High Precision UWB-IR Indoor Positioning System for IoT Applications

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Abstract— **This paper presents the design and implementation of an ultra-wideband impulse radio based indoor positioning system and its architecture. The operating mechanism of the complete system along with its hardware and software details are discussed. The system exploits the differential time difference of arrival technique for position estimation. Simulation and experimental results demonstrating the working of this in-house developed positioning system are provided. Good positioning accuracy of around 30 cm has been achieved from the implemented system for line-of-sight setting in a 7 m × 7 m indoor office environment.**

Keywords—Positioning; Ultra-wideband; Internet of Things

I. Introduction

The Internet of things (IoT) is an emerging technology which enables integration of billions of objects and complex systems over internet with the help of many technologies such as Wi-Fi, ZigBee, Bluetooth etc. Position estimation has become an essential and crucial factor in various monitoring applications of IoT. Precision localization and positioning has become an attractive area of interest for many new applications and business solutions. Although, the Global navigation satellite systems (GNSS) can provide good performance and positioning in outdoor systems, they are not very accurate when it comes to indoor locations or in GNSS-denied environments. With the ease of availability of commercial transceivers and the demand for accurate positioning systems by various industries, the research interest towards indoor positioning and navigation systems based on ultra-wideband technology has been immense.

Good localization accuracy can be achieved by using UWB pulses due to their high temporal resolution and multipath immunity [1]. Apart from achieving high accuracy, UWB can also provide larger coverage and ranging capability as well as the capacity to penetrate walls due to its large bandwidth. A typical UWB indoor localization system consists of some anchor nodes (i.e. nodes with fixed location) and the target node/s whose position is to be determined [2]. Target nodes transmit UWB pulses, which are then received by the anchor nodes. Range measurements are conducted between the anchor nodes and target nodes through this mechanism. Based on the range measurement information between the nodes, trilateration is performed and the location of the target node is determined. The most common techniques used for finding range between the nodes are received signal strength (RSS), angle of arrival (AOA), time of arrival (TOA) and time difference of arrival (TDOA) [1]. The choice of any specific position estimation technique can vary depending on the need, requirement and target accuracy. Time-based positioning techniques such as TOA and TDOA provide the best accuracy in estimating the location of a target node.

Besides, in wireless sensors network, clock synchronization among the sensor nodes is crucial for accurate ranging measurement. In terms of implementation of wireless sensor network, there are several variations can be found in literature [3], [4]. Most of them use commercially available UWB transceiver such as DWM1000 from Decawave [5]. However, the method used for synchronization share a common principle which is by using a reference node's signal as common time frame for all nodes in the network. In our case, a similar concept is employed but the synchronization scheme used is directed on the impulse synchronization level and an extension from our previous paper [6].

In this paper, an ultra-wideband impulse radio based positioning system for indoor applications is presented. A typical RF-based positioning system comprises of a network of fixed anchor nodes acting as spatial sensors and several mobile nodes whose positions need to be estimated. If a positioning system makes use of the two-way ranging technique [7], [8], its mobile nodes need to work as UWB transceivers. This will lead to a significant increase in the power demand for operating the mobile nodes as UWB receivers are likely to consume much higher power due to higher sensitivity requirement along with the large operational bandwidth. Thus, receiving a UWB signal consumes much more power than generating and transmitting the same signal. As a result, the operational hours for the mobile tag will also reduce when they are working as UWB transceivers. To overcome the limitation of constrained operational hours from UWB transceivers, the mobile tags in our system operate as UWB transmitters and the command and control is handled via UHF data links. The fixed anchor nodes of a positioning system provide more flexibility in terms of power consumption and physical size requirements. In our proposed system, each anchor node uses the BeagleBone Black (BBB) embedded platform. The advantages of BBB include good computational speed, low power consumption, reasonable hardware cost and reduced development time for the system. The BBB runs Linux for data acquisition and processing for anchor nodes.

The rest of the paper has been structured as follows. In Section II, the architecture of our indoor positioning system has

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been described. Section III presents the simulation results for verification of the proposed system algorithm. In Section IV, the measured results of the localization experiments undertaken using this proposed system are presented. Lastly, concluding remarks have been provided in Section V.

II. System Architecture

The architecture of the proposed indoor positioning system consists of a wireless network of fixed anchor nodes and mobile target nodes whose location needs to be estimated. A simplified block diagram of the overall UWB positioning system is provided in Fig. 1 and its functionality is explained as follows. The master anchor node initiates the process by broadcasting a beacon via UHF link to mobile tags. The mobile tag receives the beacon and sends the acknowledgement along with its ID to anchor nodes. Subsequently, it generates and transmits UWB pulses for position estimation. The anchor nodes acquire the UWB signals from the mobile tag as well as the reference tag and compute the signal TOA data. The reference tag is a stationary device with a known location. The TOA data is then transferred to the central server using WiFi links. The central server runs MATLAB to estimate the location of mobile tags using TDOA values computed from the received TOA data.

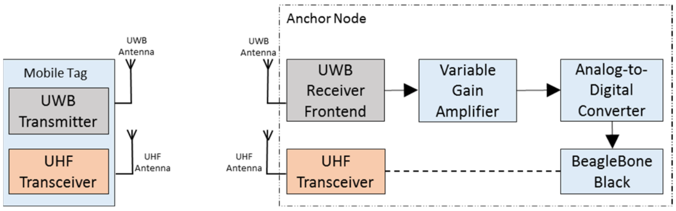

Fig. 1. Simplified block diagram of the UWB positioning system

A wireless local area network (WLAN) is created in which all the anchor nodes are the hosts in the network and the central server acts as a Dynamic Host Configuration Protocol (DHCP) server which assigns dynamic IP address to the anchor nodes. This mechanism eliminates the need to use a wired network for synchronization and data transfer purpose. The anchor nodes constantly poll the Network Time Protocol (NTP) server for time information via User Datagram Protocol (UDP) packet, and adjust their clocks based on the received timing information. This enables the anchor nodes to timestamp each TOA value from the mobile tag at different time slots. This technique also provides the facility to time synchronize the anchor nodes within the WLAN for achieving millisecond-level time accuracy. Fig. 2 illustrates the wireless data links existing within our positioning system.

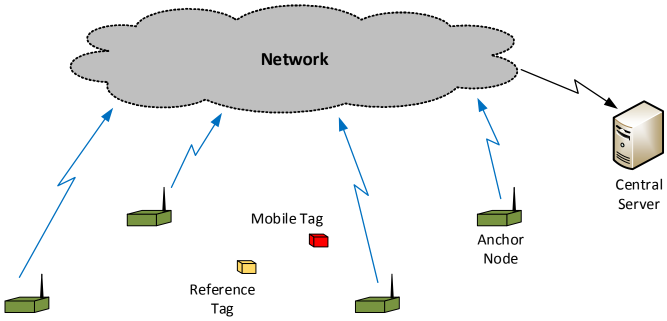

Fig. 2. Network data links of the positioning system

A. *Hardware Description*

1) *Mobile tag*

The mobile tag primarily consists of the UWB transmitter and TI RF MCU CC1310 [9]. The TI MCU CC1310 acts as a controller in the tag hardware. It maintains the UHF link with the master anchor node while handling the power management for the complete tag hardware by duty cycling at the frequency of 1 Hz which minimizes the OFF state energy consumption. The optimization of the ON state power consumption is done by activating the UWB signal with a pulse repetition frequency of 2MHz for a duration of 4ms. The UWB transmitter consists of two stages, namely an impulse generator stage and a pulse forming stage. The impulse generator is designed to generate a high power sub-nanosecond impulse. The pulse forming network then translates the generated impulse to construct the desired Gaussian UWB pulse with a high peak power of over +20 dBm [10]. Fig. 3(a) illustrates an image of the fabricated mobile tag.

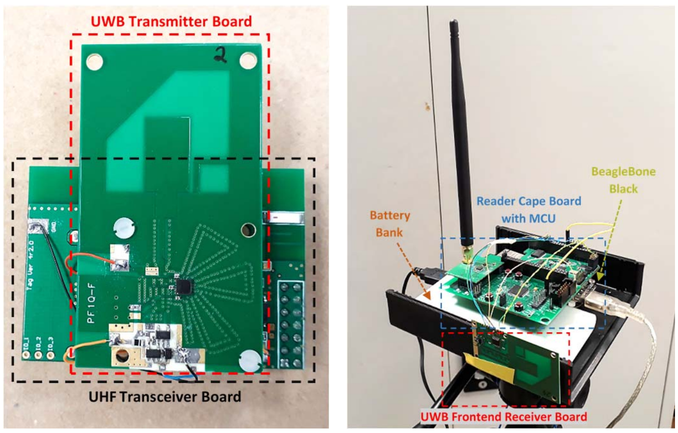

Fig. 3. Mobile tag and anchor node

2) *Anchor node*

The anchor node comprises of a UWB frontend receiver, a reader cape board, the BeagleBone Black (BBB) embedded computer and a battery bank. The UWB frontend receiver consists of a UWB antenna, band-pass filter, LNA and a mixer stage. The reader cape board contains a baseband amplifier, a low cost ADC and a CC1310 MCU. The UWB receiver detects the envelope of the UWB pulses transmitted by the mobile tag. The baseband amplifier in turn, amplifies the UWB envelop before it is sampled by the ADC.

Since UWB signals have a large bandwidth, an ADC with a high sampling frequency is required in order to follow the Nyquist sampling theorem. This will eventually lead to a need for expensive ADC chips in the system. To provide a cost effective solution, we employ the equivalent time sampling technique in our system by using a low cost ADC to sample the repetitive UWB envelops. Since the sampling of UWB envelop is based on equivalent time sampling, a lower sampling clock frequency is used, which is generated by the digital direct synthesizer (DDS) that utilizes 75 MHz temperature compensated oscillator (TCXO). The sampling frequency used in our application is about 2 MHz. Apart from its higher costs, a high sampling ADC generates a deluge of data which is difficult to handle by the general purpose microcontroller. In our system, BeagleBone Black embedded computer is used, which first acquires the ADC data and then processes the data to estimate the TOA of the received UWB signal. Fig. 3(b) illustrates an image of the fabricated anchor node.

B. *Software Description*

1) CC1310 master and slave anchor nodes

In the master anchor node, TI RF MCU CC1310 running TI RTOS is responsible for the Medium Access Control (MAC). The master anchor node starts the process by sending a UHF broadcast packet (also called as beacon) at a time interval of every one second. Upon power-up, the mobile tag receives the master beacon, generates the time slot and sends the acknowledgement back to the master anchor node in the generated time slot. The master anchor node upon receiving the acknowledgement, verifies for the time slot in its record, and allocates the time slot. In the next cycle, master node sends the beacon with the tag ID along with the allocated time slot. Once the tag finds its ID in the beacon, it looks for the allocated time slot next to the ID field. This confirms the tag registration in the network and completes the MAC functionality.

In the slave anchor node, CC1310 will always remain in the UHF receive mode to receive the tag acknowledgment. After receiving the tag acknowledgement, it extracts the tag ID from the received packet and sends the tag ID to the BBB embedded computer using the UART link. After completion of the MAC process, the master anchor node also performs the same operation as described above for the slave anchor nodes.

2) Anchor node's software components

The ARM Cortex A8 microprocessor on BBB integrates two on-chip Programmable Real-time Unit (PRU) which are clocked by a 200 MHz oscillator. This provides fast real-time response with each PRU instruction taking 5 ns. A system interconnection, based on Open Core Protocol (OCP), enables the PRU to access all resources on system-on-chip (SoC) [11]. By knowing the explicit host's resource memory addresses, PRUs are able to directly access the resource registers for read and write operations. A platform driver for the PRU is provided by Texas Instrument (TI), where PRU interrupt signal to host ARM processor is registered with kernel. The device memory is allocated and exposed to user space.

The ADC channel data that connects to the front-end receiver board is fed to the PRU via special PRU pins. The PRU's firmware then records the 16 KB frame data into the device memory allocated on Dual Data Rate (DDR) external RAM memory. On the Linux user space, our software program is running two different processes. The first process grabs the data from the device memory before it gets overwritten by subsequent data frame. Based on the data stored by the first process, the second process runs the TOA detection algorithm in Python. Since the execution speed of Python is relatively slow, Cython, a Python compiler is used to generate an executable object file from the Python code. Then, the executable file is embedded within the main application's C program.

III. SIMULATION

The simulation is performed to verify the scheme used for finding TDOA ranges and for positioning. We assume four anchor nodes here and each of them are placed at four corners in a room. Each anchor node is running on a separate clock and having a different phase in sampling clock. Therefore, in each captured frame there are signal transmitted from a mobile tag (MT) and reference tag (RT) with MT transmission signal appeared before RT transmission signal, where the RT signal acts as synchronization agent for all the anchor nodes. An experimental captured frame is shown in Fig. 4. In simulation, such experimental setup is simulated. The sampling clock frequency is assumed to be exactly same for all the anchor nodes without jitter and the transmitted UWB signal have a constant pulse repetitive frequency (PRF) throughout the simulation.

First of all, TDOA is calculated at each reader, then TDOA's of different readers are subtracted which gives, what is termed as differential time difference of arrival (DTDOA) [6]. With the obtained DTDOA, positioning algorithm of recursive least square method is applied to determine the position of the mobile tag or target node. Fig. 5 shows the position plot when mobile tags are placed at different locations. The positioning error in simulations is observed to be less than 10 cm for all the cases.

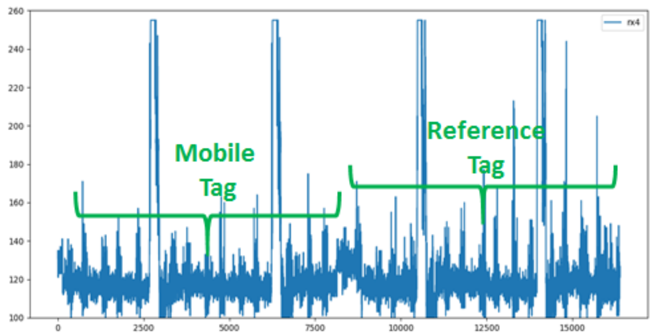

Fig. 4. Captured signal

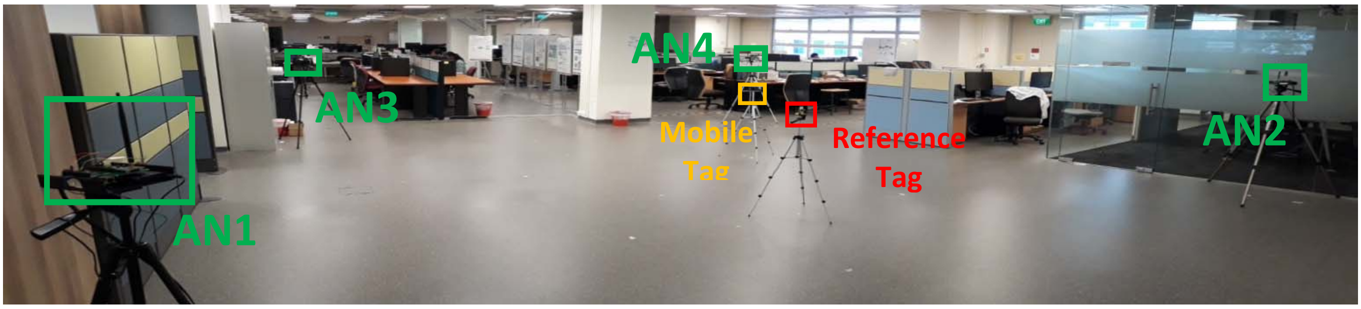

Fig. 6. Experimental setup

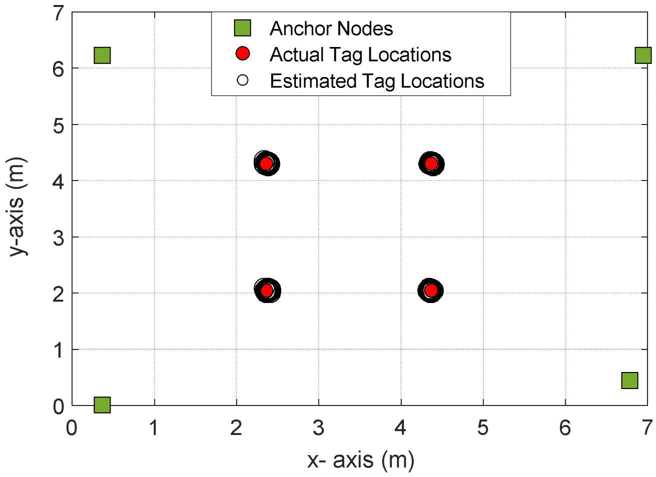

Fig. 5. Simulated positioning results

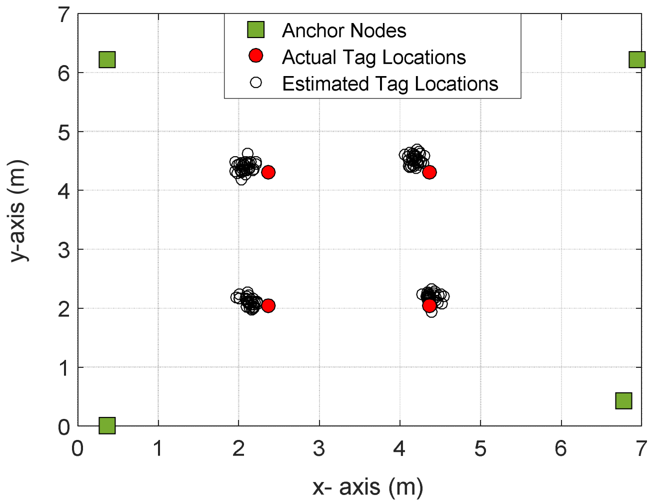

Fig. 7. Measured positioning results

IV. EXPERIMENT

To evaluate the overall system, we perform an experiment with in house designed anchor/sensor nodes. The anchor nodes are mounted on tripod and placed at four corners of the room. The room size is about 7 m x 7 m. Fig. 6 shows the panoramic view of the test bed. The height of the tripod is constant for all the anchors which is 1.45m (maximum height the tripod can support). However, for more optimized results and to avoid the signal obstruction by the people in the room, it is preferable to increase the height of the anchor nodes. The anchor nodes sampling frequency is being set such that the equivalent time is same among the anchor nodes.

A static positioning test is carried out to evaluate the accuracy of the positioning system. 4 static test points are chosen for comparison with the estimated position of mobile tag. At each static point chosen, 50 measurements data of TOA values are computed and sent to the central server, which computes the TDOA and then position is estimated. The estimated positions are shown in Fig 7. Cumulative distribution function (CDF) curves for the positioning error for 4 different locations are shown in Fig.8. The positioning accuracy is less than 40 cm for around 90% of the test points. The average positioning accuracy is 25.7 cm and the standard deviation is 9.1 cm for all the four tag locations.

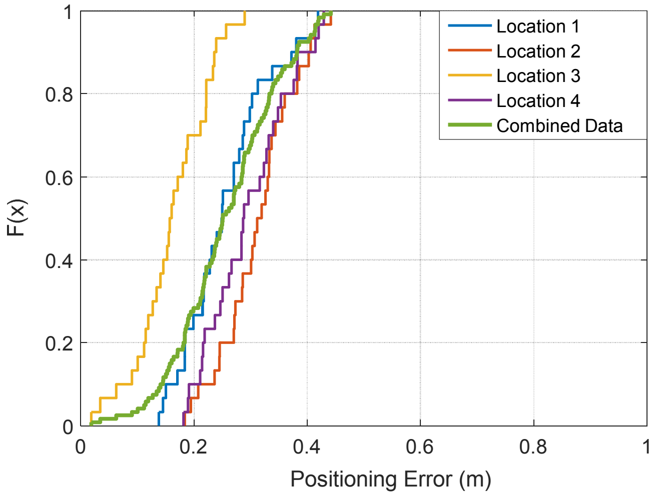

Fig. 8. Cumulative distribution plot of positioning error

V. Conclusion

In this paper, the architecture and implementation of an indoor positioning system is presented. The hardware and software building blocks involved in the system have been discussed. The MAC scheme implemented for the system is introduced. Differential time difference of arrival technique is employed to find the location of a mobile node. Both simulation and experimental results are presented to verify the performance of the positioning system. The accuracy of the system is tested for different static locations of the mobile node. A positioning accuracy of less than 40 cm with a standard deviation of around 9 cm has been achieved.

Acknowledgment

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