Advent of Practical UWB Localization: (R)Evolution in UWB Antenna Research

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***Abstract*—The UWB antenna research provides design approaches that enable transmission of sub-nanosecond pulses without any distortion. At the same time, advances in communications theory and digital signal processing enable practical ranging systems with precisions below 3 cm with pulse bandwidths of 500 MHz. Thus one could be misled to believe that the UWB antenna research is dead simply because current antenna designs can accommodate bandwidth requirements for years to come. However, this paper points out that with the UWB localization systems entering the stage of mass production, new research challenges associated with the integration of antennas in real systems occur. Using application examples, the paper introduces some of these issues. It also is concludes that antenna designers can substantially contribute towards the precision of UWB localization. To achieve this goal the antennas have to be studied in more complex scenarios and new system-oriented metrics have to be used.**

***Index Terms*—antenna, propagation, measurement.**

I. Introduction

Ultrawideband (UWB) technology has attracted substantial academic and industrial interest for over 20 years. The main driving force of the research interest is the prospect of an enormous bandwidth enabling high-data-rate communication [1], high-resolution microwave imaging [2], high-resolution wireless localization [3].

The initial theoretical works considered transmission of baseband pulses with bandwidths of up to 7 GHz [1]. Therefore, the antenna researchers have developed techniques to design antennas capable to transmit sub-nanosecond pulses almost without any distortion [4]-[7]. To design these antennas, metrics such as fidelity [4]-[7], which quantifies the distortion of the transmitted pulse, have been developed.

However, similar developments have followed at other system levels. Firstly, the extremely wideband baseband pulses were replaced by modulated pulses with a bandwidth of 500 MHz. For instance, practical systems such as ECMA-368, 802.15.4a or 802.15.6 operate with signal bandwidths of 500 MHz, i.e. pulse durations of 2 ns or more [1],[8]. The advantages of the modulated pulses are the lower requirements/costs of A/D conversion, less interference from primary users such as 802.11, and higher network capacity. In contrast, the benefits of UWB such as the ability to resolve individual multipath components and precise ranging remained unchanged. For instance, the Decawave's commercial Scensor chip using the 802.15.4a provides ranging precision below 3 cm using only 500 MHz bandwidth [8]. The operating centre frequency for world-wide deployment will fall into the 6-8.5 GHz band [1]. As a result, the UWB antennas only need to cover a relative bandwidth of less than 10%.

Results like this may easily create the impression that the research into UWB antennas is over simply because current antennas are capable of accommodating pulses with bandwidths far beyond the requirements of practical UWB systems.

However, the objective of this paper is to show that in fact there are numerous exciting challenges ahead, because from an early era of academic research, UWB technology has matured to the stage of industrial standards and commercial products. For instance, mass production of Decawave's Scensor, the first 802.15.4a-based chipsets for precise ranging and localization, has been rolled out in 2013 [9].

For UWB antenna research, this event will be of enormous significance. Not only does it mark the shift from standalone antenna design to an integrated RF design, but the emergence of real-world applications is also expected to trigger a flow of new requirements imposed on UWB antennas. It should be anticipated that UWB antenna design will go through a (r)evolution comparable to the developments in the area of antennas for mobile handsets which matured from external antennas into small integrated wideband solutions.

To illustrate this, this paper will discuss some of the challenges associated with UWB localization and outline how antenna engineers may address them. The main goal of the paper is to stimulate discussion between researchers from academia and industry and to open new research avenues rather than to provide conclusive answers.

The structure of the paper is as follows. First, the 802.15.4a standard for UWB ranging is introduced as it represents the heart of commercial localization chipsets. Then the implications of the standard on antenna design are discussed using some of the deployment scenarios encountered to date.

II. Ranging Using the 802.15.4a Standard

The IEEE 802.15.4a standard was approved in 2007 as an amendment to the original 802.15.4 standard, to complement it with increased range, better mobility, enhanced coexistence and precision ranging capability. In 2011, it was integrated in the main 802.15.4 standard as the UWB PHY [8].

Ultra-wideband naturally fits the objectives of the amendment. It allows for short pulses with steep rising edges. In a multipath environment, the various reflections can be distinguished by the receiver as pulses arriving with different time delays. Where narrowband systems would suffer from multipath fading, UWB can combine the energy from the various paths to increase the communication range and reliability. At the same time, the steep rising edges enable superior time-of-arrival ranging.

The standard was carefully crafted to exploit these characteristics. Each transmission starts with a preamble consisting of isolated pulses encoded in such a way that they result in perfect periodic autocorrelation at the receiver. By averaging the correlator's output, the receiver is able to estimate the channel's impulse response. From that, the arrival time of the first signal energy is estimated to determine the distance between transmitter and receiver.

In a basic time-of-arrival (TOA) setup, the initiating node starts a timer when a packet leaves its antenna. The other node will determine the arrival of that packet at its antenna and then reply with the time it required to process the packet and transmit its reply. Upon reception of the reply, the initiating node stops its timer and now has all the information required. The difference between the time elapsed at its end and the processing time reported by the other node corresponds to twice the time of flight and hence is proportional to the distance between the nodes. Note that the two devices did not require any other infrastructure.

Variations upon this basic scheme exist. Two-way ranging complements the ranging transaction described above with an extra transmission to the other node, which then also estimates the range. When both ranges are averaged, the influence of frequency offset between the devices is reduced [8].

In a time-difference-of-arrival (TDOA) scheme, multiple anchors share the time a packet transmitted from a tag arrives at their end. From this, the location of the tag can then be calculated. While this set-up requires synchronized anchors, the fact that tags only need to transmit packets offers a huge advantage for some power constraint applications.

Decawave's Scensor IC is the first commercially available implementation of the 802.15.4a standard aimed at wireless sensor networks and real-time localization systems. It fully exploits the benefits of UWB. It is able to take advantage from multipath propagation to reliably detect signals more than 20 dB below the noise floor. It has a range up to several hundreds of meters in line-of-sight conditions and is able to overcome severe non-line-of-sight conditions. Thanks to the time-of-flight based ranging, it is able to range down to centimeter level even in severe multipath and obstructed line of sight scenarios [9]

III. Impact of Antennas on Ranging Performance

A. What antenna properties are needed for ranging?

For precise ranging, as introduced in Section II, it is important to determine the leading edge of the arriving pulse. Thus pulse distortion is often the main parameter in antenna design. It indeed is an issue in practical localization systems. However, in this section, it will be shown that other issues, signal angular dependency of ToA, are more severe.

A practical system such as the Decawave's Scensor, is capable of ranging for distances from less than 1 to over 250 m. Thus, the analogue front-end of the receiver has to receive pulses with power varying by more than 50 dB [9]. The SNR required for precise ranging can be achieved by digital signal processing because the number of pulses in the preamble can be up to 4096 (i.e. processing gain of up to 36 dB) [8]. However, even though there is a digital gain, such a system still requires an analogue front-end with over 50 dB of linear dynamic range. Non-linearities would correspond to undesired pulse distortion.

In practical systems the pulse bandwidths are 499.2 MHz with center frequencies in the band 6 – 8.5 GHz. From a distortion perspective, it therefore is often more challenging to design the analogue front-end with linear range of over 50 dB than the design of antennas for distortion-less transmission of pulses with relative bandwidth of 10%. In fact, other antenna-related issues tend to be more severe than pulse distortion. This is discussed in Figs. 1-2.

The inset in Fig. 1 shows the CST Microwave studio model of the spline UWB antenna from [4] with signal probes for the electric field to record the electric field for 17 elevation angles (θ from 10° to 170°) placed 60 cm away from the antenna.

In the simulation, the antenna transmits a root-raised-cosine pulse with bandwidth 499.2 MHz modulated at a 6 GHz. The main plot then shows the received probe signal for θ = 90° (elevation angle of 0°) and the envelope of the signal is highlighted. This plot shows the importance of antenna evaluation in the equivalent low-pass domain (envelope signal) rather than processing the signal directly. Not only does this mimic the processing in a real system but it also allows a more precise estimation of ToA. For the envelope signal, the maximum ranging precision in our simulation is the simulation timestep. However, if the modulated signals are compared directly, one faces the issue that their time domain correlation is maximized for phase-matching of the carrier. In the case when the peak of the envelope coincides with the null of carrier, the correlation has no capability to identify this point.

The impact of the elevation is shown in Fig. 2. The two upper plots show the envelope of the received signals as a

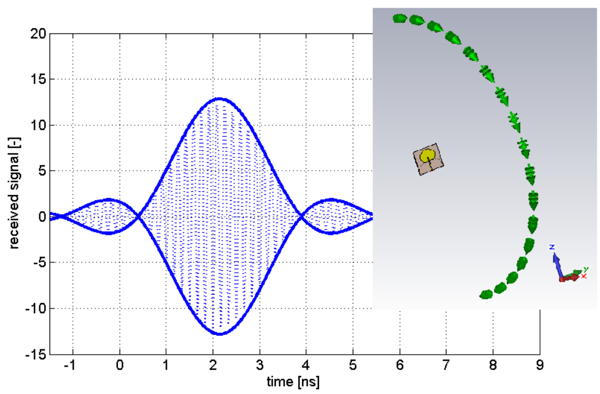

Fig. 1 Transmitted electric field signal as seen by the probe at θ = 90° (horizontal plane) Inset shows the simulation setup.

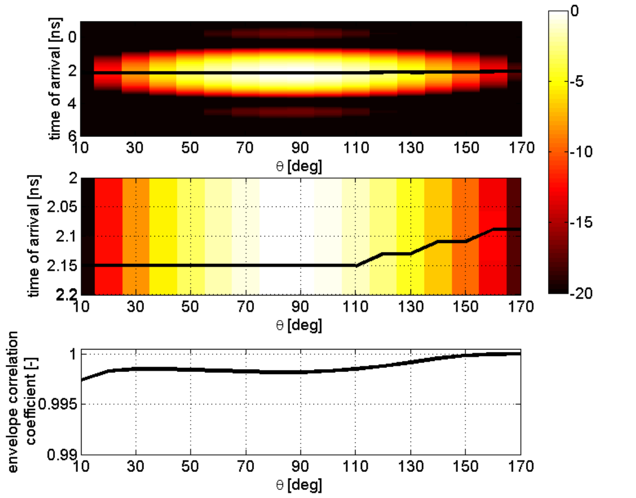

Fig. 2 TOP: the received envelope signal, MIDDLE: the received envelope signal, zoom in time axis. BOTTOM: correlation coefficient between envelopes of the transmitted and input pulse

function of θ in two time scales. The variation in signal amplitude is apparent but as discussed, this can be mitigated by signal processing which ensures sufficient SNR. A line connecting the signal peaks is shown and indicates the ToA as would be estimated by a 802.15.4 system. As can be seen the time of arrival is not constant and changes for radiation in the lower hemisphere. This is a problem for real systems as the ranging error reaches almost 2 cm.

In contrast, the last figure compares the waveforms of the signal envelope and the ideal envelope of the transmitted pulse. As can be seen, the correlation coefficient is greater than 99.5% for all cases. In other words, Figs. 1 and 2 show that indeed pulse distortion is far less problematic than the envelope delays. Thus antenna designers should consider alternative metrics such as envelope ToA for UWB antenna evaluation rather than waveform distortion metrics such as fidelity.

It is also noted that whilst theoretically envelope ToA provides the same results as group delay, however due to some practical properties envelope ToA seems superior not only because it corresponds to the real number. Firstly, in case the antenna, e.g. due to poor matching, radiates multiple pulses, observation of the complex equivalent low-pass signal in many cases still enables detection of the correct ToA whereas the reflections distort the group delay. Secondly, group delay is determined as the derivative of phase, but the phase information also contains noise, either measurement noise or numerical due to limited precision. The derivative performed over noisy signal tends to magnify the noise whereas ToA inherently reduces the noise impact as it is performed over the UWB bandwidth of the signal and the average is inherently weighted by the spectral properties of the employed pulse.

B. *Performance in Real Environment*

As mentioned in the introduction, over the last decade the progress in UWB antennas has been unprecedented. However, almost all works focus on stand-alone free-space antennas. With the advent of practical localization system, the antennas will be integrated into localization tags and placed either on tracked objects or into localization anchors.

Placement of antennas in close proximity of walls, columns or in corners may impact both the radiation properties and the measured Time-of-Arrival (ToA) as a function of azimuth and elevation angle. The target ranging precision of the system is expected to be 3 cm. Therefore, even ToA changes in the magnitudes of 0.1 ns prohibit achieving the desired ranging error. These issues associated with real deployment scenario are demonstrated by the following experiment.

A spline antenna from [4] on FR4 with thickness 0.8 mm, which is optimized for a performance in free space is placed 5 mm in front of a concrete block (see Fig. 2). The antenna transmits a root-raised-cosine with bandwidth of 499.2 MHz (compliant with 802.15.4 standard) modulated on the 6 GHz carrier. A set of 19 far-field probes is placed 600 mm away from the centre of the antenna in azimuth angles 0° - 90°. The electric field signal received by these probes is explored.

Fig. 4 explores the impact of the column on the signal. It shows the envelope received by the probes as a function of azimuth angle for antenna placement 5 mm in front of the column. The solid black lines connect the points of the peak amplitude of the signal and corresponds so to the ToA as observed by the system.

It is observed that for the antenna placed in proximity of the concrete column the baseband transmitted waveform is changed due to the presence of the column. Furthermore, the waveform changes with the azimuth angle. This impacts the ToA estimation and the pulse peak becomes a function of azimuth angle. The ToA variation is almost 0.5 ns - corresponding to a ranging error of 15 cm, well above the target ranging precision. This error caused only by the concrete column as in free-space the antenna does not manifest these properties and the delay of the radiated pulse in the horizontal plane is independent of the azimuth angle [4].

It is not surprising that the presence of the column impacts the radiation of the pulse. What is surprising is the extent of the impact of the column on results even for azimuth angles of 30°-45°. The results, therefore, show the necessity to design antennas specifically for the deployment scenarios.

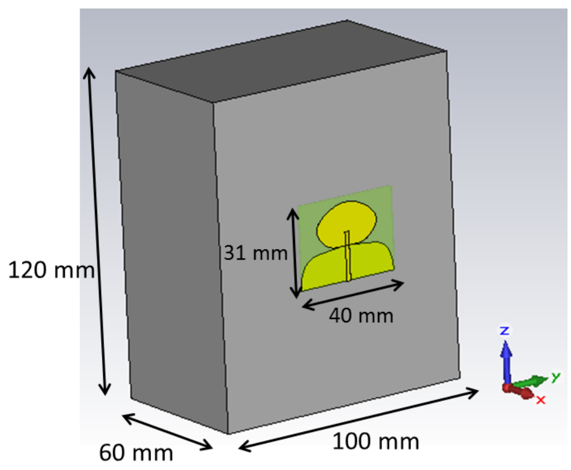

Fig. 3 A spline antenna from [4] on FR4 is placed 5 mm in front of a concrete block representing a column/pillar.

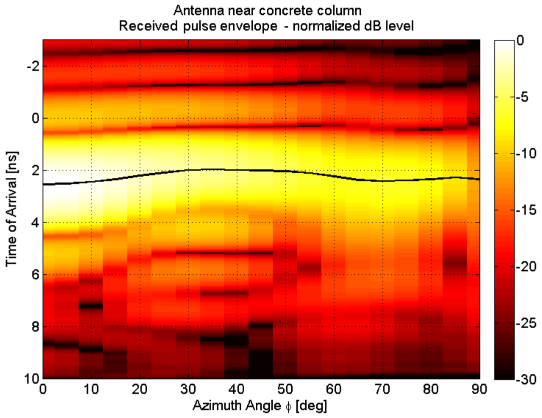

Fig. 4 The signal received by the field probes for the spline antenna from [4] when the antenna is placed 5 mm in front of a concrete column

C. Joint ToA and Angle-of-Arrival estimations

The 802.15.4 standard defines ranging only. For localization, two options are available. Firstly, it is possible to use at least three anchors to determine the node location by triangulation. Secondly, it is possible to combine range (ToA) and Angle-of-Arrival (AoA) information. The AoA can be determined from the Time-Difference-of-Arrival (TDoA) between signals received by the antenna elements belonging to a single transmitter.

The advantage of the second approach is the possibility to determine location of nodes using a single base station. The disadvantage is lower precision. For a two element array spaced by d, the TDoA (τ_{diff}), depends on the AoA (ϕ), as follows:

$$\tau_{diff} = \frac{d}{c}\sin\phi \tag{1}$$

where c is the speed of light.

However, (1) represents a theoretical dependency for two point sources. It does not consider the behavior of real antennas, which was explored in this work by the means of simulation in CST Microwave Studio.

Two UWB spline antennas from [4] (used also in III.B) were used in a 2-element array as shown in Fig. 5. Then an incident plane wave was selected as the excitation. The delay between the received baseband pulses was observed as a function of AoA of the incident wave (AoA was varied from 0° to 90° with 10° steps) for three values of antenna spacing *d*: 40 mm (antennas touching each other), 80 mm and 120 mm. The results are recorded in Fig. 6.

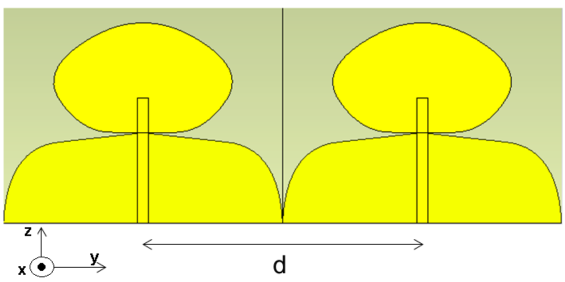

Fig. 5 Simulation setup of a two-element UWB antenna array. Antennas are fed by microstrip lines, the x-axis (ϕ=0°) is perpendicular to the drawing plane

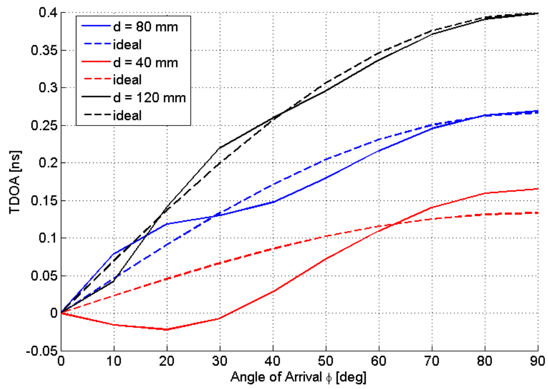

Fig. 6 Real and ideal TDOA as a function of AOA for various antenna spacings

The coupling between antennas results in deviation from theoretical results from (1), especially for close antenna spacing which is desirable for compact designs. In particular, for the close spacing the TDoA cannot be unambiguously associated with a unique AoA. Two conclusions can be reached based on Fig. 6.

The results represent an opportunity for antenna design. They suggest that it may be possible to control the relationship between TDoA and AoA by a careful antenna design. This can result in great system benefits.

Not only could it be possible to ensure that the relationship between TDoA and AoA allows a unique unambiguous AoA detection, the array design can also be used to control the shape of the TDoA-AoA function. For relationship from (1), it can be observed that the error of AoA estimate is not constant, i.e. a constant timing error (e.g. due to signal processing) results in a larger error in the AoA estimate for wave arriving from 90° degrees than from 0°. This issue would be mitigated if the TDoA-AoA relationship would be a linear function. For other scenarios, different target function may be chosen.

The hypothesis about the possibility to control and potentially tailor the TDoA-AoA relationship is investigated with a setup presented in Fig. 7. In Fig. 7, the spline antennas

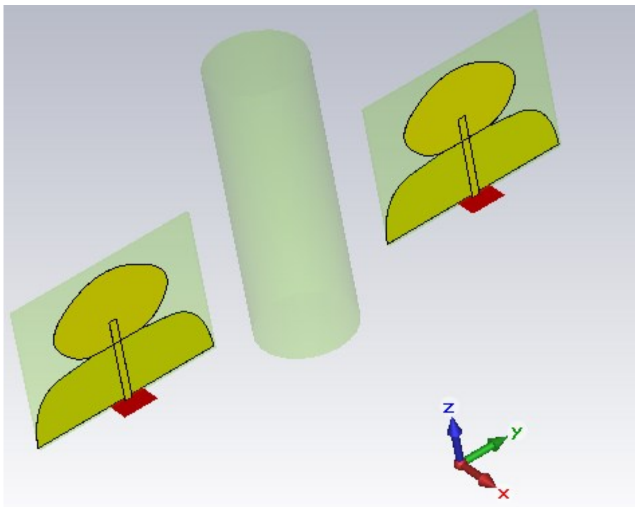

Fig. 7 Simulation setup for confirmation that a control of the TDoA-AoA relationship is possible.

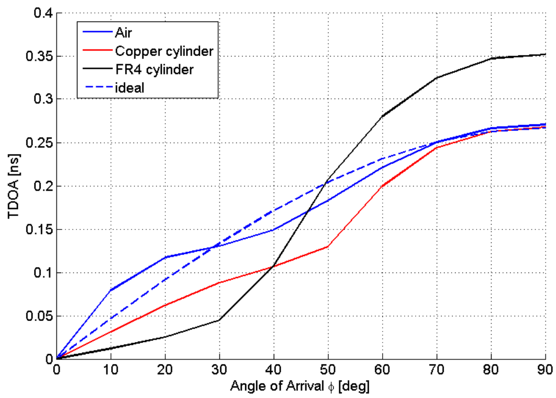

Fig. 8 TDOA-AoA relationship for various cylinder materials.

from [4] are spaced by 80 mm but between them a cylinder with radius of 10 mm and height of 60 mm is placed. The same plot as in Fig. 5 was generated for three cylinder materials: air, copper, and FR4. The results are presented in Fig. 8 which confirms the hypothesis that even a simple cylinder can be used to significantly alter the TDOA-AoA relationship.

To conclude Fig. 8 clearly shows another possible research avenue for antenna research, i.e. the antenna structure can be varied in order to directly control the TDoA-AoA relationship, which can be used to increase the precision of a simple localization system.

IV. Conclusion and Future Work

Past extensive research the field of UWB antennas has delivered a significant progress. Currently, it is possible to design antennas that introduce almost no distortion to pulses with relative bandwidths of up to 100% [4]-[7]. This is far beyond the requirements of real localization systems based on the 802.15.4a standard. Thus it may at first appear that there are no antenna research challenges left.

In this paper, however, the performance of example UWB antennas is discussed considering their deployment in realistic localization systems. The objective of the paper is to show that despite the progress there are several open challenges in UWB antennas such as:

- *Optimize antennas using system oriented measures for evaluation of UWB antennas*

It was shown that for practical systems, the main concern is the stability of ToA for arbitrary angle rather than the signal distortion simply because the relative signal bandwidths are low (below 10%).

- *UWB antennas designed for specific scenarios*

It was shown antennas optimized for standalone performance can be significantly impacted by deployment in the proximity of objects. As a result, it is necessary to make an evolutionary step towards simulation and designs in realistic scenarios environments.

- *UWB arrays with optimized TDOA-AoA relationship*

Localization combining the ToA and AoA seems attractive for asset tracking by a single base station. As shown here, the coupling between elements in compact arrays can affect the precision of the AoA estimation. At the same time, for compact arrays the precision of AoA estimation can be improved by careful antenna design. This offers the possibility to design arrays that would maximize the precision of AoA estimation in a selected direction.

To conclude, the main contribution of the paper is to show that the research into UWB antennas is not dead and to stimulate the research in directions where advanced antenna designs can contribute to the precision of localization systems. It is also shown that to achieve this goal, the antenna design and optimization procedures have to consider both the specific deployment scenarios, and new system-oriented metrics rather than descriptors suitable for standalone antennas.

It is also noted that the list of the open challenges is not conclusive and further deployment or practical systems are expected to result in further new requirements on the design of UWB antennas.

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