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Time Synchronization in ANT Wireless Low Power Sensor Network

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This thesis work is performed at Jönköping University within the subject area of Electrical Engineering. The work is part of the Master's Degree Program with the Specialization in Embedded Systems.

The authors are responsible for the given opinions, conclusions and results.

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Abstract

Short range wireless data communication networks that are used for sport and health care are sometimes called Wireless Body Area Networks (WBANs) and they are located more or less on a person. Sole Integrated Gait Sensor (SIGS) is a research project in WBAN, where wireless pressure sensors are placed like soles in the shoes of persons with different kinds of deceases. The sensors can measure the pressure of the foot relative to the shoe i.e. the load of the two legs is measured. This information can be useful e.g. to not over or under load a leg after joint replacement or as a bio feedback system to help e.g. post stroke patients to avoid falling. The SIGS uses the ANT Protocol and radio specification. ANT uses the 2.4 GHz ISM band and TDMA is used to share a single frequency. The scheduling of time slots is adaptive isochronous co-existence i.e. the scheduling is not static and each transmitter sends periodically but checks for interference with other traffic on the radio channel. In this unidirectional system sole sensors are masters (transmitters) and the WBAN server is the slave in ANT sense. The message rate is chosen as 8 Hz which is suitable for low power consumption. Hence in the SIGS system, it is necessary to synchronize the left and the right foot sensors because of low message rate.

In our thesis, we found a method and developed a prototype to receive the time synchronized data in WBAN server from ANT wireless sensor nodes in SIGS system. For this thesis work, a hardware prototype design was developed. The USB and USART communication protocols were also implemented in the hardware prototype. The suitable method for time synchronization was implemented on the hardware prototype. The implemented method receives the sensor data, checks for the correct stream of data; add timestamp to the sensor data and transmit the data to the Linux WBAN server. The time slots allocation in the ANT protocol was found. Alternative solution for the time synchronization in ANT protocol was also provided. The whole SIGS system was tested for its full functionality. The experiments and analysis which we performed were successful and the results obtained provided good time synchronization protocol for ANT low power wireless sensor network and for Wireless Bio-feedback system.

Sammanfattning

Trådlös korthållskommunikation, som används inom sport och hälsovård, kallas ofta ”Wireless Body Area Networks” (WBAN) och dessa placeras mer eller mindre på en person eller i dess omedelbara närhet. ”Sole Integrated Gait Sensor” (SIGS) är ett WBAN-forskningsprojekt där trådlösa tryckgivare placeras likt skosulor (invändiga) hos personer med olika typer av fysiska gångrelaterade problem. Sensorerna kan mäta trycket mellan fot och sko i ett antal punkter och därmed bestämma belastningen (kraften) för ett eller båda benen. Denna information kan användas i ett ”bio feedback system” för att hjälpa patienten att inte under- eller överbelasta ett ben tex. efter att en höftled bytts ut. Post-stroke-patienter kan ha försämrad förmåga att känna att de är nära att falla. Bio-feedback-systemet kan då användas för att jämföra belastningen på de båda benen och därifrån förutsäga om patienten är nära att falla och i så fall via t.ex. ljudsignal eller ett taktilt system göra patienten uppmärksam på vad som är på väg att hända. I SIGS-systemet är det nödvändigt att tidssynkronisera mätningarna från höger och vänster sensor (fot-sensor). SIGS använder ANT-protokollet för den trådlösa kommunikationen. Radiofrekvensbandet som används är ISM (2.4 Ghz). För att rymma flera kanaler på samma frekvensband används TDMA. ANT-sändarna sänder periodiskt i ”sin tidslucka” men om annan radiotrafik (ANT eller annan) upptäcks så provas med en annan tidslucka (”adaptive isochronous co-existance”). Systemet är konfigurerat för att vara enkelriktat och ”fotsensorerna” är sändare (”masters”) och WBAN-servern är mottagare (”slave”).

I detta examensarbete fann vi en metod och utvecklade en prototyp för att ta emot tidssynkroniserade data från ANT-sensor-noder i ett SIGS-system. I den använda metoden tas sensor-data emot av ANT-mottagaren i WBAN-servern. Mellan ANTmottagaren och WBAN-servern (Linux) finns en mikrokontroll-krets som tidsstämplar erhållna datapaket innan de skickas vidare till applikationsprogrammet i WBAN-servern. Alternativa metoder till tidsstämpling i mottagaren har också studerats.
Tester och analyser visar att tidsstämpling i mottagaren ger god uppskattning av samplingstidpunkten i sensorerna (”sole sensors”) i ett ANT-baserat trådlöst ”Bio Feed Back System”.

Acknowledgement

First and foremost I would like to express my gratitude to my supervisor Alf Johansson for his continuous supervision and suggestions throughout this thesis. As a master program coordinator, his long-term guidance and dedicated demanding time was very helpful in boosting our knowledge towards the electronics world.

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Keywords

Wireless Sensor Networks
Wireless Body Area Networks
Time Synchronization
Time Stamp Protocol
Global Clock Synchronization
ANT Protocol
Sole Integrated Gate Sensor
Health Care Systems

List of Abbreviations

SIGS	Sole Integrated Gait Sensor
WBAN	Wireless Body Area Network
TDMA	Time Division Multiple Access
USB	Universal Serial Bus
USART	Universal Asynchronous Receiver Transmitter
PCB	Printed Circuit Board
JTAG	Joint Test Access Group
WBSBN	Wireless Body Sensor Biofeedback Network
GSM	Global System for Mobile Communication
GPRS	General Packet Radio Service
FTDI	Future Technology Devices International
MCU	Micro-Controller Unit
MAC	Medium Access Control
RF	Radio Frequency

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1 Introduction

1.1 Wireless Body Area Network

In many developed countries, the aging population and rise in the costs of health care have stepped forward to introduce the novel technology-driven enhancements into the current health care practices. Recent advancements in the field of electronics have enabled the automation world to develop tiny and intelligent bio-medical sensors. The sensors can be worn on or implanted in the human body for different purposes. These bio-medical sensors shall send their data to an external server or PC, where the received data can be analyzed and stored for future purposes. For this purpose, using a wired connection seems too burdensome and it involves a very high cost for deployment and maintenance [17].

The use of wireless technology in the field of health care plays an important role and could be a possible solution to solve the wired connection problem. The use of a wireless interface for health care enables an easier application and is more cost efficient. The wireless technology could help the patient to experience a greater physical mobility and they are no longer compelled to stay in a hospital. This present trend could replace the bottlenecks in the past and could provide a greater enhancement for personal health care with low costs of the health care system.

In order to utilize the benefits of wireless technologies in telemedicine and for mobile Health care services in an efficient way, a new type of wireless network emerges: a wireless on-body network or a Wireless Body Area Network (WBAN) [17]. Short range wireless data communication networks that are used for sport and health care are sometimes called Wireless Body Area Networks (WBANs) and they are located more or less on a person. In WBAN, various sensors are attached on clothing or on the body or even implanted under the skin. The wireless nature of the network and the usage of wide variety of sensors in WBAN provide an environment to develop many new, practical and innovative applications to improve the health care.

1.1.1 Health care Applications

WBAN technology could provide a platform to support the elderly in managing their daily life and medical conditions. The main cause for the sudden death in the world is

Cardio Vascular Disease (CVD), representing 30% of all global deaths. An estimated world-wide population of about 17.5 million people dies of heart attacks or strokes each year [18]. These deaths could be prevented by continuous monitoring the patients and through proper health care with the help of WBAN technology.

Similarly, WBAN allows continuous monitoring of physiological parameters. To monitor patient’s health, it is not possible to monitor the patients with a shorter stay in the hospital. The use WBAN could help the patient to move freely whether in hospital or at home and it will be easier to monitor and collect the data of the patient for Doctors analysis. WBAN can also be used to offer assistance to the disabled and in treatment of many diseases.

1.2 SIGS

Sole Integrated Gait Sensor (SIGS) is a research project to develop a foot pressure activated feedback system for enhancing static and dynamic balance in elderly subjects who have suffered from a stroke. In this project, wireless pressure sensors are placed like soles in the shoes of persons with different kinds of deceases. The sensors can measure the pressure of the foot relative the shoe i.e. the load of the two legs is measured. This information can be useful e.g. to not over or under load a leg after joint replacement or as a bio feedback system to help e.g. post stroke patients to avoid falling.

1.2.1 ANT Protocol

In SIGS system, the protocol used for communication between two nodes is the ANT Protocol. ANT [8] is a practical and a proprietary wireless sensor network protocol. Its protocol stack enables the semiconductor radios to operate in 2.4 GHz ISM band. It is best suited for low power and low data rate sensor network topologies for Wireless Body Area Network (WBAN). It supports different data types in which the Broadcast data is the most basic and system default data type.

1.2.2 Time Synchronization

Time synchronization deals to provide a solution where the internal clocks of several systems may differ. Even if the clocks are initially set accurately, the real clocks will differ after some amount of time because of the clock drift in the systems which are caused by the clocks counting time, operating at slightly different rates.

Time synchronization protocols try to keep the nodes synchronized all the time irrespective of the energy constraints. By keeping synchronized all the time, the system could consume more energy. But for several wireless sensor applications, there is of no need for continuous synchronization. It could be of event-based. Depending on the requirements, the protocols could be chosen for the best efficient output.

1.3 Thesis Objectives and Tasks

The aim of this thesis is to find a method and develop a prototype to receive the time synchronized data in WBAN server from ANT wireless sensor nodes in SIGS system. The message rate used in SIGS is very low with 8 Hz, to consume less power. Hence it is essential to synchronize the system at low message rate. Whenever a data is received at WBAN / Linux server through ANT protocol, the received data is difficult to handle because of unknown sampling time. To overcome this problem, the new prototype was designed. The SIGS system shall also be tested in different environments for time synchronization and a detailed analysis will be made with suggestions for further improvements in time synchronization for ANT low power wireless sensor network.

In order to achieve this goal, a detailed study on ANT protocol and time synchronization protocols was made followed by SIGS system. With respect to the study, few decisions were considered such as suitable method for time synchronization, selection of processor for the prototype design and the software development environment. As part of the next step, hardware prototype design was developed. The developed prototype should be feasible for USB and USART communication. The suitable method for time synchronization shall be developed on the hardware prototype. The implemented method shall receive the sensor data, checks for the correct stream of data, add the timestamp value to the sensor data and transmit the data to the Linux WBAN server.

In SIGS, the sampled data need to be synchronized because of low message rate. The developed method shall provide time synchronization data for ANT wireless sensor network. But however, through this time stamp method, we shall measure as when the sensor data are sampled. The allocation of time slots in ANT protocol were also found and better solution for time synchronization is suggested. The developed system should be tested in different environments for analysis.

1.4 Thesis Layout

In this chapter, a brief introduction about this thesis is explained. We introduce with the discussion about WBAN and its application. We also discussed about the SIGS system, ANT protocol and Time synchronization. Finally, objectives and the tasks of the thesis were discussed.

In chapter 2, we describe about the theoretical background to understand the concepts of ANT Protocol and Time Synchronization Protocols. This chapter also describes about the reasons for choosing the protocol in our research.

In chapter 3, details about the WBSBN system and the reason for using this system for our thesis work shall be discussed. We will also describe about the research problem and it's provided solution.

In chapter 4, the design algorithm for the proposed solution to the research problem was discussed. The new design prototype for our research work was also described with its hardware setup, software setup and the software implementation.

In chapter 5, performance analysis of the SIGS system and ANT protocol was focused. Different testing phases and its obtained results were discussed with different graphs and tables.

In chapter 6, the summary of the contributions and the conclusion of the thesis work with plans for the future work were discussed.

2 Theoretical background

This chapter describes the theoretical background to understand the concepts of ANT Protocol and Time Synchronization Protocols. This chapter also describes about the reasons for choosing the protocol in the SIGS system.

2.1 ANT Protocol

2.1.1 Introduction to ANT protocol

ANT is a practical and a proprietary wireless sensor network protocol. Its protocol stack enables the semiconductor radios to operate in 2.4 GHz ISM band. The protocol is designed and marketed by Dynastream Innovations Inc., Canada. Its design is suited for any kind of low data rate sensor network topologies in practical wireless sensor networks (WSN), Wireless Body Area Networks (WBAN) and Personal Area Networks (PAN). All ANT powered network nodes can operate for years as compared to months for other technologies because of its energy efficient protocol.

In the OSI layer model of ANT shown in the figure 2-1, the protocol provides efficient handling of the Datalink, Network and Transport layer along with the physical layer provided by the Nordic 2.4 GHz radio. The top level Session, Presentation and Application layers are user-defined. The interface design between the ANT and Host application are made simpler for quick and easy implementation of ANT with new devices and applications.

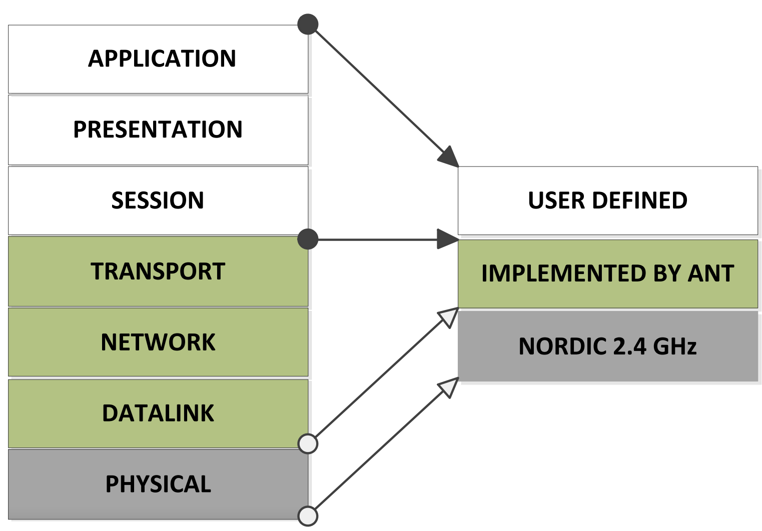


Figure 2-1 OSI layer model of ANT Protocol

ANT features,

i. It is highly resource optimized wireless protocol.
ii. Easy to use because of its maximum flexibility and scalability in its design.
iii. The protocol is fully integrated network and channel management
iv. Useful for sensor and control applications because of its low power and low cost.
v. Provides reliable data communications, flexible and adaptive network operation and cross-talk immunity.

2.2 ANT topology

The protocol is well designed such that it could support a large number of network topologies. It could be designed as a simple network which could work for uni-directional communication between two nodes to complex network for multiple node communication.

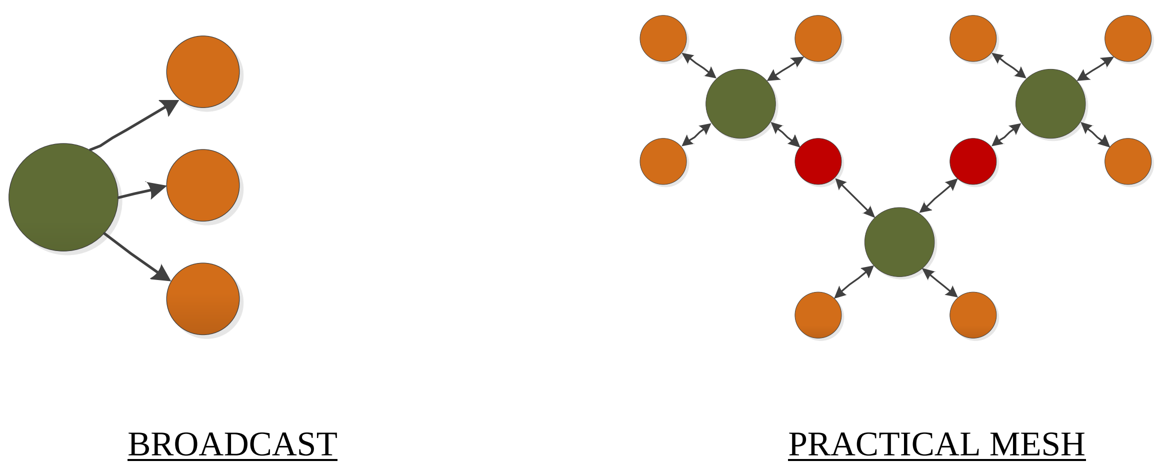


Figure 2-2 ANT Network Topology

2.2.1 ANT Node

ANT powered nodes are capable of operating both master and slave within a wireless sensor network. It could act either as a transmitter or receiver or both (transceiver). Each node in a network consists of an ANT protocol engine controlled by host controller (MCU) through serial interface. The ANT engine establishes and maintains the ANT connections, and also does the channel operation within its firmware. The host controller handles the particulars from the application to initiate the ANT communications with other nodes, which it does via a simple serial interface between host and ANT engine.

2.2.2 ANT Channel

In wireless communication, a connection between two nodes is established through channels. For a channel establishment between two nodes, one node should be a master and the other should be a slave.

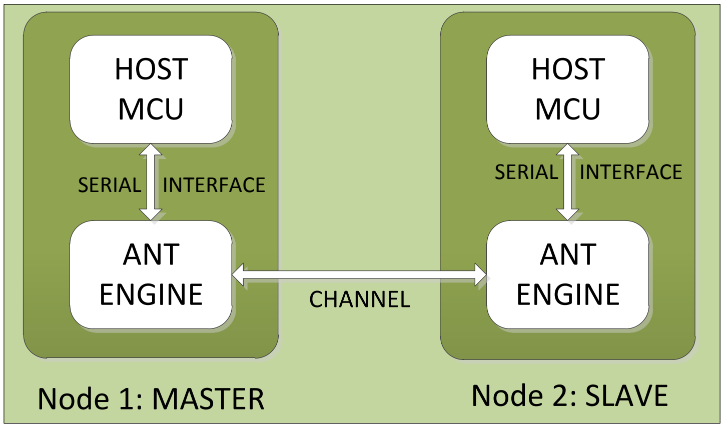


Figure 2-3. Channel communication between two nodes

The type of communication between nodes in ANT channel is determined by ANT data types such as Broadcast, Acknowledgement and Burst transfers. Whenever the Host application sends a data message to ANT engine for transmission, it specifies the data type along with the each data message it transmits.

The data messages between nodes are transferred in Forward (Master to Slave) or Reverse (Slave to Master) direction. Once the channel is opened for communication, a master device will transmit a message on each channel in their allocated time slot. The slave sends back the data to master optionally in reverse direction.

1. ANT data types

The ANT supports three types of data type. Each data type is sent in 8 byte packets over the RF channel [8]. The three data types can be sent in either the forward or reverse direction, at the channel's designated timeslot. But in case of uni-directional channels, it can only send broadcast data in the forward direction.

a. Broadcast Data

Broadcast data is the most basic and system default data type. On every timeslot, the broadcast data is always sent from Master node to Slave and vice versa only when there is a request from the slave's host MCU. When no new data is received from the host, the message will be re-transmitted as broadcast message even if the previous message sent is broadcast data or other data type.

Broadcast data is never acknowledged without any awareness of data loss. It consumes very less power and least amount of RF bandwidth because of one way transmission. It could be used at a place where occasional data loss could be tolerated such as temperature logging system etc.

b. Acknowledged Data

In bi-directional connection either of forward or reverse direction, an acknowledged data packet is sent back at the next time slot. Whenever a node sends an acknowledged data packet, the receiver responds with an acknowledgment message back to the sender. The host controller at the originating will get notified about the success or failure of the received packet from the receiver.

Acknowledged data packets consume more power and use more RF bandwidth because of bi-directional transmission, which should be taken into consideration when designing power-sensitive applications. It is ideally suited for the transmission of control data, ensuring that both nodes are aware of each other’s state [8]. For every new data transmission from master, the data types need to be specified. If no new data is provided at the next time slot, the message will be sent as Broadcast data as system default on the next channel time slot.

c. Burst Data

For large amounts of data transmission to be sent between devices, Burst data transmission is the preferred choice. It consists of a rapid series of continuous acknowledged data messages. Similar to acknowledged messages, the receiver MCU will be notified about the burst transfer’s success or failure.

In the burst data transmission the acknowledged success or failure notification will be for the entire burst transfer rather than for each packet. Any lost data packets in the burst transfer will be retried automatically and after five retries, the ANT will cancel the burst transfer and notify the host MCU with a failure message. If there are other channels in the system, care should be taken to service them with reasonable frequency.

The ANT protocol is robust and can handle the loss caused by burst transfers due to external interference. However excessive channel starvation because of channel traffic, may lead to loss of synchronization or data. Burst data transfer can create interference for other devices that are operating at the same RF frequency.

2. Channel configuration

For communication between two ANT nodes, channel need to be configured commonly in both the nodes. It needs some parameters that need to be commonly assigned in both the ANT nodes. These parameters once assigned, remains constant throughout its connection. But few parameters may be changed while the channel is open. For channel configuration, the following parameters are required.

1. Channel Type

It specifies the type of communication that will occur on the channel. The channel type is an 8-bit field and its value ranges from 0 to 255. Before establishing a channel, the channel types need to be specified. Some common channel types are given below [8].

VALUE	DESCRIPTION
0X00	Bidirectional slave channel
0X10	Bidirectional master channel
0X20	Shared Bidirectional slave channel
0X40	Slave receive only channel

Figure 2-4. Channel Type Description

2. RF Frequency

ANT Protocol uses all the available 125 unique RF operating frequencies considering the compatibility with international standard frequencies. Before establishing a channel, the RF frequency needs to be specified for both master and slave and the channel operates on single frequency throughout its operation. Even after the channel establishment, the RF frequency can be changed on fly, but their modifications need to be set at both the master and the slave.

The RF frequency is an 8-bit field and its value ranges from 0 to 255.The value assigned represents the offset in 1MHz increments from minimum frequency value of 2400MHz to the maximum frequency with 2524MHz. The following equation can be used to determine the value for the RF frequency field.

$$\text{RF Frequency value} = \frac{\text{Desired RF Frequency value (MHz)} - 2400\ \text{MHz}}{1\ \text{MHz}}$$

3. Channel ID

To establish an ANT channel, the host must specify its channel ID (for master) and the channel ID it wishes to search (for slave). The devices with matching channel IDs can communicate with each other. The channel ID is a 4-byte value which contains 3 fields.

Transmission Type
It is an 8-bit field used to define certain transmission characteristics of a device.
Device Type
It is an 8-bit field used to denote the class of each participating network device.
Device Number
It is a 16-bit field with unique number for a given device type.

The channel ID in the ANT protocol contains the device type, device number and transmission type of the master device and must be specified on the master device. On a slave device, these fields are set to determine which master device will communicate with the slave.

4. Channel Period

The channel period represents the basic channel message rate of data packets sent by the master. By default, a broadcast data packet will be sent and received. The channel message rate ranges from 0.5Hz to above 200Hz.

The channel period is a 16-bit field with its value determined by the following equation.

$$\text{Channel period value} = \frac{32768}{\text{Message rate (Hz)}}$$

The default message rate is 4Hz, which is chosen to provide good and robust performance. The maximum message rate (or the minimum channel period) depends on the computational capacity of the system.

5. Network

To communicate between two ANT nodes, they need to be members of the same network. The ANT Network has two components.

Network number:
It is an 8-bit field that identifies the available networks on an ANT device, with acceptable values ranging from 0 to the maximum number defined by the ANT implementation.

Network key:
It is an 8-byte number that uniquely identifies a network and can provide a measure of security and access control.

2.3 Why ANT Protocol

For a practical wireless network, the batteries powering nodes need to last for months (or even years) to minimize maintenance. For this purpose, Low power consumption is very essential. Most of the protocols are built to provide utmost its best solution.

ZigBee Alliance describes ZigBee to be a "low power" alternative. This is obviously true when it is compared with Bluetooth. However, Bluetooth is designed for rapid transfer of large amounts of data from devices and it uses relatively large batteries. But, when compared with ANT, 4 times lower power and 60 % BOM cost of a ZigBee node. It provides a much simpler sensor with coin celled battery for ultra low power and much simpler network development environment. The figure 2-5 below shows few technical comparisons between the 3 protocols.

Market name	ANT	ZigBee	Bluetooth
Standard	Proprietary	IEEE802.15.4	IEEE802.15.1
Battery life (with coin-cell battery)	3+ years	4 to 6 months*	1 to 7 days*
Max. network size (nodes)	2^32	2^64	7
Over the air transmission rate (kbit/s)	1000	250	1000
Range (metres)	1 to 30	1 to 100+	1 to 100+
Success metrics	Ultra-low power, cost	Power, cost	Cost, convenience
Min. node configuration	Transmit only or transceiver	Transceiver	Transceiver

Figure 2-5. Comparison between different Protocols

2.4 Time synchronization

2.4.1 Time synchronization in wireless sensor networks

For any distributed system, Time synchronization plays a key role in the system. Even in distributed wireless networks, synchronized time are used extensively. For example, operations in a distributed control system includes the monitoring of real time sensor values from different sensors, detection of alarm signals and the execution of control algorithms relevant to sensor values. Different processes are executed at different nodes need to be time synchronized for a better performance of the system.

Time synchronization deals to provide a solution where the internal clocks of several systems may differ. Even if the clocks are initially set accurately, the real clocks will differ after some amount of time because of the clock drift in the systems which are caused by the clocks counting time operating at slightly different rates. We will discuss about few protocols used for time synchronization in wireless sensor networks.

2.5 Time synchronization protocols

Time synchronization protocols try to keep the nodes synchronized all the time irrespective of the energy constraints. By keeping synchronized all the time, the system could consume more energy. But for several wireless sensor applications, there is of no need for continuous synchronization. It could be of event-based. Depending on the requirements, the protocols could be chosen for the best efficient output.

1. **Network Time protocol**

The Network Time protocol is used most widely and is a classical protocol in the internet domain devised by David L.Mills [21]. It is used to synchronize computer clock times within the computer network .The NTP clients synchronize the system clocks with the NTP time servers with accuracy in the order of milliseconds. The time servers are synchronized by external time sources, typically using GPS. The NTP proved to be effective, fault tolerant, secure and are highly scalable protocol.

However in WSN, non-determinism in transmission time caused by the Media Access Channel (MAC) layer of the radio stack can introduce several hundreds of milliseconds delay at each hop. Therefore, without further adaptation, NTP is suitable only for WSN applications with low precision demands [21].

2. Reference Broadcast Synchronization

It is one of the prominent examples of existing time synchronization protocols. In the RBS, a reference message is broadcasted. This protocol is based on receiver/receiver synchronization. When the reference message is broadcasted, the receiver's record their local time and exchange their recorded local time-stamps with each other. The main advantage of Reference Broadcast Synchronization protocol is that it eliminates transmitter-side non-determinism [21].

The disadvantage of this type of protocol is an additional message exchange is necessary to communicate the local time-stamps between the nodes. The Reference Broadcast synchronization becomes expensive in terms of additional message transfer and computation which could be a good choice for low power wireless networks.

3. Timing-Sync Protocol for Sensor Networks

The Timing-Sync Protocol for Sensor Networks is based on sender/ receiver synchronization protocol. The TPSN protocol creates a spanning tree of the network and performs pair wise synchronization on both the sides. Each node gets synchronized by exchanging two synchronization messages by time-stamping at the sender side as late as possible and time-stamping at the receiver side as earlier as possible.

The TPSN achieves two times better performance than RBS by time-stamping the radio messages in the Medium Access Control (MAC) layer of the radio stack and by relying on a two-way message exchange. The shortcoming of TPSN is that it does not estimate the clock drift of nodes, which limits its accuracy, and does not handle dynamic topology changes [21].

2.5.1 Time synchronization in ANT wireless sensor networks

For synchronization between two nodes, the ANT protocol uses TDMA techniques for its communication channels. TDMA techniques combined with the ANT multiple access channel technology plays a major role for the users to use two to thousands of nodes to be connected to an ANT network. In communication between two nodes, the messages are transmitted in forward direction at designated channel period. Once the channel is opened, the master will send the message in its allocated time slot and wait for the next allocated time slot to sent as shown in *figure 2-6*.

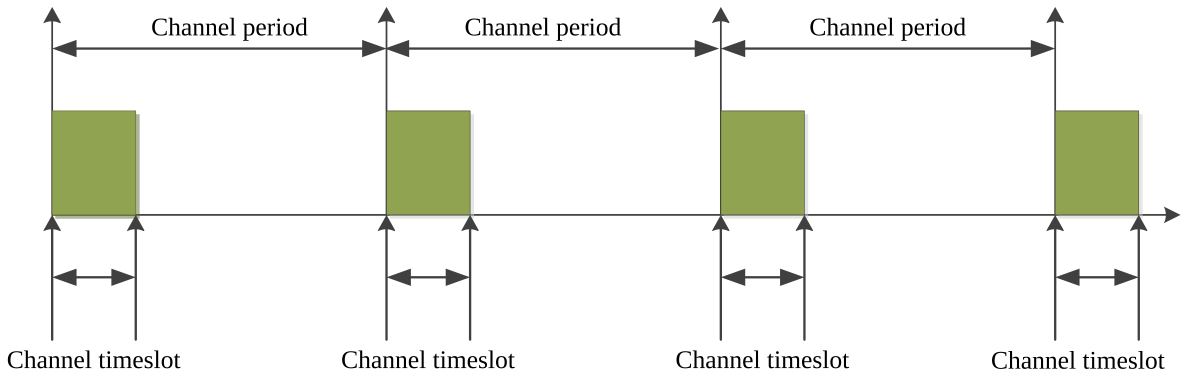


Figure 2-6. TDMA technique in ANT protocol

If two nodes try to transmit the messages to receiver, both the nodes sent the messages at their allocated time slots. As the protocol is proprietary and the scheduling of time slots is adaptive isochronous co-existence i.e. the scheduling is dynamic. However they seem synchronized, but it is unknown about how they are synchronized. So in this research, a method to know about how the timeslots are allocated and to improve the synchronization was found. The Figure 2-7 below shows about how the two nodes adjust themselves to communicate with the receiver.

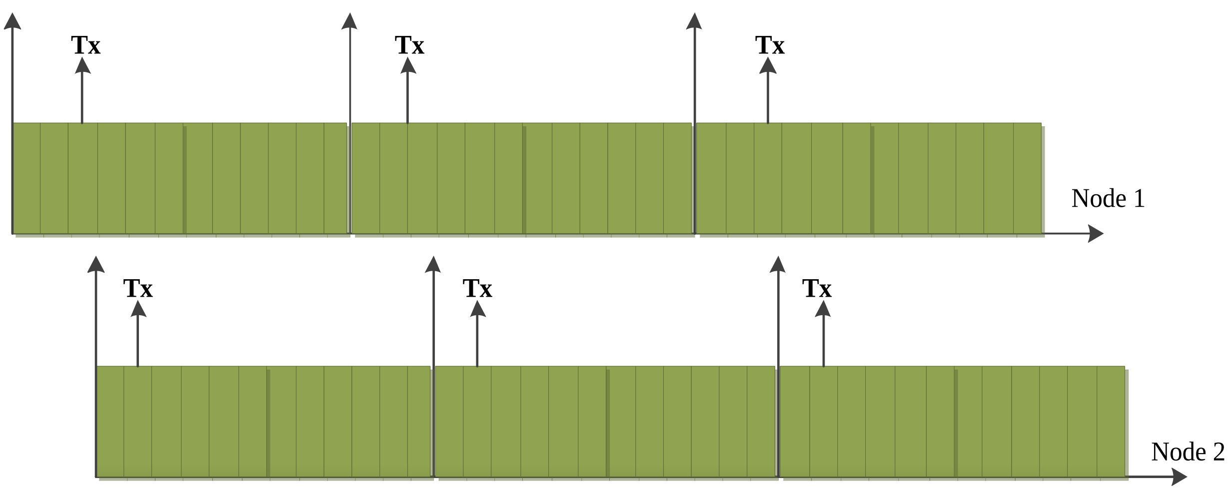


Figure 2-7. Time slots allocation in ANT Protocol

1. Time stamping

A timestamp is the recorded time of a current event in the system. The timestamp protocol is one of the protocols that are used for different synchronization purposes, such as to assign a sequence order for a multi-event transaction through which if a failure occurs, the transaction can be voided. A timestamp is used to record time in relation to a particular starting point.

For example, in IP Telephony, the Real-time Transport Protocol (RTP) assigns sequential timestamps to voice packets. Through the timestamps the receiver can check the packets in sequential order, reassemble it, and deliver it with no errors. In video processing, if there is a time stamp for each video frame and there is a reference clock, then the video player just needs to read the time stamps and wait until the right time to put each frame on the display.

In wireless sensor networks, the timestamp are very essential for each packet transfer through whom we could detect as when the packet is sent or received. It is a well known method for obtaining the estimates of clock differences between pair of nodes which can directly communicate. It is based on exchange of time-stamped packets. In this research work, timestamps are used to find exactly how the timeslots are assigned. By this method, message shall be received with timestamp data through which when the messages are created at the sender side and received at the receiver shall be known.

2. Global clock synchronization

Time-stamping could provide the information about when the messages are sent and received. We could also suggest some improvements for the better performance of synchronization. Using global time for synchronization could be of possible way for global synchronization.

For measuring the progression of time or to measure the time duration between the events, the physical clocks are used. The physical clock contains a counter, and a physical oscillation mechanism that periodically generates an event to increase the counter. This periodic event is called the micro-tick (i) of the clock. The duration between two consecutive micro-ticks is the granularity of the clock [22]. If two clocks are working concurrently, each clock oscillation might vary with a clock drift. A reference clock is possessed by the external observer who can observe all the events. It is used as reference time to measure and to check for the accurate time as per the international standard time.

a) Clock drift (ρ)

In real time applications, clocks used might vary in their oscillations. The clocks speed might vary such that the clock does not run at the exact speed as compared to other clock depending on different conditions. This phenomenon is known as clock drift. Assume that there are two clocks, physical clock (k) and the reference clock (r). The drift of a physical clock k between micro-tick i and micro-tick i+1 is the frequency ratio between this clock k and the reference clock, at the instant of micro-tick i.

Real clocks might have varying drift rates which are influenced by different environmental conditions such as, a change in the ambient temperature, a change in the voltage level that is applied to a crystal resonator, or aging of the crystal. Within specified environmental parameters, the drift rate of a resonator is bounded by the maximum drift rate ρ max which is documented in the data sheet of the resonator. Typical maximum drift rates ρ max are in the range of 10^{-2} to 10^{-7} sec/sec, or better, depending on the quality (and price) of the resonator. A good clock shall have a drift rate very close to 1. Because every clock has a non-zero drift rate, free-running clocks, i.e., clocks that are never resynchronized, leave any bounded relative time interval after a finite time, even if they are fully synchronized at startup.

b) Global time

“A global time is an abstract notion that is approximated by properly selected micro-ticks from the synchronized local physical clocks of an ensemble”[22]. For the clocks to get synchronized, the use of global clock will be a perfect possible solution. As the clocks drift with each other, the global time could provide synchronized time to adjust the clocks with respect to it.

c) Global clock synchronization

Assume that there are different nodes with clocks and a global clock in the network as shown in the *Figure* 2-8. The clocks drift with each other at different environmental conditions. In order to get synchronized, the clocks need to adjust themselves equally in order to continue their communication process. The local clocks needs to be periodically synchronized with global clock in the network in order to establish a global synchronization within the network. The global clock will generate its clock value with its time stamp and transmit periodically to the local clocks. The local clocks adjust their time with respect to the global clock. There are two types of synchronization.

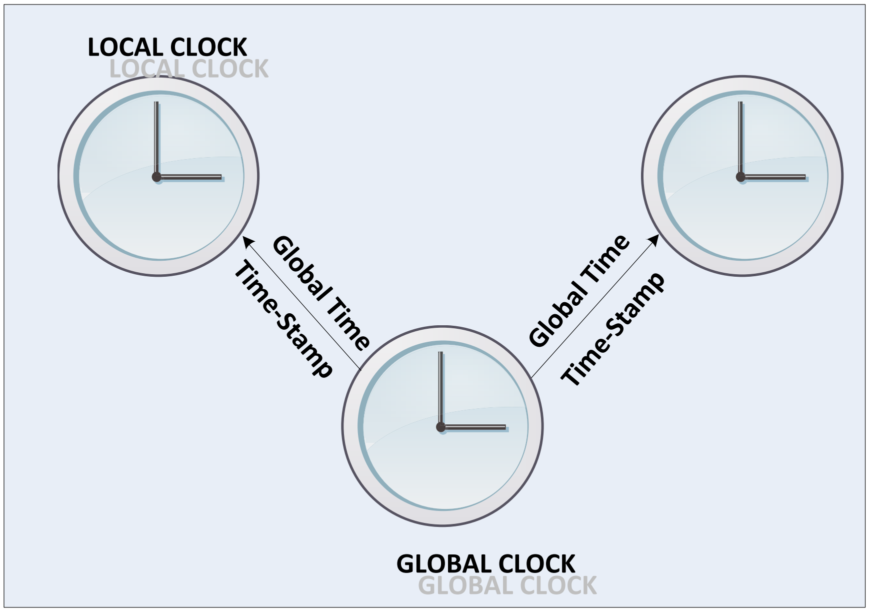


Figure 2-8 Global clock Synchronization

i) External Synchronization

To keep a clock within a bounded interval of the reference clock, it must be periodically resynchronized with the reference clock. This process of resynchronization of a clock with the reference clock is called external synchronization [22].

ii) Internal Synchronization

The drift rate of any physical clock shall drift as compared to other clocks in the network, if they are not resynchronized periodically (i.e., brought closer together). The process of mutual resynchronization of an ensemble of clocks to maintain a bounded precision is called internal synchronization [22].

3 Wireless Body Sensor Biofeedback Network

Wireless Body Sensor Biofeedback Network (WBSBN) is a research project for gait analysis and feedback. The purpose of this research project is to analyze, plan and treat the individuals who are affected with some inabilities in their foot motion while walking and to avoid the individuals from falling down who affected with stroke. In this chapter, we will discuss about the WBSBN system and the reason for using this system for our thesis work. We will also describe about the research problem and it's provided solution.

3.1 Introduction to gait analysis

Gait is defined as a manner of walking in which we move our whole body from one point to another. Gait analysis is a method used to assess the way we walk or run to highlight biomechanical abnormalities. From the earliest days, the gait analysis and its measurements are found useful in the management of patients with walking disorders [1].

At present time, patient's falls are one of the most frequent complications leading to injury and death among the elderly and disabled community [2]. Typically falls occur in the home, particularly when descending stairs or negotiating objects. The patients who are affected by brain strokes, falls into this category, which leads them to severe injury. To avoid the injuries and to reduce the incidence of falls among the patients are considered as a key priority by national and international policy makers.

To achieve with a best solution, a device need to be built with good feedback. Hence biofeedback part is proposed for this research, to investigate its effects as a balance training tool. It would be particularly interesting to integrate this phase of the study with Wireless Sensor Networks in the home. This would allow the investigators to determine the types of activities that subjects are performing when their gait deteriorates.

3.2 Feedback Systems for Health Care

Patients suffering from Cerebro Vascular Accident (CVA) have been demonstrated and it was found that there are at an increased risk of falls and fall related injuries. It was investigated that patients who had strokes and were living at home, their falls are more than twice than the rest of the elderly community [2].The falling could create a greater risk of hip fractures, orthopedic injuries and loss of independence.

In order to avoid these falls, a solution should be found to save the patients from injuries. There are numerous foot pressure measurement devices currently available on the market. Commercialy available systems include the F-Scan (Tekscan, Inc) and Pedar systems (Novel Inc), which are designed to provide precise information regarding the distribution of pressure under the foot. These devices are used particularly in laboratory settings for diagnosing the areas of high pressure under the foot. Because of wired system, usage limits the user's activity range and they are of high cost.

Most of the feedback systems have one common feature, namely that they all focus on the sensor, i.e. the input, but not so much on the feedback, i.e. the output. The feedback element offers a substantial technical challenge in developing the tool, which in turn also requires insight in Human Machine interaction (HMI) aspects, especially when if comes to designing it for people with sustained brain injuries such as clients with stroke.

3.3 Sole Integrated Gait Sensor Analysis

In this section, we discuss briefly about the WBSBN system and how it is efficient as compare to the existing systems.

3.3.1 What is SIGS

Sole Integrated Gait Sensor Analysis (SIGS) is a research project to develop a foot pressure activated feedback system for enhancing static and dynamic balance in elderly subjects who have suffered from a stroke. In this project, wireless pressure sensors are placed like soles in the shoes of persons with different kinds of deceases. The sensors can measure the pressure of the foot relative the shoe i.e. the load of the two legs is measured. This information can be useful e.g. to not over or under load a leg after joint replacement or as a bio feedback system to help e.g. post stroke patients to avoid falling.

The research was started, to design and built a system which has the ability to measure and provide immediate feedback to patients regarding the distribution of weight through their feet. It has enormous potential for the rehabilitation industry and prevention injuries. Hence the main goal of SIGS system is to develop a tool that can be used while performing activities of daily living and need to be able to warn the individuals when the load through the feet is not optimal and to encourage them to alter their loading in response to the feedback.

The SIGS system can be used to provide a real-time biofeedback of pressure distribution on plantar surface during stance phases of gait. This could be helpful to diagnose and treat patients, especially the elderly, suffer from walking disease everyday. The proposed system will also be possible to use as a biofeedback system for motion limitation after hip surgery and for balance control for post stroke patients.

3.4 System Architecture

The system was built in a star topology WBAN fashion which includes a central node and two leaf nodes as shown in Figure 3-1. The central node is a personal server which is NeoFreeRunner Smartphone along with an ANT USB stick transceiver unit. The central node could be attached to the user’s belt or it can be hanged on the user’s neck. On the other side, the leaf nodes or SIGS consist of a foot pressure sensor and an ANT transceiver unit. The leaf node will continuously transmit data to the central node whenever they are active ie., triggered by the movement sensors.

Sole Integrated Gait Sensor (SIGS)

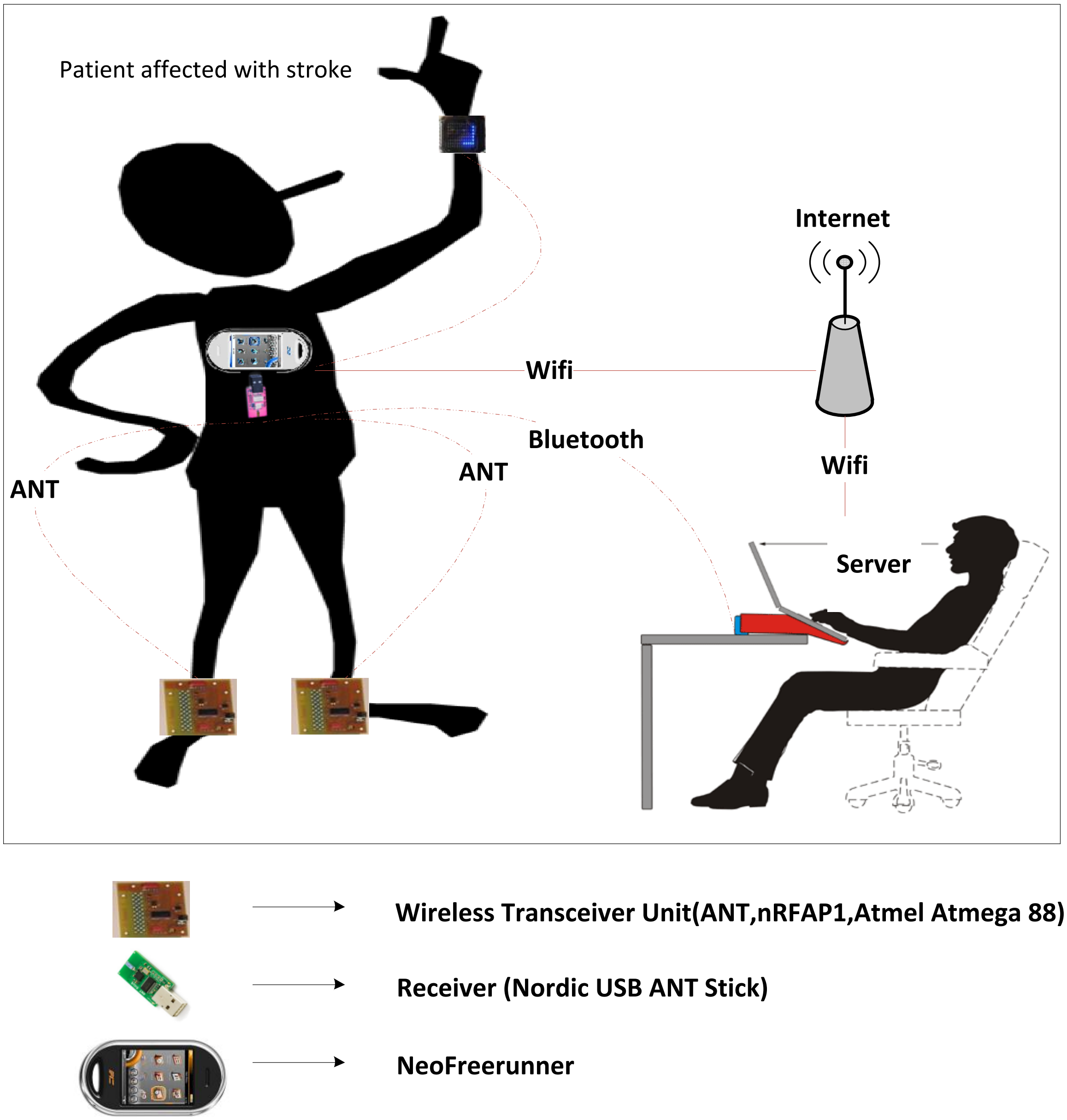


Figure 3-1 Sole Integrated Gait Sensor

3.4.1 Central Node or Personal Server

In this research, the Neo FreeRunner Smartphone is used as a personal server whose function involves the data analysis and to generate the biofeedback signals like audio warning signal. It also acts as a bridge between the WBAN and the home server as shown in the figure 3-1. The receiver ANT (Nordic USB ANT stick) is attached with the Smartphone through USB port.

1. Neo Freerunner

The Neo FreeRunner is a Linux-based touch screen smart phone developed to run Openmoko software. It was manufactured by First International Company, Inc. and was aimed at general consumer. They are even used by Linux desktop users and software developers. The Smartphone is built on ARM 920T core controller from Samsung (S3C2442B). It is a multichip module which includes processor, memories and IO and it is clocked at 400 MHz [7].

Some of the features include,

- *VGA touch screen*
- *Wi-Fi*
- *GPRS 2.5G*
- *Bluetooth 2.0*
- *GNU/Linux*
- *USB*

The application built software was developed on Linux platform to run on Neo FreeRunner. The software is responsible to receive the sensor data from ANT USB stick, which is attached to the USB port of the Smartphone. On receiving the data, the Neo FreeRunner acts as a server by alerting the patient with biofeedback, records the data if desired or forward the data to the home server or health center by Wifi, Bluetooth or GPRS/GSM.

2. ANT USB stick

The ANT USB stick makes it possible to communicate easily between the Nordic nRF24AP1 transceiver and Neo FreeRunner Smartphone. The ANT USB stick is greatly helpful in the development of hardware using the ANT protocol [8] and it is very easy to use because of its USB connection. The details about the ANT protocol are described briefly in our previous chapter of this document.

The Nordic nRF24AP1 transceiver used in the hardware is an ultra-low power single-chip radio transceiver with embedded ANT protocol for personal area networks [9]. The transceiver's RF operating frequency ranges within the 2.4 - 2.5 GHz RF ISM band. Whenever the data is been transmit from the leaf nodes , the ANT USB stick receives the data through nRF24AP1 transceiver and sends it to the Smartphone using FTDI COM port drivers by just connecting the hardware via USB with the Neo FreeRunner Smartphone.

3.4.2 Leaf Nodes or SIGS

The SIGS system as shown in the figure 3-2 acts as a leaf node which consists of a wireless transceiver unit and the foot pressure sensor from Tekscan. In this system, the Tekscan sensor is used together with the wireless sensor node to transmit the sensor data to the personal server.

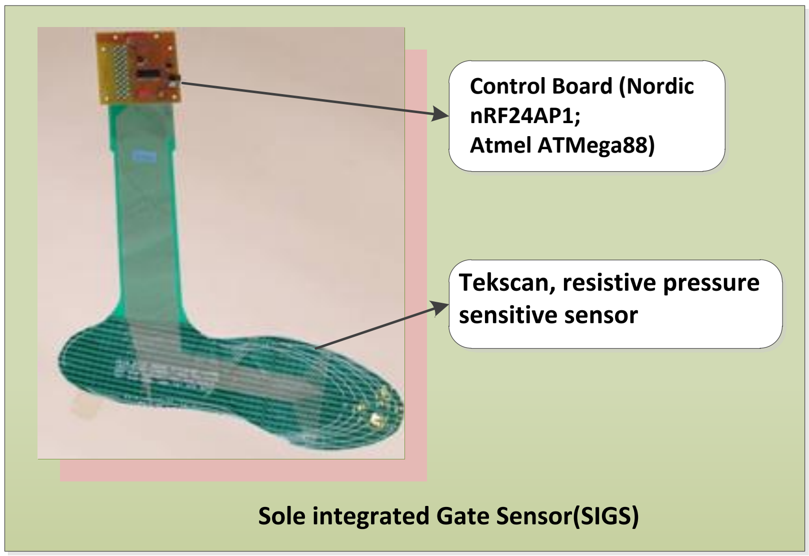


Figure 3-2 Leaf Nodes or SIGS

1. *Wireless transceiver unit*

The wireless transceiver was designed in such a way, that it shall get the sensor values from the foot pressure and sent it to the personal server through a transceiver. For this unit, a board was designed and implemented with different components on PCB.

1. *Transceiver nRF24AP1 with Trace Antenna*

This is a small breakout board with circuit for the Nordic nRF24AP1 transceiver [10]. The transceiver IC is capable of talking with other wireless products which is built on ANT protocol. In this unit, it sends the foot pressure sensor value to ANT USB Stick attached to the Neo FreeRunner Smartphone.

2. *Atmel Atmega88 microcontroller*

The ATmega88 [11] is a low-power CMOS 8-bit microcontroller based on the AVR enhanced RISC architecture. Its powerful execution of instructions in a single clock cycle, the ATmega88 achieves throughputs approaching 1 MIPS per MHz which allows the system designer to optimize power consumption versus processing speed. Its feature with high performance and lower power consumption helps the system designer in providing a best solution for low power wireless applications. The microcontroller could communicate with the ANT transceiver through synchronous serial interface.

2. F-Scan sensor

F-scan sensor [12] is extremely thin with high resolution provides the most accurate data to the user. F-scan is a system manufactured by the Tekscan Company. The pressure sensor used is F-Scan 3000 which is used for foot pressure measurements. It consists of two polyester films coated with printed conductive silver wires in a matrix. They are widely used in both clinical and biomedical studies because of its dynamic response towards pressure loading.

3.5 System Design and parameters

The F-scan foot pressure sensor has hundreds of sensor pressure sensitive resistor elements. The pressure sensors are arranged in a matrix. The sensor elements are arranged in a matrix with six columns and four rows. Twenty four values are captured from the sensors. The twelve values from the toe part and twelve values from the heal part are added and scaled to form a two words of data. These are sent to the personal server via ANT network.

In order to send the data to the personal server, it is necessary to synchronize the left and the right foot sensors. The ANT network uses the 2.4 GHz ISM band and TDMA is used to share a single frequency. The sampling rate is 8 samples/sec and the message rate is 8 messages/sec (bit rate is 1 Mbit/sec). In this unidirectional system, sole sensors are masters (transmitters) and the ANT USB stick connected to the personal server is the slave (receiver). The parameters assigned for the ANT network are shown in the *Figure 3-3* below.

The data type used in this system for communication is Broadcast [8] data type. Independent ANT logic channels (timeslots) are assigned for both the sole sensor, such that one time slot for each sole sensor. The two ANT logic channels share the TDMA cycle. Different channel ID’s need to be assigned for the transmitters such that the receiver could identify the exact data from the transmitter i.e., from right sole or left sole.

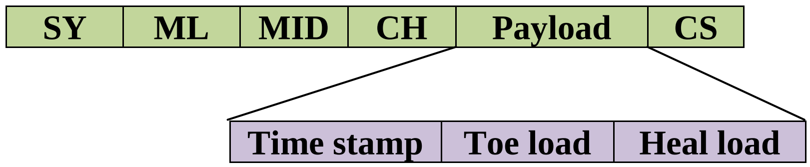
Radio channel		**66 (2466 GHz)**
Network		0 (Default public)
Network key		Public for network 0
Channel ID		
	Transmission Type	0x01
	Device Type	
	Device Number	Individual Serial #
Channel Type		Bidirectional TX (0x10)
Message Rate		8 Messages/s
Data type		Broadcast

Figure 3-3 ANT Protocol parameters

3.5.1 Time synchronization

Whenever the ANT transceiver receives the pressure sensor value from the corresponding sole pressure sensors, it checks for the free time slots in ANT channel. If the channel is free, the ANT sends the message packet to the server. Similarly, the other sole does the check for channel timeslots and sends the packet. As the message rate is 8 messages/sec, the ANT node checks for the time slot after every 125 ms and if the channel is free, it sends the data to the receiver node. The message structure of the data packet is given below as shown in Figure 3-4.

Once the packet is received by the ANT USB stick (receiver), it forwards the data to the Neo FreeRunner Smartphone (server). The transmission speed of the ANT transceiver is high and is considered to be few microseconds. The software developed at Linux platform for the WBAN server shall receive the data packet and stores in its buffer for the future reference. On receiving the data, Neo FreeRunner Smartphone acts as a server by alerting the patient with biofeedback records the data if desired or forwards the data to the home server or health center by Wi-Fi, Bluetooth or GPRS/GSM.



Field name	Bytes	Description
SY	1	Sync, 0xa4 Fixed value
ML	1	Length ,0x09
MID	1	Data type ID
CH	1	Channel number
Time stamp	2	ms(or sequence #)
Toe load	2	Raw sensor data
Heal load	2	Raw sensor data
CS	1	XOR of all previous data

Figure 3-4 ANT message structure of the data packet

3.6 Reason for the extended research

The system was tested and experimented considering different parameters. The system has a good performance in power consumption, communication latency, coexistence with both Wi-Fi and Bluetooth. This research project could provide a method to synchronize the measurements in two ANT enabled sole sensors in WBAN where gait and body motion analysis shall be used to predict falling for post stroke patients.

As discussed in chapter 2 of this document, protocol is a proprietary protocol .The scheduling of time slots is adaptive isochronous co-existence i.e. the scheduling is not static and each transmitter sends periodically but checks for interference with other traffic on the radio channel. The transmitter sends the packets in the allocated time slots. Normally there is no time stamping or sequence numbers marking of the ANT data packets and there are possibilities of packet loss.

To take care of lost data in the SIGS system the packets are given sequence numbers when they are sent from the sole sensor nodes. But however, the details about the data packets when they are sampled or received in the SIGS system are unknown. Hence the time stamping is necessary because of the fact that lost packets will make the two sole measurements totally out of phase after a while and also to measure the sampling point in the SIGS system.

In order to find out a way to synchronize the sample data from the two soles and to measure the actual sampling point in the SIGS system, few questions came across in our thesis research work.

1. How good is the time synchronization in SIGS?
2. What happens when there are any external disturbances?
3. How the time synchronization in ANT protocol works?
4. Possible way to measure the time at which the data is received at WBAN server or transmitted from the sole pressure sensors.
5. Alternative option to improve the better time synchronization for SIGS?

The systematic approach to solve the research problems and to provide the best possible solution will be discussed in the chapter 4 of this document.

4 Implementation

In the previous chapter of this document, the research problems in the SIGS system were discussed and came out with few research questions. In this chapter, the design algorithm for the proposed solution to the research problem will be discussed. The new design prototype for our research work, its hardware setup, software setup and the software implementation shall also be discussed.

4.1 Research method

For a systematic process in research, a procedural approach method shall be followed in order to increase our understanding of the phenomenon about which we are interested. ”A research method is a way of investigating an empirical topic by following a set of pre-specified procedures” [6].

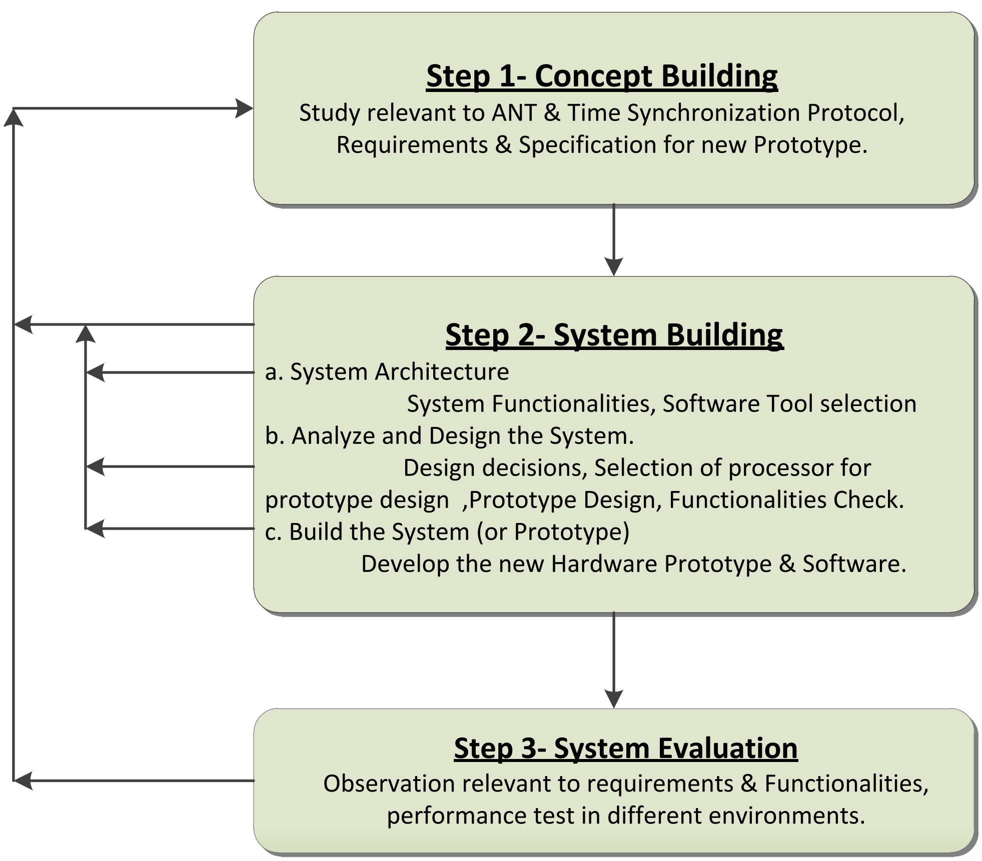


Figure 4-1 System Development Research Method

In our master thesis research work, we have followed System Development Research Method as shown in *Figure 4-1*. "The system development research approach denotes a way to perform research through exploration and integration of available technologies to produce an artifact, system or system prototype" [7]

i. Concept Building

In our research, we started with pre-study phase, in which study relevant to ANT protocol and Time synchronization was made. The reason for the research was clearly understood and relevant to that few research questions were created. The research questions were discussed in chapter 3 of this document.

ii. System Building

The reason for the research and the research questions are understood and a procedural plan was made to achieve the time synchronization. An architectural design was created for the prototype system and few design decisions were considered. The hardware design prototype was implemented and the software was developed for the system. The developed system shall receive the ANT data packet from the sole pressure sensor and should transmit to WBAN server via USB.

iii. System Evaluation

The system need to be observed with functionalities check and different tests were made in different environments. Different tests include the functionality tests, performance tests, Robustness tests. The build system provided a possible solution with respect to the research questions. A report which clearly explains the work flow, its requirements and specifications, functionalities and testing phases were documented with standard format.

4.2 Power Estimator

The power estimator is a tool provided by ANT to estimate the power consumption. It estimates the average power consumption for the selected ANT device and the expected battery life per the input usage scenario. The calculation is based on the specification documented in ANT product datasheet and only covers ANT operation. This tool provides the details about power consumption which shall be used for budgeting purpose of any system design.

In this thesis, the power estimator tool is used to estimate the power consumption of ANT product, nRF24AP1chip. The power estimation of the ANT chip shall be done and compared in two different scenarios.

4.2.1 Power Estimation with only Forward data

1. Initial setup
    a. ANT Product - AP1 chip or module
    b. Serial mode - Asynchronous
    c. Baud rate - 38400
2. Channel Data
    a. Number of channels - 1
    b. Channel 1 - Transmit channel
    c. Forward data - Broadcast
    d. Message rate - 8 Hz

Results:

Base current : 75 μA
Forward Average Current : 280 μA
Total Average Current : 355 μA

4.2.2 Power Estimation with Forward data and reverse data

1. Initial setup
    a. ANT Product - AP1 chip or module
    b. Serial mode - Asynchronous
    c. Baud rate - 38400
2. Channel Data
    a. Number of channels - 1
    b. Channel 1 - Transmit channel
    c. Forward data - Broadcast
    d. Forward Message rate - 8Hz
    e. Reverse data - Broadcast
    f. Reverse Message rate - 0.5Hz

Results:

Base current : 75 μA
Forward Average Current : 280 μA
Reverse Average Current : 17.5 μA
Total Average Current : 372.5 μA

Through this power estimation, it shall be noted that there is an increase in power consumption but relatively low, while using ANT reverse channel.

4.3 Assumptions and Design Decisions

4.3.1 Time stamping at transmitter

In the SIGS system, the packet data shall be transmitted from the two soles (transmitter) through ANT transceiver attached to the soles. The transmitted packet will be received by WBAN server (receiver) through ANT transceiver attached to the WBAN server. As soon as the ANT transceiver at the transmitter side, receives the pressure sensor values from the sole pressure sensors, the time stamping shall be done on the two bytes allocated for time stamping before it is been transmitted further to the WBAN server.

During pre-study, we come across with some issues. The clocks used to time stamp in the two soles, might vary at the time of initiation. Even both the clocks are started at the same time; there might be clock drift in the timers because of the oscillators. To make the clocks start at the same time, the clocks need to share their clock value with the Global clock for synchronization which could consume more power.

After detailed pre-study and thorough investigation, implementation of time stamp protocol at transmitter side will be a possible option, if global clock is used for synchronization.

4.3.2 Global clock

In any distributed system, the implementation of global clock synchronization could provide a possible solution for efficient synchronization. In our SIGS system, the ANT protocol is used which is a proprietary protocol whose scheduling of time slots is adaptive isochronous co-existence i.e. the scheduling is dynamic. This might cause a critical problem in real time implementation for global clock synchronization. The importance of using the ANT protocol in our SIGS system is its low power consumption and the message rate. For the implementation of Global clock, ANT reverse channel shall be used to synchronize the local clocks. It will increase the power consumption but relatively little. But however, the Global clock implementation could be possible, once the time stamp protocol is implemented in the system in order to adjust their local clocks with respect to the Global clock.

After detailed pre-study and investigation, the implementation of the Global clock for synchronization shall be a better option for SIGS system but because of power *consumption and complexity in implementation, it shall not be implemented. But its research solution for ANT protocol shall be considered for the implementation in the future work.*

4.3.3 Time stamping at receiver

In the SIGS system, the packet data shall be transmitted from the two soles (transmitter) through ANT transceiver attached to the soles. The transmitted packet will be received by WBAN server (receiver) through ANT transceiver attached to the WBAN server. As soon as the packet is received at the ANT transceiver at the receiver side, the time stamping shall be done on the two bytes allocated on the received packet.

With time stamping it is not possible to synchronize the measurements but it is possible to estimate the actual sampling point. After detailed pre-study and investigation, time stamping at receiver side could be a better solution to implement in SIGS system and it consumes less power.

4.4 Implementation methods

The objective for this thesis proposal is to find a method (methods) to make it possible for the application software in the WBAN server to get time stamped and time synchronized data from the two sole sensors (and other sensors) in the system. The suggested method shall also be demonstrated in the SIGS system. The controller used in the SIGS system is Atmel ATmega88 and in the new ANT-ARM-USB hardware prototype connected to WBAN server is ARM controller.

As per our design decisions, we opt to proceed further with the implementation of the time stamp protocol and to provide a possible research solution for global clock synchronization in the ANT protocol.

4.4.1 Time stamping in SIGS

In wireless sensor networks, the timestamps are very essential for each packet transfer through whom we could detect as when the packet is sent or received. It is a well known method for obtaining the estimates of clock differences between pair of nodes which can directly communicate. It is based on exchange of time-stamped packets. In our thesis work, we had used timestamp to find exactly how the timeslots are assigned.

1) *Protocol design for the Transmitter Communication in SIGS*

The protocol design for the transmitters attached to the soles are developed and implemented at Atmel AtMega88 microcontroller. The developed protocol shall receive the pressure sensor data from the soles and transmit to the ANT transceiver via USART. Its detailed description is described in the Chapter 3 of this document.

The entire communication process is shown in the *Figure 4-3*. The designed protocol shall work as shown in the *figure 4-2*.

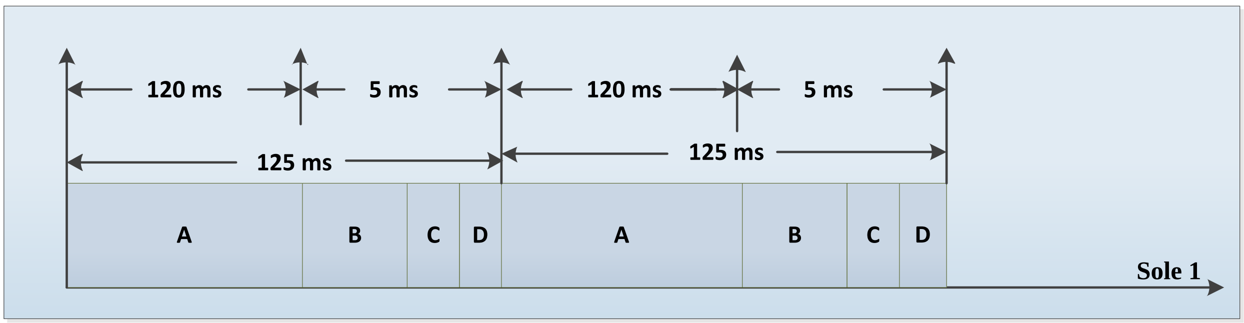
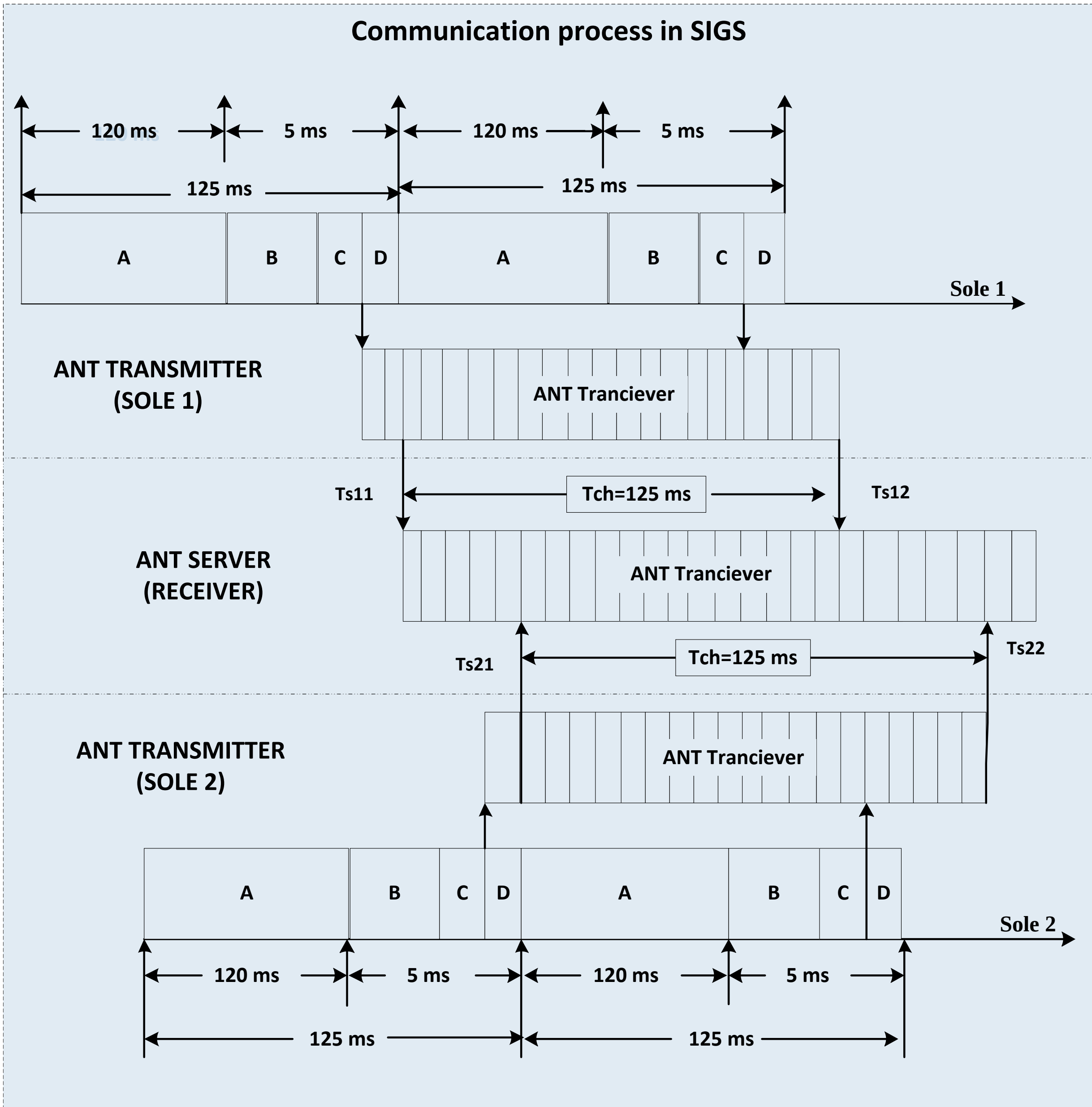


Figure 4-2 Transmitter protocol in SIGS

a) The protocol is designed in such a way; the transmitter shall send the pressure sensor data to the receiver after every 125 ms.
b) The microcontroller is programmed in such a way, that it receives the pressure sensor data after 120 ms. During this time duration A (A= 120 ms), the microcontroller goes to sleep mode.
c) After 120 ms, the controller scans for the pressure sensor data during the scanning period, B. The scanning period B shall be equal to few milliseconds.
d) Once the controller completes its scanning with the received pressure sensor data, it transmits further to the ANT transceiver at time period, C. During this time period, the ANT transceiver receives the pressure sensor via USART. The time period C shall be equal to few milliseconds.
e) The time period, D will be of very shorter time and this time period is reserved to complete the transmission process before its dedicated time. The transmitter protocol is same for the two soles.



A	Sleep mode
B	Scanning period for the pressure sensor data
C	Transmits the pressure sensor data to the ANT Transceiver
D	A small time gap allotted before the start of the next transmission.
Tch	Designated Channel Period

Figure 4-3 Communication Protocol Design in SIGS

2) *Protocol design for the ANT Transceiver communication in SIGS*

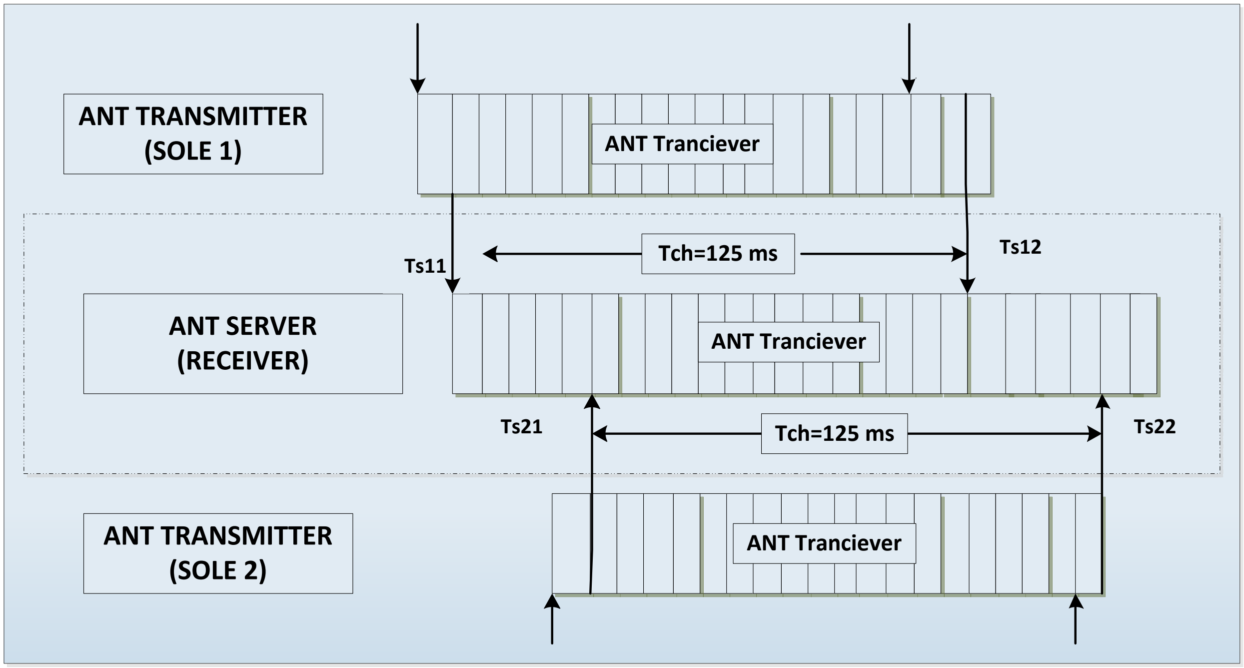


Figure 4-4 ANT Transceiver Protocol

The entire communication process is shown in the *Figure 4-3*. The two ANT transmitters from the two soles try to communicate with the ANT receiver as shown in the *Figure 4-4*. Whenever the ANT transceiver receives the pressure sensor data, it scans for the free channel time slot. As soon as the sole systems receives the data, it goes for the arbitration and whichever the sole wins the arbitration, they try to transmit the packet data at the first available time slot. As the message rate is 8messages/sec (bit rate is 1 Mbit/sec), the next data packet will be sent after 125 ms. The oscillators will not function similarly in both the sole sensor nodes and there are possibilities of clock drift between the two nodes. Hence the transmitted time varies between the two nodes as shown in the *Figure 4-4*. The time difference between Ts11 and Ts21 from two different soles provides the time synchronization error.

Time synchronization error, $\Delta T = \min\left(|Ts1n - Ts2n|, |Ts1n - Ts2n-1|\right)$ where n= 1, 2…..n.

The value of Ts1n and Ts2n is not known and hence the Time synchronization error could not be calculated. In order to find the value of Ts1n and Ts2n, time stamp protocol shall be implemented.

3. *Design for Time stamp protocol*

Exactly how the time slots are used is not known by the WBAN server as the system is implemented and therefore it is necessary to time stamp the messages when they are created or when they are received. The ANT data type used in SIGS system is Broadcast data type. It is an one way communication ie., there is no acknowledgement packet send back to sender. By time stamping method, a message with timestamp data shall be received. Through this method, time at which the messages are created at the sender side and are received at the receiver shall be identified.

The entire communication process is shown in the *Figure 4-3.* The new time stamp protocol is designed in such a way, that whenever the ANT transceiver receives the sole pressure sensor data from the ANT transmitter, it checks for the correct packet byte of the data. When the received data is verified for the exact byte of data, it does the time stamp to the data packet with present time stamp value as shown in *Figure 4-3.* Ts11, Ts12 and Ts21, Ts22 are the time stamp values of the message packets from the sole 1 and sole 2 respectively. Through this timestamp value, we could know as when the messages are created at the sender side and received at the receiver.

4.4.2 Global clock

Time-stamping could provide us when the messages are sent and received. We could also suggest some improvements for the better performance of synchronization. Using global time for synchronization is the only way for global synchronization.

As the ANT protocol uses TDMA technique and the time-slots are allocated for each node. The nodes could send packets at the dedicated time slots. At one stage, the oscillators will not work as it needs to be. So there are possibilities of data losses from the nodes because of the collision between the two nodes. So, in order to avoid losses, the use of global clock for synchronization could be a possible solution.

The main goal of the thesis is to synchronize the samples from the pressure sensors of two soles. The implementation of global clock could provide a possible solution for synchronization. The local clocks of the two sole sensors could adjust themselves with respect to the global clock. Hence the local clocks of the two sole sensors shall work identically and could sample their pressure sensor values at the same time.

For global clock, bi-direction transmission is required which consumes more power. In our SIGS system, it is possible to synchronize the local clocks of the sole sensors by implementing the Global clock with the help from ANT reverse channel. It will increase the power consumption but relatively little. But the research idea is proposed as an assumption through which further study analysis shall be done and it can be implemented in the future.

1) *Protocol design for the Transmitter Communication in SIGS*

The protocol design is the same as those of the Time stamp Protocol, but with small modifications are required. For global clock synchronization, the message shall be sent to the receiver and receive back the global time in the reverse direction as shown in the *Figure-4-5*.

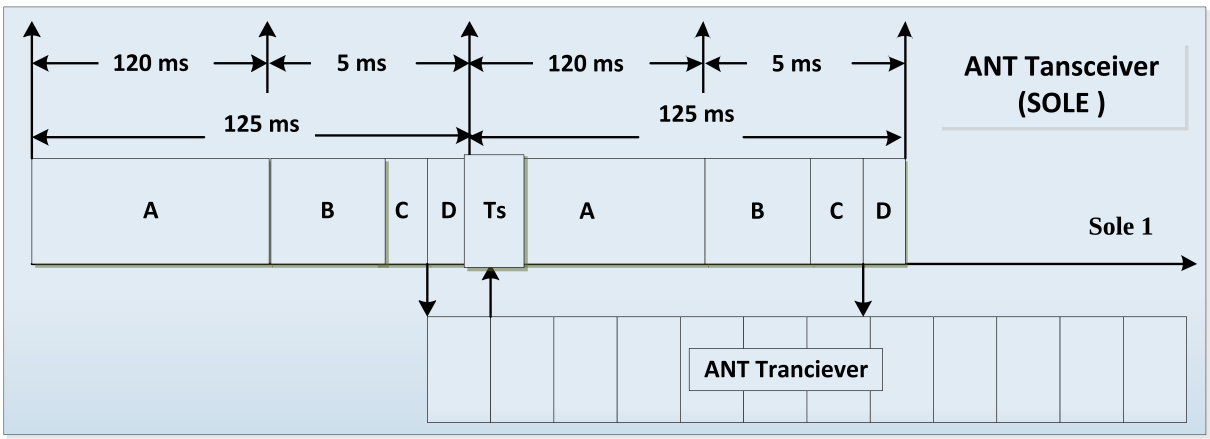


Figure-4-5 Transmitter Protocol with Global clock Synchronization

The protocol is designed in such a way; the transmitter shall send the pressure sensor data to the receiver after every 125 ms. The protocol works similar as that of time stamp protocol but with extended time slots for global clock synchronization. For global clock synchronization, we shall need a time stamp message in reverse direction in order to calculate the offset value.

The sole ANT transceiver receives the message packet and transmits to the WBAN ANT transceiver at the earliest possible available time slot. At the time resynchronization interval R_{int} , it receives the global clock value from the ANT-ARM-USB and does the required calculation at the time period, Ts.

2) Design for Global clock synchronization Protocol

The entire communication process for Global clock synchronization is shown in the *Figure 4-6.* In our research, the controller used in the SIGS system is Atmel ATmega88 and in the new ANT-ARM-USB hardware prototype connected to WBAN server is ARM controller. The clocks used in both the controllers differ from each other with varying drift rate and clock skew.

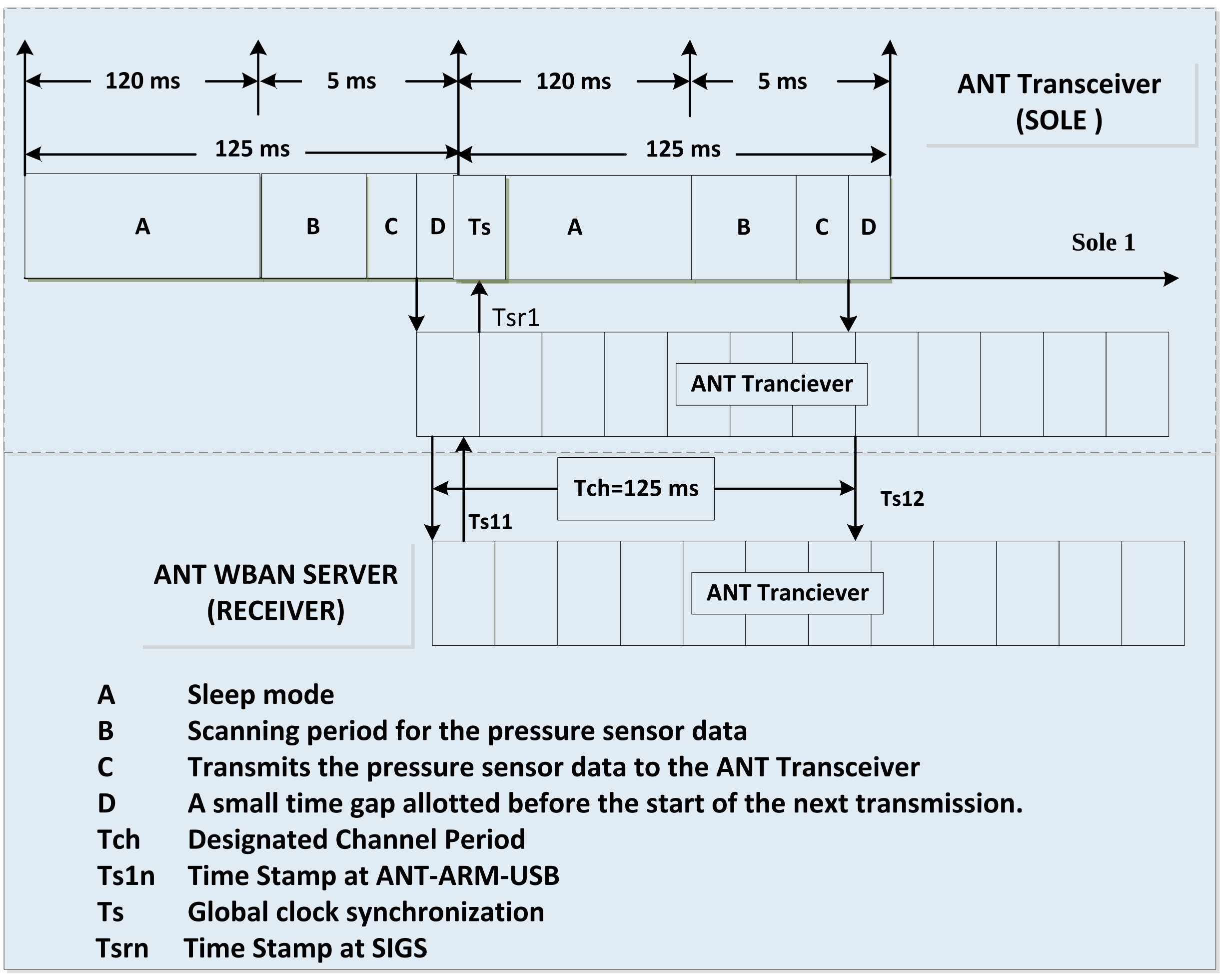


Figure 4-6 Communication Process with Global clock Synchronization

The ANT WBAN server receives the message packet from the Sole ANT transceiver after every 125 ms. The clock at the soles needs to be synchronized with respect to the global clock at the WBAN server. In order to get synchronized, the WBAN server receives the message packet at time, Ts11. The ARM controller in the ANT-ARM-USB hardware prototype stores the message packet in its buffer. As soon as the message is received at the ANT-ARM-USB, the received message is time stamped with the global clock value, Ts11 using the timer in the ARM controller.

The time stamp value of the message at the ANT-ARM-USB is sent back in the reverse direction to the Sole ANT transceiver as shown in the *figure 4-6*. For transmission in the reverse direction, the ANT transceiver uses the same channel time slot in which the message was received. The timeslots used for the reverse direction in the ANT are longer as compared to the time slots used for uni-direction [8].

Whenever the SIGS system receives the time stamp value from the ANT-ARM-USB clock, it stores the time stamp value in its buffer in Atmel ATmega88 controller. The received message packet is time stamp at time Tsrn , using the clock at the SIGS system. The controller in the SIGS system compares its own clock value (Tsrn) with the ANT-ARM-USB clock value (Ts1n).

The difference between both the time stamp values provides the time offset for the synchronization as shown in the formula below.

Time Offset, ΔT= Ts1n-Tsrn
where n=1,2,...n
Ts1n, Time stamp at ANT-ARM-USB
Tsrn , Time stamp at SIGS

The difference between the two clock values provides the time offset for the synchronization. At time period Ts, the Sole system receives the packet and does the required calculations. The Atmel ATmega88 controller in the sole system receives the time stamp value, generates the offset and adjusts its clock skew with respect to the offset value. As the controller is in idle state for 120 ms, the controller shall receive the packet value at this time duration, does the required changes and then goes back to sleep mode. The local clock in the transmitter node is now adjusted with respect to the global clock from the receiver. Both the sole transmitters shall be programmed and developed in a similar fashion.

However the adjustment in the transmitter clocks with respect to global clock doesn't provide much improvement in synchronization. But the synchronization of measurements shall provide a good improvement in synchronization. For this improvement, a specific method shall be required to implement in the system. The server shall decide the sample *time and transmit to the sole transmitters via reverse channel. Hence this can provide global synchronization for both the sole sensors to sample the measurements at the same time.*

3) *Resynchronization Interval*

In real time distributed systems, the clock ticks of each node must be periodically globally resynchronized within the network of nodes to establish a global time base with specified precision. The period of resynchronization is called the resynchronization interval R_{int} [22]. At the end of each resynchronization interval, the clocks are adjusted in such a way, that each clock is synchronized to each other.

The time ΔT denotes the offset of the clock drifts between the two clocks after the resynchronization interval. Then, the clocks shall drift again until they are resynchronized at the end of the next resynchronization interval R_{int} .The clock skew Γ indicates the maximum clock skew of the clock at the sole controller and the ANT-ARM-USB clock during the resynchronization interval R_{int} , where the clocks are free running. Two synchronized identical clock can drift from each other at the rate of max $2\rho_{max}$.The clock skew Γ depends on the length of the resynchronization interval R_{int} and the maximum specified drift rate ρ of the clock

$$Clock\ skew, \Gamma\ = 2\rho_{max}\ \times R_{int}$$

Hence the resynchronization interval is,

$$R_{int}\ = \Gamma /\ 2\rho_{max}$$

Therefore the refresh rate of the global clock in the communication cycle will be after every resynchronization interval. In our system, the maximum drift of the clock is approx. 50 ppm as provided by the manufacturer. The maximum clock skew is about 1 ms. Thus the clocks should resynchronize at the latest every,

$$R_{int}\ =\ (1 * 10^{-3})\ /\ (2 * 50 * 10^{-6})\ =\ 10\ seconds\ approx.$$

The clocks need to resynchronize after every 10 seconds. The ANT-ARM-USB will transmit its time stamp value generated from the clock counter after every 10 sec. the SIGS system will receive the clock value and set its offset with respect to its own clock time stamp value. The SIGS system clocks in the two soles shall replace its local time with the new global time after every resynchronization period. Hence the nodes in the entire communication process could produce a global synchronization with the local clocks adjusting themselves with respect to the global clock. Through this implementation method, we could achieve good global clock synchronization in the ANT communication protocol.

4.5 Hardware setup

A hardware prototype was designed considering different specifications to obtain the final task of the thesis work. The prototype should act as an interface between the transmitter and receiver which should be compatible to WBAN server (receiver). Its systematic operations and the functionality are shown in figure 4-7.

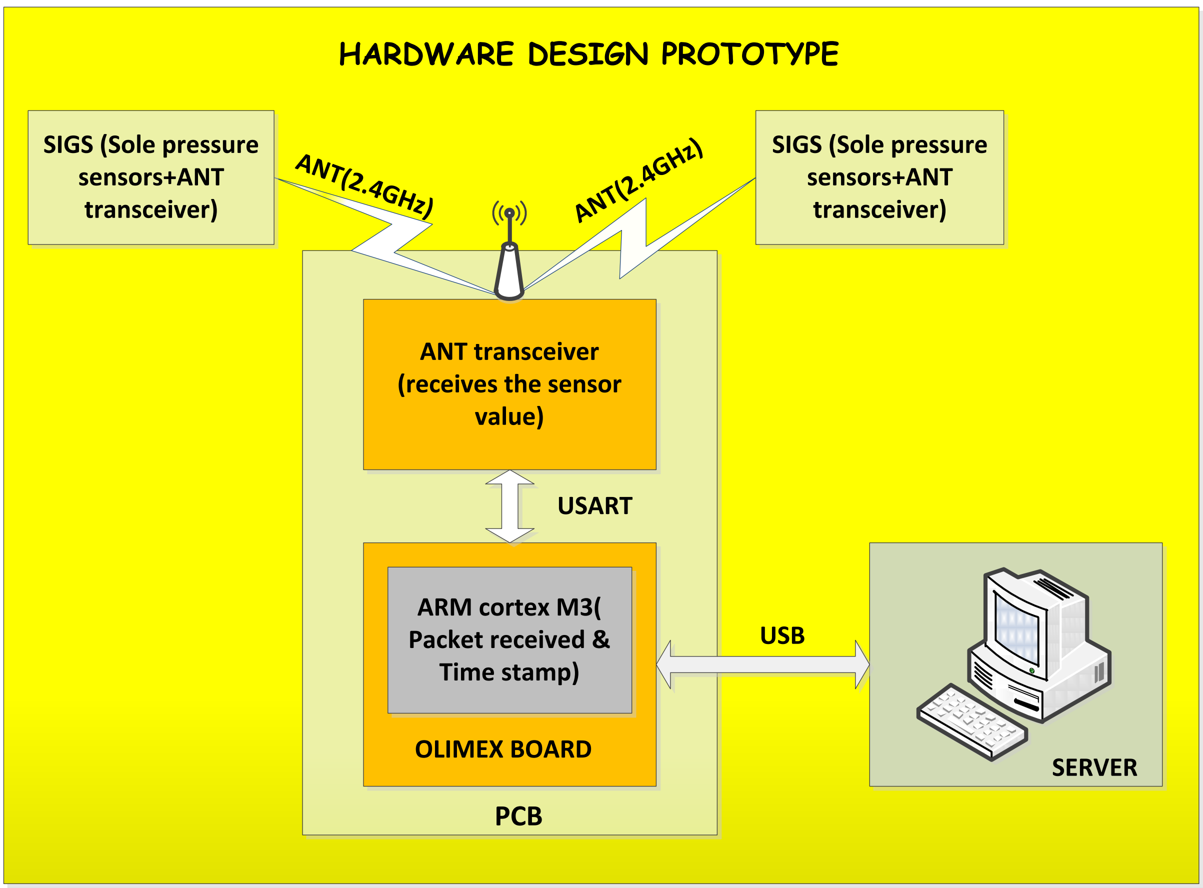


Figure 4-7 ANT-ARM-USB Hardware Prototype

The design prototype includes,

1) PCB design board
2) SIGS
3) Server
4) Communication protocols

4.6 PCB design board

For the hardware prototype design, a PCB was designed for hardware setup. The small PCB board was designed to act as an interface between Olimex board STM32-H103 and the ANT transceiver. The PCB schematic of the ANT-ARM-USB hardware prototype is shown in the *Appendix 8-2* and its snapshot are shown in *figure 4-8.*

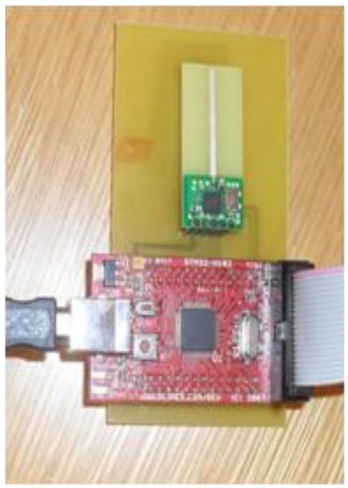


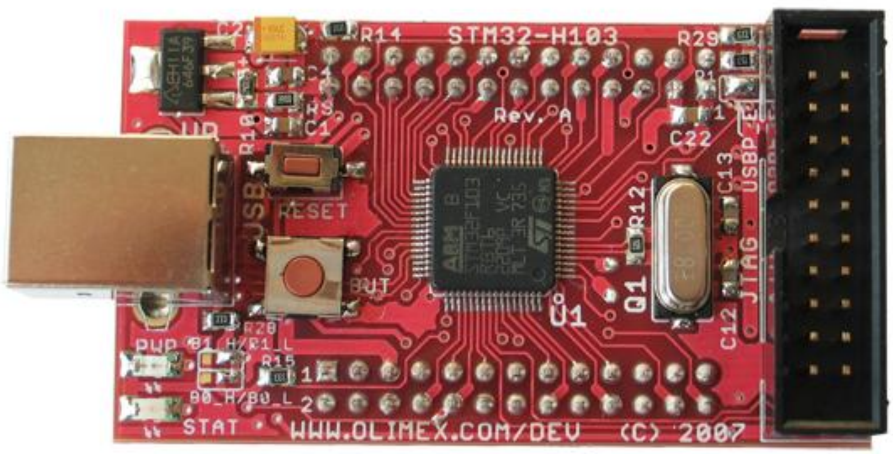
Figure 4-8 PCB design Board

The ANT transceiver will communicate with the ARM STM32F103RBT6 microcontroller in the OLIMEX board through serial interface. In our layout, we used USART2 for serial communication. The ARM STM32F103RBT6 microcontroller in the OLIMEX board shall receive the ANT parameters from the WBAN server and transmit it to the ANT transceiver via USART2.

Once the ANT parameters are received by the ANT receiver, it assigns its parameters for the nRFAP1 radio chip. Now the ANT transceiver could receive the data from the SIGS system with respect to the parameters assigned. Whenever the ANT transceiver receives the packet from the SIGS system, the ANT transceiver transmits the packet serially to OLIMEX board via USART2. The ARM controller receives the packet, does the required operation and forwards the packet to the WBAN server via USB. *The pin configurations between Olimex Board and ANT Transceiver are shown in Appendix 8-2.*

4.6.1 Olimex Board

The board used for the design prototype is STM32-H103 [13] board provided by the Olimex. It is a development board designed for the new ARM Cortex M3 family of devices produced by ST Microelectronics Inc. By using this board, we can explore the features of STM32 family and the board has many features to build simple applications. The STM32-H103board provides the perfect solution for USB peripherals development. The schematic of the Olimex board STM32-H103 is shown in the *Appendix 8-4*.The snapshot of the board is shown in the figure 4-9.



OLIMEX BOARD STM32-H103

Figure 4-9 OLIMEX Prototype Board

1. ***Microcontroller Unit***

The STM32F103RBT6 microcontroller belongs to a STM32F103RBxx medium-density performance line family which incorporates the high-performance ARM Cortex™-M3 32-bit RISC core. The core operates at a frequency range of 72 MHz. It consists of high-speed embedded memories with flash memory up to 128 Kbytes and SRAM up to 20 Kbytes. An extensive range of enhanced I/Os and peripherals are connected to the APB buses. The microcontroller operates at a range of 2.0 to 3.6 V power supply [14].

a) USART(universal synchronous/asynchronous receiver/transmitter)

The controller has 3 USART's for flexible duplex and asynchronous serial communications. Using fractional baud rate generator, it provides a wide range of baud rates. They provide hardware management of the CTS and RTS signals[14].

b) USB (Universal Serial Bus)

The STM32F103RBT6 supports USB specification version 2.0 full-speed compliant. The USB interface supports to implement a full speed (12 Mbit/s) function interface. It has software configurable Double buffered bulk/isochronous endpoint setting support. The dedicated 48 MHz clock source is generated from the internal main PLL. The USB peripheral implements an interface between a full-speed USB 2.0 bus and the APB1 bus. The USB suspend/resume are software configurable provides the device clocks to stop for low-power consumption [14].

2. *Features include*

iv. USB port where power is taken and power supply circuit.
v. Reset and oscillator circuits.
vi. JTAG port for programming and debugging.
vii. Two status LEDs and user button.
viii. Microcontroller unit: STM32F103RBT6.

3. *Applications*

a) For USB application like PC mouse, USB mass storage device, USB Audio class device, USB to Virtual RS232 port.
b) As the board consists of many GPIOs on the extension headers, it could be useful for different applications by connecting additional circuits.

4.6.2 JTAG port and Debugger

The JTAG (Joint Test Action Group) was formed to test the circuit boards and for debugging purposes. The JTAG connector allows the software debugger to talk via a JTAG port directly to the core. The software code developed could be programmed into the STM32F103RBT6 memory through Debugger via JTAG. The host software could execute the instructions step by step and the debugger used for debugging is ST-LINK manufactured by the ST microelectronics as shown in figure 4-10.

Figure 4-10. ST-LINK Debugger

The ST-LINK [15] is an in-circuit debugger was provided by the ST microelectronics. It is a programmer and debugger for STM8 and STM32 microcontroller families. The STM32F103RBT6 microcontroller uses full speed USB interface to communicate with the Integrated Development Environment.

4.6.3 Transceiver nRF24AP1 with Trace Antenna

This is a small breakout board with circuit for the Nordic nRF24AP1 transceiver [10]. The transceiver IC is capable of talking with other wireless products which is built on ANT protocol. In our PCB design prototype, the transceiver unit could communicate serially with the OLIMEX board through USART.

The wireless transceiver unit as shown in the Figure 4-11 receives the message packet from SIGS (Sole Integrated Gait Sensor) through ANT communication protocol and transmits the received message packet serially through USART to the OLIMEX board.

Figure 4-11 Transceiver nRF24AP1with Trace Antenna

4.7 Sole Integrated Gait Sensor (SIGS)

The SIGS system acts as a leaf node which consists of a wireless transceiver unit and the foot pressure sensor from Tekscan [12]. In this system, the Tekscan sensor is used together with the wireless sensor node to transmit the sensor data to the personal server. The system is used in our implementation phase for the transmission of message packet from the sole pressure sensors to the WBAN server.

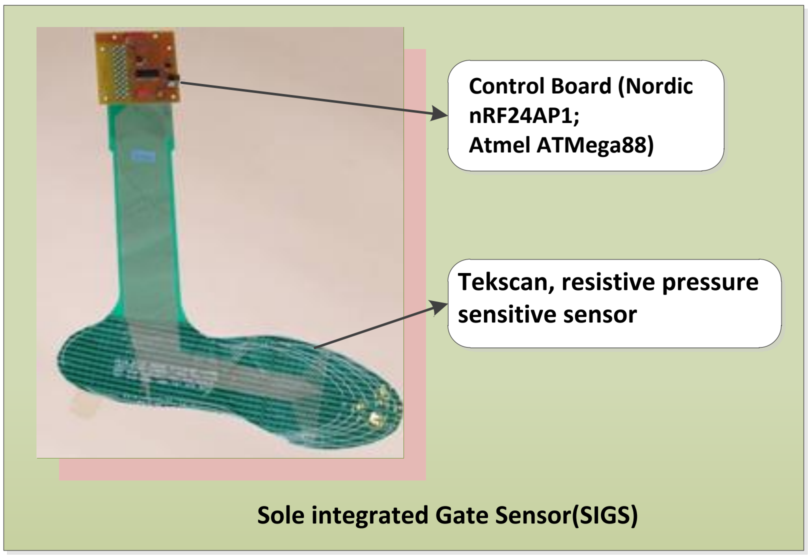


Figure 4-12. Sole Integrated Gate Sensor

The designed SIGS system is shown in the Figure 4-12. It consists of a control board with Nordic Semiconductor nRF24L01 which uses ANT proprietary protocol, Atmel ATmega88 microcontroller and small coin cell battery. The whole system design and its operation principle are described in the chapter 3 of this document.

4.8 Server

The environment in which WBAN server implemented is Linux PC for testing. In real-time, Neo-FreeRunner Smartphone as shown in Figure 4-13 was used which runs on Linux OS. The server was designed and programmed such that it could communicate with the designed prototype through USB. The new PCB design board with OLIMEX board and ANT transceiver is attached with the server via USB cable. The developed software shall be used to communicate with the PCB design board.

Figure 4-13. NeoFreeRunner Smartphone

Purpose of the server,

a) To communicate with the ANT transceiver via USB.
b) The software program developed for the Linux server sends the ANT parameter to the ANT transceiver for channel configurations.
c) Once the channel is configured, the transceiver starts receiving the packets and transmits it to the server via USB.
d) The server receives the packet and does the operation as required.

4.9 Software setup

The software setup was created in order to build an environment for software development of the hardware design prototype. The developed software shall be implemented on the hardware, to fulfill the requirements and with the specifications provided.
Tools used,

1) Atollic True Studio– Integrated Development Environment.
2) QtiPlot – For Analysis

4.9.1 Atollic True Studio

Atollic TrueSTUDIO® [16] is an Integrated Development Environment (IDE) tool for embedded systems development which uses the Eclipse IDE framework. It provides C/C++ development tool for embedded developers, with increasing efficiency for the embedded systems project. It creates a standard shift in the embedded industry with its wide feature-set and unique integration, in combination with excellent target support.

Atollic TrueSTUDIO/STM32 features a GNU compiler/debugger for ARM processors providing a high end support for STM32 (Cortex-M3) devices from STMicroelectronics. Its PC compiler & debugger support enables the developer to attain an early development before the hardware is available. Atollic TrueSTUDIO/STM32 has excellent target support, which makes easier and feasible development of embedded systems using the STM32 microcontroller devices from STMicroelectronics.

In our thesis work, the Atollic TrueSTUDIO®/STM32 Lite v1.4.0 were used in our implementation phase to develop a software program for STM32F103RBT6 microcontroller in the OLIMEX board**.** It has no code-size or usage-time limitations, and is an excellent entry-level compiler and debugger IDE.

4.9.2 QtiPlot

QtiPlot [17] is a computer program used to analyze and visualize scientific data. It can be used to present 2D and 3D data and provides an environment for various data analysis functions. In our thesis work, the data received at the WBAN server, shall be used for performance analysis through Qtiplot.

4.10 Development phase

In the previous sections, we discuss about the hardware and software setup for the implementation phase. In this section, we will discuss about the developed software algorithm for the designed hardware prototype and its implementation.

4.10.1 Software algorithm

In chapter 3 of this document, we came across with few questions and we designed an algorithm to obtain the final solution. The software was developed in Atollic TrueSTUDIO/STM32 eclipse environment provided by the Atollic. The software developed is written in C language. In our development phase, few requirements are considered at the initial stage before the start of implementation. The developed software shall work as shown in the *Figure 4-14* below.

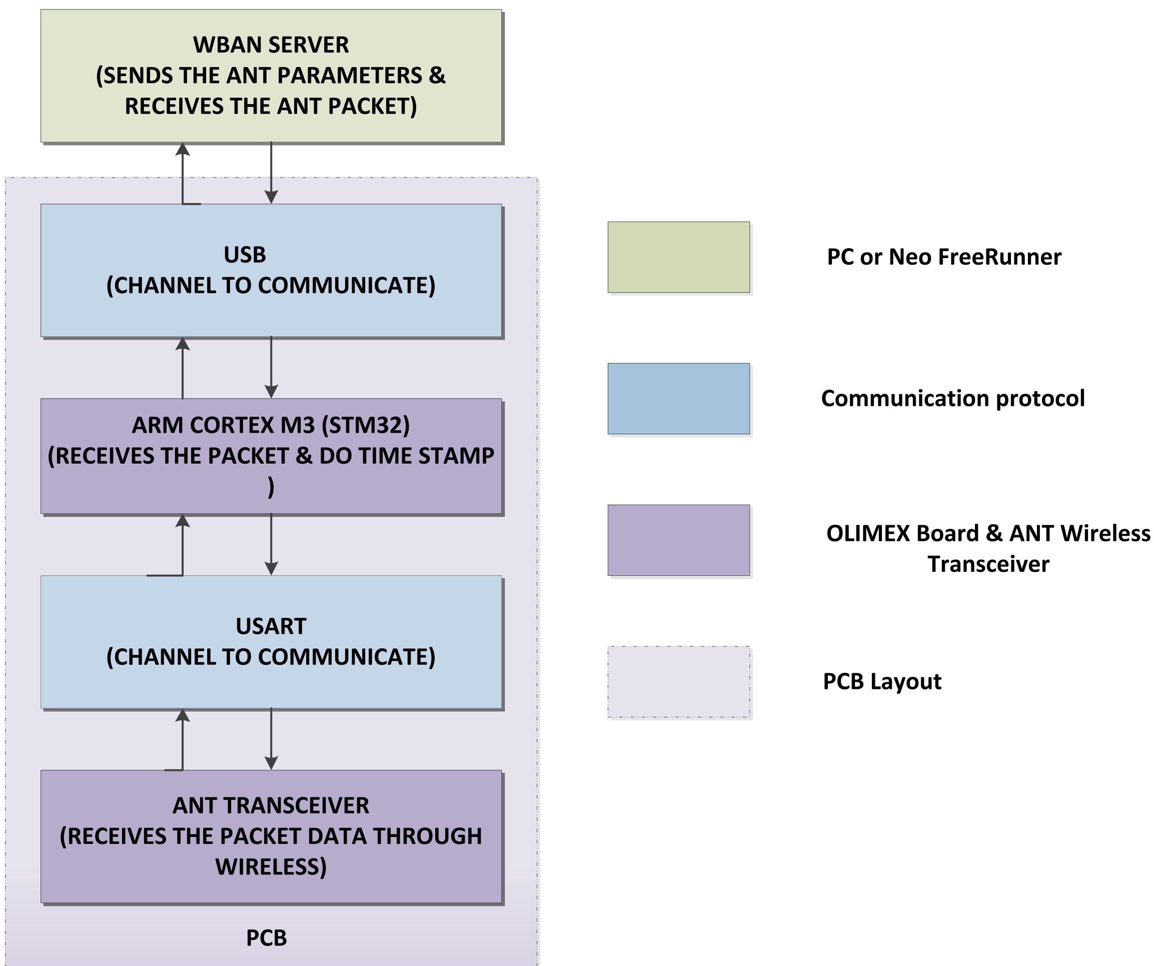


Figure 4-14. Software Algorithm

4.10.2 Configuration of the OLIMEX Board

As an initial step, relevant study was started to get familiar with the STM32 microcontroller and the OLIMEX STM32-H103 board. A simple program was created in Atollic TrueSTUDIO/STM32 development tool, and it was debugged using ST-LINK debugger. The pin configurations for the OLIMEX board were configured and the software was developed such that the software program could receive and sent data via USB. It is been tested through Hyper terminal in Windows application. The software developed will consider the OLIMEX board as a Virtual COMport when connected the PC.

The designed PCB prototype acts as a serial communication between the OLIMEX board and the ANT transceiver. As part of the next stage, the software was developed such that the OLIMEX board could communicate with the ANT transceiver through USART. The relevant pin configurations and USART settings are made for the communication in the software program.

The developed software could be able to conveniently send and receive data in both USB and USART ports. In this phase, the software in the Linux Computer shall initialize the communication between the ANT transceiver and the Linux Computer.

A software program was developed in the Linux environment. When the Linux software is run through the terminal, the software could send the ANT parameters to the ANT transceiver whose parameters resembles the same parameters as that of the ANT transceiver (Transmitter) from the SIGS. The ANT parameters assigned for this network is discussed in the chapter 3 of this document.

4.10.3 Timer Configuration for Time Stamp Protocol

1) System Clock

There are three available clock sources, which can be selected via multiplexers:

1. Internal High Speed Clock (HSI)
2. External High Speed Clock (HSE)
3. Phase locked Loop (PLL)

a) Internal High Speed Clock(HSI)

By default, the HSI is used. It has a typical frequency of 8 MHz. It can be used to as PLL input (with clock divider 2 from HSI), to generate higher clock frequencies and has a calibration register, but is not as exact as an external crystal oscillator.

b) External High Speed Clock (HSE)

If a more precise clock is needed, external clock source shall be used. This can either be a crystal/ceramic oscillator or a real external clock source. The crystal oscillator has the frequency of 4-16MHz. For our implementation, 8 MHz crystal oscillator was used.

c) PLL

The Phase locked Loop is used for multiplying its input frequency by a given factor of two to sixteen. Through the RCC_CFGR register, we can select following entry clocks:

1) 1/2 * HSI oscillator clock
2) HSE oscillator clock

The HSE oscillator clock has a clock divider which can be enabled to supply 1/2* HSE frequency for the PLL, too.

Using the PLL, you can generate clocks up to 72 MHz, depending on the device, but we shall not exceed the maximum frequency as specified in the datasheet []. The value of the PLL multiplier (PLLMUL) shall have a maximum frequency of 8 MHz * 9 = 72 MHz.

2) Bus Clock Setup

After setting up the system clock, the speeds of the internal bus must be adjusted. There are three of them to be named:

a) Advanced High Performance Bus (AHB)
b) Low speed Advanced Peripheral Bus (APB1)
c) High speed Advanced Peripheral Bus (APB2)

All three can be configured by prescaler. The APB's are subordinated to the AHB whose frequency is specified by the symbol HCLK in the Reference Manual provided by the manufacturer [14]. HCLK is controlled by the AHB prescaler whose clock is SYSCLK (system clock). It is easier to explain in equations:

i) f_ahb = SYSCLK / presc_ahb = HCLK
ii) f_apb1,2 = HCLK / presc_apb1,2

In our implementation phase, bus clock setup is assigned as below.

i) AHB= f_ahb = SYSCLK = HCLK= 72 MHz
ii) APB1= f_apb1 = HCLK / presc_apb1= HCLK/2=36 MHz
iii) APB2= f_apb2 = HCLK / presc_apb2= HCLK=72 MHz

While the AHB and APB2 frequency can be up to maximum system clock frequency (72 MHz), the low speed APB1 frequency must not exceed 36 MHz.

3) Timer configuration

In our implementation, TIM3 timer was used for time-stamping. Its general-purpose timers consist of a 16-bit auto-reload counter driven by a programmable pre-scaler.

Its configuration is assigned as below,

TIM3 clock = 36 MHz

Prescalar value is set as 35999.

TIM3 counter clock, $\text{f\_counter} = TIM3\ clock \big/ (prescalar + 1)$

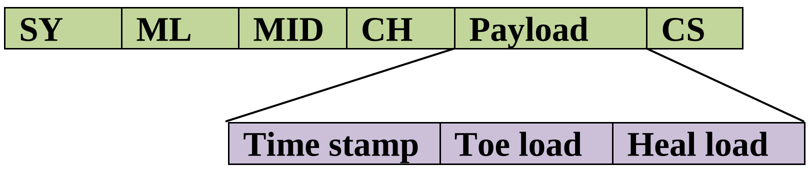
$$\underline{\boldsymbol{f\_counter = 36\,MHz / (35999 + 1) = 1MHz}}$$

Hence the, $clock\ granularity = 1/\,f\_counter = 1/\,1 * 10 - 3 = 1\,ms$

$$\underline{\boldsymbol{1\ clock\ tick = 1\,ms}}$$

4.10.4Implementation of Time Stamp Protocol

The developed software shall receive the message packet and transmit it to the OLIMEX board via USART. The message structure of the ANT transmitter was discussed in the chapter 3 of this document and it is shown in the Figure 4-15 below.



Field name	Bytes	Description
SY	1	Sync, 0xa4 Fixed value
ML	1	Length ,0x09
MID	1	Data type ID, 0x4e
CH	1	Channel number
Time stamp	2	ms(or sequence #)
Toe load	2	Raw sensor data
Heal load	2	Raw sensor data
CS	1	XOR of all previous data

Figure 4-15. ANT message structure on Network Layer

The software was developed in such a way, that it shall receive the message packet from the ANT transceiver. The USART buffer in the STM32F103RBT6 microcontroller receives the message packet from the ANT transceiver byte-by-byte at the OLIMEX Board via USART. The baud rate at the ANT receiver is selected as 38400 bits/seconds. The software receives the message packet and check for each byte of the packet data.

At each byte received via USART, the controller stores the one byte data and checks for the correct data. If the received data is correct, stores the present time stamp value and transmit the data to the USB buffer. Then, it receives the next byte of data from the ANT transceiver. If the received data is not correct, then it waits until it receives correct data at the buffer. The state diagram is shown in the FSM diagram at *Figure 4-16.*

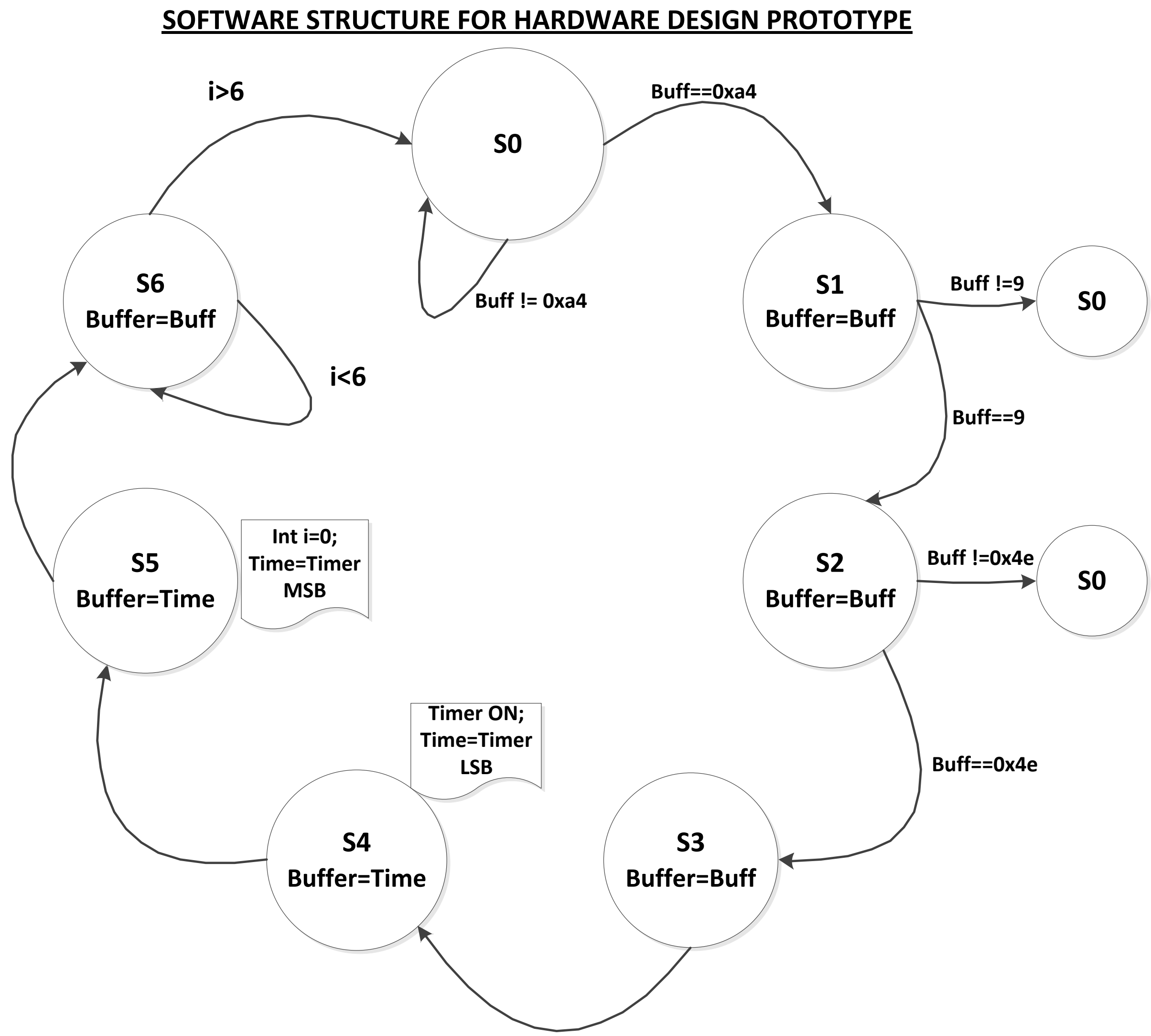


Figure 4-16. FSM for Software structure

Finite states:

1. *SO*

USART receives and checks for the first byte of the message packet. The first byte is synchronous (SY) byte with fixed value, 0xa4.

2. *S1*

USART receives and checks for the second byte of the message packet. The second byte is message length (ML) byte with Length, 9.

3. *S2*

USART receives and check for the third byte of the message packet. The third byte is Data type ID (MID) byte with ID, 9.

4. *S3*

USART receives the fourth byte of the message packet. The fourth byte contains the channel number value.

5. *S4*

USART receives the fifth byte of the message packet. The fifth byte contains the payload value which is allocated for the timestamp value. The Timer is initialized and the LSB of the counter value is used for the timestamp.

6. *S5*

USART receives the sixth byte of the message packet. The sixth byte contains the payload value which is allocated for the timestamp value. The MSB of the counter value is used for the timestamp.

7. *S6*

USART receives the remaining bytes of the message packet.

After receiving all the bytes of the message packet, it checks for the checksum at the last byte. The USB receives the message packet and stores at its buffer. The stored data at the USB buffer are transmitted to the WBAN server via USB. At the WBAN server, the USB is identified as virtual COM port.

The WBAN server in our thesis work is LINUX server. The LINUX server receives the message packet from the sole sensor via the newly designed hardware prototype. The received data by the LINUX server shall be useful for the biofeedback, which could be transmitted to the health service or act as an alarm indicator for the user.

The design and implementation work flow structure is discussed in this chapter. The designed working model fulfills the requirements or not and the different testing phases for the system will be discussed in the chapter 5 of this document.

5 Analysis and Performance results

In chapter 3, we discuss about the research problems and the relevant questions. In chapter 4, the proposed implemented solutions for the questions were described and the systematic approach to achieve the task were also explained. In this chapter, we will discuss about the performance analysis of the proposed solution and the relevant results will be shown for the proposed solutions.

5.1 Experimental Setup

For a system to get validated, different testing shall be undertaken and experimental setup need to be created. The hardware prototype and software developed shall be tested in the laboratory environment. The SIGS system with sole pressure sensors at the transmitter side is assembled and the software program developed for the system is installed. In real time two soles of the SIGS system will be used which will be embedded into two soles of the patient's shoes.

A software program is developed at the receiver side for the new prototype design is programmed into the ARM micro-controller through ST-LINK Debugger. The USB protocol implemented in software program for the new hardware prototype is the Virtual COM-port. The software program developed for ANT receiver side shall be able to communicate with ANT receiver at SIGS system in air with 2.4 GHz band. The size of the packet transmitted from the SIGS system will be equal to 11 bytes and its message structure is discussed in chapter 3 of this document. The program developed shall receive message packet at ANT receiver, transmit to the OLIMEX board via USART. The ARM controller will receive the message packet byte by byte from the USART buffer and stores in the USB buffer.

In order to test this system, the program developed for Linux computer is used. The hardware prototype will be connected to Linux computer via USB. The program developed at Linux computer shall be run through Linux terminal using the Linux commands. The steps used to run the Linux program are given in *Appendix 1*. The Linux program receives the message packet from the USB and the received data are stored in the buffer which could be useful for further analysis. Through the software developed in the Linux computer, we could define the number of samples needed for the analysis.

5.2 Testing phases

The hardware prototype and software developed are tested in laboratory environment. Different tests analyses were created to check the functionality, performance and robustness of the system.

5.2.1 Functional tests

In this test, the SIGS system is tested with the new prototype for its full functionality. The experimental setup for the testing is implemented in a laboratory with the required equipments. The two assembled SIGS system on the transmitter side is placed on the floor. They are placed one above the other such that both the sole's diagonal matches each other. The hardware prototype at the transmitter side will be connected to Linux computer via USB.

The sampling rate is 8 samples/sec and the message rate is 8 messages/sec (bit rate is 1 Mbit/sec) is set to both the transmitter and receiver. Each message contains 2 raw sensor data ie, one for the heel part and the other for toe.

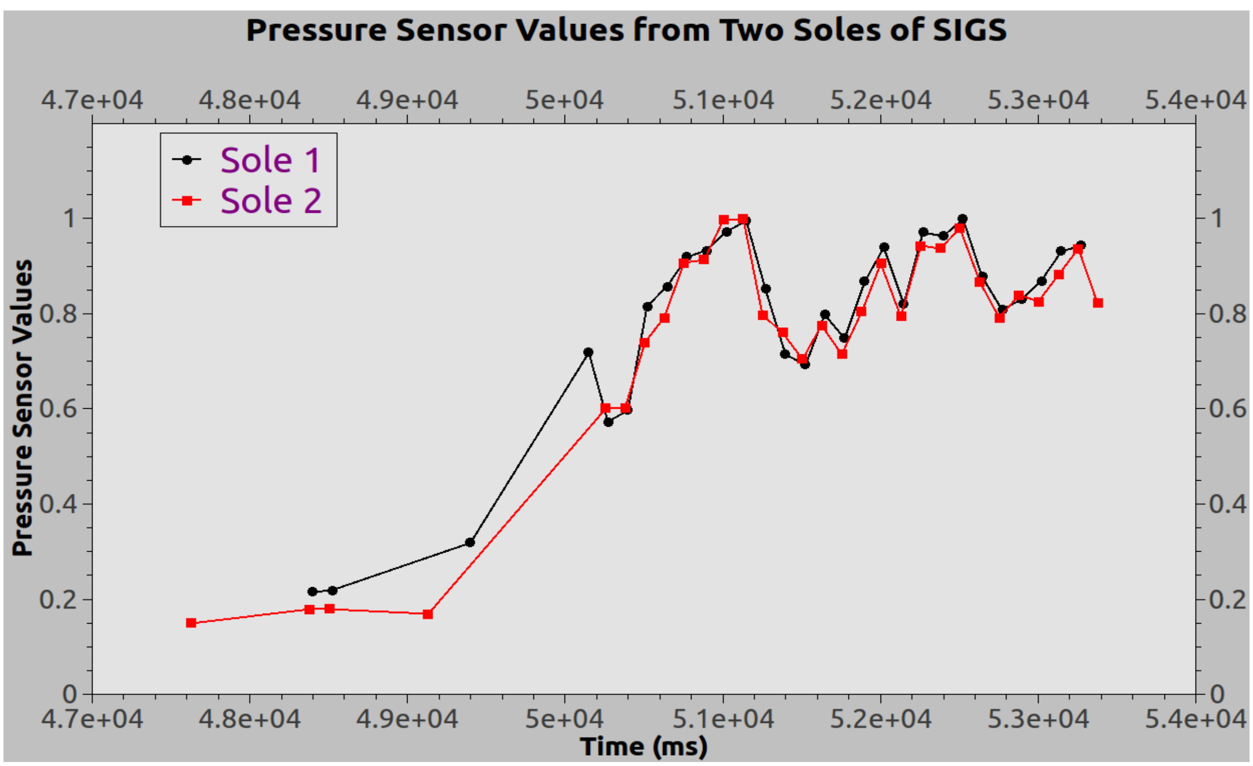


Figure 5-1 Pressure sensor values of two soles are plotted against time to check the functionality of the SIGS system

The Linux server starts receiving the pressure sensor data with time stamping values via hardware prototype. The received sensor values from the two soles of the SIGS system is shown in *Figure 5-1*. The two curves in the graph indicate the pressure sensor values of the two soles of the SIGS system received at the receiver.

Through this test we can conclude that,

1. The new prototype designed has the ability to receive the message packets from the SIGS system which is shown in *Figure 5.1* with two curves black and red indicating two soles.
2. The ANT receiver can receive the message packets from the ANT transmitter of the SIGS system.
3. The received message packet can be transmitted to the OLIMEX board in the new hardware prototype via USART. It clearly states that USART communication works fine.
4. The OLIMEX board communicates with the LINUX computer via USB and transmits the message packet. It means that USB communication works fine.
5. At what time the message packet is received at the kernel of the LINUX computer, is found through time stamp value in the message packet.
6. The two soles try to send their pressure sensor values within the designated channel period, Tch (in our experiment, Tch = 125 ms). The two soles adjust themselves with respect to each other to transmit within their time slots.

5.2.2 Performance tests

In this test, the performance of the system will be analyzed and the time synchronization in ANT protocol will be investigated. The experimental setup for the testing is implemented in a laboratory with the required equipments. To perform this test, two different experiments were selected.

1. While walking – No disturbance

In this experiment, the pressure is applied to the soles of the SIGS system while walking with two foots on the two soles of the SIGS and the LINUX Computer is placed nearer to the heart to collect the pressure sensor data from the SIGS system. The sampling rate is 8 samples/sec and the message rate is 8 messages/sec (bit rate is 1 Mbit/sec) is set to both the transmitter and receiver. The SIGS system is attached to the legs with the soles at the foot part and tried to walk on the floor with the SIGS system attached to the legs. The received pressure sensor values from the two soles of the SIGS system is shown in *Figure 5-2.*

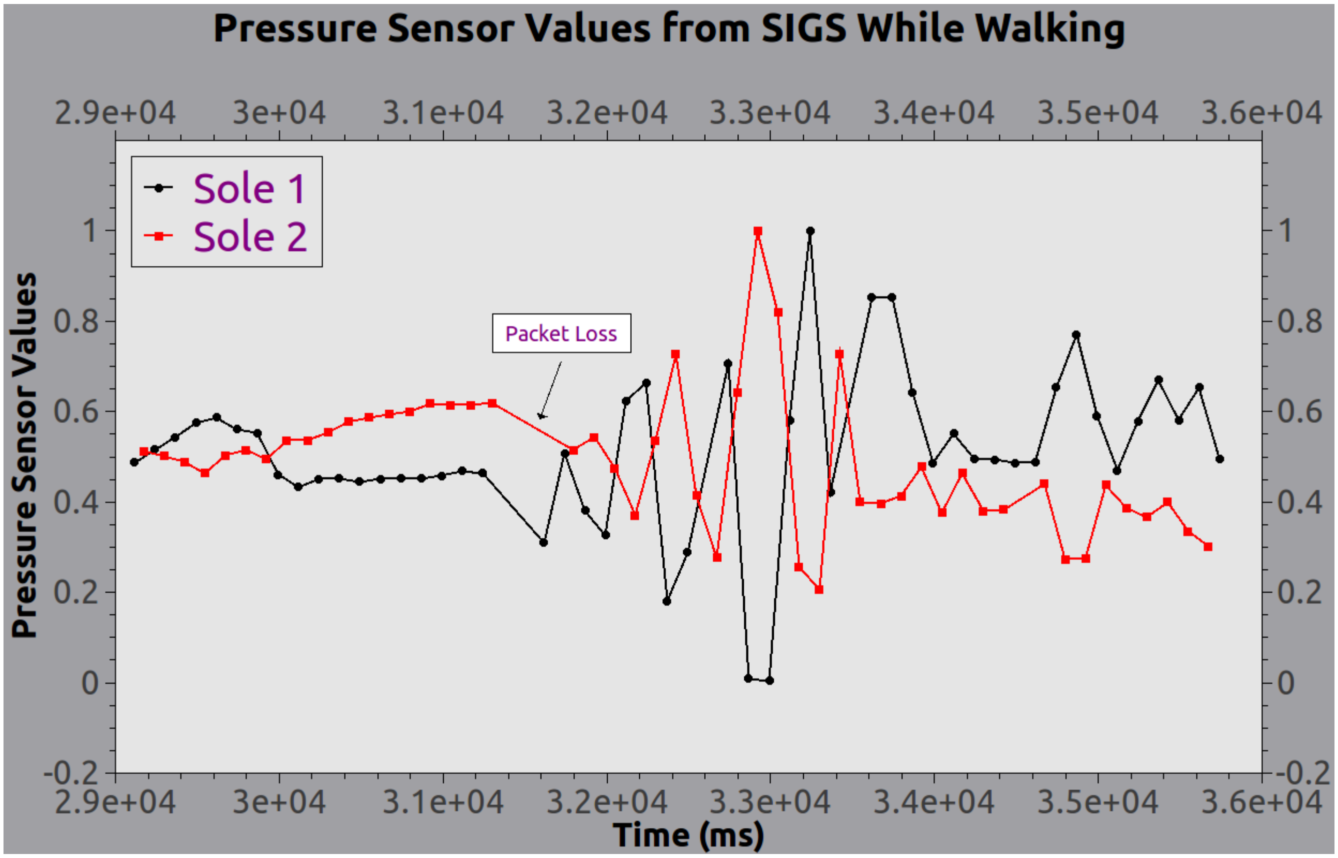


Figure 5-2 Pressure sensor values of two soles are plotted against time to check the performance of the SIGS system while walking

Test	Time taken (msec)	No. of Packets Expected	No. of Packets with respect to time	Missed Packets
Sample test	6625	100	106	6

No. of Packets request from the Linux Server = 100 Packets.
Time required to receive 100 packets = 6250 ms.
Total Time taken = 6625 ms.

Results from the experiments

The experiments were made in order to analyze the performance of the system and to investigate the time synchronization in ANT protocol. In chapter 3 of this document, reason for this extended research and the research questions were clearly stated. We will discuss few of the solutions for the research questions obtained through these experiments.

1. If sole 1 sensor wins the arbitration, it starts to transmit at once at the earliest available time slot. Sole 2 waits for a random time and starts transmission in the available time slot within the designated channel period. Sole 1 starts transmission in its allocated time slot exactly after 125 ms. It doesn't concern about the Sole 2 transmission. *Through our experiments, we concluded that the time difference between the time slots of two soles were approximately around 10- 60 msec.*

2. With the time stamp protocol, it is not possible to synchronize measurements from both the soles, but it is possible to estimate the actual sampling point. The measurements from the pressure sensors are sampled every 125ms. From *figure 5-2* , Sole 1 transmits the sampled data to WBAN server continuously after every 125ms. Similarly the Sole 2 transmits in the same fashion.
   As shown in *figure 5-3*,

   a) Calculation 1:

Sole 1 receives its 4^{th} packet, Ts14 = 29488 &
Sole 1 receives its 5^{th} packet, Ts15 = 29613

Time difference = 125 ms

Similarly,
Sole 2 receives its 4^{th} packet, Ts24 = 29543 &
Sole 2 receives its 5^{th} packet, Ts25 = 29668

Time difference = 125 ms

   b) Calculation 2:

Time synchronization error, ΔT = min (|Ts1n – Ts2n|,|Ts1n-Ts2n-1|) where n= 1, 2…..n.

Time Synchronization error, ΔT = Ts14-Ts24 =29543-29488

<u>**ΔT = 55 ms**</u>

   c) Calculation 3:

Baud rate at ANT transceiver = 38400 bits/sec
No of bytes transmitted from ANT Transceiver = 11 bytes
Hence for 11 bytes of transmission of data from ANT transceiver to ANT-ARM-USB prototype board is,
Time taken = 11 bytes * (1sec/38400)

<u>**Delay = 2.291 ms**</u>

Through these experiments and calculations, the implementation of time stamp is good enough to measure the sampling data. The soles are synchronized such that, both the soles could transmit the sampled data after every 125 ms as shown in the figure 5-3 and 5-4. The sampled data are received continuously after every 125 ms and the time stamping to all the received data is done accurately after 125 ms, which is shown clearly in figure 5-2. Hence we could conclude that, the timestamp protocol implemented in our system is good with varying delay of 2.291 msec.

3. Without Time stamping protocol, the data received at the Linux kernel is of useless. *By implementing the Time stamping protocol, we could receive a time synchronized data from the transmitter and received time stamped data could be useful for future analysis.*

2. ***Sequence numbers and Time stamping performance***

The experimental setup is the same as compared to previous experiment. The soles are placed one above the other and a varying load shall be applied as shown in the *figure 5-3.* Through the time stamp protocol, the delay between the right and left sole sensor shall be calculated. Through this delay it is possible to estimate the new signals of the soles with zero delay.

In order to estimate the new signal values with zero delay, linear interpolation shall be used. The signal from the two sole sensors shall be considered, with one as the reference signal and the other signal shall interpolate to match the sampling points.

Consider two sampled signals from the samples of two soles as Left sole [X (n)] and Right sole [Y (n)]. The time synchronization error between the sampled signals shall be considered as Δt. The time difference between the two samples in the SIGS system is T=125 ms. The new corrected signal shall be calculated from the below equation,

$$C(n) = X(n) + \frac{\Delta t}{T} \times \frac{\{X(n+1) - X(n-1)\}}{2} \qquad \text{………………….. (1)}$$

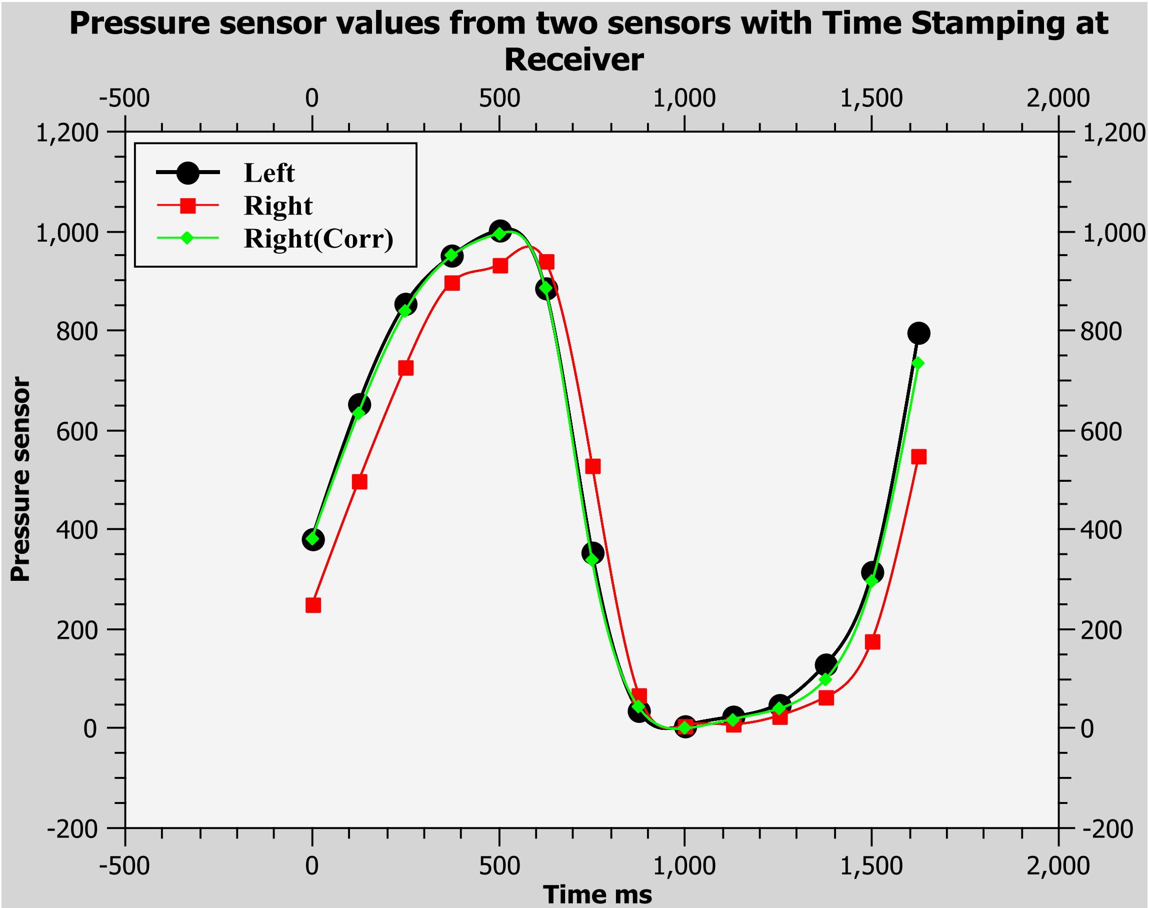


Figure 5-3 Pressure sensor values are plotted against time to check the performance of time stamping at the receiver

In this experiment, the time synchronization error between the two samples soles is 55 ms; such that the right sole is sampled 55 ms before the left sole. The sampled signal from left sole is considered as the reference signal and the sampled signal from the right sole shall interpolate to match sampling points. In figure 5-3, the sampled signal from the right sole is moved 55 ms; such that both the soles are sampled at the same time. The new corrected signal is estimated using the above mentioned equation (1).

Calculation 1:

At sampled time 250 ms,

The pressure sensor value of right sensor , X (n) = 728

The pressure sensor value of left sensor , Y (n) = 854

Time synchronization error , Δt = 55

Using the equation (1),

New corrected sampling point of right sensor , C (n) = 840

Similarly, the new corrected sampling points for all the values in the right sensor are estimated and plotted in the graph as shown in the *figure 5-3*.

Calculation 2:

The root mean square errors (RMSE) for corrected and uncorrected right sensor are estimated using the equation (2) as shown below.

For uncorrected right sensor with sequence number,

$$RMSE = \sqrt{\frac{\Sigma f\{[X(n)] - [Y(n)]\}^2}{i}} \quad \text{......................} \qquad (2)$$

RMSE = 10.6 %

For corrected right sensor with time stamp protocol,

$$RMSE = \sqrt{\frac{\Sigma f\{[X(n)] - [C(n)]\}^2}{i}} \quad \text{...........................} \qquad (2)$$

RMSE = 2.9 %

Where,

X(n) – Reference sampled signal from left sensor
Y(n) – Uncorrected sampled signal from right sensor
C(n) - Corrected sampled signal from right sensor
i - No of samples

Conclusion from the above experiment

1) *The sequence numbers shall detect only the lost frames. But through time stamp protocol, the samples are re-sampled to match with the other sampled signal. The figure 5-3 provides a good correlation in matching the sampling points.*
2) *The calculated value of RMSE is good for the corrected right sensor with 2.9% as compared to the uncorrected right sensor with 10.6 %. Hence it shall be concluded that the implemented time stamp protocol at the receiver side is good enough for the system with good matching points as compared to sequence number synchronization method.*

5.2.3 Robustness tests

In this test, the robustness of the system is tested and the packet loss with respect to external disturbance is tested. The experimental setup for the testing is implemented in a laboratory with the required equipments.

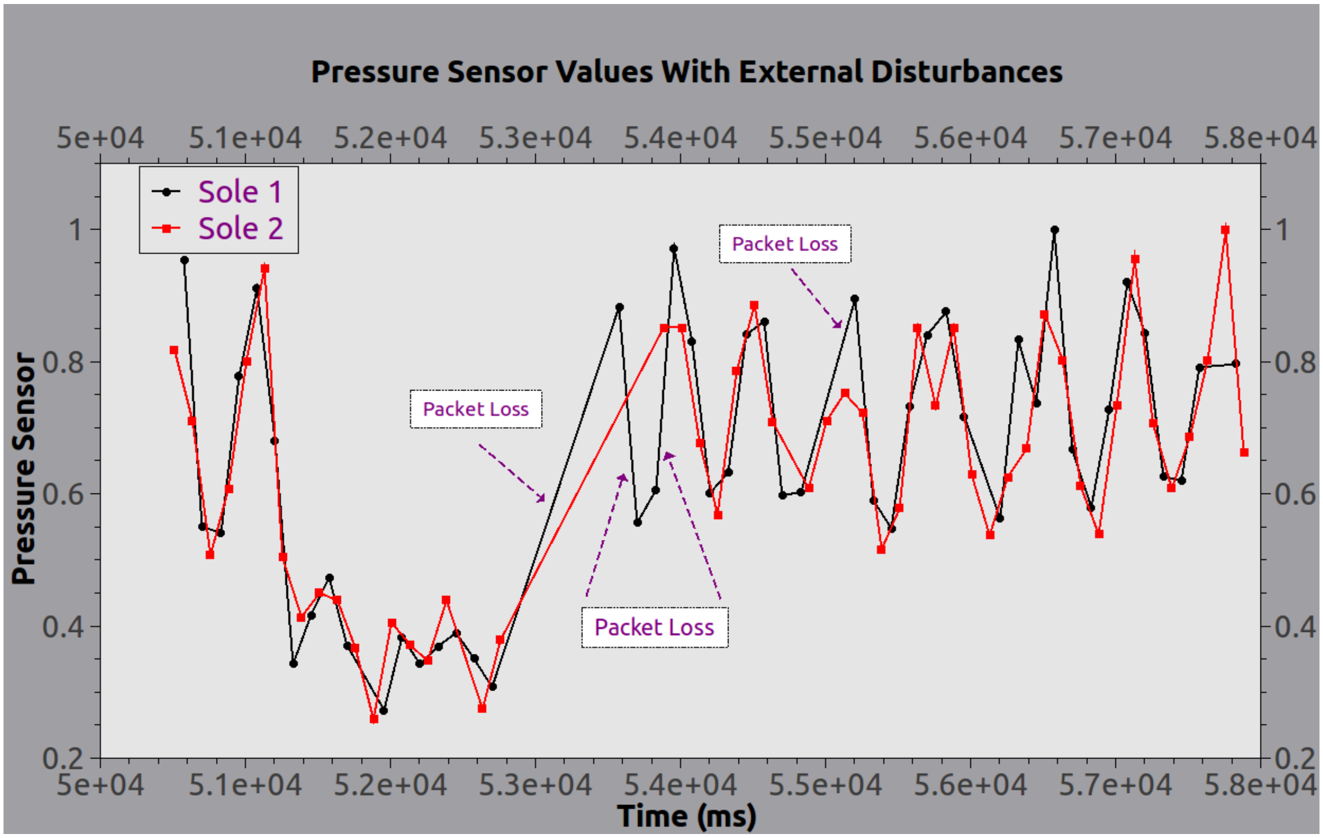


Figure 5-4 Pressure sensor values of two soles are plotted against time to check the robustness of the SIGS system with disturbances

The experimental setups were same as that of the previous experiments. The pressure is given to the soles by pressing the sole layer of the SIGS system using our foot. External disturbance is given to the system in order to disturb and to check the reaction of system due to the disturbances. In this experiment, we use mobile phone to disturb the system.

Test	Time taken (msec)	No. of Packets Expected	No. of Packets with respect to time	Missed Packets
Mobile disturbance_1	7375	100	118	18

No. of Packets request from the Linux Server	= 100 Packets.
Time required to receive 100 packets	= 6250 ms.
Packet loss	= 18 Packets.
Total Time taken	= 7375 ms.

The mobile phone is used to make a call to other mobile and the disturbance is created by keeping the mobile phone near to the receiver of the SIGS system. The disturbances were continuous and the testing was considered in worst case scenario. The received pressure sensor values from the two soles of the SIGS system is shown in *Figure 5-4.* The table shows the packet loss and the time taken to receive the total packets.

Through this test, the robustness of the system is analyzed. The external interference could not be avoided. There might be possibility of external disturbance to the system. From figure 5-4, few packet losses in the system shall be verified. As the system was run for a shorter time and the disturbance was continuous (in worst case scenario) throughout the communication process, there were few packet losses. Whenever any disturbance occurs, there are few packet losses. But however the system gets stable and receives the message packet without any packet loss within a shorter time.

5.2.4 Final test results with overall observation for protocol

In this test, overall observations from all the tests were considered. The observed values from different environmental setups were taken. The graph is plotted between the time interval and the number of observations as shown in the *Figure 5-5*. The time interval is the time difference between the two soles in the time slots of ANT communication protocol. The number of observations is the observations done through the number of tests. Whenever the channel is free, each sole transmitter tries to communicate with the ANT receiver in their dedicated time slot. If the channel is busy, the ANT transmitter tries to transmit in the next time slots.

In our SIGS system, the channel period is 125 ms. The center value of the channel period is approx. 62 ms. In our graph, the time intervals are considered in such a way that, nearest time difference value to the transmission are chosen. For example,

Transmission time of sole 1, T11= 1250 ms
Transmission time of sole 2, T21= 1306 ms

Time interval, ΔT = T11-T21= 56 ms

Similarly if,

Transmission time of sole 1, T11= 1250 ms
Transmission time of sole 2, T21= 1325 ms
Transmission time of sole 1, T12= 1375 ms

Time Interval, ΔT= T12-T21=50 ms

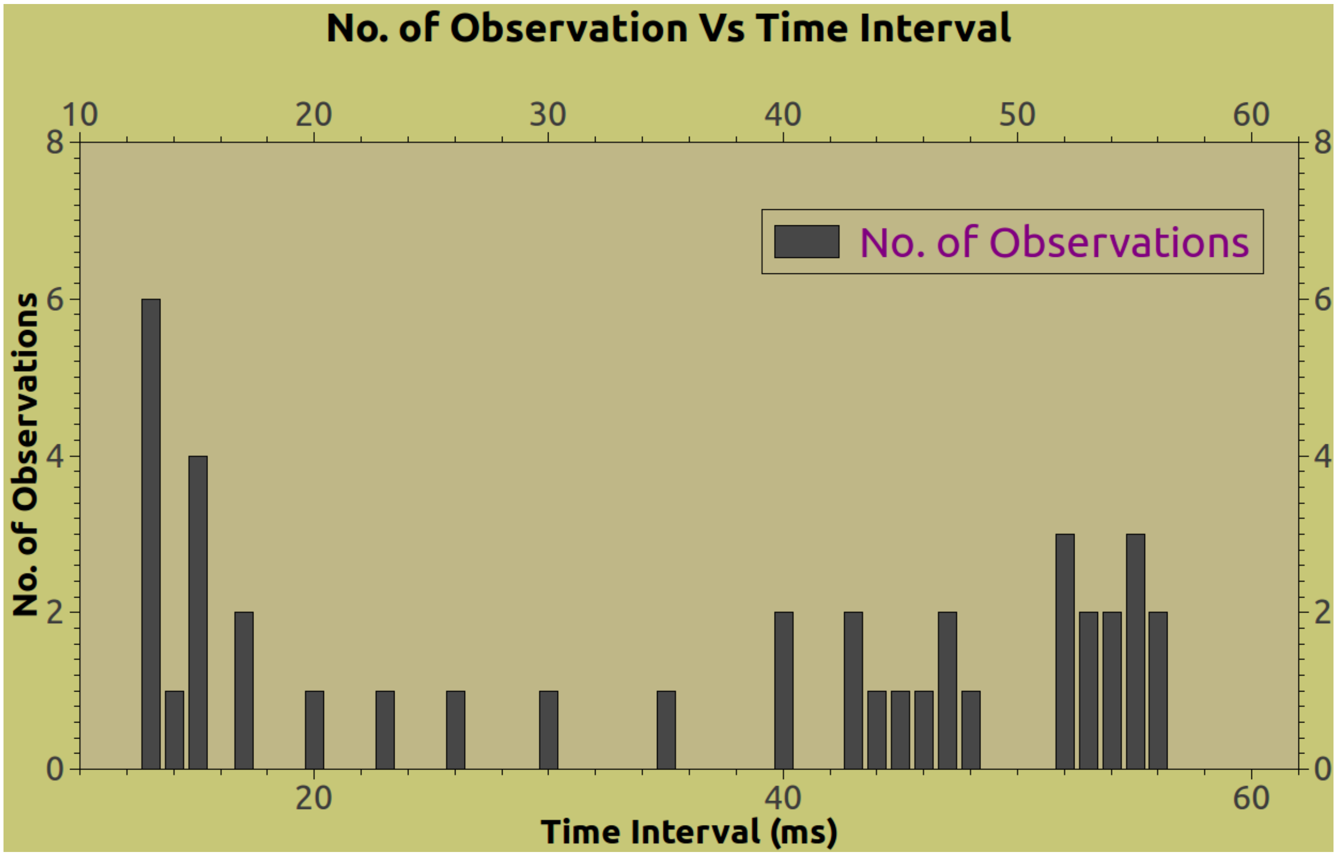


Figure 5-5 No. of observations are plotted against time to check the allocation of time slots and the time synchronization in Protocol

Through our time stamp protocol, we could observe that most of the observations obtained are randomly generated throughout the channel period. In the figure 5-5, overall maximum observations fall between 10-60 ms, such that the approximate time difference between the two soles were around 10-60 ms. Through our detailed study and experimental observations, we could assume that the protocol tries to accommodate the time slot for the second transceiver as soon as possible after the first transceiver. Whenever the ANT channel is busy, the ANT transceiver could communicate in the next available time slot which is approximately nearer to the time slot allocated for the first transceiver. Hence the transceiver could transmit before the start of the next channel period and thus the protocol could produce a better synchronization. Through the observations, it shall also be concluded that, once the time slot is allocated for the channel at the start of the synchronization, it utilizes approximately the same allocated time slot at the time of re-synchronization after every packet loss.

6 Conclusions

6.1 Summary and Discussions

In our thesis, we proposed solutions for time synchronization between ANT sensor nodes and new hardware design prototype for ANT low power wireless sensor networks. As the ANT protocol is a proprietary protocol, the scheduling of time slots is adaptive isochronous co-existence i.e. the scheduling is dynamic and unpredictable. With this thesis work, the designed method was implemented to know about the time synchronization in ANT protocol and to provide a time synchronized data to the ANT receiver. The designed synchronization method implemented was Time stamp protocol for Broadcast data-type. The implemented protocol provides us the packet data with time stamp through which we could know when the data is measured. Moreover the data with time stamp helped the receiver to store the data in its buffer and made easier for future reference.

The implemented hardware design prototype with its built-in processor could help the developer to include additional features in future for different applications. In this prototype, the tasks include USART communication protocol, USB communication protocol, time stamp protocol, send and receive sensor data via ANT protocol were implemented in both software and hardware phase with full functionality. Its functionality and performances were tested and the results obtained were successful. The designed method also provided us a way to know clearly about the time slots and time synchronization in ANT protocol which will help the new ANT users in choosing the ANT protocol for different application. The SIGS system was tested with the new hardware design prototype and the Linux WBAN server. The experimental results show that this new designed system is feasible and reliable for Wireless health care bio feedback systems.

The number of experimental test and observations provided a solution to know about the allocation of time slots in ANT protocol. The new research proposed solution for global clock synchronization in ANT protocol shall provide a better time synchronization in the system but time stamping at receiver with re-sampling of one of the sensors also provided a good result.

6.2 Future work

Through series of experiments and results, we could improve the research work with additional features. The time stamp protocol could not be implemented directly on the user space of Linux WBAN server but it is possible to implement on the Linux kernel and drivers, which might be more complex and could provide a better alternative solution. While designing the hardware prototype, the cost was not considered. As the prototype is built for testing purpose, we shall build a new hardware prototype board with fewer features with low cost processor like ATMEL which could provide required features for the specific applications in future.

The implementation of Global clock could provide a good synchronization. The time stamp protocol implemented is for Broadcast data-type which is uni-directional with low power consumption. So the Global clock can be implemented but with small increase in power consumption with much better synchronization of measurements in our SIGS system. The research solution for the global clock synchronization for ANT was provided with better time synchronization in the reverse direction. The implementation of this synchronization protocol for ANT protocol in the future could provide efficient global clock synchronization.

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8 APPENDIX

8.1 Schematic of SIGS system

In this section, we present the PCB schematic of the SIGS system designed for the soles with Atmel ATmega 88 microcontroller with ANT Transceiver and the pressure sole sensors.

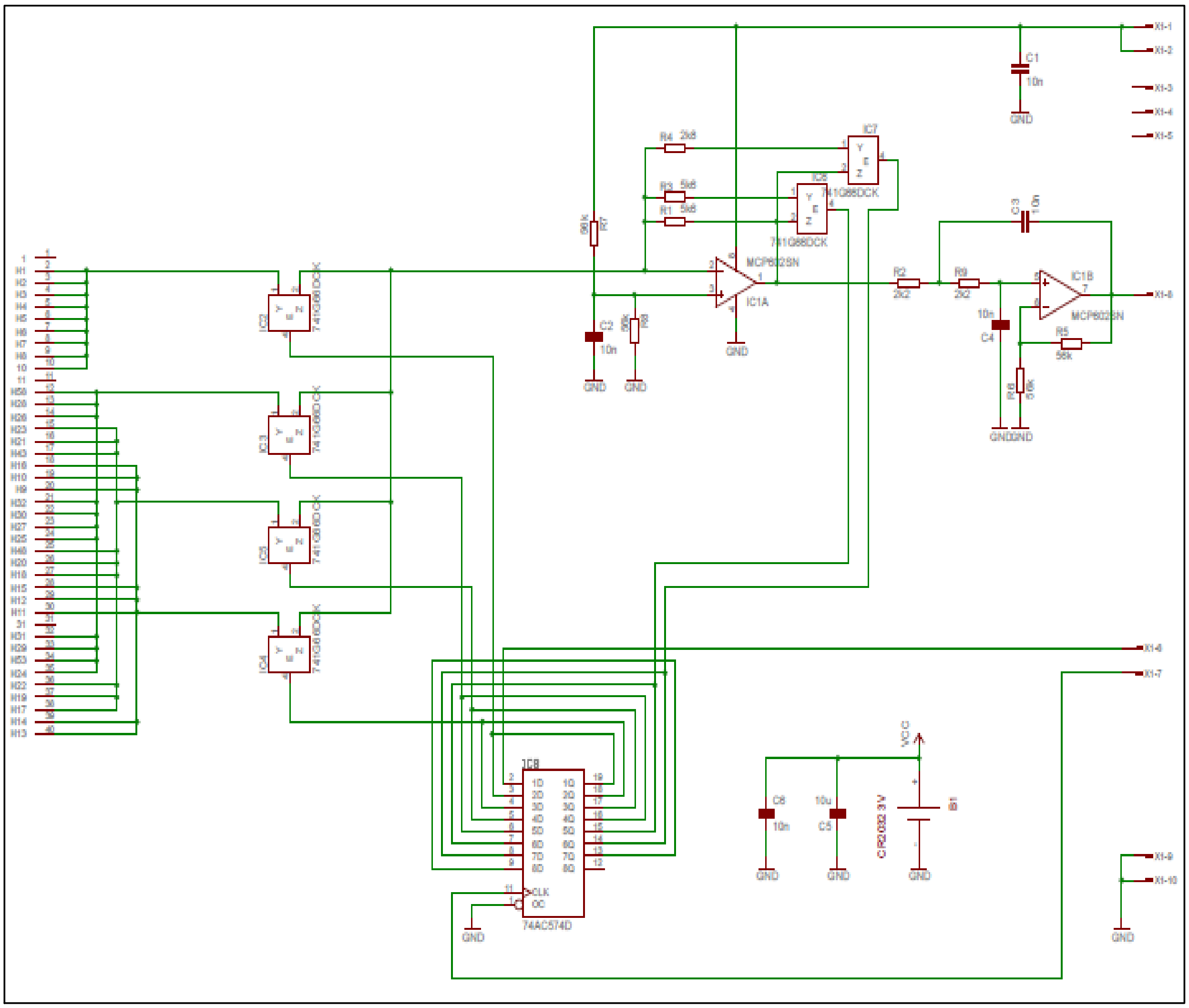

Figure 8-1 Schematic of the SIGS Sole system

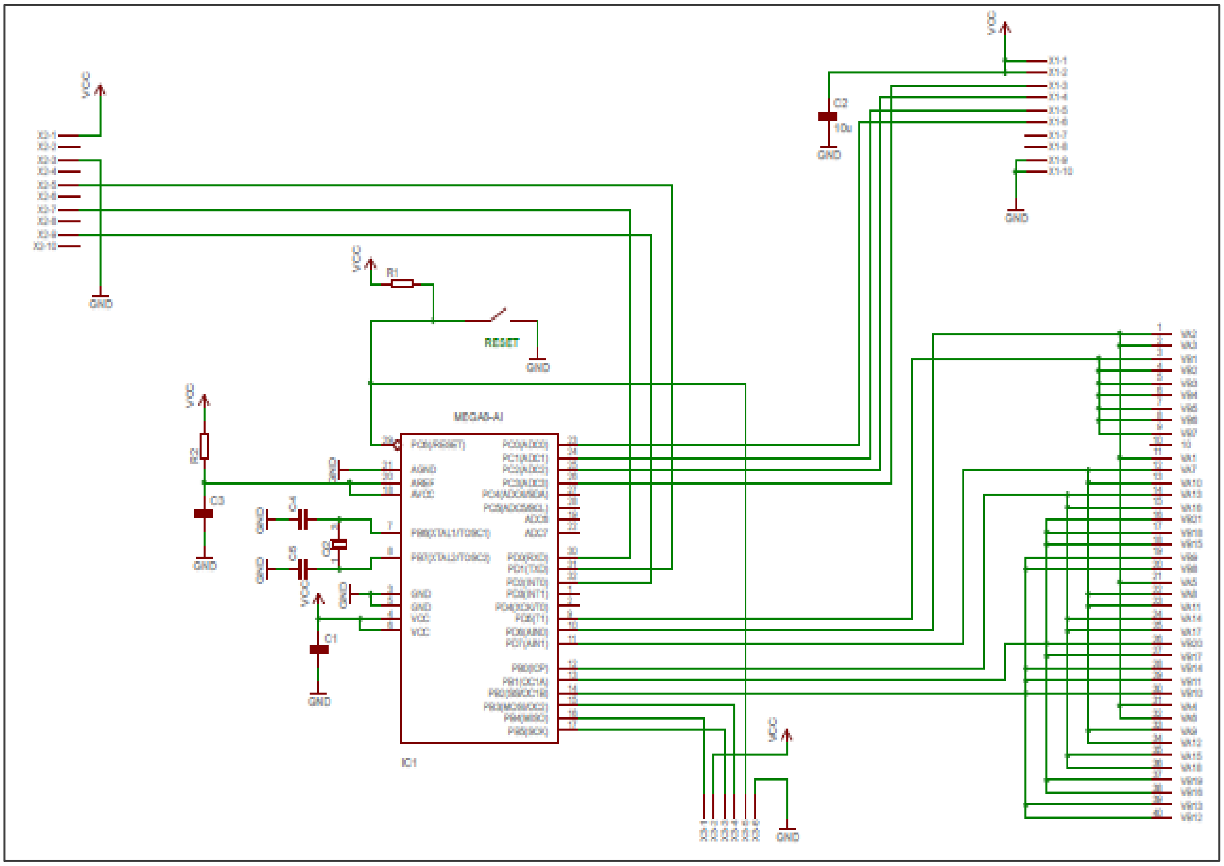

Figure 8-2 Schematic of the Sole SIGS System

8.2 Schematic of the ANT-ARM-USB Hardware Prototype

In this section, we present the PCB schematics and the pin configurations of ANT-ARM-USB hardware prototype designed for the WBAN server to receive the time synchronized data from the SIGS system.

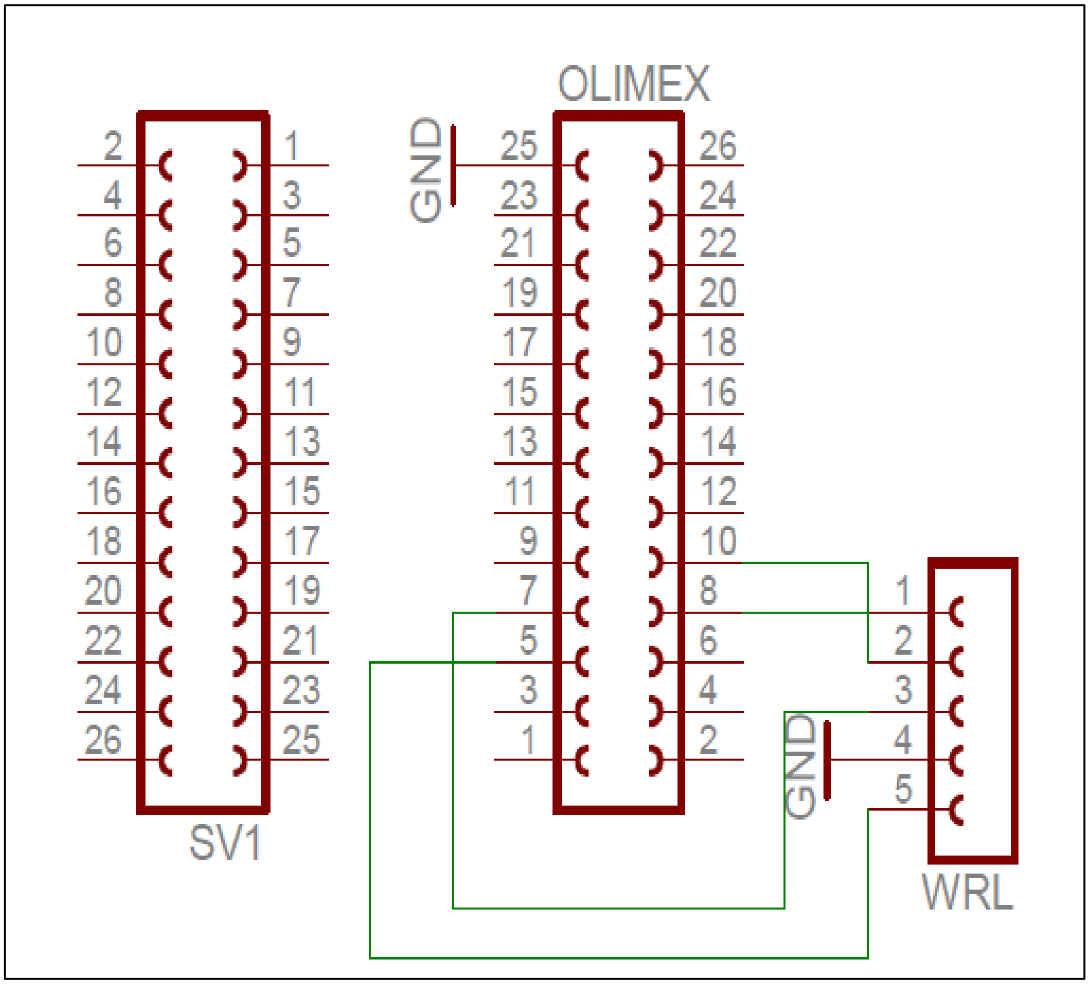

Figure 8-3 PCB Schematic of ANT-ARM-USB

Olimex Board (pin)	*ANT Transceiver(pin)*
8	1
10	2
7	3
5	5

Figure 8-4 Pin configurations between Olimex Board and ANT Transceiver

8.3 Schematic of OLIMEX STM32 H103 Development Board

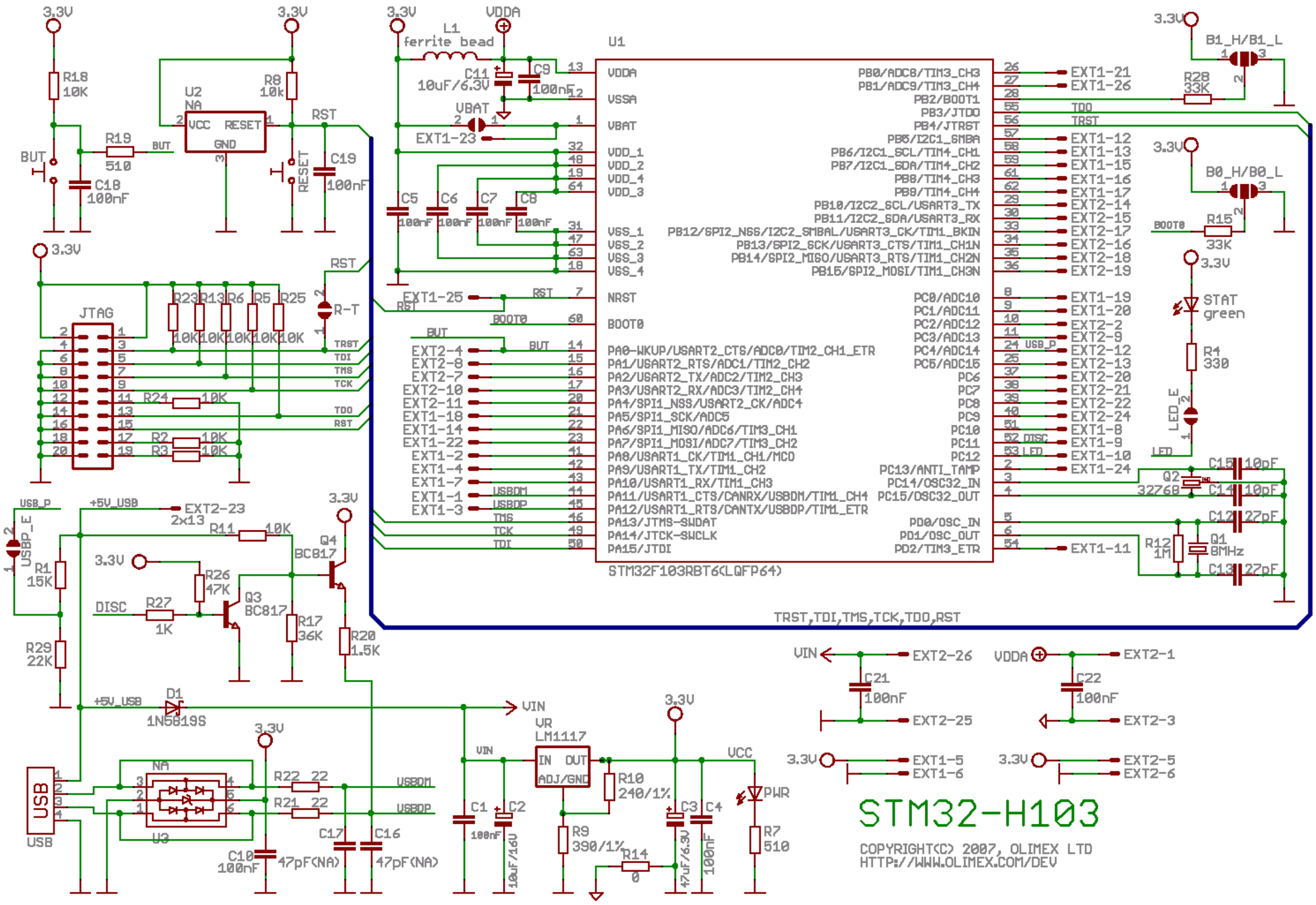

Figure 8-5 Schematic OLIMEX STM32-H103 Development Board