID_Counter counts up from zero to $2^{(m-1)}$ to scan all sensor IDs each once. We also define the term “*Sensor Cycle*” as a complete cycle for any sensor node (ID= i) in which the n-bit Data_Counter counts up from zero to $2^{(n-1)}$ within the data range. Therefore, we can define the starting event of the network system when both ID and Data counters are zero. Using an ‘f’ Hz clock rate we will have;

$$F = M \,.\, N \,.\, S \tag{4-1}$$

where:

$F = f$ Hz	(Clock frequency)
$M = 2^{(m)}$	(Total number of sensors)
$N = 2^{(n)}$	(Total data steps per sensor cycle)
S = sample/sec	(Sample rate)

The “*Network Cycle*“ based on the definition for one sample/sec is;

$$\textit{Network Cycle} = 2^{(m)} \times 2^{(n)} = f \qquad \textit{clock cycles}$$

Figure 4.10 clearly shows the scalability of such network based on number of the sensors, data range, and data transfer rate. A typical case could be found in this figure like assigning 256 sensor nodes to the network each with data resolution of 1024 steps at 256 kbps data rate.

Some examples of different cases for low data rates or the middle range are illustrated by the table in Figure 4.11.

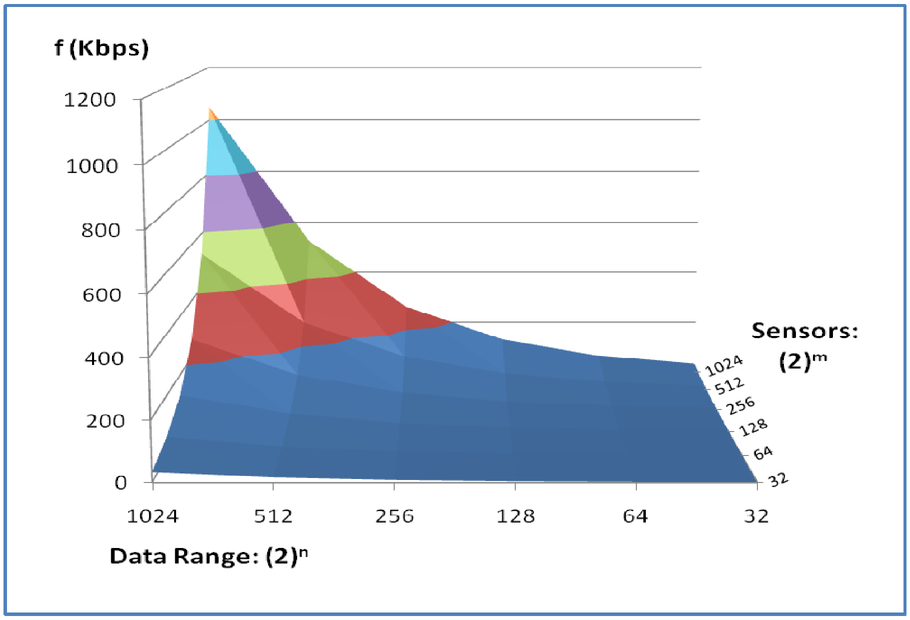
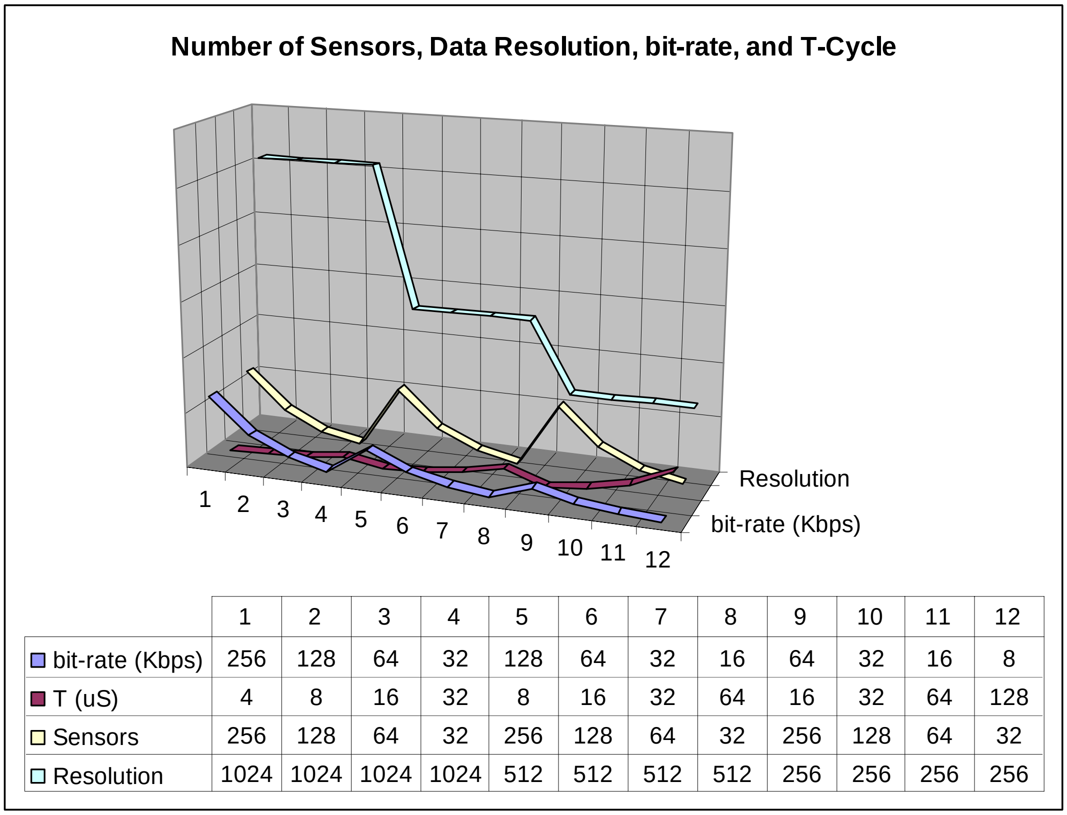


Figure 4.10: TBCD protocol scaling in number of sensors, data resolution, and data rate.



	1	2	3	4	5	6	7	8	9	10	11	12
■ bit-rate (Kbps)	256	128	64	32	128	64	32	16	64	32	16	8
■ T (uS)	4	8	16	32	8	16	32	64	16	32	64	128
■ Sensors	256	128	64	32	256	128	64	32	256	128	64	32
■ Resolution	1024	1024	1024	1024	512	512	512	512	256	256	256	256

Figure 4.11: Some examples of TBCD protocol scaling in different number of sensors, data resolution, and different data rates.

4.6 Mathematical Model Expression

4.6.1 Sensor Node Model:

The behavior of the Sensor Node can be formally expressed using an 8-tuple as follows:

SN_TBCD (C, X, Z, r, r0, y, y’, g(y))

where:

$C \in \{0, 1\}^{m}$,

$X \in \{0, 1\}^{n}$,

$Z \in \{0, 1\}$,

$r \in \{0, 1\}^{m+n}$,

$r_0 \in \{0\}^{m+n}$,

$y \in \{0, 1\}^{m+n}$,

$y' \in \{0, 1\}^{m+n}$,

$f(x,y) = Z$,

$g(y) = (y + 1) \text{ Mod } (2^{(m+n)}) - 1$

$m \text{ and } n \in \mathrm{N}$,

In this model, C is a constant as exclusive Sensor ID, X is sensor data input vector, Z is the output resulted in bit given by the condition in Equation (4-2), r is state vector, r0 is initial state vector, y is present state, y` is next state vector, f(x,y) is output function and g(y) is state transition function. The output of each sensor node is ‘1’ when the

ID_Counter hits C and the Data_Counter hits the input X value. This condition for valid BS output can be mathematically expressed as:

$$\forall\ m, n: \{[(r_{m+n-1} .. r_n) = (C_{m-1} .. C_0)] \wedge [(r_{n-1} .. r_0) = (X_{n-1} .. X_0)]\} \Rightarrow (Z=1) \qquad (4\text{-}2)$$

4.6.2 Base Station Model:

The behavior of the Base Station can be formally expressed using a 7-tuple as follows:

BS_TBCD (x, Z, r, r0, y, y', g(y))

where:

$x \in \{0, 1\}$,

$V \in \{0, 1\}$,

$ID \in \{0, 1\}^{\mathrm{m}}$,

$D \in \{0, 1\}^{\mathrm{n}}$,

$r \in \{0, 1\}^{\mathrm{m+n}}$,

$\mathrm{r}_0 \in \{0\}^{\mathrm{m+n}}$,

$y \in \{0, 1\}^{\mathrm{m+n}}$,

$y' \in \{0, 1\}^{\mathrm{m+n}}$,

Z = f(x,y) = (V, ID, D),

$g(y) = (y + 1) \text{ Mod } (2^{(m+n)}) - 1$

$m \text{ and } n \in \mathrm{N}$,

In this model, x is input, and Z is the vector of outputs (V, ID, D). These outputs are dependent on x and y, by the function f(x, y) and given the condition in Equation (4-3), r is State Vector, r_0 is Initial State Vector, y is Present State, y` is Next State Vector, f(x,y) is Output Function, g(y) is State Transition Function, V is the Output Validation (V=1 states valid output), ID is the current Sensor number whose data is sent by that sensor and presented on port D as its Data, m is the width of the ID vector and n is the width of the D vector.

The output of the BS for each Sensor Node ID is valid if and only if the input x is '1' for exactly one value in the Data Counter range. This condition for valid BS output can be mathematically expressed by the following conditions:

$$\forall\, m, n: \quad (0 \leqq i \leqq 2^m - 1) \bigwedge \left(\bigvee_{j=0}^{2^n-1} \left(\overset{i.(2^n)+j}{\widetilde{X}} \quad x = 1 \right) \Rightarrow \quad Inc(Count) \right)$$

$$\Rightarrow\ [(Count = 1)\ \Rightarrow\ (V = 1)] \qquad\qquad ;(4.3.1)$$

$$(x = 1)\ \Rightarrow\ [(\mathrm{ID}, \mathrm{D}) = \mathrm{g(y)}] \qquad\qquad ;(4.3.2)$$

where ($\overset{j}{\widetilde{X}}\, x$) represents the value of "x" at step number "j"after starting the process.

4.7 Duty Cycle

We already discussed in chapter 2 about the duty cycles for ZigBee and ANT in normal conditions. Now we consider it for TBCD algorithm. Ideally in the best case, the

TBCD algorithm transacts with only one single pulse on one clock cycle between any sensor node and the BS. This means the transmitter in the sensor node has to be active only within one clock cycle per each complete network cycle. But in typical case, a very small message in few bits could be sent instead to alleviate the environment noise effect. Then the TBCD duty cycle in both cases is;

$$DC_{TBCD\text{-}i} = 1/f$$

$$DC_{TBCD\text{-}t} = L/f$$

where $DC_{TBCD\text{-}i}$ and $DC_{TBCD\text{-}t}$ are transmission duty cycles in ideal and typical cases, f is the data rate in bps (bit per second) and L is the small message bit-width in typical case. One important reliability factor in any wireless network system is being interference free in close proximity to any other wireless network in the same environment. To guarantee this, a Network ID number (NID) could be applied to each network system by attaching to the messages. Therefore, a simple tricky method in this algorithm (TBCD) is using the same NID numbers as the same short messages in different IWBSNs. For example; an 8-bit NID can support up to 256 different WBSNs (patients with implanted sensors) in proximity to each other using automatic channel switching. As a typical example, we can assume a clock rate of 250 kbps using a 6-bit NID plus two start and stop bits providing an 8-bit short signal to be sent to the BS. This gives a typical duty cycle in TBCD as below:

$$Duty\_Cycle = \frac{L\ (bit/Network\_cycle)}{f\ (bit/Network\_cycle)}$$

$$DC_{TBCD\text{-}i} = \frac{L}{f} = 1 \div 250k = 0.0004\% \qquad \text{(ideal case, 1-bit)}$$

$$DC_{TBCD\text{-}t} = \frac{L}{f} = 8 \div 250k = 0.0032\% \qquad \text{(typical case, 6-bit)}$$

Comparing the duty cycle of "0.0032%" in TBCD versus "1.25%" for ZigBee in Equation (2-11) section 2.5.2 and "0.75%" for ANT in Equation (2-14) section 2.5.3 shows the considerable difference in gains as given in below. These results are measured only on transferring the sensor data disregarding other required transactions such as synchronization process which is demonstrated with very low duty cycle in chapter 5.

$$G_{TBCD\text{-}ZB} = 1.25\% \div 0.0032\% = 391$$

$$G_{TBCD\text{-}ANT} = 0.75\% \div 0.0032\% = 234$$

This demonstrates 391 times less energy consumption versus ZigBee and 234 times less versus ANT.

4.7.1 Gains and Comparison

Comparison between the TBCD protocol and other well known low power protocols are done irrespective to the synchronization phase which is a requirement in any type of sensor network. All results discussed in sections 5.2.3 and 4.7 are used here to calculate the gain and battery life time for protocols under study and all results are given in Table 4.1 in different cases.

The proposed protocol (TBCD) in some typical cases introduces gains of up to 234 to 312 over the ANT+ protocol and 391 to 521 over the ZigBee protocol in terms of energy consumption. Both of these protocols other than attaching excessive amount of control information to the data, are utilizing the transceivers based on different types of FSK (Frequency Shift Keying) modulators or any other PLL based modulators.

Table 4.1: Duty_Cycle, Gain and battery life time for TBCD, ANT+ and ZigBee communication protocols based on a data rate of 250 kbps each using its own transceiver hardware design.

Protocol	**Bits per Cycle**	**Duty Cycle**	**Gain VS** ZigBee	**Gain VS** ANT+	Battery Life (20mWhr)	
					Days	Hrs
TBCD (Ideal Case)	1	0.0004%	3,125	1,875	**4,336 (11.8 Yrs)**	NA
TBCD (Typical -1)	4	0.0024%	521	312	**722**	NA
TBCD (Typical -2)	6	0.0032%	391	234	**542**	NA
ZigBee	100s	1.25%	1	0.6	**0**	21
ANT+	100s	0.75%	1.7	1	**2**	5.5

These types of the modulators are suffering from another problem with a long-term start-up time to lock on their specific reference frequency. This will dissipate significant amount of energy of the tiny batteries in the tiny nodes per each round of transaction. In this work, not only a small signal in bit(s) will transmit the data, but also there is no use of the PLL-based modulators. ASK (Amplitude Shift Keying) modulators are applicable to this protocol which is explained in more details in the next section. The performances of the new and fast emerged technology of the transceivers can guaranty quick transition from sleep mode to the active mode especially in transmitter hardware.

4.8 Modulation Schemes

Modulation is a technique to wirelessly transferring any shape of the waveforms of information (data) by mixing with a high frequency sine wave. Such high frequency sine waves help in carrying the data over the air from transmitters to the receivers wirelessly and thus they are called as carrier waves in modulation techniques. The frequency of the carrier wave must be very much higher than the highest frequency of data changes in the data waveform. The carrier wave in modulators is affected by the data in either amplitude or frequency or both. This way many different modulation techniques are introduced. In general, the amplitude based modulation techniques are called as types of ASK (Amplitude Shift Keying) and the frequency based techniques are called as types of FSK (Frequency Shift Keying). ASK techniques do not need long term start up time to start data transmission after waking up from standby or sleep modes. But FSK techniques are totally different. Since they work based on the frequency changing, any small deviation in frequency would affect on the transmitted data, therefore they need to get locked on a fixed frequency through PLL (Phase Locked Loop) devices and then read and transmit the data by changing the frequency according to the data waveforms. Therefore, they must wait until the frequency is locked on the appropriate frequency by the PLL, and then start to send data. The PLL starts up times are normally long versus the small time required for small data packets to transfer. In TBCD protocol it is critically essential to turn ON and OFF the transceivers within as shortest time periods as possible. Therefore, the PLL based modulation would not be applicable to this protocol and the transmission must be under ASK based techniques only, to prevent dissipating significant amount of energy of the tiny batteries in the tiny nodes by the PLLs. One of the subversions of the ASK technique is using it in OOK (On Off Keying) mode. In this method only the zeros/ones are being modulated based on the carrier amplitude and hence the carrier wave would be in zero volt status when the data to be sent is zero. A real signal sampling in this technique is shown in Figure 4.12.

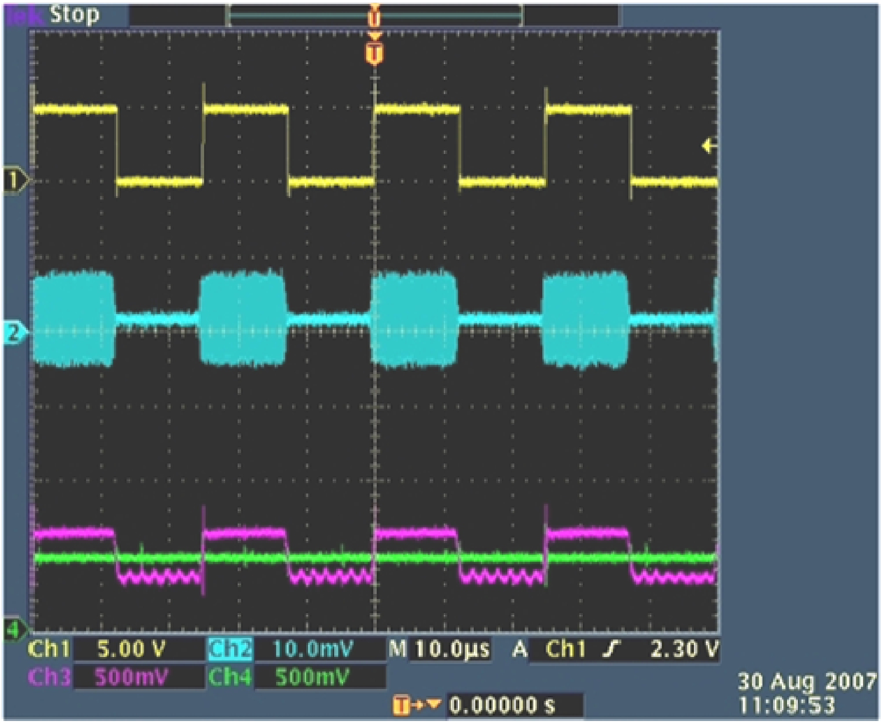


Figure 4.12: Real sampling of ON/OFF signal transmission in ch1, modulated signal under OOK (On Off Keying) subversion of the ASK (Amplitude Shift Keying) Modulation in ch2 and the same transmitted signal detected in receiver in ch3.

If we assume that the average duty cycle of logic 1s is about 50%, then we can say that the Oscillator in the transmitter or receiver would be in Off mode 50% of the time which is significantly effective in energy consumption. Therefore the OOK technique is absolutely practical and applicable for TBCD protocol. One important disadvantage of the ASK technique versus FSK technique is its weakness in very high frequency data transfers. But this is not considerable in this work since the TBCD protocol is proposed for IWBSNs and is not targeting networks involved in very high frequency data rates.

The performances of the new and fast emerged technology of the transceivers can guarantee very quick transition from sleep mode to active mode which is especially very good for the transmitter using ASK technique in terms of power consumption awareness.

4.9 Regulations Awareness

Based on the regulation of the medical section related to health care it is not allowed to expose the human body under the danger of electromagnetic wave radiation without respecting the specific standard limits. It is very important to measure the power and the effect of the wave's radiation through the tissue and limbs of the body and make sure that they are within the authorized limits. That's because the electromagnetic field will be absorbed by the body and because tissue damages and heating the limbs which could be seriously dangerous if a specific rate is not considered. This is the standard measurement in this regard called Specific Absorption Rate (SAR) as described in section 3.4. Some examinations on the body by researchers have been done to achieve the reliable results on how much power is allowed and what are the limits which are discussed in the next section. Standard regulations in the range of allowed frequency for the medical devices is also another important fact in this regards that must be taken care as described in the following section 4.10.2.

4.9.1 SAR Compatibility

Experiments have shown exposure to an SAR (Specific Absorption Rate) of 8 W/kg or more in any gram of tissue in 15 minutes or more may have a significant risk of tissue damage [57, 81]. The measurements in Oxford Journals [9] show the permitted limit for one-gram peak spatial average SAR in 0dB resulting 1W kg^{-1} in range 30MHz to 6GHz for 1W feeding power. It was tested at 236MHz for; 2.6mm skin, 105mm fat and muscle. This will clearly guarantee 100% confidence on safety of our proposed protocol in the body network system. Since the transmitted power at the sensor antenna inside the body would be enough in range 0dBm up to 5dBm (1mW to 3mW). These results show significant difference between the permitted feeding power limit and the small amount of energy radiating by implanted sensor nodes in the body. This is a comparison between about 3mW transmission power by sensor node, with a duty cycle of only a few micro seconds per one second, versus 1W power for 15 minutes as standard limit.

4.9.2 FCC Regulations

Based on the Federal Communications Commission (FCC) Regulations the frequency band 401 – 406 MHz is reserved as Radio standards in Medical Implant Communications (MICS) which is known as MedRadio, Established in 1999 [25]**.** This is an ultra-low power, unlicensed, mobile radio service for transmitting data in support of diagnostic or therapeutic functions associated with implanted and body-worn medical devices. MedRadio transmitter emissions are limited to an authorized bandwidth of 300 kHz in the 402-405 MHz band, 100 kHz in the 401-401.85 MHz and 405-406 MHz bands, and 150 kHz in the 401.85-402 MHz band. These ranges are clearly specified in Table 4.2.

Table 4.2: Authorized bandwidth range for MedRadio transmission [25].

Frequency (MHZ)	**401-401.85**	**401.85-402**	**402-405**	**405-406**
Bandwidth (KHz)	100	150	300	100

Each IWBSN system could be assigned to an individual patient using a channel width based on regulations in Table 4.2 for implantable medical devices.

4.10 Fixing the Delay error

This section presents a methodology about how to eliminate the air delay problem derived by the transceivers wirelessly. The signals received at the base station from different sensor nodes may experience different delays during the transmission. This is related to all sensor nodes and the BS. All sensor nodes must be synchronized with the BS, and the BS needs the exact delay time associated with each sensor node individually to be able to obtain the accurate data based on the alert signal coded in the time. Any delay in signal detection during wireless transmission would cause a significant error in reading the alert signal and hence to appear the alert signal in a wrong time leading to non-synchronization problem between the communication parties. Therefore, any existing unresolved delay issue in data transmission between the nodes will cause a serious problem.

The delay between the sensor nodes and the BS could vary for each individual sensor node. The proposed method in here eliminates this issue by automatically detecting the delay between each sensor node and the BS which is enough to be done once in the system network configuration. It is assumed that all sensors in the network are globally synchronized with the BS based on their local time. Then the air delay between the BS and each of them separately would be calculated through a simple method. The associated delay with each sensor will be assigned to its sensor ID stored in a LUT in the BS. This method also automatically fixes the problem by compensating associated error with individual sensors in sensor data transmission using the event of the alert signal. The topology of our designed system environment as IWBSN emulator is illustrated in Figure

4.13. It depicts the entire implemented design in a single FPGA using external wireless transceivers for each sensor node and the BS. The delay elimination method is based on simplest message passing through the nodes and the BS. The BS starts sending a signal to each individual sensor and waits for an immediate feedback from them one at a time. In Figure 4.13 $(t_2 - t_1)$ and $(t_3 - t_2)$ represent the propagation delay time from the BS to the sensor node ($D_{BS\_to\_Sensor}$) and from the sensor side to the BS ($D_{Sensor\_to\_BS}$) respectively.

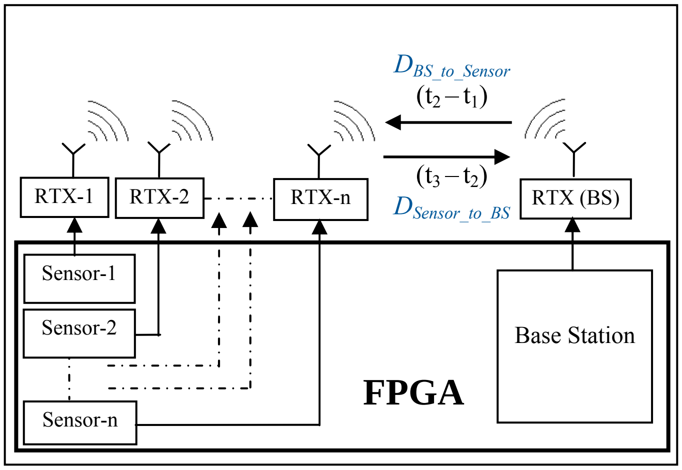


Figure 4.13: Topology of the entire system as emulator under the test. All digital sections embedded inside one FPGA.

All sensor nodes and the BS are implemented in the same FPGA, because the objective is to calculate only the delays generated through the external analog transceivers in short range distance. This is explained in more details in next section. Figure 4.14 illustrates the proposed protocol. For each individual sensor, the BS resets a counter named (Delay_Counter) at the beginning. Then sends an alert signal to the sensor and immediately starts counting up in the Delay_Counter. Once the corresponding sensor node receives and detects this alert after $(t_2 - t_1)$ sec, it then immediately sends back the feedback signal to the BS in response to this alert. Then the BS will receive and detect this feedback signal after ($t_3 - t_2$) sec. Then the total two way delay ($D_{Two\text{-}way}$) would be sum of both delays in two directions.

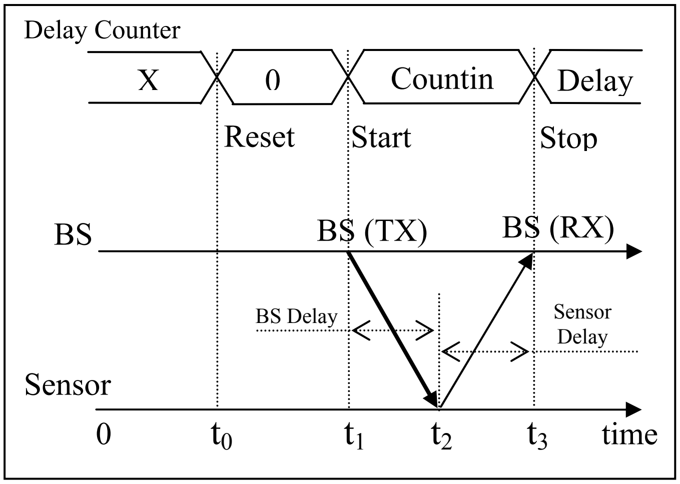


Figure 4.14: Protocol of the reading and fixing the delay problem.

Using the same hardware technology for the transceivers in all sensor nodes and the BS we can assume equal bidirectional delays in sending and receiving the signals among the nodes. By this method the one-way delay between the sensors and the BS would be easily obtained in Equation (4-5) which gives the delay for travelling the signal from the sensor to the BS.

$$D_{Two\text{-}way} = (t_2 - t_1) + (t_3 - t_2)$$

$$\textbf{if } (t_2 - t_1) = (t_3 - t_2) \qquad \textbf{then}$$

$$D_{One\text{-}way} = (t_3 - t_1) \div 2 \qquad (4\text{-}3)$$

However, when the transmission delay from the BS to the sensor node is not the same as the transmission delay from the sensor to the BS, this special case can be verified and corrected during the start-up phase. Based on the proposed protocol, the real data including required parity/error checking codes can be attached "only once" to the short alert signal, and then be sent to the BS. Since the protocol does the processes in fact on delayed signal, not on the instantaneous event right at the moment of generating the signal at the sensor node, then the BS can compare the actual data with the data obtained based on the result of the protocol on delayed signal to obtain the real delay from Sensor side to the BS direction ($D_{Sensor\_to\_BS}$). Then the difference between $D_{Sensor\_to\_BS}$ and D_{Total} can be used to find even the real delay from BS side to Sensor direction ($D_{BS\_to\_Sensor}$) and adjust all reset points in all nodes which are especially vital in synchronization phase related to next chapter. The above process is required to execute appropriately once for each sensor node by the BS to configure all devices properly.

if $(t_2 - t_1) \neq (t_3 - t_2)$ **then**

$D_{BS\_to\_Sensor} = D_{Two\text{-}way} - D_{Sensor\_to\_BS}$

4.10.1 Experimental results

In this section, we consider the following experimental results in a hardware test-bed for this part of the system in an embedded design environment in FPGA along with wireless transmitters and receivers. We call the total delay between a sensor node and the BS (D_{total}), starting from the time that the alert signal in the sensor node is forwarded to the transmitter until it is detected by the BS, and is given in Equation (4-4);

$$D_{tota} = (D_{Digital} + D_{Analog})_{Sensor} + D_{Air} + (D_{Analog} + D_{Digital})_{BS} \qquad (4\text{-}4)$$

where $D_{Digital}$ for both sensor nodes and the BS is the signal propagation time in digital circuit sections, D_{Analog} also is the signal propagation time in analog transceiver circuits and D_{Air} is the propagation time in the air between the transmitter and the receiver's antennas. Speed of the electromagnetic wave through the transmitter's antenna over the air is the same as the speed of the light in the air [40]. The distance between the implanted sensors in the human body and the mobile PDA (Personal Device Adapter) or the BS (carrying with the patient) is in a very short range less than a maximum of 2 or 3 metres. As a result, *C* (speed of the light) is fixed at exactly 299,792,458 metres per second [62].

$$C = 299{,}792{,}458\ m/sec = [299{,}792{,}458 * (100cm/10^{9}\mu s)]$$

Then with a very high accuracy the "c" would be;

$$C = 29.98\ cm/ns$$

then; $D_{Air} < 10\ ns\ (\ per\ 3metres)$

From the theoretical point of view, the critical path for this design is also obtained by the FPGA Synthesizer. The delay is reported as 12.238ns starting from the time of reading the corresponding signal with the sensor data as input, until provided output signal to the analog transmitter.

Critical path reported by Xilinx ISE Synthesizer:

```
----------------------------------------------------------
Total =      12.238ns (8.765ns logic, 3.473ns route)
----------------------------------------------------------
```

Since the complete design is downloaded and executed in the same FPGA, so the reported critical path covers the total digital delay for overall BS and the sensor node together, disregarding the analog delay in the transceiver boards. The electromagnetic carrier wave also travels this distance (3 metres) in less than 10ns (D_{Air}). In the following we will see that these small reported delays in the range of about 10ns each are too trivial to be comparable with the analog delay. The overall digital and analog delay all together are experimented and measured as in the following.

As the topology in Figure 4.13 shows, all sensor nodes and the BS under the test are emulated inside a single FPGA and each of them communicates only with its own associated transceiver (RTX_i) which are connected externally to the FPGA board. The transceiver boards (RTX Hybrid boards) in this test were distributed around the central FPGA board with reasonable distances to be as a mimic of the real testing environment and the protocols over the air. The design including the delay calculator section has been implemented into an FPGA and detected the real delay to fix any related error. This test bed has been implemented using low speed receiver and transmitter Hybrid Boards (RXD1 and TXC1) just for testing with ASK modulators. The modulation type which is used by these transceivers is OOK. The transmitter (TXC1) receives the alert signal by FPGA on its input, and propagates the 433.9MHz carrier waves carrying some test signal to the air. The receiver (RDX1) receives and detects the signal under the 433.9MHz carrier waves through the antenna and activates its digital output data which is used as the input to the BS, back again to the same FPGA. A 64 KHz digital clock signal is provided by the 50MHz clock generator on FPGA board as data transfer rate and input clock to the main design. This represents a baud rate of 64kbps data transmission at 15.25μs steps, and based on the results in Figure 4.11 it can cover up to 128 sensors each with 9-bit data resolution in range (0, 511).

$$T = 1/64K = 15.25\ \mu s \tag{4-5}$$

The D_{total} has been automatically computed by the delay calculator implemented in the FPGA, and it was used to eliminate the error derived from this delay in order to correct the shifted time of detecting the signal by that delay. The reported delay by monitoring values periodically showed that the alert signal was being detected at the BS through the air within about 40µs with a tolerance of up to 3µs because of the instability factor related to oscillators in analog transceivers and the noise. Considering the clock cycle period in Equation (4-5) in this example it means delaying by up to 3 clock cycles. The important factor which must be taken into the account for delay error correction in TBCD protocol is based on the number of clock cycles.

$$D_{total} = 3 \qquad \textit{clock cycles,}$$

The experimented delay directly by the Oscilloscope has also been measured around the same result as the above implementation (Figure 4.15). The chanel-1 (in the top) is connected to the TX alert signal to be sent from the sensor node and the channel-2 is monitoring the arrived and detected alert signal at the RX input pin of the BS on the FPGA. So, this result as shown in the picture, reports a one-way delay between the sensor node and the BS which is also again approximately about 40µs (the same as the result calculated automatically and monitored by the design in the FPGA). This way the correctness of the algorithm of the proposed communication protocol along with the experimental method to calculate and fix the delay error derived from wireless transmission, has simply been verified and approved. After comparing the analog results with the digital results (in a few ns) it is clear that the delays derived by digital circuits and also the air delay are ignorable versus the analog circuit delays. Indeed these delays in range of nano-seconds are too trivial to be considered in the calculation versus the analog delays in range of micro-seconds. Even the tolerance of the analog delay through the transmitter and the receiver is much bigger than these small digital delays. Therefore, in the calculations, it is assumed that the digital delay and the air delay are close to zero.

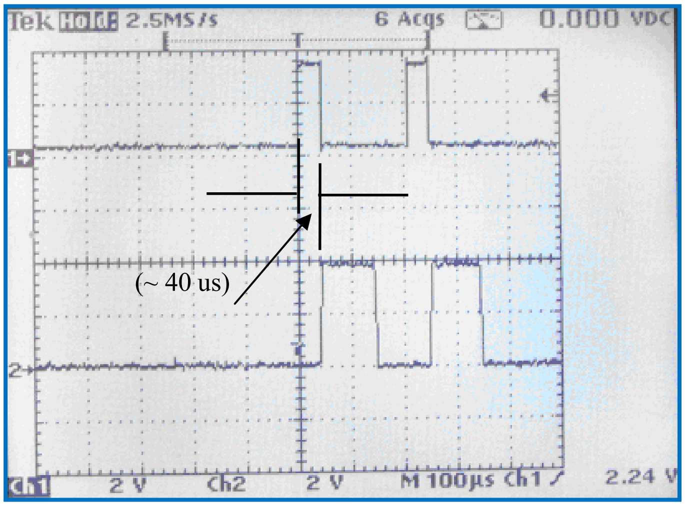


Figure 4.15: Oscillator Experimental results measured by Oscilloscope to measure the delay in signal transmission between Nodes and Base Station. Channel-1 monitors the TX signal on the transmitter and channel-2 monitors the Rx input of the BS.

4.11 Summary

In this chapter, we described the communication protocol. The protocol allows a sensor node to send information coded in time domain with least amount of energy use. This is accomplished with a single signal. The complete behavior of the base station and sensor nodes are described mathematically using the models described in this chapter. It is important to accurately estimate the signal transmission delays. This chapter also described a method for estimating the signal transmission delays. In the next chapter, we will describe the sensor node and base station synchronization algorithm which is important for the correct operation of the communication protocol.

Time Synchronization

Chapter 5

5. TIME SYNCHRONIZATION

5.1 Introduction

Clock drift in every electronic system is bounded by a factor as P_{max} with χ ppm. PPM is Part Per Million, and χ ppm clock drift means a clock in a node can shift up to χ clock cycles to the left (lower rate) or right (higher rate) per each million cycle. For 1MHz clock, χ ppm means $\pm\chi$ μs deviation in a second. Hence, even if we synchronize the whole network once, then the nodes will go out of synchronization soon in a few minutes or seconds. Thus, to establish acceptable levels of accuracy in wireless sensor networks at every instant of time, then it is substantial to do a periodic synchronization in the whole wireless network. Therefore, time Synchronization is a critical part of the infrastructure for distributed systems involved in communication. Wireless sensor networks extensively use time synchronization, but they have common requirements in lifetime, precision of the synchronization, as well as the required energy to achieve it. Time synchronization in a network system means that all network nodes choose a common cyclic time reference in a timer/counter in each node and always restart counting in their reference timer/counter all at the same time. Once a network node is lost in tracking the same time reference, then that node is not synchronized with the network anymore. This usually happens in any wireless network periodically. That's because of instability of the oscillators in each node which are generating the time reference for each network node separately and the deviation in the expected frequency in each node causes such time drifts and makes them out of synchronization in the network periodically. A typical drift value for a good clock is around ±5 to ±10 ppm or even less. Figure 5.1 illustrates some examples of different network nodes with different clock drifts with respect to the real time according to an ideal clock. For example node-A is forwarded about 55µs in advance at 10 seconds after starting network time and based on the definition this means the clock drift is bounded with +5.5ppm.

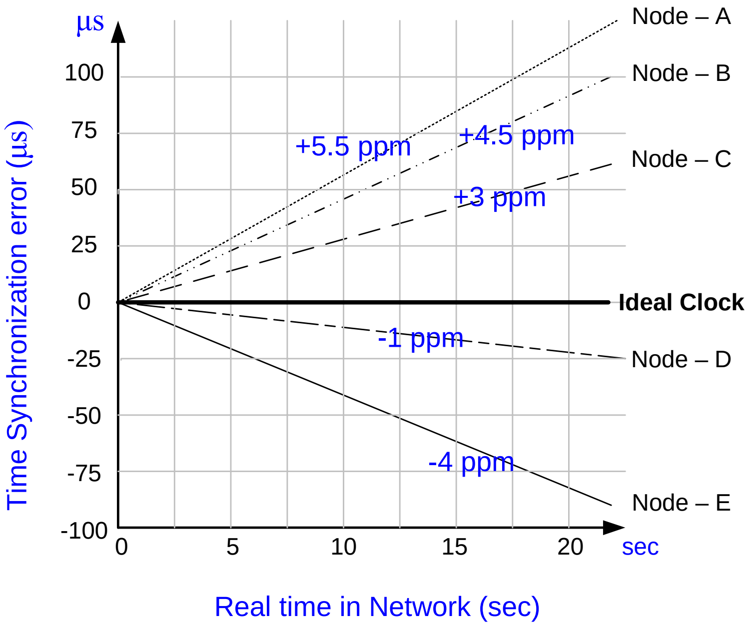


Figure 5.1: Relative time drift example for 5 different nodes with respect to the ideal clock.

In order to achieve an acceptable level of synchronization among all nodes in the networks a reliable algorithm is needed to manage it in the entire network. In order to keep the track of the synchronization within the network in stable mode, the resynchronization must eliminate any error occurred by time drifts periodically, as long as the network is working. In a wireless network, this can only be done by passing alternatively appropriate messages containing local time based information between all live network nodes. Therefore, they do also need to use a communication protocol for their data transactions within the network.

5.2 Existing Algorithms

There are many efficient and precise synchronization algorithms available and applicable to different applications in wireless networks proposed since long time. These algorithms are designed with different performances to meet different applications requirements. For example, in some wireless network applications there is not lack of energy resources available to the nodes, but the speed of data transfer might be so important. Some application may need very high level of clarity in keeping track of the synchronization for example controlling the phase shift on the clock which is more complicated to keep track on. In some applications the energy consumption is the most important issue like in IWBSNs which is extremely critical issue.

Existing time synchronization methods need to be extended and improved to meet the new needs. For example, some algorithms do not deal with any master node like Asynchronous Diffusion scheme (AD) [51]. AD supports the whole network synchronization internally between all nodes. The algorithm is very simple: each node periodically sends a broadcast message to its neighbors, and then the receiver replies with a message containing their current time. The receiver node averages incoming timestamps and broadcasts the average to the neighbors. Then the other network nodes in its neighborhood use the result as their new time. This method is very easy to implement, but dealing with large number of message transfers between the entire network nodes periodically is not an acceptable solution to low power wireless networks. As another examples, NTP which is a very well known classical synchronization algorithm [58], [20], or the interactive Convergence (CNV) algorithm [50] which both are proposed for traditional networks, or the more complex one as interactive consistency algorithm [50], they are not suited for the WSNs [70]. Reports in [24] and [60] give better clarification about how traditional or classical time synchronization algorithms are not suitable for low energy wireless sensor networks.

While many advantages are recognized by use of Reference Broadcasting Synchronization (RBS) [18, 19] in networks, but it has shown relatively high network traffic overhead and consequently high energy consumption which is a big disadvantage [21]. In RBS which is an RRS (Receiver-Receiver Synchronization) algorithm, two receiver nodes exchange timing information through their messages that both of them have received the message from a common sender (a master node). Sensor nodes send lots of beacon messages periodically to each other. Recipients use the arrival time of the messages as their reference point to adjusting their times. Then the offset between any pair of nodes is calculated by exchanging the local timestamps. Or we can say; the receivers record their local time when receiving the reference broadcast, and then they exchange their recorded time. This way, they are aware of their time offsets with each other. When each node takes the average of its time offsets to all other nodes that have observed the same reference, a relative network time is achieved among all receivers. The disadvantage is that the number of message exchanges is very high and the communication between the nodes is much and thereby consuming high energy.

TPSN (Timing-synchronization Protocol for Sensor Networks) is an SRS (Sender-Receiver Synchronization) algorithm [27] similar to RBS algorithm. But both TPSN and RBS algorithms suffer from the variation in time propagation. TPSN uses only symmetric links, and the difference in delays on such similar links is trivial and therefore difficult to achieve precise calculations. The results in [27] have shown that the traditional approach using sender-receiver synchronization is better than receiver-receiver synchronization in wireless sensor networks.

A better technique is Delay Measurement Time Synchronization (DMTS) [64]. This technique avoids round trip delay estimation. It synchronizes multiple receivers with the sender at the same time while transacting with less number of messages than the RBS method. In this method a master node broadcasts its time stamp messages. All the other network nodes measure the time delay and set their time by master time plus measured time transfer delay. This way, all the nodes that have received the time stamp message can get synchronized with the master node. The accuracy in DMTS is very much related to accuracy of the measured delay. But the DMTS also is involved in many challenges such as; energy consumption, scalability, computation cost and user application support which again this method also suffers from power consumption and requires large energy resources.

Therefore, a perfect low energy time synchronization algorithm could not be easily achieved among available algorithms. In fact, none of the standard clock/time synchronization methods like in [58, 50] is energy efficient for IWBSNs. They transact with very long messages passing through the network, since any one of them is first depended on a standard communication protocol to transact with their messages in the network. Therefore, if one of these synchronization methods is employed in IWBSNs, again the same problem as studied in details about high power consumption in chapter 3 will come up and degrades and destroys all advantages of the TBCD protocol required for IWBSNs. Therefore, the TBCD protocol will need its own appropriate ultra low energy synchronization algorithm. TBCD without a low power synchronization algorithm will not be valuable. Hence, a new ultra low power synchronization algorithm has also been proposed in this work and explained in details with proof of concept.

This chapter outlines the synchronization requirements applicable to TBCD ultra low energy communication protocol proposed for IWBSNs and demonstrates its ability to overcome the energy issue. Experimental results also characterize and describe its performance for creating reliable localized time within all sensor nodes wirelessly with high degree of precision in synchronization using very small fraction of energy versus other proposed algorithms.

5.3 Proposed Synchronization Algorithm

Generally in most algorithms a master node sends primary messages within a period of time alerting the other nodes to get ready for their time stamp in the subsequent cycle. Then, as illustrated in Figure 5.2, in the next cycle each node will receive and read a time stamp and later adjusts its time reference based on that, to reach synchronization instant with the master.

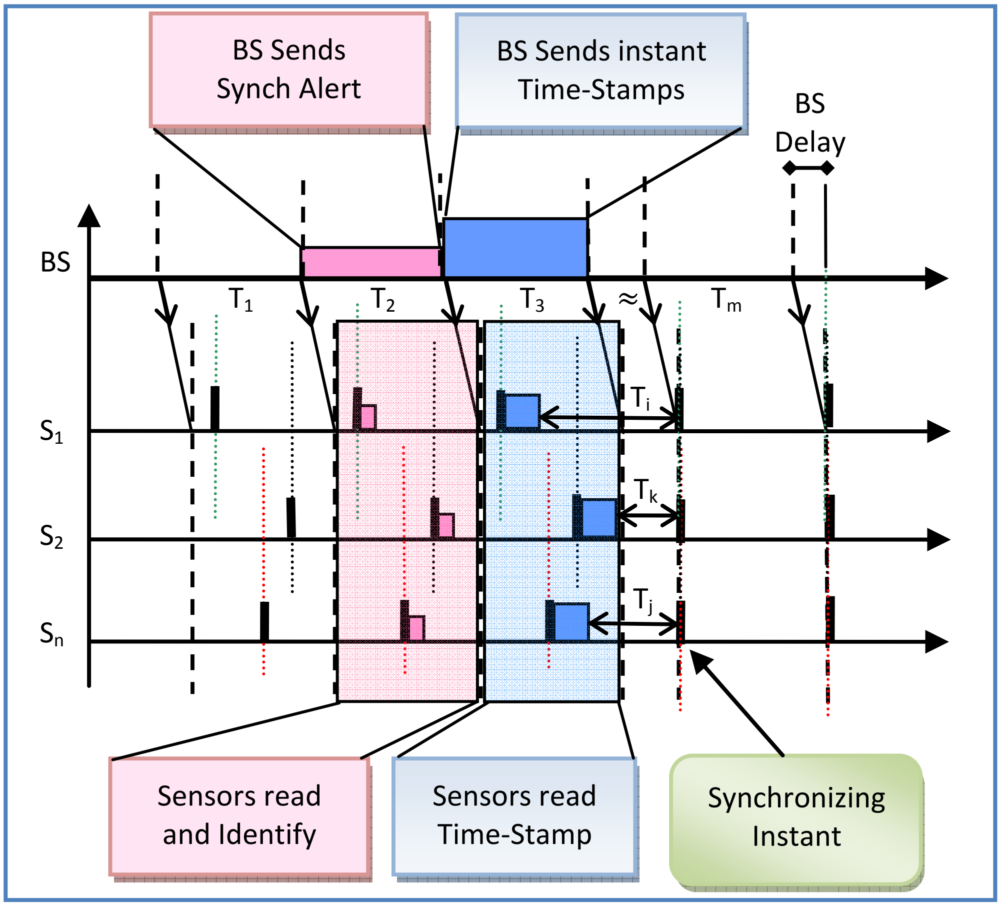


Figure 5.2: Time Synchronization scheme.

The less re-synchronization rate results the less energy consumption and the more error probability. The communication and synchronization protocols proposed in this work are complementary parts that are applicable to low-range/low-energy sensor networks. These protocols are targeting especially IWBSNs that can only transact with very small messages through the network. Indeed, the design methodology of the synchronization algorithm in this work will considerably mitigate the load work in the BS and more importantly in the sensor nodes. Considerable amounts of energy will be saved in the sensor nodes by avoiding long messages passing. Therefore, it keeps the network in standby mode as long as possible, satisfying the requirements for IWBSNs along with TBCD communication protocol, as it will be demonstrated in this section.

To analyze the proposed synchronization algorithm, we assume m-bit for the ID_Counter and n-bit for the Data_Counter in each node as defined in TBCD communication protocol. The delay derived from wireless data transmission between the nodes and the BS can be considered a constant for each node. It can be easily calculated (as described in section 4.10) and taken into the account for each sensor node. We use again the terms “Network Cycle” and “Sensor Cycle” already defined in section 4.5. Here we also define the term “NT (ID, D)” which represents the instant cyclic time within the network cycles in unit of state number, and is given in Equation (5-1). Thereby, NT (0, 0) represents start of each network cycle in the network.

$$\mathrm{NT}\ (\mathrm{ID}, \mathrm{D}) \in \{0, 1\}^{m+n} \qquad (5\text{-}1)$$

$$\mathrm{m}, \mathrm{n} \in \mathrm{N}$$

5.4 Base Station Algorithm

In this synchronization algorithm, there are two different small messages to be sent from BS to all Sensor Nodes. This can be explained as follows.

1- **Message number-1:** This message is a single small message sent by the BS to all sensor nodes to let them identify the synchronization message-1. This message will be sent only once at the beginning of each network cycle [NT(0, 0)]. This will notify the sensor nodes to reset their network time NT (ID, D) by resetting their ID and Data Counters. Message number-1 is called "network Time ReSeT message" and is named "T_RST_{msg}".

2- **Message number-2:** The message number-2 will be sent by the BS many times per network cycles, but will be used very rarely by the sensor nodes, which is describe later. First we should consider this fact that; fortunately the BS is rich in energy resource. Therefore dealing with more number of small messages as many as required in the base station has no energy restriction. This message (message-2) is sent at beginning of every sensor cycle by the BS. Beginning of each sensor cycle is represented by the network time as; [NT(ID, 0)] which means whenever the Data_Counter in the BS becomes zero. The message number-2 will be used only in crucial conditions like at the initialization phase or whenever the sensor node gets totally out of synchronization because of noise or any other circumstances. This message is composed of two sections. The first section is another small message to identify the synchronization message-2 and distinguish with message-1. The second section at the end of this message is carrying the instantaneous value of the ID_Counter in BS at the time of broadcasting the message which represents a time stamp in the network. This message is called "network Time StaMP message" and is named "T_SMP_{msg}". In the next section by describing the sensor nodes algorithm, we will elaborate more on how the sensor nodes use these small messages and get synchronized with the BS quickly consuming least amount of energy. The general algorithm for the Base Station is:

General Synchronization Algorithm for Base Station:

```
Initialization, and calculating air delay between BS and Sensors
Start:  if      (Data_Counter =0)'event        then
        if          (ID_Counter  = 0)          then
                send $T\_RST_{msg}$ to all Sensor nodes
        elsif       (ID_Counter  > 0)          then
                send $T\_SMP_{msg}$ to all Sensor nodes
        end if
    end if
    loop Start      // restart
end:
```

The following state table in Table 5.1 highlights a high level abstraction of BS algorithm followed by the corresponding Moore Machine state diagram in Figure 5.3.

Table 5.1: Synchronization state table for Base Station as the master node

Current State	ID	Data	Next State	Actions
Initial	X	X	S0	**Reset System**
S0	0	Data > 0	S1	**Send T_RST_{msg}** Send SCS_{Msg} + ID_{BS}
S1	ID > 0	0	S2	Send NCS_{Msg}
	0	0	S0	Send SCS_{Msg} + ID_{BS}
S2	ID > 0	Data > 0	S1	Send NCS_{Msg} **Send T_SMP_{msg}**

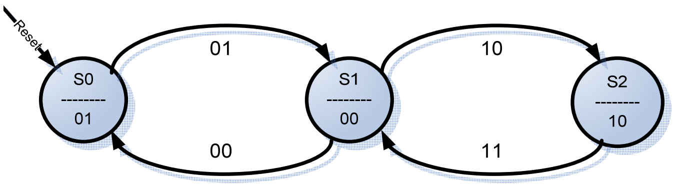


Figure 5.3: State Diagram of the synchronization algorithm for BS.

The transition condition and the outputs of the states are:

Transition Condition: *[ID, D]*

Outputs of the states: *[T_RST, T_SMP]*

where ID and D are current status of the ID_Counter and Data_Counter, T_RST (Time ReSeT) is the signal to enable the process so that the BS sends Time ReSeT message (T_RST_{msg}) to the Sensor Nodes, and the T_SMP is the signal to enable the process so that the BS sends Time StaMP message (T_SMP_{msg}) to the Sensor Nodes. Note that the T_SMP_{msg} always includes the instant ID of the BS as a tail attached to the message.

5.5 Definitions

It is desirable to have ideal oscillators and clock generators with unique frequency in the BS and all sensor nodes, but this is inaccessible. Even the most advanced technology of the Quartz Crystals cannot guarantee this. The sensor nodes should wakeup as accurately as possible at their appointment moment scheduled with their master (BS). This is especially very difficult in low-energy network systems, because of the clock drifts especially when they are in long term low power sleep mode. We use the following definitions to describe the rest of the work.

5.5.1 Sampling rate

Sampling rate in a star sensor network introduces a time period in which a sensor node sends its sampled data to the master node (BS) once within this cycle. This time period was already called Network Cycle.

5.5.2 Time Deviation

Each sensor node may have a maximum of $\pm k\ ppm$ clock deviation per network cycle with respect to $\pm x\ ppm$ clock drift per second assigned to its local oscillator.

Then the deviation time is the minimum required period of time based on $\pm \boldsymbol{k}$ clock drift in which the receiver node (sensor node in here) wakes up and has the chance to receive the synchronization message broadcasted by the master (BS in here). Then if the time period of the sensor node in active mode is less than the deviation time, then it may miss the synchronization message. Figure 4.5 is a nonrealistic illustration of these definitions.

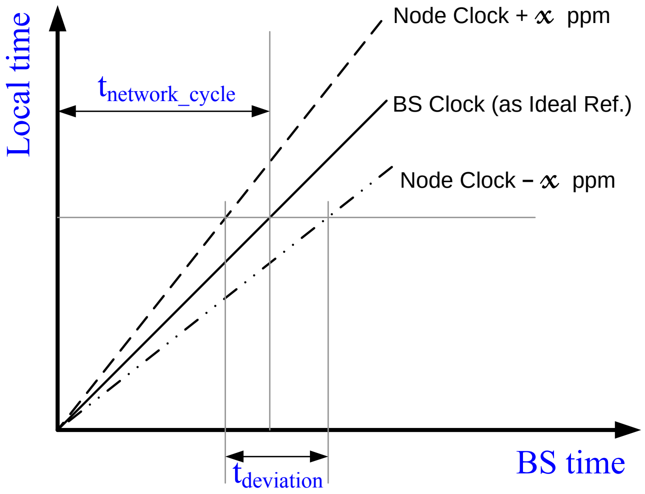


Figure 5.4: Clock drift illustration at a sensor node in worst case with respect to the ideal clock.

The relation between the clock drift value per one second and the clock frequency (f) is given in Equation (5-2).

$$P\_max_{(1MHz)} = \pm x \quad ppm$$

$$\boldsymbol{P\_max_{(fHz)}} = \pm \frac{\boldsymbol{x \times f}}{\boldsymbol{10^6}} \tag{5-2}$$

The deviation time is directly related to the maximum possible clock drift (worst case) with respect to the ideal clock as reference (BS clock in here). Then obviously the longer network cycle period ($t_{network\_cycle}$) which means lower sampling rate generates longer deviation time ($t_{deviation}$). The goal is minimizing the overall power consumption.

According to Equation (5-2), the number of clock drifts is proportional to the clock frequency, and then obviously it is proportional to inverse of the sampling rate. Because the higher sampling rate means the lower network cycle which covers less number of clock cycles. Therefore, if we add another parameter as sampling rate "S" to the formula in Equation (5-2), then it will represent the clock drift "k" in a network using an fHz clock with a sampling rate of "S" by Equation (5-3).

$$\boldsymbol{k} = \pm \frac{\boldsymbol{x \times f}}{\boldsymbol{10^6 \times S}} \qquad (5\text{-}3) \qquad ; \boldsymbol{Clock\ Drift\ for\ fHz\ in\ Network\ Cycle}$$

If a sensor node in a wireless network is expected to be properly synchronized with the BS, then its clock deviation by $\pm k$ part per network cycle must be taken into the account in the process.

5.5.3 STP

We define the Synchronization Tuning Period (STP) of the time within the network cycle for all network nodes in which the sensor nodes wake up and wait in listening mode for the synchronization message broadcasted by BS. This is important to let the sensor nodes seek the initial synchronization messages within as short period of time as possible at each cycle. The BS sends the corresponding synch message (T_RST_{msg}) at start of each network cycle based on its local timer generated by its own oscillator. The goal in here is to resynchronize each sensor node with the local time of the BS at starting of each network cycle in BS. This will reset and adjust the Data_Counter to eliminate any error as small number of clock cycles shifted to the left or right by clock deviation. The STP range is defined by k clock cycles given in Equation (5-3) before and after start of each Network Cycle. Then the STP range would be given in Equation (5-4) with respect to the Equation (5-3) and the definition for Network Time in Equation (5-1).

$$\boldsymbol{STP\,range} \in \boldsymbol{NT\,(0,0)} \pm \boldsymbol{k} \tag{5-4}$$

5.6 Sensor Node Algorithm

Each sensor node reads any of those two messages (T_RST_{msg} or T_SMP_{msg}) when needed and applicable. Any sensor node should be able to get into the network from any unknown and unpredictable time/event. This means that any sensor node can join the network starting from any random state. This would also consider the effect of any kind of noise on the corrupting the synchronization as well. According to the BS algorithm, each sensor node is supposed to receive the T_RST_{msg} message within the STP period [at: *NT(0, 0)* ± *k*], or T_SMP_{msg} message at the beginning of every sensor cycle. We consider all possible conditions in the two following cases;

Case-1 The sensor node is completely unsynchronized:

The sensor could be completely out of synchronization either because of noise or just activated in the network. In such rare cases, none of the ID and Data counters in the sensor node match their corresponding counters in the BS. Normally the sensor nodes based on this algorithm go to active mode and turn their receivers ON at the beginning of each network cycle [NT(0, 0) at sensor node]. If the sensor node could not detect the small T_RST$_{msg}$ message within its own STP range, then it will continue trying to seek any of the two messages within its entire sensor cycle (0). Because the time period between two consequent messages sent by the BS is one complete Sensor Cycle. This will guarantee that the sensor node in worst unsynchronized case will keep its wireless receiver in active mode for no more than one sensor cycle. After the sensor node receives any of the two messages, it makes corresponding decision to adjust its local network time. If the arrived message is “T_RST$_{msg}$“, then it resets both its ID and Data Counters. And if the arrived message is “T_SMP$_{msg}$“, then it only resets its Data_Counter and loads its ID_Counter with the arrived instant ID$_{BS}$ attached to the message as tail. At this moment, the Sensor Node is synchronized with the BS and can follow the simple process of reading only the small message at starting of each Network Cycle described as next case.

Therefore the characteristics of the message “T_SMP$_{msg}$“ are;

(a) Being broadcasted at start of every sensor cycle.

(b) Carrying the instantaneous ID of BS.

The purpose of this is to help the sensor nodes that are in crucial situation completely out of synchronization and cannot catch the message-1 (T_RST$_{msg}$) within the STP range. By this means, the sensor node that is lost in the real network time, can turn its receiver ON and wait for any of the two messages. And this will not last longer than a sensor cycle period. And then once the sensor node receives the synch message, it can immediately turn its receiver OFF and save the energy. This is another big advantage here, that the sensor node does not have to stay in ON status until the end of the sensor cycle, unless in worst case which rarely happens.

Case-2 The sensor node is recently synchronized and fine tuning is required:

This may happen all the time at every network cycle. The STP range has the most important role in avoiding high energy consumption in the synchronization processes. It lets the wireless receiver in sensor nodes to stay in sleep mode at all the times except within this range. Indeed, all other synchronization algorithms are suffering from very long term listening periods for synchronization messages. Next in section 5.7 we will show that how the duty cycling of this synchronization algorithm is so small by an example using "k" factor. By estimating a proper size for the STP range using the "k" factor, we can persuade all sensor nodes to seek for only small message of "T_RST_{msg}" within the short STP period. The sensor node after receiving the "T_RST_{msg}" can then reset its counters to fix any small error occurred by up to "k" clocks deviation, without waiting for long time for Time-Stamp messages. To do this, the sensor node could turn its wireless receiver ON only at the start of this range waiting to receive the small T_RST_{msg} message. Again in here like what described for case-1 the advantage is that the sensor node does not have to stay in ON status until the end of this period (STP). Because the message may arrive at any time within this range and once the node receives the message, then it can immediately turn its receiver OFF and save more energy.

The synchronization algorithm for the sensor nodes is given below:

General Synchronization Algorithm for Sensor Nodes:

```
Initializing and calculating air delay between BS and Sensor Nodes
Obtain  Constant "k"     // STP_range = NT (0, 0) ± k clock cycles
Start:  if   Sensor Node in STP_range                    then
            Power On the Receiver and wait for messages
            if       $T\_RST_{msg}$ message detected        then
                     Reset ID and Data Counters
                     Power Off the Receiver
            elsif    $T\_SMP_{msg}$ message detected        then
                     Reset the Data_Counter
                     Load ID_Counter with arrived ID by message
                     Power Off the Receiver
            elsif    $to_1$ (Time-Out1) activated           then
                Power Off the Receiver and wait for $to_2$
                on  $to_2$ (Time-Out2) exit
            end if
        end if
loop Start  // restart all
end.
```

The state table shown in Table 5.2 is a high level abstraction of Sensor Nodes algorithm followed by the corresponding Moor Machine state diagram in Figure 5.5.

Table 5.2: Synchronization state table for Sensor Nodes.

Current State	**Within Range?**	**Message(s)**	**Next State**	**Actions**
Initial	X	X	S0	**Reset System**
S0	X	T_RST_{msg}	S1	**RX_Power ON** Reset Data (↑) Reset ID (↑) Load ID (↑) **Reset Timer (↑)**
	X	T_SMP_{msg}	S2	
	X	to_1 (Time-Out-1)	S3	
S1	YES	X	S0	**RX_Power OFF** **Reset Data (↑)** **Reset ID (↑)** Load ID (↑) Reset Timer (↑)
S2	YES	X	S0	**RX_Power OFF** **Reset Data (↑)** Reset ID (↑) **Load ID (↑)** Reset Timer (↑)
S3	X	to_2 (Time-Out-2)	S0	**RX_Power OFF** Reset Data (↑) Reset ID (↑) Load ID (↑) Reset Timer (↑)

A watch dog timer is used to help the sensor nodes to save the small amount of energy in the tiny battery in the sensor node by controlling the receiver power within the specific range. Signal to_1 is used to power OFF the receiver after this time out when the sensor node in waiting for message for unexpected long time. After this time out, signal to_1 will be activated to report an error indicating no message arrived. Then it transfers the control to state-3 in Table 5.2 where the receiver is powered OFF. In this state the sensor node waits in sleep mode for enough longer period of time as defined by Time-Out(2) to prevent much energy waste. This state saves the sensor's energy when errors such as "no message from BS", or "problems in receiver" and etc occur. When the to_2 signal alerts in this state, the control will go back to the state-0 and start over again.

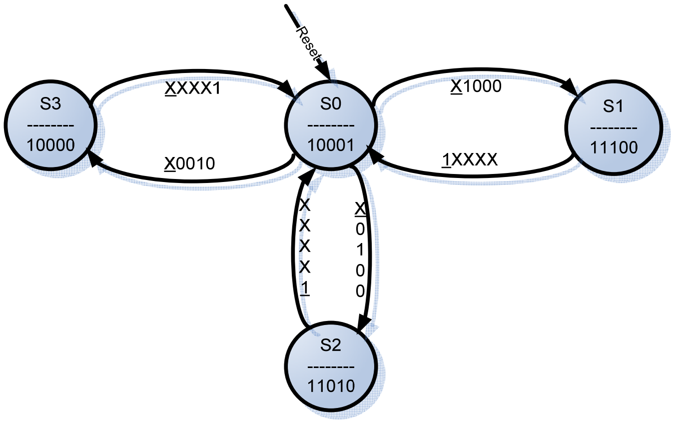


Figure 5.5: Moor machine State Diagram of the synchronization algorithm for sensor nodes.

The transition condition and the outputs of the states in the above state diagram for the sensor nodes are given as follows:

Transition Conditions: *[R, T_RST, T_SMP, to_1, to_2]*

Outputs of the states: *[P, RD, RID, LID, RT]*

where signal "R" notifies if the network time is within the STP range, signals "T_RST" and "T_SMP" notify arriving the time-reset and time-stamp messages respectively. The two predefined constants to_1 (Time-Out(1)) and to_2 (Time-Out(2)) are used for watch dog timer by tracking the network time.

In the output signals, "P" is the receiver power ON/OFF control, RD and RID are signals to reset the Data and ID counters, LID is a signal to load the current ID_{BS} into the sensor node's ID counter (ID_{BS} is attached to "T_SMP_{msg}" message), and RT is the signal to reset watch dog timer (time-out controller).

5.7 Duty Cycle and impact on Power Consumption

In order to present a good scalability of the network, we assume much higher data resolution with large number of sensor nodes distributed in the network. For example, according to Equation (4-1), assuming a data transfer rate of 256 kbps (2^{18} bps) in the network, the system could support 256 sensor nodes (8-bit), and each in data range of 1024 steps (10-bit). In such cases, after the first round of synchronization is done during the initialization phase, from then on as described in the synchronization algorithm for sensor nodes, only one synchronization message will be seeking per each network cycle. And the message is T_RST_{msg} to reset the network time NT (ID, D). Hence, disregarding the length of the first synchronization message (T_SMP_{msg}) in initialization phase, the synchronization duty cycle would be given in Equation (5-5).

$$\boldsymbol{SDC = \frac{l \times S}{f}} \tag{5-5}$$

Where SDC is the synchronization duty cycle, l is the length of the message in bits, S is sampling rate per second and f is the clock frequency.

Therefore for the above example assuming an 8-bit synchronization message and one sample per second, the synchronization duty cycling is as follow:

$SDC = 8 \div 256k = 3E\text{-}5 = 0.003\%$

And indeed this leads to a very low power Consumption.

K factor is defined by maximum clock deviation. This can also determine how frequent re-synchronization would be required. The advanced technology can offer very low power and high performance crystal oscillators. For example; an oscillating circuit functioning in 350 nA with a 5MHz quartz crystal oscillator has been developed [72] by a frequency deviation of about 2ppm at 2.2V. Proportionally, in our previous example with a clock rate of about 250 KHz at one sample per second, according to Equation (5-2) this oscillator can function by the following instability factor:

$$P\_max_{(250KHz)} = \pm\frac{2 \times 250KHz}{10^6} = 0.5\ Hz \qquad ;\ Clock\ Drift\ for\ 250KHz$$

This implies that the network time in this case will deviate at most by one clock cycle every two complete network cycles. Therefore, by bringing the frequency down to the required data rate, it will proportionally function better while results lower power consumption. It means based on small “k” factors, even may be resynchronization would be enough only once every few network cycles.

5.8 Simulation

The synchronization algorithms for the complete network system have been modeled and simulated in Matlab Simulink environment. In order to distinguish the DATA ranges and the ID cycles in the simulation results, this model is first defined with 16 sensor nodes each capable of scanning 16-step data resolution. The simulation results are shown in Figure 5.6 and Figure 5.7. Figure 5.6 shows how a sensor node joins the network randomly from an unknown and unsynchronized state. As shown in this figure, a sensor node enters into the network at unspecific time by incorrect ID and DATA status. Subsequently, the Figure 5.7 magnifies some critical portion of the events with better illustration of how the synchronization has been achieved. The comments embedded in the figure clearly illustrate the sequences on the events in the algorithm.

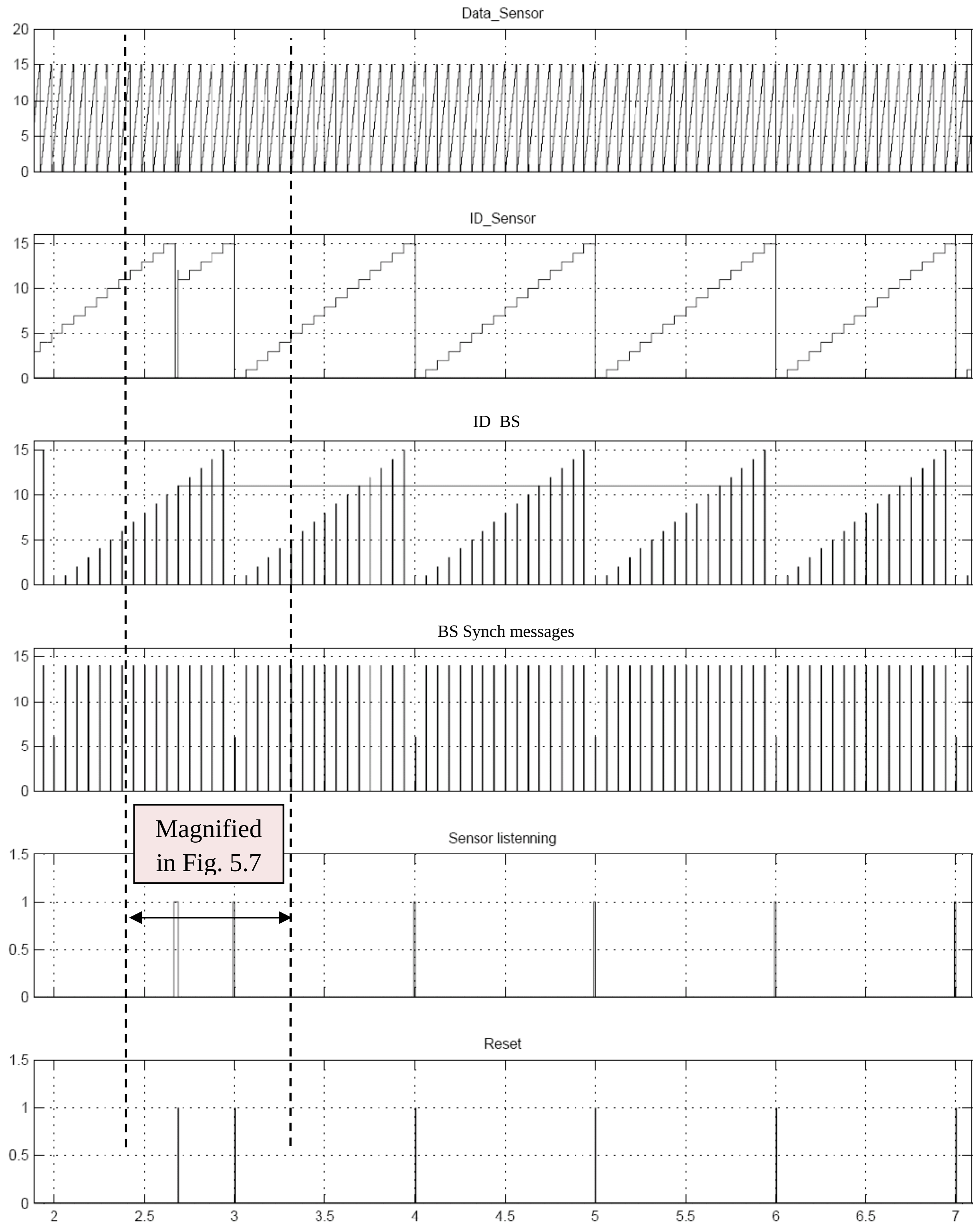


Figure 5.6: simulation results of the synchronization algorithm for TBCD communication protocol modeled in Matlab Simulink for 16 nodes each with 16-step Data resolution.

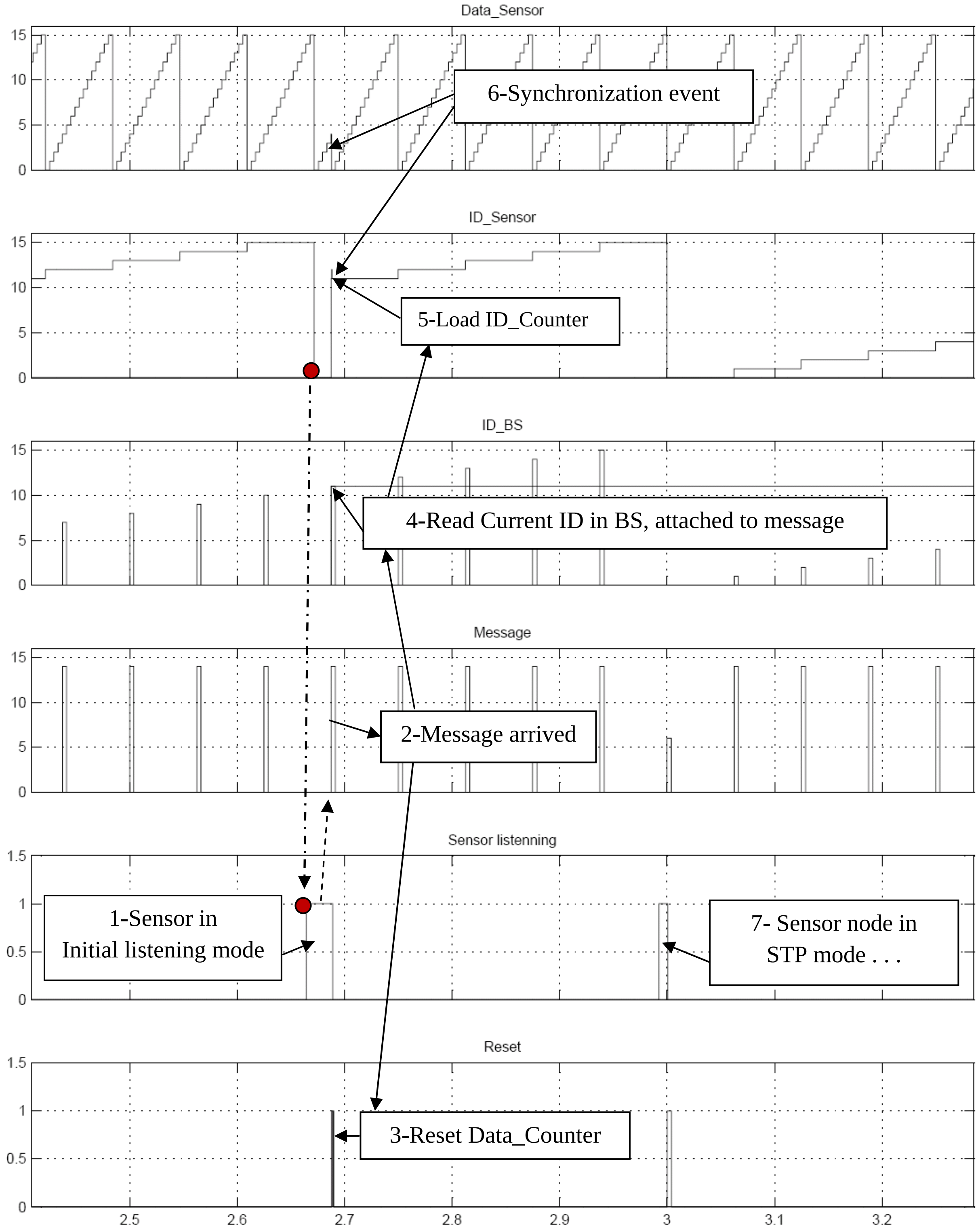


Figure 5.7: Magnified portion of the critical events in previous Figure.

5.9 Summary

In this chapter, we described the sensor nodes and the base station synchronization scheme in detail. The synchronization algorithm like the communication protocol is designed to be very energy efficient. We showed that the existing synchronization algorithms are not energy efficient for IWBSNs and cannot be used for such low energy application. Then the proposed novel low power algorithm in this work was presented in detail along with the proof of the concept. We demonstrated that how this algorithm can take significant part in saving the energy by its very small duty cycle.

In this chapter, we have verified the correctness and analyzed performance of the synchronization algorithms through modeling in computer simulation environment.

Conclusion
and
Future work

Chapter 6

6. CONCLUSION AND FUTURE WORK

6.1 Conclusion

Better and timely diagnosis of diseases and illnesses can benefit from implantable sensor technologies. Implantable sensor can provide accurate and real time patient data to adaptively control and customize treatments and drug delivery to individual patient needs. This will result in better patient care, better quality of life for the sick, and a significant reduction in cost for health care providers. A major hurdle in this regards is that the power consumption of a typical sensor node is so high that only a few days up to a few weeks of operation is practically possible with the current state of the art technologies. Such a short lifetime makes it unsuitable for implantable sensor node applications. We have analyzed and proposed novel solutions to this problem.

In this thesis, we have identified and analyzed the sources of energy use in sensor nodes meant for IWBSNs. Our analysis shows that improving the efficiency of a communication protocol results in the most significant amount of saving in the energy use. We have proposed a new energy efficient communication protocol and corresponding synchronization and delay estimation algorithms. The TBCD communication protocol efficiently encodes the data in time domain and guarantees accurate information transmission from the sensor nodes to their central base station (master node). The encoding scheme is very efficient as only a single signal needs to be sent for complete and accurate transmission of data from the sensor to the base station.

The proposed delay estimation and synchronization algorithms guarantee that even under worst case conditions sensor nodes can successfully synchronize with the base station and stay stable. The synchronization process involves base station listening and determining if a sensor node is present and alive. The novel synchronization algorithm does this very efficiently with very few steps and thus consumes very low amount of energy. We have verified the functional correctness of the communication protocol and synchronization algorithms using extensive computer simulations.

We have demonstrated that implementation of the communication protocol will lead to a significant increase in the lifetime of a senor node. Using this proposed communication protocol the lifetime of a sensor node can be increased by several orders of magnitude making it suitable for long term implantation into living tissues. In this thesis, our energy use analysis of the IWBSN components clearly shows that we can increase the life time of a sensor node from a few days/weeks to up to a few years using the proposed communication protocol with the current state of the art technologies.

The novel ideas and the communication protocol and the delay estimation and synchronization algorithms presented in this thesis are general enough for use in other low energy sensor network applications where amount of data to be sent is small. In this thesis, we have also provided a model for the sensor and base station communication. This includes the details of initial synchronization, delay estimation, and data transmission steps. We showed the correctness of the communication protocol and the delay estimation and synchronization algorithms through simulation.

6.2 Future work

As a future work, the performance analysis of the communication protocol can be done in terms of error rates under various non-ideal channel conditions. For example, how does the attenuation of signal as it propagates through the human tissue and the addition of other noise affects the performance of the communication protocol in terms of error rates. Based on our work in this domain, we believe that it would be very interesting to study the effect of noise on the performance of the synchronization algorithm. We believe that the functional correctness of the proposed communication protocol and the synchronization algorithms can be formally verified using formal verification techniques such as model checking. Due to the uncertain nature of the sensors and base stations coming online, probabilistic analysis of the functionality and performance of the communication protocol can also be done. Implementation of a practical prototype, for implantation in an animal perhaps, is another possible direction to physically verify the protocol in real life environment.

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