Ultra-wideband Technology-based Ranging Platform with Real-time Signal Processing

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Abstract—The ultra-wideband (UWB) technology is recognized as an ideal candidate to provide accurate localization in challenging indoor environments where other technologies, e.g., WiFi or ZigBee cannot yield good accuracy due to their signal bandwidth limitation. The energy detection receiver is currently one of the most promising low complexity non-coherent architectures that neither requires high sampling rates nor information about the channel. Despite a vast body of research on UWB ranging and localization, relatively little knowledge is available regarding practical implementations of the proposed ideas. Although there are some testbeds already proposed and built, most of them imply a sort of correlation and require very high sampling rates (in the order of several GS/s) which are still difficult to realize in hardware. Moreover, the majority of the platforms does not support visualization of results in real-time. In this paper, a UWB-based ranging platform with real-time signal processing is presented. It is based on the time-of-arrival (ToA) technique and relatively simple to implement non-coherent energy detection (ED) receiver architecture. Our first measurement results indicate that it is possible to achieve ranging accuracy of 1-3 cm with the sampling rate of 1 GS/s and with max. 3 bits of the A/D resolution.

Index Terms—Ultra-wideband, ranging platform, energy detection receiver

I. INTRODUCTION

Ultra-wideband Impulse Radio (UWB-IR) has several unique characteristics that make it a promising candidate for future wireless localization. The large absolute bandwidth, in US from 3.1 to 10.6 GHz [1] and in Europe from 6 to 8.5 GHz [2], corresponds to a very fine time resolution in the order of hundreds of picoseconds which translates to spatial resolution in the order of centimeters. The very fine time resolution allows a direct path to be easily distinguished from the reflected paths. This is of paramount importance in indoor environments where other localization systems suffer from the multipath phenomenon. The presence of low frequency components in the UWB signal spectrum enables penetration of the UWB signals through the walls. UWB devices are permitted to transmit very weak signals [1], [2] so that other systems sharing the same spectrum, including for instance IEEE 802.11a WLANs, are protected. Low interference, possibility of high device density and low probability of detection and interception (LPD/I) are these characteristics of the UWB technology that are of particular importance for military applications. Furthermore, the UWB technology promises prospects for long-life battery operation and low cost thanks to simple transceiver implementations.

However, the same properties provide design challenges, such as scalability, synchronization and power control. Portable devices impose strict requirements on the size and shape of the antenna which has to radiate effectively in a wide frequency band and under varying propagation conditions sometimes including near-field, e.g., when carried on the human body or close objects. To ensure a further development of the UWB technology and a wide presence of its products on the commercial market of tomorrow, these challenges must be properly addressed and resolved.

Despite a vast body of research results on UWB ranging and localization available, knowledge about practical implementations of the proposed ideas is limited [3]-[7]. Moreover, most of the implementations [5], [6], [7] are down-scaled versions of real systems with respect to the operating frequency or, due to the inherent correlation, require very high sampling rates which obviously are not realistic in practical applications. Furthermore, some of the platforms require off-line data processing [6], [7].

In this paper, a UWB technology-based ranging platform with real-time signal processing is presented. It is based on the ToA method and energy detection receiver architecture. The ranging platform consists of a signal generator, UWB pulse generator, sampling oscilloscope, phase-locked loop (PLL) evaluation board, and UWB antennas. All signal processing done by the receiver is performed by a software application written in Visual Basic and operating in real-time on the oscilloscope. Our first measurement results indicate that it is possible to achieve accuracy of 1-3 cm with the sampling rate of 1 GS/s and with max. 3 bits of the analog-to-digital (A/D) resolution.

The presented platform enables real-time experiments with different algorithms and hardware components and may serve as a proof of concept for the chosen approach in the UWB technology development. Moreover, it allows for verification of the ranging system performance and provides insights into the technology limits and the effects of bandwidth and system parameters.

This paper is organized as follows. Section II presents the theoretical limits on the performance of time-based systems and in particular the ToA-based solutions. Section III fo-
cuses on the architecture of the considered ranging platform and its components. Section IV provides results of the first measurements with a discussion. Finally, Section V presents conclusions.

II. THEORETICAL LIMITS ON THE PERFORMANCE

As in communication systems, also in localization systems the larger the signal bandwidth, the higher the potential for a better performance. The mathematical relationship for a given signal bandwidth, between the signal-to-noise ratio (SNR) and the ranging performance expressed in variance of the estimate for the range is given by the Cramer-Rao bound (CRB) and for time-based localization systems operating on additive white Gaussian channels is [8]

$$\sigma_r^2 \geq \frac{c^2}{4\pi^2 f^2 B^2 SNR} \left(1 + \frac{1}{SNR}\right), \quad (1)$$

where $\sigma_r^2$ is the variance of the range estimate, $B$ is the signal bandwidth and $c$ is the speed of light.

The CRB indicates that for a given signal bandwidth and SNR, the ranging performance cannot be better than a certain value. Fig. 1 shows the CRB for localization systems of different signal bandwidth. As can be seen from this figure, the larger the signal bandwidth, the better distance estimation can be achieved. In Europe, for UWB systems, there is a 2.5 GHz bandwidth available with the emission level limit of -41.3 dBm/MHz. According to theory, this allows for very fine ranging. However, in a real localization system the actual performance will be worse due to numerous factors related to hardware implementation, i.e. oscillator frequency drifts, jitter, sampling artifacts, interference and channel effects, i.e. multipath propagation and fading.

III. RANGING PLATFORM ARCHITECTURE

The considered UWB ranging platform consists of a transmitter, a receiver, and a trigger unit. As a transmitter, a Picosecond 3500D Pulse generator is used. It is able to produce an ultra short pulse of a full width of 65 ps at half the maximum (fwhm) and of an amplitude of 8 V. This pulse is transmitted at the 0.5 MHz repetition rate. The -10 dB bandwidth of the signal after antennas is equal to 7.10 GHz with the cut-off frequencies being equal to 1.91 GHz and 9.01 GHz. The trigger unit that provides the time synchronization signal between the transmitter and the receiver, consists of a Tektronix AWG 7122B Arbitrary Waveform Generator and an Analog Devices AD9516 PLL evaluation board that adjusts the trigger signal in frequency and amplitude as required by the Picosecond generator and the oscilloscope. As a receiver, a LeCroy WE100H sampling oscilloscope with a 30 GHz analog bandwidth is used. The high level block diagram of the platform is shown in Fig. 2. The unknown distance between the two UWB SMT-3TO10M-A SkyCross antennas operating in the 3-10 GHz band is determined by means of the ToA method based on measuring the propagation time. The two UWB antennas are mounted on a rail guide allowing for distance change and are connected to the measurement equipment via high quality Sucoflex 104PE cables. These cables have the $S_{21}$ parameter for frequencies < 12 GHz being better than -1.1 dB and -1.7 dB for 1m and 1.5 m cable length, respectively. Fig. 3 shows the measurement setup. The distance measurement
uncertainty due to the measurement setup is lower than 0.5 mm. The line-of-sight scenario is considered.

All signal processing operations at the receiver side, i.e., signal squaring, integration, and A/D conversion, threshold selection, and distance calculation are performed by a Visual Basic application operating in real-time on the sampling oscilloscope. Fig. 4 shows the signal processing operations performed by the considered ED receiver. Compared to the traditional ED receiver architecture where sampling is performed in the middle of the integration windows which are separated by the sampling interval $\Delta t = t_s$ as shown in Fig. 5, it is proposed to shift the integration windows by small time $\Delta t_p$. When a variable and controllable integration window is provided and the integration window is controlled in a time-successive way – so that the sampling points of successive integration windows are changed by a time delay from a current integration window to a later integration window smaller than half of the integration window – a higher time resolution with low sampling rate can be achieved. Fig. 6 shows the proposed method. It requires $N$ signal acquisitions and hence $N$ repetitions of the UWB signal. The element responsible for shifts of the integration window is the time delay unit. In a practical implementation, a programmable delay line and a power detector may be used as a time delay unit and signal squaring device, respectively. The integration operation may be performed by a simple integrator or the input stage of an ADC.

Visual Basic support is one of the custom features of LeCroy oscilloscopes that allows to create and deploy a measurement or algorithm directly on the oscilloscope in real-time. The logical structure of the developed software application of the ranging platform is shown in Fig. 7. To give a user the possibility to control the platform parameters including the integration window size which is reciprocal to the sampling rate, resolution of the ADC given in number of bits, number of acquisitions, real and calibration distance, and visualization mode, a graphical user interface (GUI) shown in Fig. 8 has been developed and implemented. One of the important features that has been realized, is the calibration procedure during which cable propagation offsets are being determined provided the calibration distance is known. The estimated distance together with the error are shown in real-time on the implemented GUI. After selecting input parameters, the
calibration procedure may be started by pressing the button 'Calibrate'. Next, the user has to select the visualization mode: with or without integration and threshold and also choose the type of integration: with or without shifting. The options are confirmed by pressing the button 'Select'. The last operation is calculation of the distance which is started by pressing of the 'Calculate distance' button. The estimated distance and the ranging error are shown on the GUI in real-time. The option to automatically save the results (MAE and standard deviation of the absolute error) into a text file is also provided.

An optimal estimate of ToA may be performed by means of a conventional matched filter / correlation receiver [9]. However, the knowledge of the received pulse that is required for this type of receiver may not be available in practice. Moreover, the waveform distortion induced by the near-field coupling between antenna and the propagation environment poses challenges on the accurate waveform representation in the receiver. Another key disadvantage of the matched filter receiver is that it requires Nyquist or higher rate sampling and, as a result, is not feasible for low cost UWB devices.

A low complexity alternative to the matched filter receiver is the energy detection receiver [10]. It does not require any a-priori knowledge neither about the received pulse shape nor about the channel and yet, as it will be shown, can achieve good results with lower sampling rates. The output samples of the energy detector after integration without the proposed integration window shifting method can be expressed as

\[ z[n] = \int_{(n-1)T_s}^{nT_s} |r(t)|^2 dt, \] (2)

where \( r(t) \) is the received signal, \( T_s \) is the integration interval with the sampling rate being \( 1/T_s \). The received samples after A/D conversion with 3 bits of resolution are compared with the energy threshold. In our ranging platform, the threshold is based on the energy of the samples as follows

\[ \xi = \xi_{\text{norm}} \left( \max\{z[n]\} - \min\{z[n]\} \right) + \min\{z[n]\}, \] (3)

where \( \xi_{\text{norm}} \) denotes the normalized threshold and, based on [11], it is set to 0.8. The first energy sample that exceeds the threshold determines the measured time-of-arrival, which is assumed to be in the middle of the integration interval. The ToA determines the distance estimate. The samples are further averaged to improve the ranging accuracy.

IV. MEASUREMENT RESULTS

The ranging accuracy is quantified by means of the mean absolute error (MAE), which is defined as

\[ \text{MAE} = E\{|\hat{d} - d|\}, \] (4)

where \( \hat{d} \) is the range estimate and \( d \) is the true range.

The accuracy of the ToA estimation depends on many factors that include a clock drift and jitter, A/D conversion, interference and channel effects, and receiver architecture. In the presented platform, max. time jitter of the sampling oscilloscope and AWG equals 0.5 ps and 20 ps, respectively. These jitter values correspond to the maximum ranging error due to the jitter solely of 0.15 and 6 mm. Fig. 9 and 10 show the results by means of MAE and standard deviation of the absolute error, respectively. The results correspond to a line-of-sight scenario with distance ranging from 1 to 95 cm and 20 ranging values per given distance point used for averages. As can be observed, the MAE and its standard deviation are functions of distance and system parameters, i.e. the integration window size and the number of acquisitions. As expected, for low distances, where the SNR is high, the best performance can be achieved for small integration window sizes. Moreover, increasing the number of acquisitions brings additional performance improvement. The minimum value of the MAE is reached at a distance of 20 cm for which the calibration took place. For the integration window size of 1 ns and 20 acquisitions, the minimum time resolution equals to 1 ns/20 acq. = 50 ps, which translates to the distance resolution of 1.5 cm. The periodic 'saw'-like variations of the MAE, related to the 'quantization error'-like effects known from A/D converters along with the standard deviation of the absolute error equal to zero, are a perfect example of the accuracy introduced by the proposed method. At distances larger than 75 cm this effect is not that clearly visible due to the lower SNR. Furthermore, for the integration window size equal to 0.5 ns and 75 acquisitions, this effect is not visible. It is
due to the time resolution equal to 0.5 ns/75 acq. ≈ 6.7 ps, which translates to the distance resolution of 2 mm. For this case, jitter effects and uncertainty in determination of the true distance may become important. As shown in Fig. 10, for 20 acquisitions, the standard deviation of the absolute error is lower than 1.3 cm and for 75 acquisitions, it is lower than 0.7 cm.

V. CONCLUSIONS

In this paper, we have presented a UWB ranging platform with real-time signal processing. The implementation details have also been provided. The ranging platform constitutes a helpful tool to verify and test feasibility of a vast range of theoretical ideas regarding, for instance, receiver architectures, pulse shapes, and threshold setting algorithms. It is also instrumental in assessing the performance of a “close to the hardware” implementation and providing insights into the technology limits and impact of the system parameters. Our first measurement results yielding accuracy in the 1-3 cm range with 1-2 GS/s sampling rate are very encouraging. Future work includes analysis of the impact of interference and practical hardware implementation of parts of the ranging platform.

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