Final Report for AOARD Grant FA2386-11-1-4117

"Indoor Localization and Positioning through Signal of Opportunities"

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Abstract: An indoor positioning system using a network of synchronized low cost battery powered sensor nodes utilizing ultra wideband impulse radio technology is described. The system components such as battery powered beacon transmitters and receivers to be utilized in the sensor nodes are developed. A receiver array for the positioning of the user is also developed. The receiver array is powered through a USB interface to a notebook computer and the digitized data are processed in MATLAB through the same interface. A self calibration algorithm for the positioning of sensor nodes is presented and experimentally tested. Preliminary tests show good ranging accuracy in the decimeter range.

1: Introduction

Navigation in outdoor environment with good view to satellite signals is aided by localization and positioning using Global Satellite Navigation System (GNSS). However there are many environments where GNSS signals are weak, severely impaired by multipath propagation or unavailable. Examples of these environments are inside buildings and underground. In urban environment, there are many wireless signal transmissions such as cell-phones, wireless networks, ultra wideband, television broadcasting, etc, collectively known as signal of opportunities which may be used for localization and positioning. Many of these signals already exist in the environment for communication purposes.

This research project is aimed at studying the issues involved with positioning in dense indoor and underground environments with target accuracy of better than 1 meter. These environments suffer from frequent blockages and have severe multipath signal propagation from source to target resulting in biased ranges and large range errors if the signal does not have sufficient bandwidth with the required time resolution for resolving the multipath signals. To resolve these issues, we advocate the use of a network of synchronized low cost battery powered sensor nodes with large wireless signal bandwidth which can be easily deployed in the environment. These sensor nodes act as beacon transmitters for positioning and synchronize to a common clock frequency which may be from signals of opportunities with large signal amplitude and wide area coverage in indoor and underground environments. The sensor nodes perform mutual calibration to determine their locations which are assumed to be fixed. The mobile user computes its location through the time difference of arrival using signals received from multiple beacon transmitters. Figure 1 illustrates this use scenario.

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14. ABSTRACT
An indoor positioning system using a network of synchronized low cost battery powered sensor nodes utilizing ultra wideband impulse radio technology is described. The system components such as battery powered beacon transmitters and receivers to be utilized in the sensor nodes are developed. A receiver array for the positioning of the user is also developed. The receiver array is powered through a USB interface to a notebook computer and the digitized data are processed in MATLAB through the same interface. A self calibration algorithm for the positioning of sensor nodes is presented and experimentally tested. Preliminary tests show good ranging accuracy in the decimeter range.

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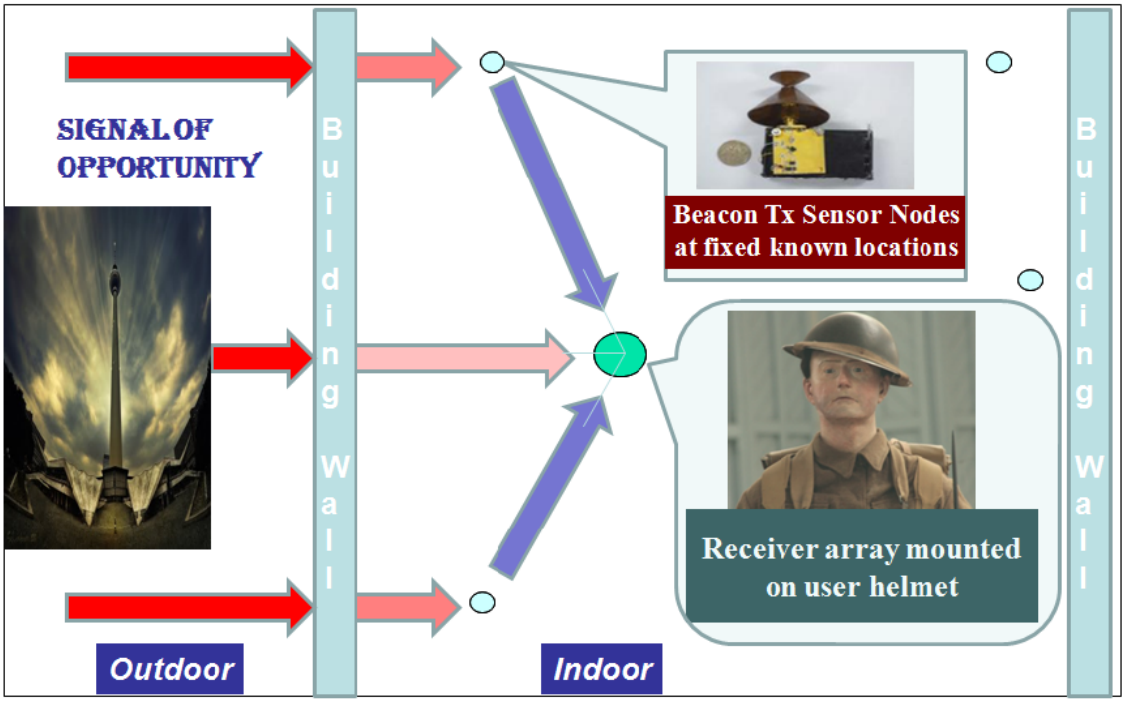

Figure 1: Indoor localization system using signal of opportunity and ultra wideband impulse radio

2: Apparatus developed for Experimentation

In the above reporting period (26th September 2011 to 26th March 2013) of this research project, we developed the following:

(i) Low cost battery powered sensor node. It consists of a low power ultra wideband impulse radio transmitter and battery powered sampling receiver for receiving ultra wideband impulse radio signals.

Two versions of the ultra wideband impulse radio transmitter were developed. The first version as shown in Figure 2 has peak power of around 23dBm while the second version as shown in Figure 3 has peak power of 30dBm.

Figure 2: 23dBm beacon transmitter

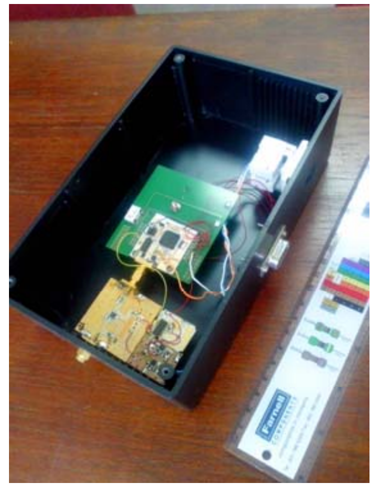

Figure 3: 30dBm beacon transmitter

A MSP430F2616 Texas Instrument low power microcontroller is used to generate the beacon transmitter frame format and other power control functions. The 30dBm beacon transmitter pulse shape in time domain is as shown in Figure 4. With a 10dB attenuator at the output, the peak to peak output voltage into 50 ohms is around 5V. The envelope shape is Gaussian with around eight carrier cycles with centre frequency of around 4GHz. The 50% envelope width is around 0.7nS.

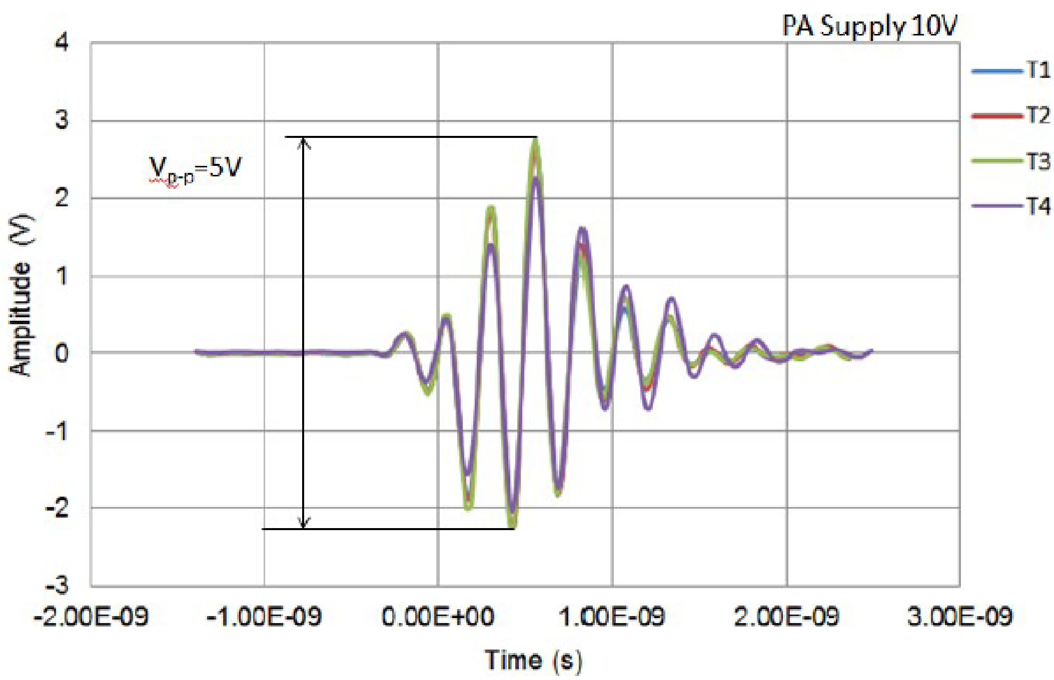

Figure 4: Overlaid pulse shape of four 30dBm beacon transmitters in time domain

The developed sensor with 23dBm ultra wideband impulse radio beacon transmitter and receiver is shown in Figure 5. Circular polarized antenna is integrated in both the transmitter and receiver. A three stage band-pass filter is employed at the receiver to reject interferences especially wireless local area network around the 2.4GHz and 5.2GHz bands. Signal conditioning circuit is included in the receiver to lengthen the received pulse width so that it can be recognized by the Texas Instrument MSP430F2616 microcontroller.

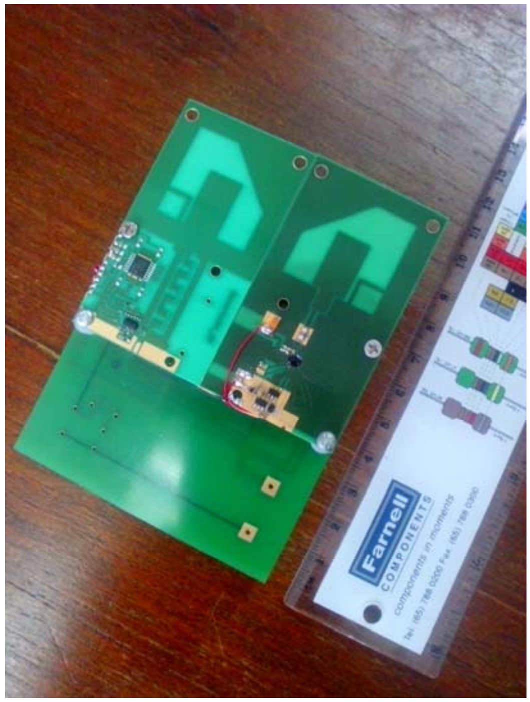

Figure 5: Battery powered Sensor with ultra wideband impulse radio transmitter and receiver

(ii) An ultra wideband impulse radio receiver array with four receiving channels and sampling receivers for measuring time of flight with sub-nanosecond time resolution. The receiver array is connected and powered from the USB port of a notebook computer. The digitized signals from the four channel receiver are processed using MATLAB running in the notebook computer. MATLAB codes are developed for identifying the transmitter ID and computing the position of the mobile user using time difference of arrival.

Each receiver channel consists of a RF front-end board consisting of amplifiers to amplify the ultra wideband impulse radio (UWB-IR) signal followed by a non-coherent detector to detect the envelope of the UWB-IR signal. This is followed by a baseband amplifier with variable gain control. The RF front-end board can be directly integrated with the locator box as shown in Figure 6 or connected to the locator box through UTP cable as shown in Figure 7. In the locator box, each receiver channel has a baseband amplifier with variable gain control followed by an 8 bit ADC. The digitized signal from the 4 channels ADCs are fed to a Cypress USB client chip through FIFOs. The sampling clock of the 4 ADCs is from a frequency synthesizer whose frequency and phase is controlled from the USB client chip. The gain control of the baseband amplifiers is also from the USB client chip. Analog Devices firmware loaded into the Cypress USB client chip is used as application programming interface with MATLAB running on the notebook computer. MATLAB codes are written to control the gain, frequency synthesizer settings and ADC captured data length. The receiver sensitivity for each receiver channel is around -65dBm. Using repetitive signals and equivalent time sampling, sub-nanosecond time resolution is obtained from the measurements with the sampling clock set in the MHz range.

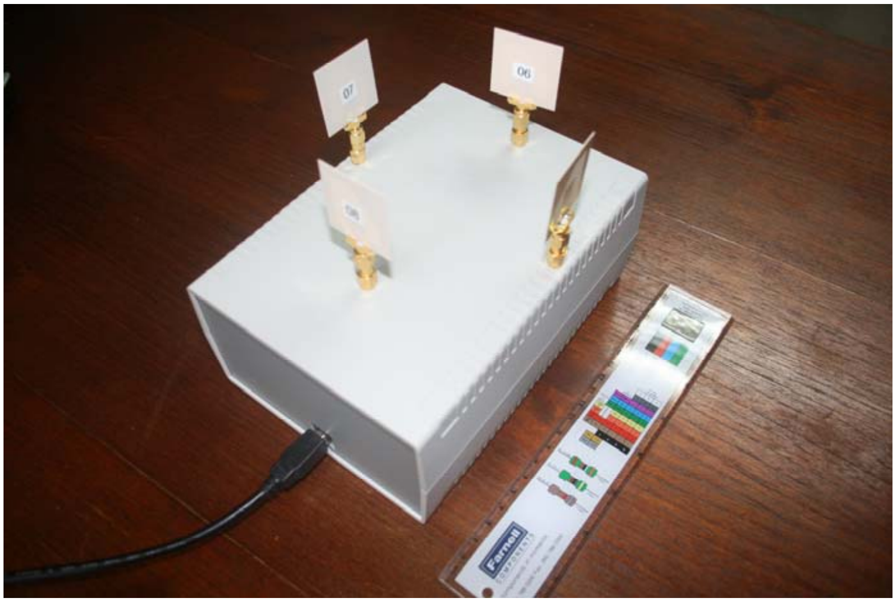

Figure 6: Locator box with 4 channels integrated receiver front end

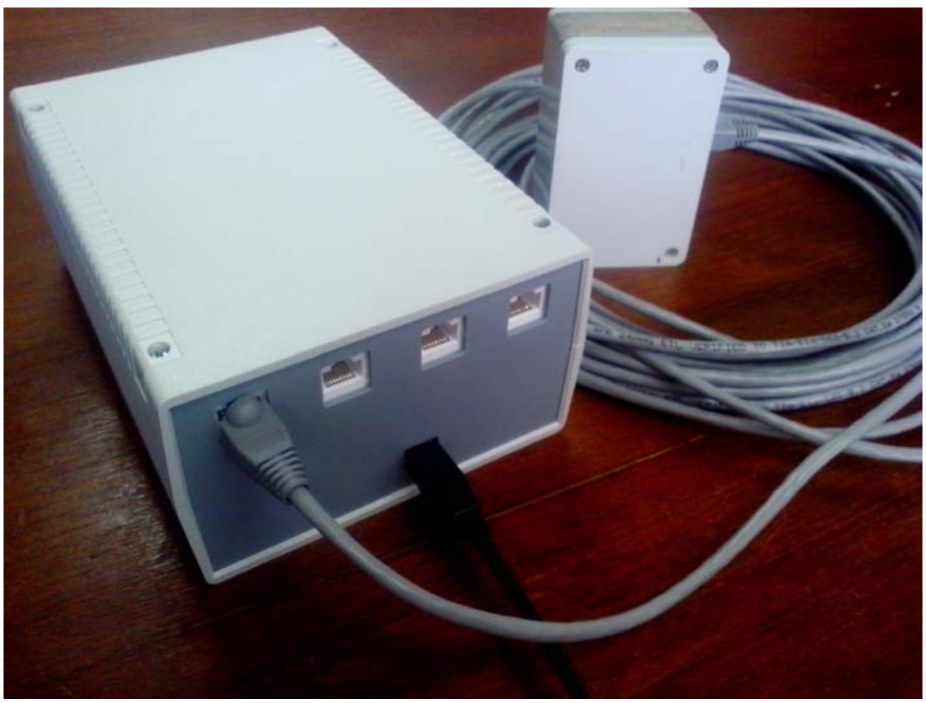

Figure 7: Locator box with UTP connected receiver front-end

The above development tap on our research group published works in [1], [2], [3]

[1]: J. Xia, C.L. Law, Y. Zhou and K.S Koh, “3-5 GHz UWB impulse radio transmitter and receiver MMIC optimized for long range precision wireless sensor networks”, IEEE Transactions on Microwave Theory and Techniques, Vol. 58, No. 12, Dec 2010, pp 4040-4051

[2]: Y.Z. Shen and C. L. Law, “Compact UWB band-pass filter with high suppression at 2.4 and 5.8 GHz”, IET Electronics Letters, Vol 48 (14), pp 851-853, June 2012

[3]: Y.Z. Shen and C. L. Law, “A Low-Cost UWB-RFID System Utilizing Compact Circularly Polarized Chip-less Tags”, IEEE Antennas and Wireless Propagation Letters, Accepted for publication, Oct 2012

3: Results and Discussion: Describe significant experimental and/or theoretical research advances or findings and their significance to the field and what work may be performed in the future as a follow on project. Fellow researchers will be interested to know what impact this research has on your particular field of science.

The apparatus developed in section 2 above are used to test out various issues associated with the use scenario shown in Figure 1. One of which is the ability to determine range between sensor nodes and accuracy of range in line of sight (LOS). As illustrated in Figure 1, the location of the mobile user is determined from beacon transmitters in the sensor nodes with known location. With ad hoc planting of sensor nodes, there is a need for solutions which can determine the sensor nodes location in an ad hoc manner. Our proposed solution is to use peer to peer transmissions between the sensor nodes to determine their relative ranges and then apply positioning algorithm to determine their positions using these ranges. For example, when the beacon transmitter in Sensor_1 is transmitting, the received time of arrival of the beacon_1 signal can be recorded in all the sensors which are assumed to be driven by a common sampling clock frequency. The beacon transmitter transmits one UWB-IR pulse in each sampling clock period and the delay from the sampling clock edge of receiver in Sensor_1 with respect to the sampling clock edge of receiver in Sensor_i is Td1i and assumed to be constant in subsequent pulses. Each beacon transmitter take turns to transmit a frame of data consisting of repetitive ranging pulses followed by the identity of the beacon. The repetitive ranging pulses are used to facilitate sub-sampling to achieve sub-nanosecond time resolution using MHz sampling rate. The range D_{1i} between Sensor_1 and Sensor_i can be computed from the differences in measured time of arrival at the sensors as:

$$D_{1i} = c\,[(TOA_{1i} - TOA_{11}) + (TOA_{i1} - TOA_{ii})]/2 \qquad (1)$$

Where c is the velocity of light and TOA_{1i} is the measured time of arrival at Sensor_i with beacon_1

An experiment using the locator box shown in Figure 7 is setup to mimic 4 sensors which are represented by 4 receivers placed at the following ranges between them in centimeters: D_{12} = 311 ; D_{13} = 264 ; D_{14} = 320 ; D_{23} = 508 ; D_{24} = 234 ; D_{34} = 386. A beacon transmitter is placed at one of the receiver location at a time with LOS to all the receivers and the corresponding time of arrival at the receivers is measured. The range between receivers is computed using equation (1). The sampling clock frequency of the 4 receivers is from the same frequency source and the time delay between sampling clock edge of Receiver_1 compared with Receiver_i is dependent on the UTP cable length difference connected between the receiver front end board and the locator box. The results of 601 range measurements are shown in Figure 8 for (TOA_{12}-TOA_{11}). UTP CAT 5E cables of 3 meters and 10 meters are connected to Receiver_1 and Receiver_2 respectively. The permittivity (ε_r) of the UTP cable is 2.3 and at D_{12} = 311 cm, (TOA_{12}-TOA_{11}) = [D_{12} + (10-3)Sqrt(ε_r)]/c = 45.75nS. The results in Figure 8 shows that the UWB-IR system measured mean value of (TOA_{12}-TOA_{11}) is around 41.9nS which is around 3.85nS short of the actual separation. The error spread is around 2nS which corresponds to around 60cm. Figure 9 shows the corresponding results of (TOA_{21}-TOA_{22}) = [D_{12} + (3-10)Sqrt(ε_r)]/c = -25.02nS. The results in Figure 9 shows that the UWB-IR system measured mean value of (TOA_{21}-TOA_{22}) is around -21.2nS which is around 3.8nS long of the actual separation. The error spread is around 1.5nS which corresponds to around 45cm. The bias in the measured length is likely to be due to the incorrect estimation of the UTP cable length difference hence resulting in the bias being of opposite sign for (TOA_{12}-TOA_{11}) and (TOA_{21}-TOA_{22}). They will cancel out in the evaluation of D_{12} as shown in equation (1). Figure 10 shows the UWB-IR system measured D_{12} which has a mean value of 309 cm which is 2cm short of the actual 311cm. This difference is within the accuracy of measuring the physical distance between Receiver_1 and Receiver_2 as there are uncertainties in the phase centre of the receiving antennas and the transmitting antenna. The standard deviation of the range error spread is around 6cm. Further measurements with the system for the other sensor ranges yield the following results: D13=300cm with standard deviation of 7cm, D23=546cm with standard deviation of 9cm, D14=359cm with standard deviation of 22cm, D24=255cm with standard deviation of 11cm and D34=417cm with standard deviation of 11cm.

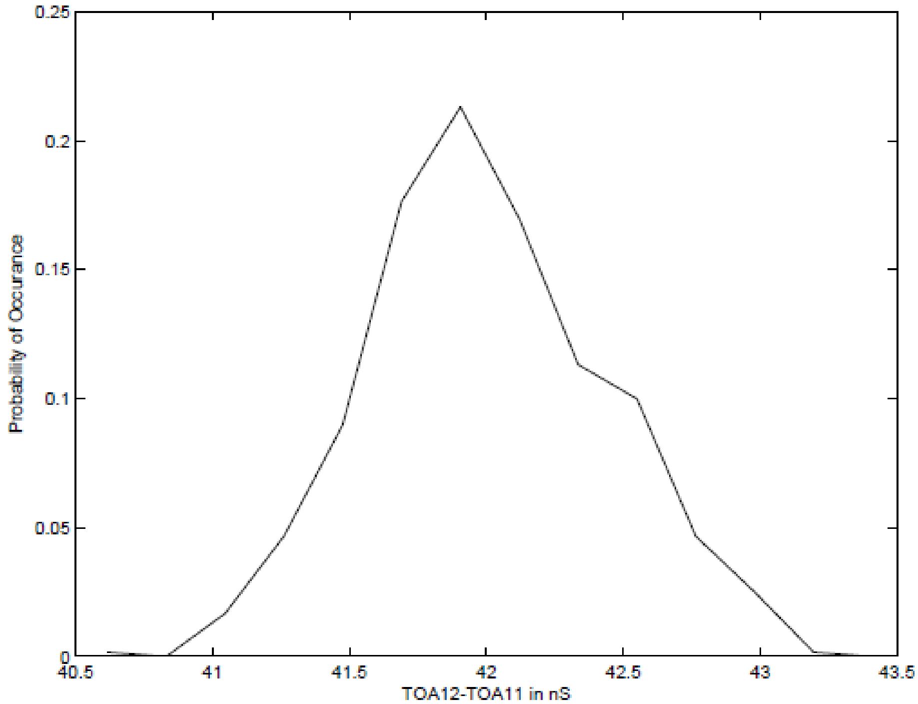

Figure 8: Probability Distribution Function of system measured (TOA_{12}-TOA_{11})

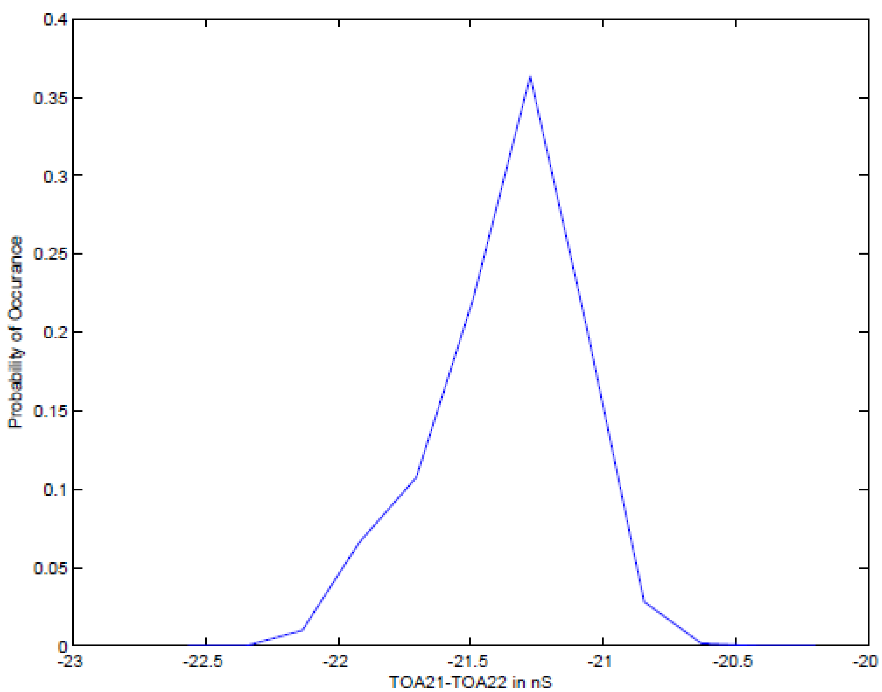

Figure 9: Probability Distribution Function of system measured (TOA_{21}-TOA_{22})

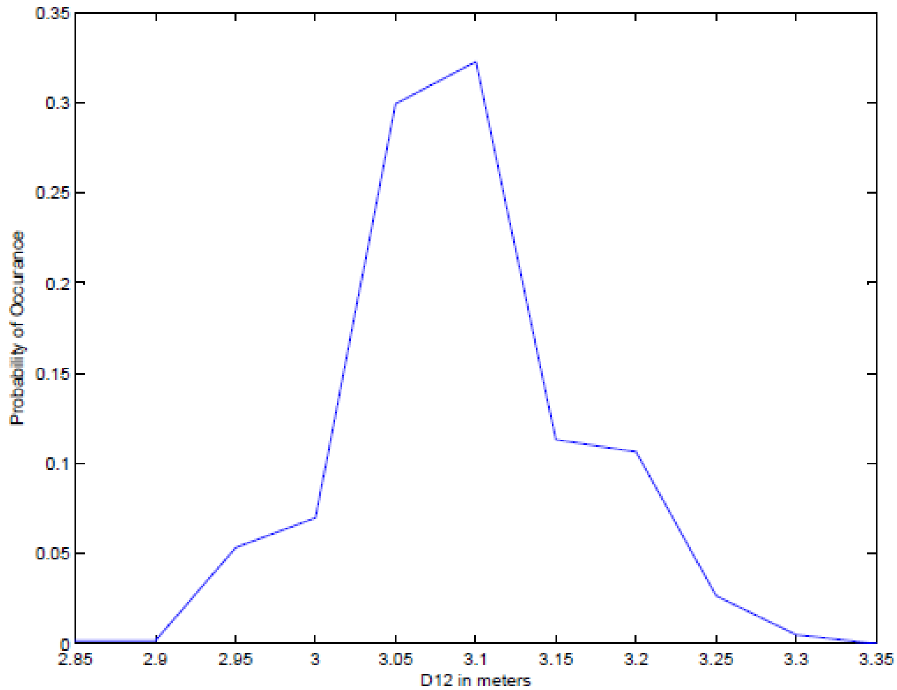

Figure 10: Probability Distribution Function of system measured D_{12}

Future work involves the following:

(i) Synchronizing the clock frequencies of the sensors shown in Figure 5 to a common clock frequency using signal of opportunity which may be another UWB-IR signal or wider coverage signals such as digital TV or radio transmissions,
(ii) Signal processing to overcome closely spaced multipath signals, and
(iii) Multi-sensors range data fusion algorithm for improving user positioning accuracy and reliability

List of Publications and Significant Collaborations that resulted from your AOARD supported project: Nil

DD882: See attached document.