Development of UWB-IR based low power asset tracking system with precise location information

Gupta, Ankur

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**DEVELOPMENT OF UWB-IR BASED LOW POWER
ASSET TRACKING SYSTEM WITH PRECISE
LOCATION INFORMATION**

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Abstract

Global Positioning System (GPS) and Global Navigation Satellite System (GNSS) are currently widely used for measurement of real time location of assets in tracking applications. However, in densely cluttered indoor environments, direct line of sight signal from satellite is weak and the received signal is dominated by reflected signals (multi-path signals). This causes the receiver to track the multi-path signals resulting in degraded position information or the signal may be so heavily attenuated that it goes below noise floor of the receiver and makes it difficult for the receiver to detect the signal. There is also strong demand for indoor positioning applications driving the need for indoor localization. The goal for this thesis is to develop a low power asset tracking system for the indoor applications.

This thesis is commenced with design of energy efficient tags that will be carried by people or objects to be tracked in the indoor environment. The design of tags includes the hardware and firmware development with the aim of achieving energy efficiency as tags are powered by coin size battery. The tags transmit Ultra-Wideband (UWB) signals for the purpose of localization and are commanded through a sub-1 GHz wireless data link. The tags designed to be used in this system are UWB transmitters only. This is done to achieve the low power design parameter for the system as UWB receivers are likely to co-

consume higher power and tags are powered by a coin size battery leading to less operational hours. For the purpose of command and control along with consideration of the low power design parameter, an ultra-low power sub-1 GHz wireless data link is used in comparison to 2.4 GHz band, which is used in many applications resulting into difficulty of achieving the reliable data link. The firmware code is developed for tags to perform sub-1 GHz wireless communication. The three design strategies are presented and implemented in design of tags which aid in achieving the extended battery life. The current measurement results are presented along with computation of battery life. Using battery capacity as 240 mAh in conjunction with the implementation of three design strategies in tag, the battery life of 86 days is achieved at the update rate of 1 Hz with sub-1 GHz Tx power of +10 dBm and UWB Tx power of +23 dBm.

The development of indoor localization system is accomplished with design of reader/sensor nodes which includes the hardware and firmware code development. The reader nodes are distributed in indoor environment to receive the UWB signals for the purpose of localization. The localization technique used in the system is based on time difference of arrival (TDOA). The sub-1 GHz wireless data link is used by the reader nodes for intent of command and control. The firmware code is developed for the reader nodes to achieve control over the whole process of indoor localization using the sub-1 GHz wireless data link. The reader cape hardware is designed to be mounted over BeagleBoneBlack (BBB) board. Using low cost ADC, the equivalent time sampling is performed in the reader nodes to sample the UWB signals transmitted by tags.

The sampled UWB signals are processed in the BBB board to find time of arrival (TOA) information. The TOA data from all readers nodes is transmitted to the central server where TDOA is computed and localization is performed using difference of TDOA's.

In this system, the energy efficient Medium Access Control (MAC) scheme is designed and implemented for multiple tags indoor localization environment. This scheme is based on centralized architecture controlled by master reader node. The master reader node provides feedback to tags using the sub-1 GHz beacon about allocated time slots. This feedback about the allocated time slots prevents the charge consumed in case of re-transmissions of acknowledgment packets, resulting from collisions due to simultaneous transmission by the tags. The time synchronization is performed between the master reader node and the tags in order to maintain the start time for listening of beacon in the tags in every cycle. This synchronization removes the ideal listening time in the tags. Also, using an ultra low power MCU (CC1310), the charge consumption during the listening of the master reader beacon in the tags is minimized. With this implementation of MAC scheme in the system, the charge consumed in the tags during one cycle is found to be 40 μ C.

In last, to perform 1D range measurement between reader nodes, the range equation is derived using TDOA in consideration with the clock skew and the clock offset at each of the devices. The experimental set up is developed including 2 reader nodes and 2 reference tags (co-located at readers) for performing 1D range measurement along with the implementation of MAC

scheme. The measurement results are presented for different distances between the two reader nodes and from the measurement results, the accuracy is found to be less than 20 cm.

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Chapter 1

Introduction

1.1 Motivation

Ultra-wideband (UWB) based indoor positioning systems are commonly used in indoor applications for instance to track and locate important asset and personnel [1]. It provides higher accuracy in the positioning due to the advantage of using impulses with nano second durations as compared to the GPS which suffers a degradation of the performance in the indoor environment [2], [3], [4]. UWB signals are defined by Federal Communications Commission (FCC) as having -10 dB bandwidths greater than 500 MHz with the maximum average transmitted power density as -41.3 dBm/MHz with a peak power limit of 0 dBm/50MHz in the 3.1-10.6 GHz band.

A typical positioning system may consist of radio frequency identification (RFID) tags along with the network of sensors which work in union to provide the positioning information in indoor environments [5]. Two-way ranging systems use UWB transceivers at each node for the purpose of positioning

and medium access control (MAC). However, in such a two way ranging system, it is difficult to achieve the low power design constraint for the battery powered nodes as UWB receivers are likely to consume higher power due to larger operational bandwidth along with the higher sensitivity requirement. TDOA based systems use 2.4 GHz band for MAC and UWB technology for positioning. The 2.4 GHz band is an ISM band used in different commercial applications (ZigBee, BLE, Wi-Fi) resulting in lesser availability of the spectrum bandwidth for the reliable link and for higher throughput [6]. On the other hand, sub-1 GHz communication acts as an alternative choice for MAC as it provides better range in the indoor environment when compared with 2.4 GHz band for the similar transmitted power.

1.2 Overview

The low power asset tracking system developed during this work can be outlined as a combination of UWB technology for the intent of positioning along with sub-1 GHz communication for the intent of command and control. This thesis presents the research and development involved in the design of the different aspects of the asset tracking system such as the design of RFID tags, the reader/sensor system and the implementation of the energy efficient MAC scheme. The goal for this thesis is to develop the energy efficient tags for achieving the extended battery life and to provide the peer to peer range measurement between the reader systems. Also, this thesis targets to handle the multiple tag indoor localization environment by providing an energy efficient

MAC scheme using the centralized architecture controlled by master reader system.

1.3 Contributions

This work in the development of low power asset tracking system uses the UWB transmitter and the UWB receiver based on the prior work [7]. The major contributions from this thesis in the indoor localization system development include:

- Design and implementation of the hardware circuit in the form of printed circuit board (PCB) for the power management of tag. The state transition diagram for firmware used in the tags is proposed for the positioning mode which helps in achieving the power management. The firmware code is developed using the proposed state transition diagram. The three design strategies are presented and implemented in the design of tags in the form of hardware and firmware for achieving extended battery life. The power consumption results are presented and the battery life computation is performed with each measurement.
- Design and implementation of the hardware circuit in the form of PCB for the reader cape to be mounted on BBB board. The complete system description is provided for the functioning in different phases. The equivalent time sampling is performed in the system to sample the UWB envelope with low cost ADC. The firmware code is developed for the

readers for the intent of command and control in the whole system using sub-1 GHz wireless data link.

- An energy efficient Medium Access Control (MAC) scheme is presented and implemented in the form of firmware code in reader systems and tags. The state transition diagram is proposed for the tags in the MAC mode. The power consumption results are presented in comparison with other standard MAC schemes.
- The range equation using time difference of arrival is derived in consideration with the clock skew and the clock offset at different devices. The presented algorithm aids in the range computation between the readers using the UWB signals from the co-located reference tags and also helps in synchronizing the reader clocks to the closest values. The measurement results are presented for the 1D ranging between the two readers.

1.4 Thesis Organization

The thesis impels in chapter 2 with the background and literature review. Chapter 3 presents the details about the design for battery powered tags. The system overview and the reader hardware details are presented in chapter 4. Chapter 5 describes the energy efficient MAC scheme which can be implemented practically in the indoor localization systems using centralized architecture. A mathematical formulation of the algorithm for computing the peer to peer ranging is proposed in chapter 6 along with 1D measurement results.

Finally, this thesis ends up with chapter 7 which includes conclusions and future work.

Chapter 2

Background and Literature Review

2.1 Overview

This chapter provides the literature review and background theory that is required for development of the asset tracking system. Section 2.1 reviews the UWB technology as it is utilized for the positioning of mobile tags. The next section describes the ranging techniques that can be implemented using the UWB technology. Section 2.3 discusses the sub-1 GHz technology as it is used in the project for the implementation of MAC for wireless network. A brief summary about the commercial UWB based localization system is described in the following section. Section 2.6 provides the literature review related to the research work in the localization system and the last section presents summary for the chapter.

2.2 UWB Technology

In late 1800s, Marconi created the first wireless transmission from an impulsive spark [8]. However, the benefits of large bandwidth of the impulsive spark were never considered at that time. The origin of UWB technology can be mapped to approximately 50 years later after Marconi's experiment. During that time, pulsed based transmission gained momentum in military applications in the form of impulse radar. In 1974, Morey developed the UWB based radar system for penetrating ground. From that time, the subsequent developments in the UWB technology had made it more popular. In 1998, the Federal Communication Commissions (FCC) started the review of the UWB technology and in 2002, FCC defined the spectrum for the UWB technology for the commercial use [9].

FCC defined the UWB signals as the signals with the -10 dB bandwidth greater than 500 MHz with the maximum average transmitted power density as -41.3 dBm/MHz with a peak power limit of 0 dBm/50MHz in 3.1-10.6 GHz band [10]. The figure 2.1 provides a comparison between the power spectral density of a UWB signal with that of a narrowband and wideband signal. It can be seen from the figure due to the low power density, the UWB signal can co-exist with the other signals and provide minimum amount of interference to the other signals.

UWB technology mainly fall into two categories:

- 1) Impulse Radio (IR)

FIGURE 2.1: Comparison of power spectral density of narrowband, wideband and UWB signals

2) Multi-band Orthogonal Frequency Division Multiplexing (MB-OFDM)

IR-UWB is based on transmission of very short duration pulses with very low energy. The figure 2.2 shows the UWB pulse generated by UWB transmitter. The duration of the pulse is around 1ns with the peak to peak voltage of 6V which corresponds to around 0.36nJ of the energy. The MB-OFDM divides the UWB frequency spectrum in multiple orthogonal frequency bands.

FIGURE 2.2: UWB pulse generated by UWB transmitter

2.2.1 Advantages of UWB technology

In comparison to the narrowband technology, the UWB technology offers various advantages. Due to the ultra-wide bandwidth, UWB technology has good immunity to interference from the narrowband technology [11]. Also due to the wider bandwidth the higher data rates can be achieved with the low S/N requirement [12]. This can be understood with the Shannon's channel capacity theorem, which states that the channel capacity is directly proportional to the bandwidth for a fixed S/N and given by equation (1) as:

$$C = B * \log_2 (1 + S/N) \text{ --- (1)}$$

Based on the UWB receiver sensitivity, a low value of S/N can be fixed and then corresponding to the bandwidth, a higher data rate can be achieved.

In addition, due to FCC regulation on the average power density, the UWB signals can coexist with the narrowband signals and thus providing the electromagnetic compatibility (EMC) and minimize the electromagnetic interference (EMI) with the other signals. Also due to the presence of combination of the high and low frequency spectrum, UWB technology has better penetration capability through obstacles [13].

Furthermore, IR-UWB offers good immunity to the multipath effects. Due to the wider bandwidth resulting into nanosecond time duration, it can resolve the multipath effects in the indoor environment. The wide bandwidth also helps in achieving the fine time resolution resulting into the better accuracy in

the positioning as compared to the narrowband system [14].

Lastly, the IR-UWB is a carrier-less technology which does not require the oscillators and the mixer in receiver as compared to the narrowband receiver resulting into the simple RF circuits along with low cost which makes it a better candidate for the cost effective wireless applications [15].

In this system, IR-UWB technology is used for the purpose of ranging and positioning of the tags in the indoor environment. The next section describes the use of UWB technology in computing the range in the indoor environment.

2.3 Ranging using UWB technology

Ranging based on the UWB technology can be mapped mainly into two categories [16], [17], [18]:

- 1) Ranging on time basis
- 2) Ranging on the received signal strength (RSS).

2.3.1 Ranging on time basis

Time based ranging uses the measurement of time of arrival (TOA) τ , which is the signal propagation delay and finds the distance $d = \tau * c$ where c is the speed of electromagnetic wave. This is achieved by computing one-way TOA, two-way TOA or time difference of arrival (TDOA). A brief introduction about the three techniques is presented here.

1) One-way TOA:

In one-way TOA ranging, node A transmits its packet at time t_1 with the packet containing the time information t_1 to node B. Node B receives the packet at time t_2 . If the clocks of the two nodes are synchronized, then TOA at node B is given by

$$\tau = t_2 - t_1 \text{ --- (2)}$$

, and d can be computed as

$$d = \tau * c \text{ --- (3)}$$

where c = speed of electromagnetic wave. If the nodes are not perfectly synchronized, then the synchronization error will cause the error in the range computation. The time synchronization between nodes can be achieved using different techniques as given in literature [19], [20].

2) Two-way TOA:

In two-way TOA ranging, node A transmits its packet at time t_1 to node B. Node B receives at time t_2 and with a processing delay τ_d it sends back its packet to node A. Node A receives the packet of node B at time t_3 . Then at node A

$$t_3 - t_1 = 2\tau + \tau_d \text{ --- (4)}$$

If τ_d , the processing delay at node B is known, then

$$\tau = \frac{(t_3 - t_1 - \tau_d)}{2} \quad (5)$$

and d can be computed as

$$d = \tau * c \quad (6)$$

where c = speed of electromagnetic wave. The two-way ranging has the advantage over one-way ranging that the ranging between the nodes can be performed without the time synchronization. However, the error in the computation of τ_d will cause the ranging error.

3) Time Difference of Arrival (TDOA):

TDOA based ranging uses the difference of time of arrival to compute the distance between the nodes. Let us consider a scenario in which a tag position is to be determined using TDOA. The readers are fixed nodes and are synchronized. Then the UWB signal transmitted by the tag will be received by the readers and TDOA can be computed from the TOA's values¹.

2.3.2 Ranging on the received signal strength (RSS)

Ranging based on RSS uses the fact that the lower the value of RSS, the larger will be the distance between the two nodes. In this method, the receiving

¹The reader can find details about the set-up and the detailed derivation for the range equation using TDOA in chapter 6.

node B estimates the distance of node A by measuring the RSS and uses path loss model to convert RSS into the distance estimates. The main disadvantage with this method is that the cluttered indoor environment may cause a significant amount of fading to the signal, resulting into lower RSS and inaccurate distance estimate.

It is also possible to combine these techniques to form hybrid ranging techniques. A number of hybrid techniques are presented in the literature as TOA/RSS, TDOA/RSS [21], [22] and Two-way TOA/TDOA [23].

In this project, the time based ranging technique is employed in the form of TDOA. The next section describes about sub-1 GHz technology which is used for the medium access control implementation.

2.4 Sub-1 GHz technology

The sub-1 GHz technology is attaining the widespread use in the indoor applications. The advantages offered by sub-1 GHz over 2.4 GHz technology makes it a better choice for the indoor applications. One application for sub-1 GHz technology can be to provide the medium access control in an asset tracking system operating in the indoor environment. Texas Instruments (TI) has developed an ultra-low power MCU (CC1310) chip that has capability for sub-1 GHz communication [24]. The advantages related to sub-1 GHz technology can be described as:

- 1) Longer range connectivity

- 2) Robust and reliable link capability
- 3) Low cost technology

2.4.1 Longer range connectivity

FIGURE 2.3: A Tx-Rx model with an obstacle

Figure 2.3 shows the basic model for a sub-1 GHz transmitter and the receiver along with obstacle. If we assume the power transmitted is P_t with P_r is the received power and d is the distance between the Tx & Rx with f as the operating frequency. Then, using the Friis transmission equation

$$P_r \propto \frac{P_t}{d^2 f^2} > \text{Sensitivity Limit @ acceptable BER}^2 \text{ --- (7)}$$

From (7), if we fix the sensitivity limit for the receiver and assume the P_t as constant, then

$$d \propto \frac{1}{f} \text{ --- (8)}$$

which means that the lower operating frequency offers the longer range and this is the one of the advantages of sub-1 GHz over 2.4 GHz technology.

---

²BER refers to Bit Error Rate

Also if we assume P_t as constant, then the distance d can be increased by lowering the sensitivity of the receiver. To illustrate this concept, let's consider figure 2.4. Figure 2.4 shows BFSK³ modulation being used for the two technologies in consideration with oscillator inaccuracies. The black arrows show the ideal case for both technologies with f_0 as the centre frequency. For BFSK modulation, f_1 represents the bit "1", f_2 represents the bit "0" and are given by:

$$f_1 = f_0 + \delta f$$

$$f_2 = f_0 - \delta f$$

Now consider two cases:

FIGURE 2.4: BFSK modulation shown for sub-1 GHz and 2.4 GHz in consideration with oscillator inaccuracies

Case 1: For Sub-1 GHz

If centre frequency $f_0 = 922$ MHz and if we consider the oscillator instability of ± 10 ppm in both the Tx and Rx and considering the worst scenario where

³BFSK stands for Binary Frequency Shift Keying

the clock drift between the Tx oscillator and the Rx oscillator is 20 ppm then the maximum frequency shift in the f_0 will be $\pm 18.44 \text{ KHz}$ as shown in yellow arrows in figure 2.4. The receiver bandwidth has to be decided in such a way so as to cater this variation in the frequency. Let B_1 be receiver bandwidth for this case.

Case 2: For 2.4 GHz

If centre frequency $f_0 = 2400 \text{ MHz}$ and if we consider the oscillator instability of $\pm 10 \text{ ppm}$ in both the Tx and Rx and considering the worst scenario where the clock drift between the Tx oscillator and the Rx oscillator is 20 ppm then the maximum frequency shift in the f_0 will be $\pm 48 \text{ KHz}$ as shown in blue arrows in figure 2.4. To handle this frequency variation, let B_2 be receiver bandwidth for this case.

It can be clearly seen that B_2 is greater than B_1 . As the receiver bandwidth increases, the noise power will also increase. Since P_t is kept constant so signal power is constant. This results in the decrease in S/N for the acceptable BER. Hence the sensitivity of the receiver for 2.4 GHz technology will degrade, resulting into the decrease in the range. However, the sub-1 GHz technology has lower receiver bandwidth, resulting in the better sensitivity and hence it offers the longer range capability.

2.4.2 Robust and reliable link capability

The sub-1 GHz technology has better penetration capability through obstacles and also has got better bending capability through corners as compared to 2.4 GHz technology, resulting in the better coverage. The 2.4 GHz band is used in almost all the indoor applications using WiFi, Bluetooth, ZigBee, resulting in the lesser availability of the spectrum bandwidth for the reliable link as compared to sub 1-GHz which is less crowded and thus provides a robust and reliable link for the communication [24].

2.4.3 Low cost technology

The 2.4 GHz technology has less receiver sensitivity as can be seen in the previous descriptions. Due to the lower sensitivity, it has got the lower range for the same transmitted power. The range extenders in the form of other nodes are required frequently, resulting in the increase in overall system cost. On the other hand, due to the longer range capability, the sub-1 GHz provides the cost effective solution using a fewer extender in covering a larger area assuming the same transmitted power.

In this system, the sub-1 GHz technology is used to provide the medium access control for the wireless sensor network between tags and the reader system. This is done with the help of the firmware code development for TI RF MCU CC1310 chip in the tags and the readers.

2.5 Commercial UWB based Localization System

Different UWB based localization systems are currently available in the market. Some of them use proprietary technology while some are based on IEEE 802.15.4a standard.

Ubisense Real Time Localization System (RTLS) follows proprietary technology for the localization and for the medium access control. Ubisense system uses UWB technology with the localization technique as angle of arrival (AOA) and Time Difference of arrival (TDOA) to determine the tag location. For the purpose of MAC, the Ubisense system utilizes the 2.4 GHz ISM band. This system offers an accuracy better than 20cm [25].

Decawave offers DW1000 radio communication chip based on IEEE 802.15.4a standard. This chip is CMOS based UWB transceiver which can be converted into the tags and sensors for the complete localization system. For the purpose of ranging, this chip utilizes time of arrival (TOA)/TDOA as the ranging technique. In this system, the MAC is also performed with the UWB technology only. The ranging accuracy of better than 10 cm can be achieved with this system [26].

2.6 A review on related research work

This section provides an overview of related research work being carried out in the field of indoor positioning systems. The research area related to Internet of Things (IoT) has been advancing as it enables a connectivity between objects

and human beings [27]. In this scenario, the real time data information from sensors placed on objects along with their location is an important requirement [28] and hence, to succeed in this goal, the real time indoor positioning system becomes a necessary contender [29], [30]. The real time positioning system can rely on different technologies which include infrared (IR), optical, ultrasound and radio frequency (RF) [31]. Among RF based technologies, the adoption of UWB signals in such systems helps in resolving multi-paths and achieving high localization accuracy [32]. The increased popularity for such systems comes mainly from low cost and energy efficient design for mobile tags. Moreover, the additional interest is related to such systems when UWB signals are used to measure the range between asynchronous anchor nodes while preventing human involvement in set up of coordinate system for the anchor nodes before the start of localization. This thesis intends to describe the research work related to three areas in the asset tracking system as described below.

1. How to design low cost and energy efficient architecture for mobile tags in the positioning system while operating with small coin cell?
2. How to design energy efficient medium access control scheme for multiple tags environment in the positioning system?
3. How to prevent human involvement in procedure of range measurement between anchor nodes before the start of localization while performing clock synchronization between them?

The related literature review is presented for each problem separately.

How to design low cost and energy efficient architecture for mobile tags in the positioning system while operating with small coin cell?

The research work available worldwide involves different solutions for architecture of mobile tags in the indoor positioning system. In [33], the authors used an approach in which mobile tags find their own positions using two-way TOA ranging. The authors proposed to generate frequency ramp signal with phase locked loop (PLL) and used FPGA to process the time information using two-way TOA ranging. This architecture for mobile tags is not cost effective and also power consumption is likely to be high due to the usage of FPGA and PLL in mobile tags. In [34], the authors conducted an experimental study for the UWB based positioning system. However, their design for mobile tags has limitations in terms of power consumption as they propose to use FPGA for generating the trigger signal for UWB pulse generator circuit and also conducted their measurements with the help of oscilloscope as a receiver. In [35], the authors provided solution with the usage of signal generator and the oscilloscopes for the measurement which is not applicable for low cost and low power consumption solution for positioning system. In [36], the authors proposed to use UWB transceiver for the mobile tag. However, their complete solution for the mobile tag involves the usage of time to digital converter (TDC) along with UWB transceiver which will effectively increase the overall cost and the power consumption. In [37], the authors presented a solution for mobile tag using Global Navigation Satellite System (GNSS) receiver along with UWB radio modules. In such solution using two way TOA ranging technique, the power consumption for mobile tags will be high due

to the presence of GNSS receiver along with UWB receiver. The work in [38] presented an analysis on the problem of human tracking using UWB signals. However, in their work, measurements were conducted using Pseudo-Noise (PN) generator and power amplifier as transmitter and real time sampling oscilloscope as receiver. Also, they have not shown any concern in the area of power consumption for mobile nodes.

In this thesis, chapter 3 describes a practically feasible low cost and energy efficient architecture for mobile tags in the indoor positioning system by using the UWB transmitter and the ultra low power sub-1 GHz transceiver.

How to design energy efficient medium access control scheme (MAC) for multiple tags environment in the positioning system?

Energy efficient MAC schemes play a pivotal role in positioning system as mobile tags are energy limited and need to access a common channel for data transmission. The main sources of energy wastage in the mobile tags in a sensor network can be mapped to ideal listening, collisions, data overhead and overhearing. In order to reduce the wastage of energy in the mobile tags, researchers have been developing ideas for energy efficient MAC schemes. MAC schemes are mainly classified under two categories: contention-free schemes and contention-based schemes [39]. Contention-free schemes are based on Time Division Multiple Access (TDMA) and are energy efficient as re-transmissions resulting from collisions will be avoided due to transmission

in time slots. On the other hand, contention-based schemes include ALOHA based schemes and Carrier Sense Multiple Access (CSMA) based schemes. ALOHA based schemes are generally used in distributed architecture where the concern on energy savings in the mobile tags is less. CSMA based schemes employ channel sampling and can provide energy efficiency in the nodes if an ultra low power receiver is used for listening the channel.

There are different approaches available in literature for reducing ideal listening in order to bring energy efficiency in mobile nodes. In [40], the authors proposed to use an ultra low power wake-up receiver (WRx) for continuous channel monitoring while the main receiver is switched on only for data reception. This approach can be called as Always-On WRx MAC scheme. It provides energy efficiency to node as the main receiver is switched on only when data is available for reception. In [41], the authors presented a scheme called as Duty-Cycled Wake up MAC (DCW-MAC). In this MAC scheme, authors proposed to use a duty cycled ultra low power WRx along with the main receiver. When wake up preamble is detected by wake up receiver, the main receiver is switched on for data reception. DCW-MAC is better than Always-On WRx MAC scheme in terms of energy efficiency due to duty cycling of WRx but for both the schemes, the architecture for mobile node involves the usage of two receivers i.e an ultra low power wake-up receiver and the main receiver.

The other asynchronous duty cycled listening scheme include B-MAC [42], X-MAC [43] in which a node wakes up periodically without time synchronization. In B-MAC, a long preamble is sent and the node uses low duty cycled, low power listening to hear the long preamble and thus provides energy saving in the nodes. However, in B-MAC, the nodes suffer from the problem of overhearing due to long preamble. On the other hand, X-MAC employs the concept of sending strobed preamble as compared to the long preamble in B-MAC, and thus, helps in preventing the overhearing problem in the nodes. Also, it embeds target node address in the preamble so that non target nodes can go back to sleep mode. However, in X-MAC, due to the strobed preamble, the nodes has longer listening period as compared to B-MAC.

For TDMA based MAC schemes, a variety of schemes are available in literature. In [44], authors proposed a Self-Organised TDMA Protocol (SOTP) for MAC in the sensor network. This scheme is under the category of contention free mechanism involving the centralized architecture which in turn brings the energy efficiency to mobile tags. In [45], authors proposed Slot Periodic Assignment for REception (SPARE) MAC scheme. This scheme is based on TDMA along with contention free mechanism and thus provides energy efficiency to the mobile tags. However, the scheme includes large delay and the extra signalling overheads. In [46], authors presented an energy efficient MAC scheme utilizing the centralized architecture with a head node but they proposed to transmit a batch of packets for a new tag to join the network which will cause an increase in power consumption during the registration in the network.

In this thesis, chapter 5 describes the energy efficient medium access scheme for the system. In this MAC scheme, the main sources of energy wastage are reduced in order to bring energy efficiency in mobile tags. The problem of ideal listening is avoided by providing time synchronization between master reader node and tags which helps in starting the listening mode in tags at right time. Also, an ultra low power RF MCU CC1310, designed by Texas Instruments, is used in tag architecture which provides the ultra low power listening in the tags during the listening of master beacon. The other major source of energy consumption in the mobile tags is the problem of re-transmissions due to collision of acknowledgement packets. This problem is avoided by using centralized architecture in which master reader node provides feedback for assigned time slots to the tags. The tags use the assigned slots corresponding to their IDs for transmission of acknowledgement packet followed by UWB data transmission.

How to prevent human involvement in procedure of range measurement between anchor nodes before the start of localization while performing clock synchronization between them?

The research area related to localization along with clock synchronization has been advancing. The problem of finding peer to peer range between anchor nodes becomes more interesting when the anchor nodes are asynchronous in nature. During start, the clock synchronization has to be performed between

the anchor nodes before finding the range between them. The clock synchronization among the anchor nodes can be classified on the basis of two parameters: frequency and phase of the clock [47]. The first category includes the fully synchronized clocks in the anchor nodes with same frequency and phase. The second category includes the clocks with same frequency but with different phase and the last one includes the uncoupled clocks with different frequency and phase.

Several works have analysed the problem of clock synchronization along with localization in the positioning system. A phase synchronized range finding scheme involving anchor nodes is proposed in [48]. The authors proposed the solution to problem of Self-Calibration by the measurement of time of flight data and converting the non-linear least squares cost function minimization problem to bilinear matrix formulation while assuming that the transmission time from the anchor nodes is known. In [49], the authors proposed an initialization method by assuming the positions of anchor nodes and the clock offset is determined by TOA measurements while placing the target node close to the anchor nodes. However, in this paper, the authors assume that the clocks of the anchor nodes are frequency synchronized. In [50], the peer to peer range finding problem is solved for all the cases of clock synchronization. The authors proposed to use semi definite programming to solve maximum likelihood (ML) estimation problem. However, such a solution of using the optimization tool in every anchor node is computationally extensive as anchor nodes are limited in processing capability when compared to a computer.

In this thesis, chapter 4 and chapter 6 describe the solution to this problem by providing the mechanism for phase and frequency synchronization among clocks for anchor nodes. The chapter 6 also presents the results of 1D ranging between anchor nodes using UWB signals while preventing human involvement in the range measurement. The phase synchronization is achieved by difference of time difference of arrival technique and frequency synchronization is achieved by adjusting the sampling frequency for analog to digital converter (ADC) in each of the anchor node on the basis of observed pulse repetition frequency (PRF) for UWB signals.

2.7 Summary

This chapter has presented the background theory for the UWB technology that is being used for the purpose of the positioning in the system. Furthermore, the different ranging techniques are introduced using the UWB technology. The sub-1 GHz technology is presented along with the advantages over 2.4 GHz technology. This sub-1 GHz technology is introduced in this chapter as it is used in the system for the purpose of the medium access control. A summary about the UWB based commercial localization systems is presented. Finally, a review on the related research work is described.

Chapter 3

Design of Battery Powered Tag

3.1 Overview

In indoor positioning system, Radio Frequency Identification (RFID) tags are critical components as with the aid of these RFID tags, location of an asset or a personnel can be tracked. These mobile RFID tags come under the category of active tags and are powered by coin cell battery. Typically, wireless mobile nodes are powered by the battery which lasts from several days to several months, depending upon the power consumption of the node. Thus the power consumption of the tag acts as one of the major constraint parameter in design. The design targets to provide the optimum battery life for the mobile tags and provides a good performance index in terms of the battery life for the indoor positioning system. The block diagram in figure 3.1 shows the basic interconnections between various components of the RFID tag.

The figure 3.2 shows photograph of Tag PCB. The left picture shows the complete Tag PCB including UWB TX section PCB on the top and UHF section

FIGURE 3.1: Basic block diagram of the tag

PCB below the UWB TX PCB whereas right picture shows the PCB for UHF section (bottom PCB in the left picture) along with power management circuit. The circuit was designed for performing power management in the tag PCB and the software code was developed for UHF transceiver chip. The design strategies were implemented in the form of hardware and software for achieving energy efficiency in the tags. However, UWB TX PCB was used from the previous design work [7].

FIGURE 3.2: Photograph of tag PCB

At a high level, the UHF section of the tag shown in figure above consists of a CR2032 coin cell battery, a low IQ boost converter (TPS 61291), an ultra-low power wireless MCU (CC1310), an ultra-low leakage switch (TPS 22860/TPS 22902) and a voltage doubler (LM2663/TPS61220). The ultra-low power MCU (CC1310) controls power to all the remaining circuitry by putting the switch and the doubler in off-state when not in use while maintaining itself in standby mode.

This chapter begins with description of the hardware involved in the design of tag. The next section discusses about the firmware description including the proposed state transition diagram for the tag in positioning mode. Furthermore, the section about design strategies explains the different ways of achieving the energy efficiency in the tag design. The measurement results section provides in depth view for the tag design by computing the battery life. Also the measurement results are presented for the UHF receiver sensitivity and the UHF transmitter power. Finally, this chapter ends up with the summary.

3.2 Hardware Description

The figure 3.1 shows the block diagram representation of RFID tags. The RFID tag works in conjunction with reader/sensor system to provide the tracking information of an asset and achieves a longer battery life through the use of duty cycling with an ultra-low power MCU (CC1310). During the start, the

voltage regulator (TPS61291) works in bypass mode and passes battery voltage to CC1310 device. CC1310 when initializes using the battery voltage, enables TPS61291 in boost mode which in turn provides the 3.3V as the power supply voltage. This 3.3V is used as the power supply to CC1310 and low-leakage switch (TPS 22860/TPS 22902). The switch when gets the enable signal from CC1310, outputs the 3.3V which in turn used by the voltage doubler (LM2663) to double the voltage and generates 6.6 V. The two voltages (3.3V and 6.6V) along with the SPI data generated by CC1310, used by the UWB TX board to generate and transmit the UWB pulses. The moment CC1310 finishes its cycle of operation, it disables the switch which in turn disables the voltage doubler and cuts down the power to the UWB TX board while maintaining the standby mode for itself. Because the on-state is very short (the time when the devices have power), and off-state current consumption from the coin cell battery is very low, the estimated battery life is long. The following sub sections describe each hardware module involved in the design.

3.2.1 Coin cell battery

The power source for RFID tag is a 3V CR2032 lithium-ion coin cell. The selection of the CR2032 coin cell battery as the power source was due to the ubiquity of that battery type, particularly in small size systems, such as a RFID tag.

The voltage characteristics of a lithium-ion CR2032 coin cell battery is almost

ideal. The output voltage remains relatively constant throughout the discharge life, until the cell is nearly depleted. When the remaining charge in the coin cell battery is nearly depleted, the output voltage drops off relatively quickly.

Immediately following the battery is a low forward voltage Schottky diode and a bulk capacitor. The Schottky diode prevents damage to the hardware if the coin cell battery is inserted with the reverse polarity. The bulk capacitor is sized to prevent too much voltage drop, particularly during the initial transition into the on-state.

3.2.2 Boost converter

In this design, the TPS61291 device was chosen to regulate the battery voltage to 3.3V. With a battery voltage of 3.0V, the TPS61291 maintains an efficiency level greater than 95% at the load current range of 1 mA to 100 mA. Even at the depleted coin cell voltage of 2.0V, the TPS61291 device maintains an efficiency level greater than 90% over the typical load current range of 1 mA to 100 mA.

3.2.3 Ultra-Low power wireless microcontroller (MCU)

In this design, UHF communication is being used for the purpose of MAC. However, because power consumption is always a concern in battery-based applications, the radio and processor must be low power.

FIGURE 3.3: PCB layout for the TagVer4r2.0

With Texas Instruments, ultra-low power wireless microcontroller (MCU) CC1310, a combined radio and microcontroller enables longer battery life for RFID tag. Due to the combination of radio and the MCU in a single chip, this TI chip provides a good form factor in the design of the tag PCB [51], [52].

3.2.4 Low-Leakage load switch

In conjunction with CC1310 MCU, this tag design uses a low-leakage load switch to shut down power to the voltage doubler (LM 2663/TPS61220) and the UWB TX board during off state. In this design, the TPS22860/TPS22902 device was chosen as the switch for disconnecting the voltage doubler and UWB TX board from the power supply.

3.2.5 Voltage doubler

This design uses LM2663/TPS 61220 as the voltage doubler. The LM2663 doubles the input voltage (3.3V) to 6.6V which is the requirement of the UWB TX board. The TPS 61220 constraints the voltage level to 6V. LM 2663 uses the concept of switched capacitors to double the voltage level whereas TPS61220 is an inductor based voltage regulator.

There are currently two different versions for the tag design 1) TagVer4r2.0 and 2) TagVer4r2.1. The figure 3.3 and 3.4 shows the PCB layouts of circuit including CC1310 MCU UHF Transceiver along with control circuit for the power management. These are four-layer FR-4 PCBs with a dielectric thickness of 12 mils between layer 1 and layer 2, 20 mils between layer 2 and layer 3 and 20 mils between layer 3 and layer 4. The dimensions for these boards are 5.8cm x 4.1cm. The difference between the two version is the voltage doubler section. The TagVer4r2.0 uses LM2663 as voltage doubler to generate 6.6V for UWB TX board whereas TagVer4r2.1 uses TPS61220 to generate 6V for UWB TX board.

3.3 Firmware Description

The firmware used in the design of state of the art low power consumption tag is CC1310. The CC1310 uses TI-RTOS (SYS/BIOS) for its operation and has got five different modes in the tag design. The modes are given as:

- 1) Standby mode

FIGURE 3.4: PCB layout for the TagVer4r2.1

- 2) UHF Active mode
- 3) UHF RX mode
- 4) UHF TX mode
- 5) UWB TX (SPI data) mode

The figure 3.5 shows the firmware state transition diagram for the tag in Positioning Mode. The state transition diagram can be explained as:

3.3.1 State 0: START (Power-up reset)

When the battery is plugged into the board, CC1310 gets reset. It's a form of hardware reset. In this state, it does the SYS/BIOS initialization, enters into

FIGURE 3.5: State transition diagram for tag firmware(CC1310) in positioning mode

the main function, starts the BIOS and looks for the scheduler to perform its intended function and moves to the State 1.0.

3.3.2 State 1.1: UC STANDBY mode

This state is the standby mode for CC1310. In this state only real time clock (RTC, low speed clock, 32.768 KHz) is running. Whenever the scheduler does not find any posted command in the queue and if there is a sufficient time available before the next command to be posted, it puts the UC into the standby mode.

3.3.3 State 1.0 & 2: UC UHF active mode

This state represents the active mode for the UC. Whenever the scheduler finds any posted command in the queue, it puts the UC into the active mode along with the required peripheral to be used. In this mode, the system CPU is running with the high speed clock (48 MHz). In this state the current consumption includes the core current plus the peripheral current consumption. For this stage, the RF core power is also ON, which means that the UC is now ready for the radio operations.

3.3.4 State 3: UC UHF RX mode

This state is the radio RX state. In this state, tag receives the UHF packet from reader. The moment the RF packet entry is done in the RX buffer, a callback is being executed to process the packet data and to collect address information from it. Once the address collection is done, the UC goes back again to the state 2. If the received packet has got the valid address data, then

it goes from state 2 to state 4 with a time gap based on the medium access control time slot allocation otherwise it will go back to state 1.1 and the cycle repeats. The time duration for this state is 3ms. This state also manages the time synchronization with the reader. It executes a simple strategy. During the start-up/power reset, UC sets the Rx duration for 1s initially because the packet arrival time is unknown to the UC and the moment the RF packet entry is done and the callback is being hit for the first time, it resets the timer and sets the RX duration for 3ms. To keep in sync with the reader continuously after first time, it continues to reset the timer every time the RF packet entry is done and the callback is being executed while maintaining the RX duration for 3ms.

3.3.5 State 4: UC UHF TX mode

This state is the Radio TX state. In this state, tag acknowledges reader by sending the UHF packet if a valid packet is being received. The time duration for the UHF TX mode is 0.5ms. Irrespective of the command being received from the reader to start the UWB TX or not, UC goes back to state 1.1. This is done to ensure the legitimate power management as during this period of 1.5ms, the RF core will be completely OFF with no more commands pending for the RF core operation. Also it aids in hampering the freeze of the application as the application may freeze sometimes if the UWB TX (SPI data mode) is being triggered immediately after UHF TX while the RF core is still powering down. If the received packet contains a command (0x32 or 0x55) for the UWB

TX mode, the UC goes from state 1.1 to state 5 otherwise it remains in state 1.1 and waits for the next cycle. The total time gap between UHF TX mode and UWB TX mode (if requested in the command) is 2ms.

3.3.6 State 5: UC UWB TX mode

This state represents the UWB transmission. In this state, UC goes into SPI Master Data mode while other peripherals are power OFF. The time duration for this mode is around 5.5ms. In this mode, UC generates the SPI data (@1.5MHz) along with the control signal (a 3.3V pulse of duration slightly more than 5.5ms), used by the UWB TX board to transmit the UWB pulses. This 3.3V pulse acts as a control signal for the power supply management¹ of the UWB TX board. At the end of this mode, UC goes back to state 1.1 and waits for the next cycle. The wakeup time for the next cycle is being adjusted to around 998ms.

3.4 Design Strategies for Energy Efficiency

In this section, the three design strategies are described which are implemented as a combination in tag design. The design strategies target to achieve energy efficiency in the tag design. The first strategy concerns with minimization of the OFF state energy consumption while the second and third strategies handle optimization of the ON state energy consumption. These three

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¹The reader may wish to find more details about power management in the hardware section described previously.

design strategies give a general idea to achieve the energy efficiency and can be applied individually in the different designs based on availability of resources and design architecture. The following subsections describe the three strategies.

3.4.1 First strategy

As a first strategy, the concept of duty cycling the complete system is introduced in the design. The whole operation of the system is kept for the duration of 10 ms with the cycle of 1 Hz. To implement this, the system level power down techniques based on the operating states of MCU are used. The different operating states for the MCU are: The Active or Full-On state that works with the fastest clock of 48 MHz, the Standby state that works with slow clock of 32.768 KHz and the sleep state which is a shutdown mode. During the ON state, MCU will be operating with the fastest clock. During the OFF state, MCU controls power to all the remaining circuitry by putting the switch, doubler and UWB transmitter in the power down state while maintaining itself in the standby mode with the RTC (low speed clock, 32.768 KHz) being active and thus the minimization of the OFF state energy consumption is obtained.

3.4.2 Second strategy

The second strategy concerns about chip level power reduction for the MCU during the ON state by introducing the voltage scaling down from 3.3 V to 1.8

V while achieving the optimum delay throughout the operation. This brings the efficient saving to energy consumption during the ON state.

To illustrate the concept behind strategy 2, consider figure 3.6. The figure shows instantaneous power vs time curve for three different approaches. From the left side of the figure, it can be seen that the approach 1 consumes higher instantaneous power but faster in operation whereas the approach 2 consumes less instantaneous power but slower in operation. In the instantaneous power vs time curve, the area under the curve represents the energy consumed during the operation. In the right side of the figure, the energy consumed for the three approaches is shown. It can be seen that the area under curve for approach 1 and approach 2 is same. Even though, the instantaneous power consumed by the approach 2 is less but due to longer duration, it consumes same energy as compared to approach 1. However, approach 3 consumes less energy as it consumes the less power while maintaining the same duration as compared to approach 1 and hence an energy efficient approach. The approach 3 explained above is used as strategy 2 in the tag design.

In general, it is known that,

$$Power \propto Voltage^2 \text{ — — — — — — — — — — (9)}$$

So to reduce the power consumption, the voltage scaling from 3.3V to 1.8V for the MCU is introduced while maintaining the optimum delay to improve the energy efficiency. This scaling is done by enabling the dc-dc converter through

the software running in MCU. This dc-dc converter scales down the voltage down from 3.3 V to 1.8 V for the MCU.

FIGURE 3.6: Design strategy 2

3.4.3 Third strategy

The third strategy is related to the energy saving method during the ON state by selecting appropriate ceramic capacitors. In this strategy, the energy saving is achieved by lowering the capacitor value placed at the output of voltage doubler. In general, whenever there is a change in voltage, the current flows through the capacitor. The basic equation governing this concept is given by:

$$I = C \frac{dV}{dt} \text{ --- (10)}$$

where, C = value of the capacitance, I = the current through the capacitor. For a rate of change of voltage, a larger capacitor is likely to consume more current as compared to a smaller capacitor. The capacitor value is adjusted to maintain the instantaneous load current requirement.

3.5 Measurement Setup

To conduct the current measurement for computation of battery life, voltage drop across a resistance is measured for tag PCBs. The figure 3.7 shows the location where the 6 ohm resistance is connected in series using the breadboard. The voltage drop across the resistance is measured using the oscilloscope. Using the Ohm's law,

$$I = V/R \text{ --- (11)}$$

the voltage drop across the resistance is converted into the current values. This method is used for obtaining the measurement results as shown in the next section.

FIGURE 3.7: Current measurement setup

FIGURE 3.8: Current measurement for the firmware CC1310

3.6 Measurement Results

3.6.1 Power consumption of the tag firmware MCU (CC1310)

The figure 3.8 shows current consumption of the firmware alone for a complete cycle.

This figure shows various modes of the firmware being observed during the current measurement for the complete cycle. The number 1 to 8 shown in the figure indicates eight phases for previously described five modes of CC1310 (uC) in the firmware section. Here the resistor used for the voltage measurement is 6 ohm ². The details are described below:

²All the current measurements in this section 3.6 are conducted by connecting a series resistance of 6 ohm after coin cell and the voltage drop across the resistance is measured using oscilloscope.

1) PHASE 1: In this phase, CC1310 is in standby mode with a current consumption of 1uA measured with the multimeter. This phase can be treated as a starting point of the cycle. Even though this is a standby mode, the RTC is still running.

2) PHASE 2: This phase shows the transition of CC1310 from standby mode to UHF Active mode. The current rises from 1uA to 4mA. This current consumption includes the core current (system CPU ON + 48MHz clock) along with the peripheral current which in this phase is RF Core.

3) PHASE 3: This phase represents UHF RX mode of CC1310. In this mode, CC1310 is in active mode with front end radio power ON and the radio configured in Rx mode. The voltage measured in this mode is 52mV which translates into the current of around 8.6mA for a period of 3ms. The average charge for the UHF Rx mode is around 25.8uC.

4) PHASE 4: This phase shows the transition of CC1310 from UHF RX mode to UHF Active mode. The current decays from 8.6mA to 4mA in a duration of 1ms. This current consumption includes the core current (system CPU ON + 48MHz clock) along with the peripheral current which in this phase is RF Core. The average charge for UHF Active mode is around 4.6uC.

5) PHASE 5: This phase represents UHF TX mode of CC1310. The voltage measured in this mode is around 120mV which translates to a current of around 20mA for a duration of 0.5ms. The average charge for the UHF TX mode is 10uC. This corresponds to transmit power of +10dBm.

6) PHASE 6: This phase represents the standby mode with RTC running. It

is similar to phase 1. The current consumption for this phase is 1uA with a duration of 2.5ms.

7) PHASE 7: This phase shows UWB TX (SPI data) mode of CC1310. The duration of this mode is around 5.5ms. The current consumed for this phase is around 2.6mA. This includes the core current (system CPU + 48MHz clock) along with SPI peripheral current consumption. The average charge for this mode is around 14.3uC.

8) PHASE 8: This mode is standby mode, identical to phase 1 described above. In this mode, CC1310 waits for the next cycle to start. The cycle time for this measurement is 1sec.

The total charge consumed during phase 3 to 7 = 25.8uC (UHF RX mode, phase 3) + 4.6uC (phase 4) + 10uC (UHF TX mode, phase 5) + 14.3uC (UWB TX (SPI data) mode, phase 7) = 54.7uC.

Calculations for the battery life for firmware only operation (no other hardware) with 1Hz update rate are described below.

$$I_{off} * T_{off} = 0.001 \text{ mA} * 990 \text{ ms} = 0.990 \text{ mAs.}$$

$$(I_{on} * T_{on} + I_{off} * T_{off}) / \text{Total Time} = (54.7 + 0.990) / 1000 = 0.05569 \text{ mA.}$$

$$\text{Battery capacity (CR 2032)} = 240 \text{ mAh.}$$

$$\text{Battery life in hours} = 240 / 0.05569 = 4309 \text{ hours}$$

$$\text{Battery life in days} = 4309 / 24 = 179 \text{ days.}$$

FIGURE 3.9: Current measurement for the TAGVer4r2.0

3.6.2 Power consumption of TAG VER4r2.0

The figure 3.9 shows current consumption for the complete TAGVer4r2.0. The various stages are explained below³. The resistor used in the measurement is 6 ohm.

1) UHF RX: In UHF RX mode, the measured value of the current is 10mA. The duration for this mode is 3ms.

2) UHF TX: In UHF TX mode, the measured current is 20mA. The duration for this mode is 0.5ms. This corresponds to the transmit power of +10dBm.

3) During this period, the load switch, the voltage doubler & UWB TX are in power ON state. The current is measured to be around 83 mA for a duration of 1ms.

³The reader may consider the firmware description for more details as explained above.

4) UWB TX: In this mode, both the power supplies (3.3 V & 6.6 V) to the UWB TX board are ON along with SPI data from CC1310. The duration is around 4.5ms. The measured current for this mode is 8mA.

5) In this mode, UWB TX board, power switch and voltage doubler are in power down mode. CC1310 is in standby mode and regulator is in boost mode. The current during this mode is measured using multimeter as 10uA.

Calculations for the battery life for TAGVer4r2.0 with 1Hz update rate are described below.

$$I_{off} * T_{off} = 0.010 \text{ mA} * 990 \text{ ms} = 9.9 \text{ mAms.}$$

$$I_{on} * T_{on} = 10 \text{ mA} * 3 \text{ ms} + 20 \text{ mA} * 0.5 \text{ ms} + 6 \text{ mA} * 1 \text{ ms} + 83 \text{ mA} * 1 \text{ ms} + 8 \text{ mA} * 4.5 \text{ ms} = 165 \text{ mAms}$$

$$(I_{on} * T_{on} + I_{off} * T_{off}) / \text{Total Time} = (165 + 9.9) / 1000 = 0.1749 \text{ mA.}$$

$$\text{Battery capacity (CR 2032)} = 240 \text{mAh.}$$

$$\text{Battery life in hours} = 240 / 0.1749 = 1372 \text{ hours}$$

$$\text{Battery life in days} = 1372 / 24 = 57 \text{ days.}$$

This implies that the TAGVer4r2.0 can operate continuously for 57 days.

The figure 3.10 shows UWB TX pulse voltage measured using oscilloscope.

The UWB TX module used is PF1Q-F (without antenna) which is having the SMA connector for the RF output. The module was directly connected into scope using 10dB attenuator to prevent the over-voltage to the scope channel.

FIGURE 3.10: UWB TX pulse for the TAGVer4r2.0

The power supply voltages (3.3V and 6.6V) were given from switch and voltage doubler. From figure 8, it can be seen that the peak voltage of the UWB pulse is 1.5 V. Considering 10 dB attenuator the peak power of the UWB pulse can be calculated as +23.5 dBm.

3.6.3 Power consumption of TAG VER 4r2.1

The figure 3.11 shows current consumption for the complete TAGVer4r2.1. The various stages are explained below ⁴. The resistor used in the measurement is 6 ohm.

1) UHF RX: In UHF RX mode, the measured value of the current is 10mA. The duration for this mode is 3ms.

2) UHF TX: In UHF TX mode, the measured current is 15mA. The duration for this mode is 0.5ms. This corresponds to the transmit power of +10dBm.

⁴The reader may consider the firmware description for more details as explained above.

FIGURE 3.11: Current measurement for the TAGVer4r2.1

3) During this period, the power switch, the voltage doubler & UWB TX are in power ON state. The current is measured to be 50mA for a duration of 1ms.

4) **UWB TX:** In this mode, both the power supplies to the UWB TX board are ON along with SPI data from CC1310. The duration is around 4.5ms. The measured current for this mode is 6mA.

5) In this mode, UWB TX board, power switch and voltage doubler are in power down mode. CC1310 is in standby mode and regulator is in boost mode. The current during this mode is measured using multimeter as 10uA.

Calculations for the battery life for TAGVer4r2.1 with 1Hz update rate are described below.

$$I_{off} * T_{off} = 0.010 \text{ mA} * 990 \text{ ms} = 9.9 \text{ mAms.}$$

$$I_{on} * T_{on} = 10 \text{ mA} * 3 \text{ ms} + 15 \text{ mA} * 0.5 \text{ ms} + 6 \text{ mA} * 1 \text{ ms} + 50 \text{ mA} * 1 \text{ ms} + 6 \text{ mA} * 4.5 \text{ ms} = 120.5 \text{ mAms}$$

$$(I_{on} * T_{on} + I_{off} * T_{off}) / \text{Total Time} = (120.5 + 9.9) / 1000 = 0.1304 \text{ mA.}$$

$$\text{Battery capacity (CR 2032)} = 240 \text{mAh.}$$

$$\text{Battery life in hours} = 240 / 0.1304 = 1840 \text{ hours}$$

$$\text{Battery life in days} = 1840 / 24 = 77 \text{ days.}$$

This implies that the TAGVer4r2.1 can operate continuously for 77 days.

FIGURE 3.12: UWB TX pulse for the TAGVer4r2.1

The figure 3.12 shows UWB TX pulse voltage measured using the oscilloscope. The UWB TX module used is PF1Q-F (without antenna) which has the SMA connector for the RF output. The module was directly connected into scope using 10dB attenuator to prevent the overvoltage to the scope channel. The power supply voltages (3.3V and 6V) were given from switch and voltage doubler. From figure 10, it can be seen that the peak voltage of the UWB pulse is 1.5 V. Considering 10 dB attenuator, the peak power of the UWB pulse can be calculated as +23.5 dBm.

TABLE 3.1: Comparison between the TAGVer4r2.0 and TAGVer4r2.1

Parameter	TAGVer4r2.0	TAGVer4r2.1
Battery Life	57 days	77 days
UWB Power Supplies	3.3V & 6.6V	3.3V & 6V
UWB TX Pulse Voltage	3V p-p	3V p-p

3.6.4 Comparison between the TAGVer4r2.0 and TAGVer4r2.1

Table 3.1 shows comparison between TAGVer4r2.0 and TAGVer4r2.1. The table entries corroborate that the TAGVer4r2.1 ensures better performance in terms of battery life while generating the same UWB TX pulse voltage as compared to TAGVer4r2.0. However, TAGVer2.0 demonstrates a greater flexibility in the design process by the implementation of various design strategies and could provide longer battery life as compared to TAGVer4r2.1 as shown in the following subsection.

3.6.5 Measured current with the implementation of design strategies

a) With Strategy 1:

The figure 3.13 shows plot for measured current for complete tag using strategy/method 1. As mentioned earlier, the strategy 1 is implemented for the minimization of the OFF state current. It can be seen in the figure 3.13 that the OFF state current is achieved to be a minimum value by duty cycling the complete system using MCU at 1 Hz. This OFF state current was measured

using multimeter and found to be 10 μ A. It should be noted that during the OFF state, the MCU is in standby mode while the regulator is still providing 3.3 V to the MCU. Note: The design strategies have been demonstrated using TAGVer4r2.0.

FIGURE 3.13: Measured current for the complete cycle of the tag using strategy 1

Calculations for the battery life for TAGVer4r2.0 with strategy 1 and 1Hz update rate are described below.

$$I_{off} * T_{off} = 0.010 \text{ mA} * 990\text{ms} = 9.9 \text{ mAms.}$$

$$I_{on} * T_{on} = 20*3 + 42*0.5 + 11*1 + 84 * 1 + 8.5*4.5 = 214.25 \text{ mAms}$$

$$(I_{on} * T_{on} + I_{off} * T_{off}) / \text{Total Time} = (214.25 + 9.9) / 1000 = 0.22415 \text{ mA.}$$

$$\text{Battery capacity (CR 2032)} = 240 \text{ mAh.}$$

$$\text{Battery life in hours} = 240 / 0.22415 = 1070 \text{ hours}$$

$$\text{Battery life in days} = 1070 / 24 = 45 \text{ days.}$$

With implementation of strategy 1, the battery life for the TAGVer4r2.0 was computed as 45 days.

b) With Strategy 1 + Strategy 2:

Next, the strategy 2 is introduced after implementation of strategy 1 in design for optimization of ON state energy consumption. Strategy 2 brings up voltage scaling down from 3.3 V to 1.8 V for MCU. The figure 3.14 shows plot for measured current for the strategy 1 alone and strategy 1 + strategy 2. It can be seen that there is a significant reduction in the current for combination of strategy 1 and strategy 2. The similar calculations were performed as shown in previous subsection, to find the battery life for combination of two strategies.

FIGURE 3.14: Comparison of measured current for the strategy 1 alone and strategy 1 + 2

Calculations for the battery life for TAGVer4r2.0 with strategy 1 + 2 and 1Hz update rate are described below.

$$I_{off} * T_{off} = 0.010 \text{ mA} * 990\text{ms} = 9.9 \text{ mAms.}$$

$$I_{on} * T_{on} = 10*3 + 20*0.5 + 6*1 + 83 * 1 + 8*4.5 = 165 \text{ mAms}$$

$$(I_{on} * T_{on} + I * T_{off}) / \text{Total Time} = (165 + 9.9) / 1000 = 0.1749 \text{ mA.}$$

$$\text{Battery capacity (CR 2032)} = 240 \text{ mAh.}$$

$$\text{Battery life in hours} = 240 / 0.1749 = 1372 \text{ hours}$$

$$\text{Battery life in days} = 1372 / 24 = 57 \text{ days.}$$

With the introduction of strategy 2 in conjunction with the strategy 1 for TAGVer4r2.0, the battery life is extended by 12 days.

c) With Strategy 1 + Strategy 2 + Strategy 3:

Lastly, the strategy 3 is introduced along with other two schemes for further optimization of ON state energy consumption. The figure 3.15 shows plot of current measured with the strategy 1 + 2 + 3. It can be seen that there is a reduction in the peak current drawn at the start of UWB TX mode with the decreasing values of capacitor. The capacitor values are changed from 1 uF to 100 nF. Please note that this capacitor is placed at the output of voltage doubler and can be seen in figure 3.1.

The similar calculations were performed as shown earlier, to compute the battery life for all the capacitors value and the results are summarized in the table given in the next subsection.

Note: The current measurement shown in figure 3.9, 3.11, 3.13, 3.14, and 3.15 are smooth profiles as compared to current profile for the firmware alone as

FIGURE 3.15: Variation of the peak current for the different values of the cap with strategy 1 + 2 + 3

shown in figure 3.8. This smoothness in the profiles is due to the effect of the bulk capacitor (22uF) placed (from supply line to ground) next to series Schottky diode to the battery. This 22uF capacitor along with the 6 ohm series resistor, used for measuring the current using the voltage drop, forms a combination which acts like a low pass filter and resulting into the smoothness into the profiles. However, the bulk capacitor is not in picture for the current measurement in the firmware alone as the 3.3V from the external battery is directly connected to the MCU and thus bypassing the effect of bulk capacitor. The main purpose of this bulk capacitor is to prevent the excess voltage drop on the battery in the complete tag hardware design during the initial moments in ON-phase in every cycle.

TABLE 3.2: Comparison of battery life with combination of strategies

S.No.	Strategy	Battery Life
1	Strategy 1	45 days
2	Strategy 1+2	57 days
3	Strategy 1+2+3 with 440 nF cap	64 days
4	Strategy 1+2+3 with 220 nF cap	72 days
5	Strategy 1+2+3 with 100 nF cap	86 days

3.6.6 Comparison of battery life with combination of strategies

From the table 3.2, it can be seen that the battery life for strategy 1 is 45 days whereas it is extended by 12 days and comes out to be as 57 days when strategy 1 & 2 is applied in conjunction. Next, strategy 3 is being deployed along with these two strategies and it can be observed that with the decreasing values of capacitors, there is a decrease in the average ON state current, resulting in the increase in battery life. With 100 nF capacitor configuration, the battery life is extended further by 29 days as compared to strategy 1 + 2 and it comes out to be as 86 days.

3.6.7 UHF RX sensitivity measurement

The UHF RX sensitivity measurement is done using TagVer4r2.0. The test set up is as follows: The tag PCB is tuned to be UHF transmitter whereas CC1310 evaluation module (EM) is being tuned as UHF receiver. The tag PCB was placed at the distance of 3m from the EM. The EM was plugged into Smart RF board and 70dB attenuator was connected at antenna port as shown in

figure 3.16. Figure 3.17 below shows the EM connected to the Smart RF Studio 7 software using USB cable plugged into laptop. This software is developed by Texas Instruments (TI) and available from TI website. The total packets observed during the measurement were 100 with a rate of 1 packet received per sec. The average value for Received Signal Strength Indicator (RSSI) along with the Packet Error Rate is shown below in the figure 3.18.

The various parameters for the tests are:

- 1) TX Power = +10dBm.
- 2) Distance between TX and RX = 3m
- 3) Attenuator at RX = 70 dB
- 4) Frequency used = 922.7 MHz
- 5) Computed path loss = 41.28 dB

The observed average RSSI was -102 dBm with the Packet Error Rate of 12%.

The method shown above for measuring UHF Rx sensitivity of tag in form of measuring UHF Rx sensitivity using EM module from TI justifies as both the tag and the EM have got the similar MCU CC1310. Also EM hardware provides a convenience to use attenuators to reduce the signal level up to the sensitivity limit along with the acceptable packet error rate while maintaining the UHF Tx power as +10dBm in the near distance operation as shown in figure 3.16. Furthermore, before conducting the above mentioned test, matching of antenna element is also performed with RF chain in the tag with the design

FIGURE 3.16: EM tuned as UHF RX along with 70dB attenuators at the antenna port

FIGURE 3.17: Connection between the EM module and the laptop using USB

of the two element matching network circuit using the series & shunt arm capacitors. The measurement for the return loss is being conducted using VNA after design of the network and return loss plot is shown in figure 3.19. It can be seen that the return loss of -13.93 dB is achieved at the frequency of 922

FIGURE 3.18: Snapshot of the SmartRf Studio software showing the RSSI along with the Packet Error Rate

FIGURE 3.19: Return loss measurement for the UHF antenna element along with the matching network.

MHz with the design of matching network.

FIGURE 3.20: UHF TX burst waveform

3.6.8 UHF TX power measurement

The UHF TX power measurement is done using TAGVER4r2.0 by disconnecting UHF antenna matching network and UHF antenna from the RF chain and connecting RF cable (RG-179) with the loss measured using VNA as 1.2dB @ 922 MHz. From the software, UHF TX power is programmed to be +10 dBm. The waveform for the TX burst was observed using oscilloscope as shown in figure 3.20.

From figure 3.20, it can be seen that the peak voltage for the burst is around 800 mV which can be transformed into the power using $P = V^2/(2 \cdot R)$. Taking $R = 50 \text{ ohm}$, power can be calculated as +8 dBm. Considering the cable loss as mentioned above, the TX power comes out to be as +9.2 dBm. It can be seen that the measured power for the UHF transmitter is +9.2 dBm which is nearly equal to the corresponding transmitter power tuned in the software as

+10 dBm.

3.7 Summary

This chapter has described complete design of the state of art power consumption tag. The described hardware architecture aids in achieving energy efficiency. The proposed state transition diagram for the firmware is used to control power consumption of the complete design and helps in achieving the state of the art power consumption. The three design strategies are presented and implemented in design of tags for providing longer operational hours. Furthermore, current measurement results are presented along with the battery life calculations. The results related to UHF Tx power and UHF Rx sensitivity are also described.

Chapter 4

Design and Implementation of the System

4.1 Overview

The complete system design for localization application include tags, reader systems and medium access control scheme. This system design uses UWB transmitter and UWB receiver based on prior work [7]. The equivalent time sampling is employed to sample envelop of the UWB pulses captured by the UWB receiver using low cost ADC. The complete implementation in conjunction with the medium access control brings up the system for measurement results. This chapter begins with description about the reader system in terms of hardware components¹. The next section discusses about the equivalent time sampling. Furthermore, the section 4.4 provides the details about functioning of the complete system and finally this chapter ends up with summary.

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¹The reader may find more details about RFID tags in chapter 3 and about Medium Access Control in chapter 5.

FIGURE 4.1: Basic block diagram of the reader/anchor node

4.2 Reader Hardware

The reader hardware primarily consists of the UWB receiver, back end base-band amplifier, Analog to Digital Converter (ADC), Digital Direct Synthesizer (DDS), D - Latch, TI MCU CC1310 and BeagleBone Black (BBB) board. The figure 4.1 shows block diagram of the reader system. The UWB signals transmitted by tag antenna is received by antenna of UWB receiver and converted to baseband signal. The baseband signal is amplified further using the back end baseband amplifier. This baseband signal is being converted to digital samples by the ADC. The clock enable signal² is generated by MCU CC1310 based on UHF acknowledgement packet being received from tag. This signal is used by BBB to enable the ADC. The sampling clock for the ADC is generated by the DDS based on desired frequency and resolution to be used in equivalent time sampling [53], [54]. The digital samples are being used by

²Clock Enable signal is a digital signal which always remains in high state and goes to low state for enabling of ADC. In fact, this signal acts like an interrupt to BBB indicating the start of UWB data transmission.

BBB to process the time of arrival information from the tags. The figure 4.2 shows the PCB layout designed for the ReaderCapeVer1.0 whereas the figure 4.3 shows the PCB layout designed for the ReaderCapeVer2.0. The main difference between the two layouts design is that the ReaderCapeVer2.0 layout design includes the circuit of reference tag on bottom side of PCB in conjunction with the reader circuit on top side of PCB. These reader cape boards are designed to mount on BBB board and thus form the complete system. The figure 4.4 shows the photograph of the reader system with a co-located reference tag with reader cape board mounted over the BBB board. The figure 4.4a provides the front view of the complete system showing the UWB Tx board for the reference tag whereas the figure 4.4b depicts the top view for the system showing the reader cape over BBB board along with the two sub-1 GHz antenna for the reader system and for the reference tag³.

FIGURE 4.2: PCB layout for the ReaderCapeVer1.0

³The circuit for the reference tag is located on the bottom side of the reader cape PCB

 FIGURE 4.3: PCB layout for the ReaderCapeVer2.0

4.3 Equivalent Time Sampling

UWB signal envelopes are generally higher bandwidth signals. To perform the real time sampling following the Nyquist rate on these high bandwidth signals requires an ADC with very high sampling frequency along with high analog bandwidth. If we consider the bandwidth of the UWB envelop as 1 GHz then following the Nyquist rate we need the ADC with minimum sampling frequency of 2 GHz. These high end ADCs are generally available with very high cost and thus resulting in an overall increase in the system cost. On the other hand, performing equivalent time sampling using the lower cost ADCs provides an alternative cost effective solution to sample the higher bandwidth repetitive signal. The figure 4.5 illustrates the equivalent time sampling being performed on the UWB envelopes. It can be seen from the figure 4.5 that black curves indicate the UWB envelopes repeating every interval whereas the red

(A) Front view image of the reader system

(B) Top view image of the reader system

FIGURE 4.4: Image for the complete reader system with the co-located tag.

curve indicates the constructed UWB envelop using the equivalent time sampling. The purple dot indicates the point of sampling that is being shifted in every cycle to capture a new point [55].

To illustrate this concept, let's consider the UWB signal PRF⁴ of 2 MHz which is equivalent to 500 ns duration. If we assume the resolution of 0.1 ns, then the equivalent time sampling interval will be 500.1 ns. The first sample point will be collected at 500.1 ns then the second sample point will be collected at 1000.2 ns and so on, resulting in the construction of the UWB envelop as can be seen in figure 4.5. The resulting sampling frequency will be 1999600.08 Hz.

Along with the advantage of allowing the use of low cost ADC in sampling the repetitive signal, the equivalent time sample shows significant effect on the signal PRF due to the clock drifts in the transmitter and the receiver. Let us consider a scenario, the tag is transmitting at the PRF of 2 MHz and has

⁴PRF stands for Pulse Repetition Frequency

FIGURE 4.5: An example of equivalent time sampling on UWB envelopes

oscillator with a clock drift of ± 10 ppm. In receiver, the oscillator has clock drift of ± 100 ppm and performing equivalent time sampling with 0.1 ns resolution, the sampling clock generated by the DDS will be 1999600.08 Hz (= $1/500.1$ ns). If we consider the ideal case of zero clock drift, then the difference between two frequencies δf is given by:

$$\delta f = 2000000 - 1999600.08 = 399.92 \text{ Hz}$$

If we consider the clock drift in transmitter and receiver clocks, then the PRF of transmitter will be 2 MHz ± 10 ppm which corresponds to 2 MHz ± 20 Hz and the receiver sampling clock will be 1999600.08 Hz ± 100 ppm which corresponds to 1999600.08 Hz ± 199.960008 Hz (0.01%). Then, the maximum difference of frequencies δf_{max} is given by:

$$\delta f_{max} = (2000000 + 20) - (1999600.08 - 199.960008) = 619.880008 \text{ Hz}$$

Similarly, the minimum difference of frequencies δf_{min} is given by:

$$\delta f_{min} = (2000000 - 20) - (1999600.08 + 199.960008) = 179.959992Hz$$

which means that δf can be written as

$$\delta f = 399.92Hz \pm 219.960008Hz$$

that comes out to be as 55% variation in the δf due to clock drifts as compared to the 0.01% variation in the sampling clock of receiver. Hence it can be seen that the equivalent time sampling magnifies the effect of clock drift.

4.4 System Functioning

Figure 4.6 shows model of the complete system. The model consists of 4 reader systems, 4 reference tags and 4 mobile tags. The objective of the system is to provide the positioning information about the mobile tags. Out of the 4 reader system, one reader acts as the master reader denoted by MR in the model whereas the remaining 3 reader systems act as slave readers denoted by SR. The reference tags are indicated by RT and the mobile tags are referred as MT.

The whole system process can be divided into two phases⁵:

1) Calibration Phase

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⁵Each of these phase is started with Medium Access Control scheme for allocation of the time slots.

FIGURE 4.6: System model

2) Positioning Phase

4.4.1 Calibration Phase

The calibration phase is the initial phase of system. The intent of this phase is to synchronise reader clocks and to find peer to peer range between the readers using the UWB signals from reference tags. The figure 4.7 shows the system model during the calibration phase. During start of the calibration phase, the master reader performs the medium access control for the reference tags by allocating time slots and sending the time slot information along with their ID's in sub-1 GHz beacon. The reference tags listen to the beacon, find their ID's and the corresponding time slot information. Using the allocated time slots, the reference tags transmit their UWB pulses. These UWB pulses will be used by the readers to synchronize their clock by adjusting the PRF and

to find time of arrival of both the reference tags and which in turn is used to compute time difference of arrival (TDOA). Range computation is done using the difference of TDOA [56], [57].⁶

FIGURE 4.7: System calibration phase

4.4.2 Positioning Phase

The positioning phase comes in limelight after the calibration phase is completed. Similar to the calibration phase, this phase is also started by medium access control performed by the master reader and thus allocating time slots to mobile and reference tags⁷. In this phase, position of the mobile tags is computed based on TDOA information. In each of the time slot, mobile tag and reference tag UWB pulses are being transmitted. These pulses are received by all the readers and TOA values are computed. All the readers send their TOA information to the central server where the final computation is done using TDOA and the position of the mobile tag is displayed.

⁶The reader may find details about results for this phase in the form of 1D ranging between the two readers in chapter 6.

⁷The reader may find more details about the medium access control scheme in chapter 5.

FIGURE 4.8: System positioning phase

4.5 Summary

This chapter has provided a brief introduction about the system architecture by describing the hardware circuit design for the reader system. The next section discussed the equivalent time sampling being performed using low cost ADC. Finally, the overall system functioning is presented in the calibration phase where the readers synchronize their clocks and find distance between them and later the positioning phase where the position of mobile tag is computed once the calibration phase is completed.

Chapter 5

Medium Access Control

5.1 Overview

The localization system provides positioning information of mobile tags using UWB data. For multiple tag environment in such a system, medium access control (MAC) scheme plays a cardinal role as the tags need to access common channel to transmit successfully the acknowledgement packet along with UWB data to reader systems. The various schemes available for the MAC implementation mainly fall into two taxonomies for orthogonal protocols, in which the overlap of the packets results in the collision: the first category includes the scheme based on the contention free mechanism and the second category depends on the contention based mechanism. Figure 5.1 shows the different schemes under the two categories [39], [58].

In contention based scheme using persistent random access, Aloha protocol allows tags to transmit data at any instant of time in a random fashion. If two tags transmit at the same time, a collision will occur resulting in failure

FIGURE 5.1: MAC classification

of transmission. The tags wait for random time and transmit packet again resulting in lower throughput with higher delay in achieving steady state. On the other hand, Slotted Aloha (S-ALOHA) divides the time frame in different slots reducing vulnerable period, resulting in better throughput as compared to pure ALOHA. However, both pure ALOHA & S-ALOHA causes a significant increase in power consumption in the wireless nodes (tags) due to increase of overheads in the form of multiple retransmissions, resulting from the collision of packets. The other scheme CSMA uses random access for channel along with carrier sensing technique to avoid collision of packets. However, carrier sensing scheme is not suitable for battery powered tags as the tags need to listen the channel on regular basis to check for the availability, resulting into the higher power consumption.

This chapter begins with introduction of novel medium access scheme that can

be implemented practically in the localization system using centralized architecture while providing optimum power consumption for tags. Then the state transition diagram of the tag in the medium access mode is presented. The next section shows comparison of power consumption result for this scheme with the other standard schemes and finally this chapter ends with summary.

5.2 A novel Medium Access Scheme

This work presents a novel Medium Access Control (MAC) scheme which comes under the category of contention based protocols similar to pure ALOHA and S-ALOHA. However, it utilizes the concept of feedback for generated time slot given to tag at the start of every new cycle. This scheme targets to provide minimum power consumption for the tags as the feedback is given at the start of each cycle and each tag can go to sleep mode immediately after completing its cycle without extra overheads. As this scheme is a centralized scheme controlled by the master reader, joining of the new tag in the network is managed centrally by the central master reader and thus provides a robust mechanism for the medium access control along with the power saving using single hop communications only. However, this MAC scheme utilizes two different frequencies during the whole operation. The figure 5.2 shows the allocated frequencies used during the MAC process by the reader and the tags. The whole system works as follows: The master reader starts process by sending a sub-1 GHz broadcast packet, also called as the beacon at frequency 922

MHz. The active tags receive the beacon, generate time slot number using the true random generator, put their time slot number information in the acknowledgement packet as a 1-byte data along with their IDs and send the acknowledgement back to the master reader in generated time slot using frequency 922.7 MHz. After receiving the acknowledgement packet, the master reader then checks the time slot matrix for the generated time slot by the tag, allocates time slot based on the search through matrix mechanism and updates the matrix by inserting a zero entry once the slot is verified for the tag¹.

FIGURE 5.2: Frequency allocation during MAC process

After the slot verification, reader confirms the registration for the tag into the network by sending the allocated time slot information in the form of slot number as a 1-byte data back to the tag in the broadcast packet for the new cycle. The tag upon reception of the new broadcast packet looks for the assigned slot number by the reader corresponding to its ID, compute the slot

¹The reader may find more details about the slot verification procedure by the master node in section 5.2.2

FIGURE 5.3: Reader sub-1 GHz beacon packet format with the payload.

time using the slot number, sends its acknowledgement and starts to transmit its UWB data using the allocated time slot if requested by the reader. If the tag finds the zero entry in place of time slot number (next to its ID), it regenerates the new time slot number using the random generator and withheld its UWB transmission until it successfully registers in the network with an allocated time slot. The zero entry for the time slot indicates to the tag that its registration was unsuccessful ². The figure 5.3 depicts the reader sub-1 GHz beacon with payload showing the two tags registered into the network with the second byte as 0x32 indicating the tags for the UWB transmission after successful registration into the network whereas the figure 5.4 shows the tag sub-1 GHz acknowledgement packet with the payload. The three key ideas behind this scheme are as follows:

²The reader may find more details in section 5.2.3

FIGURE 5.4: Tag sub-1 GHz acknowledgement packet format with the payload.

- 1) Random slot generation by the tags
- 2) Slot verification by the central reader system
- 3) Feedback to the tag for the time slot.

Figures 5.5 and 5.6 shows the flow chart information for reader and tag in MAC scheme.

5.2.1 Random slot generation by the tag

To forbid the overlapping of the generated time slots, true random generators are being used in each tag in place of pseudo random generator. Each random number generator is a true random generator inbuilt inside TI MCU CC1310. It uses 24 ring oscillators to create the entropy and maximize the entropy to

FIGURE 5.5: Reader flowChart for MAC

generate a 64-bit random number. MCU takes around minimum of 256 system clocks to generate the first random output and minimum of 64 system clocks to regenerate a new output. The amount of entropy in each random number and the speed of generation takes a trade-off. This means that if we increase the number of system clocks for generating the random number, the amount of entropy (randomness) will be more but at the same time the time taken for the generation of number will also be more. Moreover, as the time for generation increases, the amount of power consumed during the random number generation in each tag will also be higher. For the optimised values,

FIGURE 5.6: TAG flowChart for MAC

the minimum number of cycles are used as 2048 and the maximum number of cycles are used as 8192 for the random number generator. The generated random number is stored in a 64-bit register with each MSW and LSW as 32-bit long. The generated random number is read as 16-bit unsigned integer from the LSW and converted back to a number between 1 to 50 using a modulo operation. The number from 1 to 50 represents the time slot number while

assuming the total number of time slots as 50. Based on the time slot number and assuming each slot duration of 20 ms, the tag generates the time slot using the formulae as:

$$TimeSlot(ms) = 20 * TimeSlotNumber + 2 \text{ --- (12)}$$

where 2 represents the starting of the first time slot in ms and Time Slot Number represents the random number from 1 to 50 generated by the true random generator in the tag.

For instance, if the randomly generated slot number is 37, then the time slot will be computed using (12) and is given by:

$$TimeSlot = 20 * 37 + 2 = 742ms$$

5.2.2 Slot verification by the master reader system

The master reader system when initiates its process, generates a time slot matrix with each slot duration of 20 ms as shown below:

[2 22 42 62 82 102 122 142 162 182 202 222 242 262 282 302 322 342 362 382 402
422 442 462 482 502 522 542 562 582 602 622 642 662 682 702 722 742 762 782
802 822 842 862 882 902 922 942 962 982]

This matrix is saved in the master reader and when the tag sends its acknowledgement packet along with its ID and time slot number information, the master reader extracts the time slot number information from the received packet,

calculates the time slot using (12) and uses a search through mechanism. In this process, the master reader scans the time slot matrix and stops at the index when it finds the calculated time slot value. Then, it allocates the same value as time slot for the tag. For instance, if the time slot number used by the tag is 37. The reader finds this number using the acknowledgement packet, calculates the time slot using (12) which comes out be as 742 ms and scan this time slot through the time slot matrix. The reader will stop the scan in the matrix at 742 and allocates 742 ms slot as the time slot to this tag and updates the time slot matrix with the zero entry as shown below in red color:

```
[2 22 42 62 82 102 122 142 162 182 202 222 242 262 282 302 322 342 362 382 402
422 442 462 482 502 522 542 562 582 602 622 642 662 682 702 722 0 762 782 802
822 842 862 882 902 922 942 962 982]
```

During the next cycle if any other tag generates the same time slot number, the master reader will insert a zero entry next to its ID and in such situation, a tag has to regenerate the time slot number using the random generator. Once the slot is verified by the reader by assigning a new time slot number other than zero, it confirms the tag registration.

MAC mode: In MAC mode, a tag attempts to register in the network. In this mode, the tag listens to the master beacon at frequency 922 MHz and tries to find its ID. If the ID is not available, then the tag generates a random time slot using random number generator and transmits its packet using the generated time slot at frequency 922.7 MHz. Figure 5.7 shows the partitioning of 20 ms time slot in the MAC mode. Once the master reader receives the tag

acknowledgement packet, it updates the beacon with the tag ID along with the time slot number. During next cycle, the tag listens to the beacon again and if the tag finds its ID along with the non-zero entry as the time slot number, the registration of tag is completed in the network and this will be the end of the MAC mode. If the tag finds its ID with a zero value as the time slot number in the received master beacon, it confirms to the tag that its registration was unsuccessful in the network. It will re-generate the random time slot number and transmits its acknowledgement packet using the generated time slot. This cycle repeats until the tag finds a non zero entry as the time slot along with its ID in the received master beacon. Once the tag finds the non zero entry as the time slot number along with its ID in the received master beacon, it confirms to the tag that its registration was successful in the network and this will be the end of the MAC mode.

Positioning mode: The positioning mode starts after the end of the MAC mode as described previously. In this mode, a registered tag listens to master beacon at frequency 922 MHz, sends its acknowledgement packet at frequency 922.7 MHz and starts the UWB data transmission by using the assigned time slot by the master reader. The acknowledgement packet along with the UWB data will be received by master and slave reader nodes and using the UWB data, the position of the tag is estimated. Figure 5.8 shows the partitioning of the 20 ms time slot in the positioning mode.

Note: The time duration for each of the slot is assumed to be as 20 ms to ensure that the UWB data will not overlap by the consecutive transmission

FIGURE 5.7: Division of the time slot in MAC mode

FIGURE 5.8: Division of the time slot in positioning mode

from the two slots. For both the modes, there is some reserved space kept for the future use. For the MAC mode, a new tag uses the time space in a slot after 11 ms from the start of the slot for sending its acknowledgement packet at the frequency 922.7 MHz for the registration into the network as can be seen in figure 5.7. This is done to ensure that a new tag can join the network any moment without interrupting the positioning mode of the previously joined tags. The time division in the positioning mode starts from the UHF TX of the mobile tag in the form of the acknowledgement packet, followed by the UWB data from mobile tag, UWB data from reference tag³ and the reserved space for the future use as shown in figure 5.8. The figure 5.9 shows histogram plot for the time gap variation of the start of UWB data for mobile tag with respect to the UHF acknowledgement received by the reader from the mobile

³The term reference tag can be considered as a tag co-located at the reader.

tag. The x- axis in the histogram represents the time gap in microseconds (us). It can be seen from the plot that mean value of time gap between the UHF acknowledgement received by the reader from the mobile tag and the start of the UWB data for the mobile tag is around 210 us.

FIGURE 5.9: Time gap variation in the start of UWB data for mobile tag with respect to UHF acknowledgement received by the reader from the mobile tag.

The figure 5.10 shows histogram plot for the time gap variation between the end of the UWB data for mobile tag & the start of UWB data for reference tag with respect to UHF acknowledgement received by reader from the mobile tag. The x- axis in the histogram represents the delay in microseconds (us). It can be seen from the plot that mean value of the time gap between the two tag's UWB data is around 76 us. For both the histogram plots, 100 measurements of the time gap were collected from the oscilloscope by triggering the scope on the UHF acknowledgement packet received by the reader from the mobile tag. The purpose of these histogram plots is to know the variation

between the different UWB data as this process is being triggered by UHF beacon which is transmitted by master reader at the start of every one second. The main reason for the variation is due to existence of oscillator instabilities in each of the devices, causing a difficulty in achieving fixed delay value in both the cases. Also these histogram plots corroborate that there is no overlapping of the UWB data between mobile & reference tags even in the worst case of variation.

FIGURE 5.10: Time gap variation between the UWB data for mobile tag & the reference tag with respect to UHF acknowledgement received by the reader from the mobile tag.

5.2.3 Feedback to the tag

During the start of each cycle, the master reader broadcasts a packet. This packet also contains information about the allocated time slot number along with tag IDs. This provides a feedback for each tag about the slot confirmation. Once the tag finds a non-zero entry after its ID, it assumes the successful

registration in network and can look for UWB transmission if requested by the master reader. If any tag finds a zero entry after its ID. It provides a confirmation to the tag that its registration in the network is not successful and it will generate a new time slot using random generator and wait for next cycle to get the confirmation about the registration. As this feedback is provided to each tag in the form of a broadcast packet at the start of every new cycle, it aids in achieving the energy efficiency in the tag as the tag needs to wake up to listen this broadcast packet at the start of every cycle only.

5.3 Use of two different frequencies during the MAC process

In this scheme, the two different frequencies are used for master reader beacon and for acknowledgement packet transmitted by tags. The master reader transmits its beacon at 922 MHz while the tag transmits its acknowledgement packet at 922.7 MHz. To illustrate the effect of single frequency usage, let's consider a scenario when a new tag starts its registration process into the network and there is only one frequency used during the whole process which means the master reader and the tags transmit at one frequency. A new tag starts the process by listening to the reader beacon. Since it is not aware of the starting time of the master reader beacon, it will open its receive window for 1 sec initially, assuming start of new cycle is 1 sec. Suppose it receives the master reader beacon after 100ms of opening of its receive window and

collects the master reader beacon data from the receive buffer. Now the existing tags in the network will be transmitting their acknowledgement packets based on the allocated slots after the reader beacon using the same frequency. Let's say, one existing tag transmits its packet at 722 ms after the beacon which means that the new tag receive window of 1 sec is still open to receive this tag packet also along with master reader beacon which in turn will overwrite the master reader beacon data in the receive buffer of the new tag. To avoid such scenarios of receive buffer overwrite due to single frequency usage, the two different frequencies are employed into the scheme for the transmission of the master reader beacon and the tag acknowledgements. Also using the two different frequency scheme may help in providing the scalability to the system into multi zone/cell environment.

5.4 State Transition Diagram of the Tag Firmware in MAC

The figure 5.11 shows the firmware state transition diagram for the tag in Medium Access Mode. The state transition diagram in medium access mode is identical to the state transition diagram for the positioning mode described previously in chapter 3. In the MAC mode, the different state that arises in comparison to the UWB Tx data for the positioning mode ⁴ of the tag is the random generator mode.

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⁴The reader may refer to chapter 3 for the details about the state transition diagram in the positioning mode for the tag.

5.4.1 State 0: START (Power-up reset)

When battery is plugged into the board, CC1310 gets reset. It's a form of hardware reset. In this state, it does the SYS/BIOS initialization, enters into the main function, starts the BIOS and looks for scheduler to perform its intended function and moves to the state 1.0.

5.4.2 State 1.1: UC STANDBY mode

This state is the standby mode for CC1310. In this state only real time clock (RTC, low speed clock, 32.768 KHz) is running. Whenever the scheduler does not find any posted command in the queue and if there is a sufficient time available before the next command to be posted, it puts the UC into the standby mode.

5.4.3 State 1.0 & 2: UC UHF active mode

This state represents active mode for the UC. Whenever the scheduler finds any posted command in the queue, it puts the UC into the active mode along with required peripheral to be used. In this mode, the system CPU is running with high speed clock (48 MHz). In this state the current consumption includes the core current plus the peripheral current consumption.

FIGURE 5.11: State transition diagram for tag firmware(CC1310) in medium access mode

5.4.4 State 3: UC UHF RX mode

This state is the Radio RX state. In this state, a mobile tag receives UHF packet from master reader also called as beacon. The moment the RF packet entry is done in RX buffer in the mobile tag, a callback is being executed to process the packet data and to store in memory. Once the data is stored in the memory and if it is a valid packet ⁵, the UC goes back again to the state 2. As the new tag is getting through the registration process in the network, the initial state of the firmware will be moved directly to the state 4 using initial condition of state variables as zero. If the received packet has got the valid address data⁶ along with the time slot number as 0x00, then it goes from state 2 to state 4 for generating the random time slot number. If the received packet has got the valid address data along with the time slot number as 0xFF then it will go to state 5 otherwise it will go back to state 1.1 and the cycle repeats. The time duration for this state is 3 ms. This state also manages the time synchronization with the master reader. It executes a simple strategy. During the start-up/power reset, UC sets the Rx duration for 1sec initially because the packet arrival time is unknown to the UC and the moment the RF packet entry is done and the callback is being hit for the first time, it resets the timer and sets the RX duration for 3 ms. To keep in sync with the master reader continuously after first time, it continues to reset the timer every time the RF packet entry is done and the callback is being executed while maintaining the RX duration for 3 ms.

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⁵Valid packet in the reader beacon means the data value of 0x32 or 0x00 as the second byte.

⁶Valid address data means the corresponding tagID

5.4.5 State 4: Random generator mode

This state is the random generator mode for the MCU. If the time slot number allocated by the master reader is 0x00 or a new tag is joining the network, then the random number generator mode is used to generate the random time slot number and it goes from state 4 to state 5 for the transmission of acknowledgement packet. The time duration for this mode is around 200 us.

5.4.6 State 5: UC UHF TX Mode

This state is the Radio TX state. In this state, a mobile tag acknowledges master reader by sending the UHF packet using the allocated time slot number or by the randomly generated time slot number. The time duration for the UHF TX mode is 0.5ms. The tag sends acknowledgement packet with its ID and the time slot number information. If the state 5 is executed after state 2, this means that the tag registration is successful as the master reader has allocated a time slot. It goes back to state 1.1 and tag starts the next cycle with the positioning mode as described earlier in chapter 3. If the registration was unsuccessful as the allocated time slot is zero, then the tag goes back to state 1.1 and continues to be in the MAC mode until it successfully registers in the network.

FIGURE 5.12: Comparison of charge consumed for the three MAC schemes

5.5 Power Consumption Comparison for Different MAC schemes

The figure 5.12 shows power consumption comparison in terms of charge consumed during the one cycle of this scheme against the different standard schemes. It can be seen that this scheme consumes the minimum power as compared to the other schemes for MAC. The key difference here is the utilization of the feedback given to the tag at start of every cycle along with central master control that helps in reducing the power consumption of tags by reducing the overheads in the form of retransmissions or to listen to the channel for the availability.

To illustrate further about the comparison result between different schemes,

charge consumption calculation is being conducted for one cycle of 1 sec duration. Each cycle consists of the charge consumed during the Rx of the broadcast packet and the Tx of acknowledgement packet by the tag. The Rx window is kept open for 3 ms and the Tx is completed in 0.5 ms as explained previously in chapter 3 firmware description of the tag. From the current measurement in the chapter 3, the current for the Rx is 10 mA whereas for the Tx @ +10 dBm is around 20 mA. The MAC scheme presented in this thesis uses only one Rx and one Tx for one cycle, then charge consumed for one tag in one Rx and one Tx operation in one cycle

$$= 10mA * 3mS + 20mA * 0.5mS = 40uC$$

As this MAC scheme is based on centralized architecture, master reader allocates the time slots to the tags based on the availability. However, for the ALOHA schemes which are based on the distributed architecture, each tag contends to find out its own slot in the random way. This results into the collision of packets causing an increase in the overhead in the form of retransmissions. If we consider a case of success with 20 retransmissions in one cycle for one tag with each retransmission include one Rx, then charge consumed for one tag in 20 Rx and 20 Tx operation in one cycle for ALOHA schemes

$$= 10mA * 3mS * 20 + 20mA * 0.5mS * 20 = 800uC$$

Also, for CSMA scheme, if we consider the case of success of getting the time

slot and open the Rx window to listen the channel for the duration of 150 mS over a period of 1 sec with each Rx window is for 3 mS then charge consumed for 50 Rx and one Tx operation in one cycle for CSMA

$$= 10mA * 3mS * 50 + 20mA * 0.5mS = 1510uC$$

With the above calculations, it can be seen that this work MAC scheme consumes a very low power for the medium access as compared ALOHA & CSMA schemes.

5.6 Summary

This chapter has introduced the novel Medium Access Scheme that can be implemented in the centralized architecture using a concept of master reader. It is based on feedback given to tag at the start of every cycle for the allocated time slot. This scheme also presents an idea with which a new tag can join the network any time without interrupting the other tags in the network and gets the time slot for UWB transmission. Also, a new state transition diagram is proposed for the tags in the medium access mode. Finally, the comparison result is presented in terms of power consumption of this MAC scheme with other schemes.

Chapter 6

Range Measurement

6.1 Experimental Setup and Overview

The experimental set up for 1D range measurement between two readers is shown in figure 6.1. The setup consists of two readers and two reference tags (co-located at the readers). The master reader is placed at origin while the slave reader is placed at distance d along the x -axis as shown in figure 6.1. The master reader starts the process for the slot allocation using MAC and in turn the reference tags transmit their UWB pulses for the ranging in the sequenced time slots.¹

The readers receive the UWB pulses from both the reference tags and compute TDOA and the difference of the TDOA is calculated at the master reader to find the distance between them. The intent here is to demonstrate calibration phase for the system while providing the synchronization of the reader sampling clocks by adjusting the DDS frequency in both the reader so as to

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¹Sequenced time slot means that within a 20 ms time slot, the UWB data transmission from RT2 will be followed by the UWB data transmission from RT1.

FIGURE 6.1: System model for 1D ranging between two reader nodes

get the PRF close to the true value and to perform the automatic range computation between the readers by using UWB signals from the reference tags. The calibration phase also helps in preventing human being involvement in measurement of range between readers which is required for setting up of coordinate frame before the start of localization.

This chapter begins with the proposal of mathematical formulation for 1D ranging between the two readers using TDOA ranging technique. The following section shows the measurement results for the ranging between two readers and finally this chapter ends up with summary.

6.2 Proposed Mathematical Formulation for 1D Ranging between two Readers

Let us assume that reference tag 2 (RT2) is located at SR2 and reference tag 1 (RT1) is located at MR1 as shown in figure 6.1 and also, consider that within a 20 ms time slot, UWB data from RT2 will be transmitted first followed by UWB data transmission from RT1 and d is the unknown distance between the two readers. Then the time of arrival equation for RT2 UWB signals on MR1 is denoted by TOA_{MR1}^{RT2} and given by:

$$TOA_{MR1}^{RT2} = (T_{O_{MR1}} + T_{RT2} + n_{MR1}^{RT2} t_{PRF}^{RT2} + p_{delay})(1 + \delta_{RT2}) - - - - - (16)$$

where, $T_{O_{MR1}}$ = Time offset at master reader MR1 in terms of samples,

T_{RT2} = Start time at reference tag RT2 in terms of samples,

n_{MR1}^{RT2} = UWB envelop index at MR1 in one frame of 16k samples,

t_{PRF}^{RT2} = PRF observed at MR1 for RT2 after equivalent time sampling in one frame of 16k samples,

p_{delay} = the propagation delay from RT2 to MR1 in terms of samples.

δ_{RT2} = Clock skew for RT2.

Similarly,

the time of arrival equation for RT2 UWB signals on SR2 is denoted by TOA_{SR2}^{RT2} and given by:

$$TOA_{SR2}^{RT2} = (T_{O_{SR2}} + T_{RT2} + n_{SR2}^{RT2} t_{PRF}^{RT2} + p_{delay})(1 + \delta_{RT2})$$

where, $T_{O_{SR2}}$ = Time offset at slave reader SR2 in terms of samples,

T_{RT2} = Start time at reference tag RT2 in terms of samples,

n_{SR2}^{RT2} = UWB envelop index at SR2 in one frame of 16k samples,

t_{PRF}^{RT2} = PRF observed at SR2 for RT2 after equivalent time sampling in one frame of 16k samples,

$p_{delay} = 0$ as RT2 is located at SR2

δ_{RT2} = Clock skew for RT2.

So rewriting the above equation with $p_{delay} = 0$ we get,

$$TOA_{SR2}^{RT2} = (T_{O_{SR2}} + T_{RT2} + n_{SR2}^{RT2} t_{PRF}^{RT2})(1 + \delta_{RT2}) \text{ --- (17)}$$

The time of arrival equation for RT1 UWB signals on MR1 is denoted by

TOA_{MR1}^{RT1} and given by:

$$TOA_{MR1}^{RT1} = (T_{O_{MR1}} + T_{RT1} + n_{MR1}^{RT1} t_{PRF}^{RT1} + p_{delay})(1 + \delta_{RT1})$$

where, $T_{O_{MR1}}$ = Time offset at master reader MR1 in terms of samples,

T_{RT1} = Start time at reference tag RT1 in terms of samples,

n_{MR1}^{RT1} = UWB envelop index at MR1 in one frame of 16k samples,

t_{PRF}^{RT1} = PRF observed at MR1 for RT1 after equivalent time sampling in one frame of 16k samples,

$p_{delay} = 0$ as RT1 is located at MR1.

δ_{RT1} = Clock skew for RT1.

Rewriting the above equation with $p_{delay} = 0$ we get,

$$TOA_{MR1}^{RT1} = (T_{O_{MR1}} + T_{RT1} + n_{MR1}^{RT1} t_{PRF}^{RT1})(1 + \delta_{RT1}) - - - - - (18)$$

The time of arrival equation for RT1 UWB signals on SR2 is denoted by TOA_{SR2}^{RT1} and given by:

$$TOA_{SR2}^{RT1} = (T_{O_{SR2}} + T_{RT1} + n_{SR2}^{RT1} t_{PRF}^{RT1} + p_{delay})(1 + \delta_{RT1}) - - - - - (19)$$

where, $T_{O_{SR2}}$ = Time offset at slave reader SR2 in terms of samples,

T_{RT1} = Start time at reference tag RT1 in terms of samples,

n_{SR2}^{RT1} = UWB envelop index at SR2 in one frame of 16k samples,

t_{PRF}^{RT1} = PRF observed at SR2 for RT1 after equivalent time sampling in one frame of 16k samples,

p_{delay} = propagation delay from RT1 to SR2 in terms of samples.

δ_{RT1} = Clock skew for RT1

Performing (16)-(17), we get²

$$TOA_{MR1}^{RT2} - TOA_{SR2}^{RT2} = (1 + \delta_{RT2})[(T_{O_{MR1}} - T_{O_{SR2}}) + (n_{MR1}^{RT2} - n_{SR2}^{RT2})t_{PRF}^{RT2} + p_{delay}]$$

Now, here t_{PRF}^{RT2} is considered to be same in both the readers due the adjustment being made before this computation. $n_{MR1}^{RT2} = n_{SR2}^{RT2}$ as the same index UWB envelop is compared for RT2 in both the readers and if we assume the difference of measured TOA as $TDOA^{RT2}$, then

$$TDOA^{RT2} = (1 + \delta_{RT2})[(T_{O_{MR1}} - T_{O_{SR2}}) + p_{delay}] - - - - - (20)$$

Similarly, performing (19)-(18), we get

$$TOA_{SR2}^{RT1} - TOA_{MR1}^{RT1} = (1 + \delta_{RT1})[(T_{O_{SR2}} - T_{O_{MR1}}) + (n_{SR2}^{RT1} - n_{MR1}^{RT1})t_{PRF}^{RT1} + p_{delay}]$$

Now, here t_{PRF}^{RT1} is considered to be same in both the readers due the adjustment being made before this computation. $n_{MR1}^{RT1} = n_{SR2}^{RT1}$ as the same index UWB envelop is compared for RT1 in both the readers and if we assume the difference of measured TOA as $TDOA^{RT1}$, then

$$TDOA^{RT1} = (1 + \delta_{RT1})[(T_{O_{SR2}} - T_{O_{MR1}}) + p_{delay}] - - - - - (21)$$

---

²In this algorithm, t_{PRF} is made nearly equal in the both readers by adjusting the DDS frequency of both the readers to closest value to theoretical prf.

From equation (20),

$$(T_{O_{MR1}} - T_{O_{SR2}}) = \left[\frac{TDOA^{RT2}}{(1 + \delta_{RT2})} - p_{delay} \right] - - - - - (22)$$

Substituting the value of $(T_{O_{MR1}} - T_{O_{SR2}})$ from equation 22 into equation 21, we get

$$TDOA^{RT1} = (1 + \delta_{RT1}) \left[- \left[\frac{TDOA^{RT2}}{(1 + \delta_{RT2})} - p_{delay} \right] + p_{delay} \right]$$

$$2p_{delay} = \left[\frac{TDOA^{RT1}}{(1 + \delta_{RT1})} + \frac{TDOA^{RT2}}{(1 + \delta_{RT2})} \right]$$

or,

$$p_{delay} = \frac{1}{2} \left[\frac{TDOA^{RT1}}{(1 + \delta_{RT1})} + \frac{TDOA^{RT2}}{(1 + \delta_{RT2})} \right] - - - - - (23)$$

Since, p_{delay} is in terms of sample index as $TDOA^{RT1}$, $TDOA^{RT2}$ are in terms of sample index and can be converted into time units by multiplying with the equivalent time sampling resolution say Δt , and furthermore the unknown distance d can be computed by multiplying p_{delay} with the speed of EM wave. Then the distance d is given by,

$$d = \frac{c\Delta t}{2} \left[\frac{TDOA^{RT1}}{(1 + \delta_{RT1})} + \frac{TDOA^{RT2}}{(1 + \delta_{RT2})} \right] - - - - - (24)$$

where, δ_{RT1} = clock drift for reference tag 1 with respect to the correct rate.

δ_{RT2} = clock drift for reference tag 2 with respect to the correct rate.

$$TDOA^{RT1} = TOA_{SR2}^{RT1} - TOA_{MR1}^{RT1}$$

$$TDOA^{RT2} = TOA_{MR1}^{RT2} - TOA_{SR2}^{RT2}$$

c = speed of EM wave.

Δt = equivalent time sampling resolution.

Note: Here the TDOA values are computed from the samples and the samples are being acquired by conducting the experiment for the complete system. The effect of δ_{RT1} , δ_{RT2} is already present in the samples with the correction is being made in the reader sampling frequency so that the observed PRF value is close to the true PRF value. So the computation for the distance in the following section is directly done by adding the two TDOA values as can be seen in equation 24.

The next section presents measurement results of the UWB envelops at each reader and range is computed between the readers by using the above described equation.

6.3 Set up Details for 1D range measurement

To perform 1D ranging between the two readers, the test set up is developed by making one reader as a master reader MR1 with a co-located reference tag RT1 and the other reader as a slave reader SR2 with a co-located reference tag

RT2. The two readers are connected to a laptop using a wireless local area network (WLAN). The laptop acts a DHCP server and allocates the IP addresses for both the readers. Once the WLAN is established, the Tera Term application is used in the laptop to connect to these two readers using the allocated IP addresses and the initial configuration for the readers is performed in the form of setting the DDS frequency and the gain for both front end and back end base band amplifiers. Once the initial configuration is done for both the readers, the process is initiated by MR1 by transmitting the beacon and allocating a time slot for the two reference tags in which RT2 transmits its UWB data followed by RT1 UWB data. The UWB data is collected from both readers in the laptop using WinSCP application. Then the spyder python console is used to plot the collected data. The figure 6.2, 6.3 and 6.4 below show the pictures for the measurement test set up for the two reader along with the two reference tags.

FIGURE 6.2: Photograph for the measurement setup for the 1D ranging

FIGURE 6.3: Photograph of Master reader (MR1) along with reference tag 1(RT1)

6.4 Measurement Results

The figure 6.5 and 6.6 show the captured data for the two readers using the setup described in the previous section. Here the DDS frequency is adjusted to 1999500 Hz which gives the equivalent time sampling resolution of 0.125 ns. The front end and the back end base-band amplifiers gain is adjusted to the gain code of 4. The distance between the two readers is kept as 5m, 7m, 10m and 15m. The range is computed from the recorded files for all the four distances.

The table 6.1 shows captured TOA data values from recorded files for the UWB envelop for both tags for master reader MR1 whereas table 6.2 shows captured TOA data values from recorded files for the UWB envelop for both the tags for slave reader SR2³.

Using equation 24, derived in section 6.2, the range computation is done from

³In the tables, TOA value is written first for the 2nd UWB envelope and it is done for both the tags.

TABLE 6.1: Captured TOA values for two UWB envelopes for both the tags at MR1

S.No.	$\text{TOA}_{\text{MR1}}^{\text{RT2}}$		$\text{TOA}_{\text{MR1}}^{\text{RT1}}$	
1	8459	4459	15821	11854
2	5688	1684	13281	9311
3	7306	3302	15813	11845
4	7354	3349	14896	10930
5	5608	1599	14075	10102
6	6781	2777	13314	9345
7	6892	2890	13279	9313
8	7434	3425	15249	11285
9	5090	1084	15246	11279
10	7390	3383	12935	8968

TABLE 6.2: Captured TOA values for two UWB envelopes for both the tags at SR2

S.No.	$\text{TOA}_{\text{SR2}}^{\text{RT2}}$		$\text{TOA}_{\text{SR2}}^{\text{RT1}}$	
1	6476	2485	14671	10709
2	5407	1410	13787	9829
3	4712	718	14031	10077
4	5753	1756	14106	10147
5	5613	1617	14888	10928
6	6846	2846	14183	10226
7	7770	3780	14955	10999
8	5222	1229	13863	9908
9	6105	2109	13078	9126
10	6584	2590	12950	8994

FIGURE 6.4: Photograph of Slave reader (SR2) along with reference tag 2(RT2)

the TOA data. The table 6.1 and 6.2 show the TOA data for the 15m distance. This is done to show the complete process of calculating the range. However, for the other distances TDOA values are shown directly for the collected TOA data and range is computed using equation 24 along with root mean square error computation. For the computation, the values used for the different parameters are: $c = 300000000$, $\Delta t = 0.125$ ns,

$$TDOA^{RT1} = TOA_{SR2}^{RT1} - TOA_{MR1}^{RT1}$$

$$TDOA^{RT2} = TOA_{MR1}^{RT2} - TOA_{SR2}^{RT2}$$

The table 6.3, 6.4, 6.5 & 6.6 show the range computation using equation 24 along with the computed TDOA's for both tags⁴. It also shows the error in the measurement. The error is computed as $e = \text{Measured Distance} - \text{Actual}$

⁴The values of TDOA's are in the form of sample indexes and acquired samples are already having the effect of clock skew at both the reader and tag with the correction being applied to the readers sampling clock so as to adjust the PRF close to the theoretical. So both the TDOA's can be added directly as can be seen in equation 24.

FIGURE 6.5: Captured data for the both the tags in MR1

TABLE 6.3: Measured range values with the actual range as 5m.

S.No.	TDOA^{RT1}	TDOA^{RT2}	Distance,d(m)	Error,e(m)
1	2425	-2157	5.025	0.025
2	-1851	2143	5.475	0.475
3	1948	-1692	4.8	-0.2
4	1514	-1244	5.0625	0.0625
5	1331	-1056	5.15625	0.15625
6	1367	-1095	5.1	0.1
7	2111	-1838	5.11875	0.11875
8	-2855	3105	4.6875	-0.3125
9	620	-332	5.4	0.4
10	1818	-1545	5.11875	0.11875

Distance.

The table 6.7 shows the summary of the range measurement results along with the root mean square error values. It can be seen from the results that the bias error for the distance estimation is between 0.0944 m and 0.2006 m whereas the root mean square error (RMSE) varies from 0.1633 m to 0.3122 m.

TABLE 6.4: Measured range values with the actual range as 7m.

S.No.	TDOA ^{RT1}	TDOA ^{RT2}	Distance,d(m)	Error,e(m)
1	-762	1133	6.95625	-0.04375
2	-370	753	7.18125	0.18125
3	-212	588	7.05	0.05
4	-33	399	6.8625	-0.1375
5	-51	428	7.06875	0.06875
6	1667	-1306	6.76875	-0.23125
7	-932	1315	7.18125	0.18125
8	-1204	1588	7.2	0.2
9	714	-331	7.18125	0.18125
10	550	-164	7.2375	0.2375

TABLE 6.5: Measured range values with the actual range as 10m.

S.No.	TDOA ^{RT1}	TDOA ^{RT2}	Distance,d(m)	Error,e(m)
1	941	-408	9.99375	-0.00625
2	2578	-2053	9.84375	-0.15625
3	-482	1026	10.2	0.2
4	1914	-1388	9.8625	-0.1375
5	-545	1085	10.125	0.125
6	918	-373	10.21875	0.21875
7	-409	956	10.25625	0.25625
8	895	-367	9.9	-0.1
9	-378	928	10.3125	0.3125
10	2278	-1762	9.675	-0.325

TABLE 6.6: Measured range values with the actual range as 15m.

S.No.	TDOA ^{RT1}	TDOA ^{RT2}	Distance,d(m)	Error,e(m)
1	-1150	1983	15.61875	0.61875
2	506	281	14.75625	-0.24375
3	-1782	2594	15.225	0.225
4	-790	1601	15.20625	0.20625
5	813	5	15.15	0.15
6	869	-65	15.075	0.075
7	1676	-878	14.9625	-0.0375
8	-670	1477	15.13125	0.13125
9	-1386	2212	15.4875	0.4875
10	15	806	15.39375	0.39375

FIGURE 6.6: Captured data for the both the tags in SR2

TABLE 6.7: Table showing the summary for the range measurement results.

S.No.	Actual Distance(m)	Measured Mean Distance (m)	RMSE (m)
1	5	5.0944	0.2430
2	7	7.0688	0.1663
3	10	10.0388	0.2063
4	15	15.2006	0.3122

6.5 Summary

This chapter has provided measurement results for the complete system in the form of 1D ranging along with the MAC time slot allocation performed by the master reader for the two reference tags. The mathematical formulation for the 1D ranging is described and finally the chapter is completed by presenting the measurement results and the distance between the two readers is calculated using the proposed mathematical formulation.

Chapter 7

Conclusion And Future Work

7.1 Conclusion

This thesis presents the design and development related to various peripherals involved in the low power asset tracking system. These peripherals include the state of art low power consumption tag, the reader/sensor systems and the energy efficient medium access control scheme for multiple tag indoor environment.

As a first part in the development of the system, the state of art low power consumption tag is designed and developed. The hardware circuit and the firmware state transition diagram is proposed in view of power management for complete tag. The three design strategies are implemented in design for achieving the energy efficiency. With the implementation of first strategy, the battery life of 45 days is achieved whereas the battery life is prolonged by 12 days with the implementation of strategy 2 along with strategy 1, which is computed as 57 days. The further augmentation of the battery life is attained

with the implementation of strategy 3 along with the other two strategies. With 100 nF capacitor configuration for strategy 1 + 2 + 3, the battery life of 86 days is delivered which gives a span of additional 29 days from the battery life computed for strategy 1 + 2. With this framework of implementation along with the battery capacity as 240 mAh, the tags designed in this work can support up to 86 days of continuous operation at the update rate of 1 Hz with UHF TX power as +10 dBm and UWB TX peak power as +23.5 dBm.

The second part covers the design & development related to reader/sensor system. The functioning of the complete system is proposed in various phases along with the firmware and the hardware circuit for the reader system. The energy efficient MAC scheme is designed and implemented for the system. With this proposed MAC scheme, the charge consumed for the tags in one cycle is around 40 μC as compared to 800 μC for ALOHA & 1510 μC for the CSMA protocol. It can be concluded that this MAC scheme performs better in terms of power consumption as compared to the ALOHA & CSMA.

In last, measurement results are presented for finding peer to peer range between the reader systems using the co-located reference tags along with implementation of MAC scheme. These measurement results demonstrate the functioning of various peripherals in conjunction with each other resulting into the development of complete asset tracking system. The range computation is done with the help of the derived equation and the accuracy better than 0.2 m is achieved in the ranging. Table 7.1 compares the performance of this work with the commercial UWB based localization system.

TABLE 7.1: Comparison of commercial UWB based system with the system developed in this work.

S.No.	Parameter	Decawave System	This work
1	Positioning Technology	UWB	UWB
2	MAC Technology	UWB	Sub-1 GHz
3	Ranging Technique	TOA/TDOA	TDOA
4	UWB Tx peak power	+9.3 dBm	+23 dBm
5	Current Consumption in MAC mode	One Tx = 70mA, One Rx = 30mA	One Tx = 20mA, One Rx = 10mA
6	Accuracy	10 cm	20 cm
7	Time from sleep mode to Rx ready in Tags	3ms	174us
8	Current Consumption in active state in tags	12mA	2.5mA

7.2 Future Work

The recommended future work can be to provide the scalability for system by extending the system from single cell into multi cell/zone environment. This can be done with the help of proposed MAC scheme in which the neighbouring cells can be operating in different frequencies for sub-1 GHz communication and can allocate the time slot successfully for the mobile tags for UWB transmissions.

7.3 List of Publications

1. R. W. C. Ling, A. Gupta, A. Vashistha, M. Sharma, C. L. Law, "High Precision UWB-IR Indoor Positioning System for IoT applications", IEEE World Forum on Internet of Things (WF-IoT), Feb. 2018.

2. A. Vashistha, **A. Gupta**, C. L. Law, "Self Calibration of the anchor nodes for UWB-IR TDOA based Indoor Positioning System", IEEE World Forum on Internet of Things (WF-IoT), Feb. 2018.

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