UWB Ranging Accuracy

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***Abstract*—The accuracy of ranging of commercially available ultra–wide–band radio module was evaluated. Such modules are capable of very precise measurements of Time of Arrival of RF signal and consequently very precise range measurements or localizations. We measured and compared the distances with the reference distance using one of these commercial modules. The results were very promising for indoor localization because the modules achieved ranging accuracy below 10 cm.**

Keywords*—*UWB Ranging, IEEE 802.15.4-2011, WSN

I. Introduction

Localization is a crucial mechanism for obtaining the locations of data sources within wireless sensor networks (WSN). WSN consists of small so-called sensors equipped with environmental sensing devices, power sources, radio and processor units. Sensors can communicate with each other or with the base–station. In many cases the sensors are randomly deployed within fields where the locations information does not exist in advance. Some localization systems must be performed on sensors' fields for locating each sensor.

Two physical values are primarily measured, separately or in combination, when positioning RF equipped sensor nodes: (i) time of RF signal flight (ToF) and (ii) the power of the received RF signal. The distances or angles between the nodes are then calculated (via trilateration or triangulation) from these primary values for determining the locations of each node. Nodes within a wireless network are usually equipped with IEEE 802.15.4a radio modules. IEEE 802.15.4a provides low cost and low energy consumption modules. The standard uses direct sequence spread spectrum (DSSS) techniques working in the 868/915 and 2450 MHz bands with 5 MHz bandwidths for each channel. Physical layers specify the Received Signal Strength Indicator (RSSI) which is used in localization techniques. The range or angle between nodes can be calculated from RSSI. RSSI measurements are disturbed by the reflection of signals from obstacles between transmitters and therefore positioning error is significant, especially inside buildings [4]. To achieve better positioning accuracy IEEE 802.15.4a-2007 specifies additional PHYs using impulse radio (IR) ultra-wideband (UWB). UWB enables sub-meter accuracy in buildings because of using 500 and more MHz bandwidth. The recent developments in UWB enable the producing of low cost chips equipped with UWB which are capable of measuring very accurate distances.

In this paper we evaluated low cost UWB modules. DW1000 modules from Decawave [7] enable very accurate Time of Arrival measurements of RF signal. The rest of the paper is organized as follow: Section II is a short summary of IEEE 802.15.4 standards, Section III describes the used hardware, Section IV the results and last section the conclusion.

II. IEEE 802.15xx Wireless Personal Area Network Standard

IEEE 802.15 is a working group of the IEEE standards committee which specifies the Wireless Personal Area Network (WPAN) standard. This standard includes 7 task groups: IEEE 802.15.1 – WPAN/Bluetooth, IEEE 802.15.2 – Coexistence, IEEE 802.15.3 – high rate WPAN, IEEE 802.15.4 – low rate WPAN, IEEE 802.15.5 – mesh networking, IEEE 802.15.6 – Body Area Networks and IEEE 802.15.7 – visible light communication. The IEEE 802.15.4 is the most widespread and used in applications in respect to the all task groups. This task includes Wireless Sensor Networks (WSNs) and ZigBee. Locating or positioning of nodes is a very important task within WSN. IEEE 802.15.4 includes 7 amendments from **a** to **g** for this purpose. We will discus from these amendments about IEEE 802.15.4a and IEEE 802.15.4f because they deal with localization in WSNs[6].

A. IEEE 802.15.4.a

IEEE 802.15.4a (formally called IEEE 802.15.4a-2007) is an amendment to IEEE 802.15.4 specifying additional physical layers (PHYs) to the original standard. The principal interest was in providing higher precision ranging and location capability (1 meter accuracy and better). The original 2003 version physical layer in IEEE 802.15.4 specifies two physical layers based on direct sequence spread spectrum (DSSS) techniques: one working in the 868/915 MHz bands with transfer rates of 20 and 40 kbit/s, and one in the 2450 MHz band with a rate of 250 kbit/s. IEEE 802.15.4a-2007 specifies two additional PHYs using impulse radio (IR) ultra-wideband (UWB) and chirp spread spectrum (CSS). The UWB PHY designates to frequencies within three ranges: below 1 GHz, between 3 and 5 GHz, and between 6 and 10 GHz. The CSS PHY designates to the 2450 MHz ISM band. There is an optional ranging capability or the IR-UWB option where the CSS signals can only be used for data communication [1]. The bandwidth of UWB must be 20 % of the carrier frequency or at least 500 MHz. In IEEE 802.15.4a a device with ranging capability is called RDEV and RFRAME is the ranging frame. The RFRAME is indicated by setting a ranging bit in the PHY header of the IEEE.802.15.4a packet. A range between two RDEVs is determined typically via two-way exchange of an RFRAME and tracking its arrival time [2], [3]. The based method is called two-way ranging (TWR). Fig. 1 shows the scheme of two-way ranging protocol. The transmitter observes a round trip time $T_{RT} = T_{RR} - T_{SB}$ and a turn

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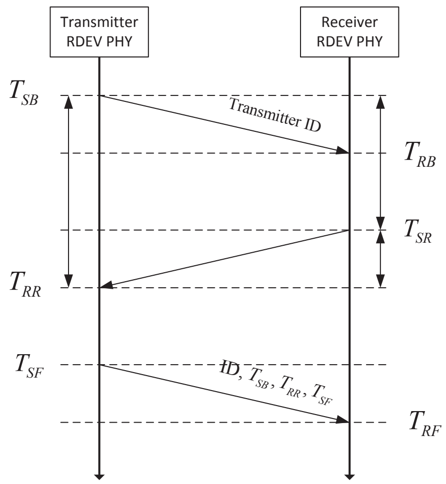

Figure 1. TW-Ranging Method

around time $T_{TA} = T_{SF} - T_{RR}$, where T_{SB}, T_{RR} and T_{SF} are the transmitter send-time, receive-time and future send - time, respectively. The receiver observes a round trip time $R_{RT} = T_{RF}T_{SR}$ and a turn around time $F_{TA} = T_{SR}T_{RB}$, where T_{RB}, T_{SR} and T_{RF} are the receiver receive-time, send-time and future receive-time, respectively. The value of the transmission time T is computed at both transmitter (Tt) and receiver (T_r).

$$2T_t = (T_{RR} - T_{SB}) - (T_{SR} - T_{RB}) \tag{1}$$

$$2T_r = (T_{RF} - T_{SR}) - (T_{SF} - T_{RR}) \tag{2}$$

The receiver or transmitter then average these two round trip times to remove the effects of clock differences [3].

$$T = \frac{T_t + T_r}{2} \tag{3}$$

The distance between transmitters is then:

$$d = T \cdot c \tag{4}$$

where c is the speed of light.

In 2011, the 'a' amendment was incorporated within the main body of the standard and was denoted as IEEE802.15.4-2011.

B. The IEEE 802.15.4–2011 UWB physical layer

The general structure of the UWB frame begins with a synchronisation header consisting of the preamble and the SFD (start of frame delimiter), after which the PHY header (PHR) defines the length (and data rate) of the data payload part of the frame. Fig. 2 show the general structure of the UWB frame. The synchronisation header is made up of single pulses. One symbol is divided into approximately 500 time intervals in which a negative or positive pulse may be sent, or no pulse. The frequency of the interval is 499,2 MHz which is the fundamental frequency within UWB. The sequence of pulses sent during the symbol interval is determined by a preamble code. The preamble length is defined by how many times the sequence (symbols) are repeated. Longer

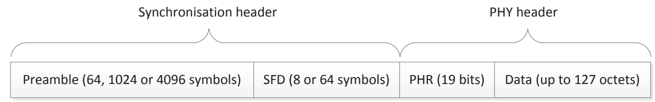

Figure 2. UWB – frame [8]

preambles make it easier for the receiver to lock on to the message, thus improving the channel matching and the first path determination. The preamble sequence has a property of perfect periodic autocorrelation which allows a receiver to determine the exact impulse response of the RF channel between transmitter and receiver. This allows the receiver to make use of the received energy from the multiple paths. The receiver can also resolve the channel in detail and determine the arrival time of the direct (shortest) path, even when it is attenuated. This brings precision of ranging with the UWB modules. The SFD marks the end of the preamble and the precise start of the switch into the BPM/BPSK modulation of the PHR. The time-stamping of this event is very deterministic in terms of symbol times and it is this in conjunction, with determining the first arriving ray within that symbol time, that allows the accurate time-stamping needed for precision ranging [8].

III. Hardware

The Decawave evaluation kit (EVK1000) consists of two transmitter boards. These boards are equipped with DW1000 IEEE802.15.4-2011 UWB compliant IC and a Cortex M4 microcontroller. On the developer's page PC software is available for the configuration of the DW1000 and range measurement between two transmitters. Real time location system software is also available. Boards also has dip switches for manual configuration of the boards. Each board can act as an anchor or tag. The anchor usually has a fixed location, whilst tag is a mobile node. DW1000 is configurable via SPI. The eser can define many parameters such as: channel number, data–rate, preamble length, pulse repetition frequency (PRF), etc. In order to evaluate the ranging using DW1000, we set different parameters within different experiments. The parameter settings are shown in Table I. The module enables 7 different channels at different carrier frequencies (from 3,5 to 6,5 GHz) and bandwidths (from 500 to 900 MHz), data rate from 110 kbps to 6,81 Mbps, RPF from 16 MHz to 64 MHz and preamble lengths from 64 to 4096 bit. Two–way ranging protocol is implemented within the module as we discussed in section II-A. As the module measures sub–nanoseconds it is important to compensate delays introduced by PCB, external components, antenna and internal DW1000 delays [8]. The best way to calibrate modules is to measure a distance at a known distance and adjust the measurements with offset. In such a way we can calibrate measurements, as shown in the next chapter.

A. Channel response and first path determination

Asmultipath effects cause delayed paths from the transmitter to the receiver, DW1000 must determine direct path. All the delayed paths cause inaccuracies of time measurements (as is discussed in II-B). Fig. 3 shows channel response of LOS (Line–Of–Sight) real environment taken by DW1000 module.

TABLE I. OPERATIONAL MODES

Mode	Channel [GHz]	Data Rate [bps]	Bandwidth [MHz]	Preamble [bit]	PRF [MHz]
1	4,0	110 k	500	1024 bit	64
2	4,0	6,8 M	500	128 bit	64
3	6,5	110 k	500	1024 bit	16
4	6,5	6,8 M	500	128 bit	16
5	6,5	110 k	900	1024 bit	64
6	6,5	6,8 M	900	128 bit	64

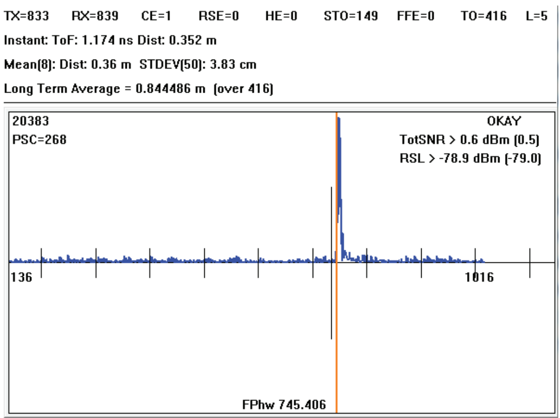

Figure 3. First path determination in LOS

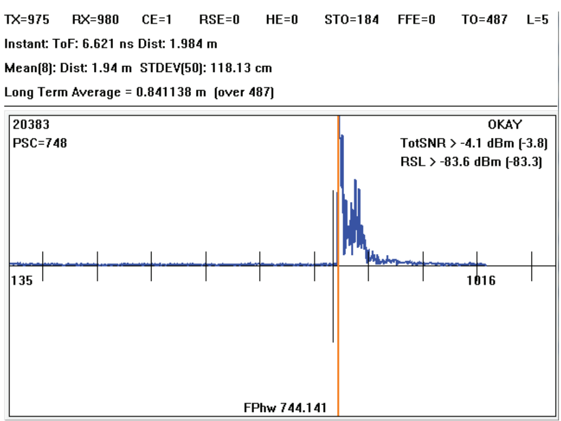

Figure 4. First path determination in NLOS

The orange vertical line shows the detection of direct path. The response from Fig. 4 is taken indoors in NLOS (Non–Line–Of–Sight) condition. It can be observe that there are many paths after the first path denoted as an orange vertical line. These are delayed paths and are unconsidered regarding time of arrival estimation. In Figs. 3 and 4, the PSC number indicates the number accumulated of preamble symbols . The numbers below the mid line are the accumulator index (nanosecond) values, whilst the FPhw value beside the orange line is the DW1000 IC reported leading path (sub-nanosecond) position [9].

IV. EXPERIMENTAL RESULTS

The experiment were carried–out outdoors and indoors. Transceivers were placed on a 1 m high tripod. Between

Figure 5. Experimental set-up

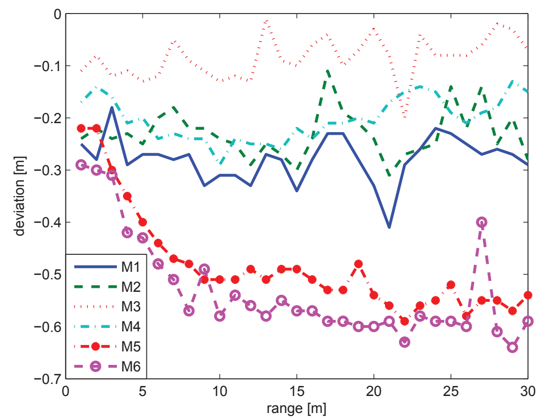

Figure 6. Outdoor distance measurements with non-calibrated module

transceivers were LOS. Measurements were taken at known distances from 1 to 30 m. Fig. 5 shows two transceivers mounted on a tripod. Measurements were taken at different operational modes of the module as in Table I. Figs. 6 and 7 show the distance measurements between transceivers and deviations from the pre–set distance. Fig. 6 shows the non-calibrated module, which means the antenna delay was set improperly and because of that the deviation was larger. In [8] it is explained how to compensate delays caused by antenna, PCB, etc. Fig. 7 shows the well–compensated delays in comparison with previous case. Denotations M1–M6 represent different types of operational modes.

Besides the outdoor experiments we also took indoor experiments. The indoor environments are much more difficult in the manner of determining the correct positions because of the many obstacles from which the signal can reflect. Indoor experiments were taken in an underground garage with steel armoured walls. Figs. 8 and 9 show the distance deviations taken using both calibrated and non-calibrated modules, respectively. We can observe that the deviations are slightly the same as within the outdoor measurements. This means DW1000 has a good mechanism for first path determination. Table II shows the root–square–errors for all the sets of measurements. The results were improved after calibration of the antenna delay. Calibration had a large influence, especially on the outdoor measurements, as it can be observed from Table II.

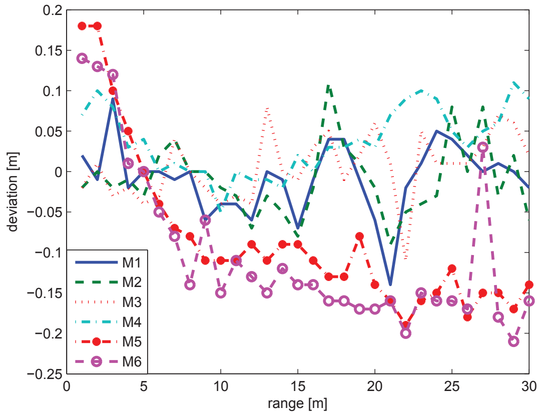

Figure 7. Outdoor distance measurements with calibrated module

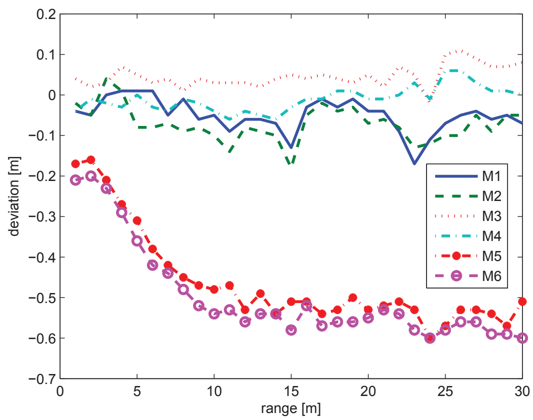

Figure 8. Indoor distance measurements with non-calibrated module

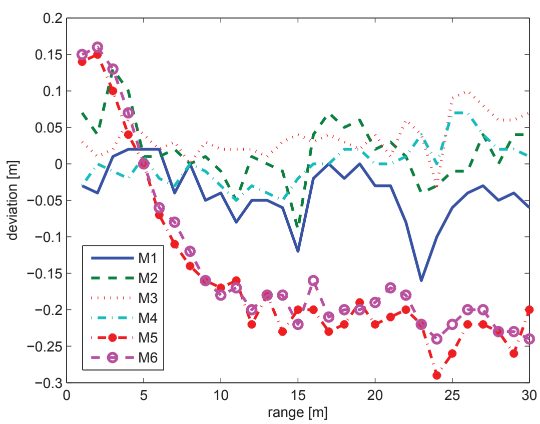

Figure 9. Indoor distance measurements with calibrated module

Experiment's results show us that the modules are capable of precise measurements of distances regardless of indoor/outdoor environments. In both indoor and outdoor environments the range measurements were inside of 10 cm in line of sight. Modes from 1–4 returned almost the same precise results under 6 cm on average. Modes 5 and 6 where channel bandwidth was set at 900 MHz (see Table II) there accuracies of the measurements were higher but did not exceed 20 cm. These two modes have not been considered in user manuals yet. Maybe there needs to be some additional setting of the module. However 900 MHz modes are promising especially in non line of sight because of higher bandwidth and consequently lower impact of reflected signals.

TABLE II. RMS ERRORS OF DIFFERENT OPERATIONAL MODES

Mode	Outdoor non–calibrated [m]	Outdoor calibrated [m]	Indoor non–calibrated [m]	Indoor calibrated [m]
1	0.2819	0.0434	0.0644	0.0570
2	0.2347	0.0464	0.0838	0.0471
3	0.0937	0.0405	0.0534	0.0450
4	0.2064	0.0555	0.0315	0.0297
5	0.4941	0.1271	0.4773	0.1925
6	0.5404	0.1403	0.5112	0.1807

V. CONCLUSION

In this paper we evaluated one of the first commercially available low cost radio modules which is capable of measuring the Time of Arrival using UWB. The DW1000 radio chip is designed for ranging and localization besides communications. We measured the range with EVK1000 evaluation kits within different environments, outdoor and indoor and compared the obtained ranges with the true ranges. As we have shown during the paper the modules are very precise and can measure distances below 10 cm. In LOS there was practically no different between indoor or outdoor environment. We can conclude that the DW1000 UWB radio modules are very useful for indoor localizations and have significant potential for those kinds of applications.

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