Time of Arrival Based on Chirp Pulses as a means to Perform Localization in IEEE 802.15.4a Wireless Sensor Networks

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Abstract — **This paper introduces the technology Time of Arrival (TOA) based on chirp pulses (according to IEEE 802.15.4a) as a means to perform localization in Wireless Sensor Networks (WSN's) active at 2.4 GHz. Advantages and disadvantages of the technology are discussed and act as a guideline for improving localization accuracy. Tests concerning TOA are performed by means of the location engine of Nanotron. Adapting this engine leads to improved localization results. It is shown that TOA measurements are susceptible to reflections and dynamic environments.**

Index Terms — **Chirp Pulses, Localization, RF, Time Of Arrival, Wireless Sensor Networks**

I. INTRODUCTION

Nowadays location dependent services (LDS) are a hot item in the field of mobile communications. One can only think of the huge amount of possibilities localization can provide. Fields of application are situated in the area of domotics, healthcare and tourism. Domotics systems could use localization to detect the presence of people in different rooms inside a building. According to the location of a person, specific actions can be taken, such as switching the light on or off, closing the curtains or turning on the heating [14]. Besides domotics, hospitals can also use localization to improve their services. Nodes used for localization can be attached to valuable devices (defibrillators, heart monitors) to track them inside the hospital. Lost items can be located throughout the whole building. At last, tourist attractions can also use the benefits of localization. It can be used as a guide through parks, museums.

This paper tackles the idea on how to use TOA to perform indoor localization in wireless sensor networks. We focus on sensor networks based on the IEEE 802.15.4a standard which is compatible with the ZigBee Specification [13]. The whole system is elaborated to operate at 2.4 GHz.

The basic terminology which is used in this paper defines two types of nodes in a network. On one hand, reference nodes exist; the positions of these nodes are well known. On the other hand there is a blindfolded node; its position is unknown. Collaboration of the reference nodes and the blindfolded node leads to the calculation of the position of the blindfolded node.

Many technologies exist to determine the distances between the blindfolded node and the reference nodes. For example, there is the possibility to use Received Signal Strength (RSS) [14], Angle Of Arrival (AOA) [12] or TOA [1],[8]. This paper deals with TOA based on chirp pulses according to the IEEE 802.15.4a standard. The nanoLOC development kit [3] produced by Nanotron has been used in our research to detect problems concerning the TOA technology.

Besides these technologies – which lead to the calculation of inter-node distances[1] – an appropriate technique is needed to determine the position out of these distances, *i.e.* the co-ordinates of the blindfolded node. In most cases, at least three reference nodes are needed to calculate a position in a 2D-pane. Least-squares tri-lateration or multi-lateration [6] and maximum likelihood estimation are common techniques to do so.

In this paper, section II demonstrates how the TOA technology can be applied in location tracking. In section III the test equipment is discussed, *i.e.* the nanoLOC development kit and the necessary adaptations towards our own application to improve localization results. This leads to section IV which tackles the test results concerning TOA measurements in different test environments., taking a closer look at the performance of the TOA technology in real office environments with moving objects and signal reflections. Finally the conclusions are summarized in section V.

II. CONCEPT OF TOA

TOA is a widely used technology to perform localization. It is for example used in radar systems. The basic TOA technology describes the reference nodes and the blindfolded node, co-operating to determine the inter-node

[1] In this paper 'inter-node distance' indicates the distance between the blindfolded node and a reference node.

distances by using timing results. The blindfolded node will send a message to each of the reference nodes to measure the distance. The moment the blindfolded node transmits a message, it attaches a timestamp (t_1), indicating the clock time in the blindfolded node at the start of the data transmission. At arrival of the message at the reference node, the clock time in the reference node is stored as timestamp (t_2). The difference between timestamp (t_1) and (t_2) indicates the time needed for the signal to travel from the blindfolded to the reference node through the air. Fig. 1 explains TOA.

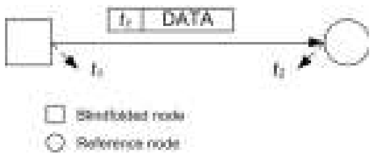

Fig. 1 Time Of Arrival measurement between the blindfolded node and the reference node. The blindfolded node starts sending a message at t_1. The reference node receives the message at t_2.

The travel time of the signal through the air from one node to the other is directly related to the distance between the blindfolded and the reference node. This distance is determined by use of equation (1).

distance = travel time . speed of light[2]

$$d[m] = (t_2 - t_1)\,[s]\,.\,c\left[\frac{m}{s}\right] \qquad (1)$$

The blindfolded and reference node must be perfectly synchronized in order to retrieve adequate results. This is one of the most important disadvantages TOA is suffering from. To avoid this problem a slightly different technology has been introduced, Round Trip Time (RTT), also called Two Way Ranging (TWR). All time measurements are performed in the same node so synchronization of the blindfolded and the reference node is no longer needed. The RTT measurement is explained in Fig. 2.

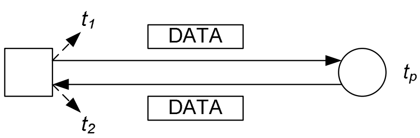

Fig. 2 Round Trip Time measurement between the blindfolded node and the reference node. Both time measurements are performed in the same node. This cancels out the need for synchronization. One cannot neglect the processing time (t_p) in the reference node.

In the latter case, the blindfolded node initiates the measurement by transmitting a ranging message to the reference node. The internal clock time (t_1) is stored as the starting time of the transmission. When the reference node receives this packet, it is processed and a response is returned to the blindfolded node. The moment the blindfolded node receives the first bit of the response, the clock time is stored as t_2. The time difference directly leads to the travel time of the packet in one direction and its corresponding distance. Of course, one should not forget to take the processing time (t_p) of the reference node into account.

Besides the synchronization problem, TOA suffers from another difficulty. On one hand, TOA is said to perform very good in Line-Of-Sight (LOS) situations (a direct path between the two nodes does exist). On the other hand, TOA performs badly in Non-Line-Of-Sight (NLOS) situations. This situation indicates that the direct path between the blindfolded node and the reference node is blocked, possibly due to objects. Only signals following reflected paths, which need more time to travel, will reach the reference node. This leads to erroneous results for the inter-node distance.

III. TEST EQUIPMENT

A. NanoLOC development Kit

In order to become more familiar with TOA, we based our system on the available nanoLOC development kit of Nanotron [3]. The kit is based on the IEEE 802.15.4a standard and is compatible with the ZigBee Standard. This kit provides five development boards (four reference nodes and one blindfolded node) on which a localization application is flashed. The four reference nodes, each provided with a wireless transceiver (NA5TR1), cooperate to determine the position of the blindfolded node. Beside these boards, a USB-dongle with a wireless transceiver is provided. The latter is able to communicate with the blindfolded node. Plugging this dongle into the PC makes it possible to use location information in the application graphical user interface (GUI). The blindfolded node communicates to each reference node in order to determine their mutual distance. The blindfolded node transmits the four measured distances to the USB-dongle connected to the PC on which the position of the blindfolded node is calculated.

Fig. 3 depicts the setup.

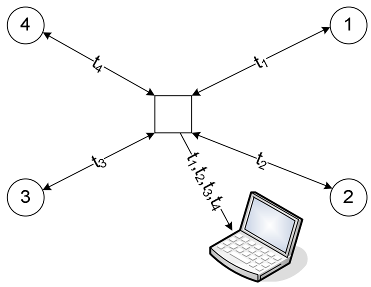

Fig. 3 Basic elaboration of the localization system. The blindfolded node communicates with all reference nodes to determine the four inter-node distances. These are transmitted wirelessly to the USB-console attached to the PC.

The technology used to retrieve the inter-node distances is called Symmetric Double-Sided Two-Way Ranging (SDS-TWR). This technology includes the normal TWR (section 2) but extends it by adding SDS. 'Symmetric Double-Sided' measurement means that both, the blindfolded and the reference node, will initiate a TWR measurement. 'Symmetric' points out that the blindfolded node and the reference node need the same amount of processing time to return an answer on the receipt of the ranging message. The

[2] $c \approx 3.10^8$ m/s

mean of both measurements is used to calculate the position of the blindfolded node [2]. As an advantage, crystal offset errors are diminished; for symmetric systems it is halved [4],[5]. SDS-TWR is explained in Fig. 4.

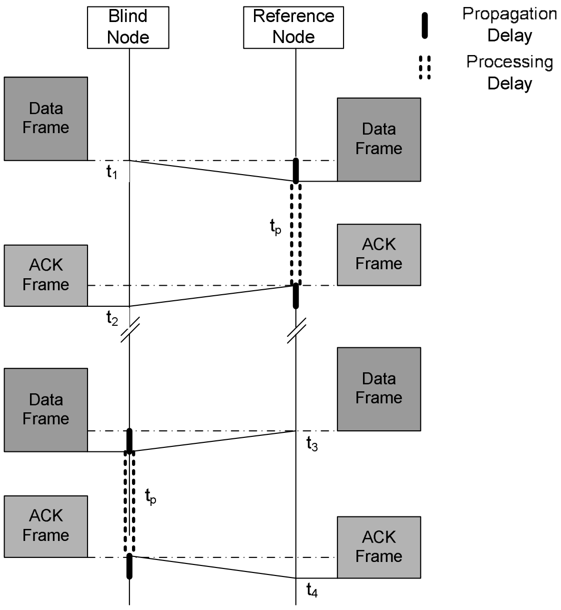

Fig. 4 Symmetric Double-Sided Two-Way Ranging. Both the blindfolded node and the reference node initialize an inter-node measurement. Afterwards both results are averaged.

B. *Adjustments towards own application*

On top of the SDS-TWR technology, used to determine inter-node distances, an appropriate technique to determine the position of the blindfolded node is required. The choice was made to work with the Least-Squares multi-lateration technique [6]. This is a fast working technique that does not require a lot of calculation power and time[3], it is one of the most straight-forward techniques. A disadvantage is that the accuracy of the localization depends directly on the accuracy of the measured distances. More information on how to use this technique can be found in [6].

In our application, we have used two possibilities to perform localization. In the first place, we used static localization, and secondly we used dynamic localization. If the blindfolded node in the test stays on the same place for a longer period of time, the static localization provides the best results. It calculates the average of several measurements. This leads to a good position of the blindfolded node on the GUI of our system. By averaging the measurements, we avoid flickering of the position of the blindfolded node. This flickering appears due to measurement errors. But if a situation occurs in which the blindfolded node moves around, this static localization will not perform very well. Averaging the measurements leads to slow adaptation of the represented position in comparison with the real-time changing blindfolded node. For this type of test cases, a dynamic localization algorithm is developed.

[3] This property is desired in real-time tracking of an object in wireless sensor networks.

This type of localization is based on the use of an Infinite Impulse Response (IIR) filter with the equation of formula (2). By the use of this IIR, the measured distances are filtered.

$$\hat{x}_t = \alpha . x_t + (1-\alpha).\hat{x}_{t-1} \qquad (2)$$

The real-time measured distance x_t determines only partially the newly calculated distance $\hat{x}_t$ between the blindfolded node and the reference node. The previously calculated distance $\hat{x}_{t-1}$ is also taken into account. How much the last measured distance influences $\hat{x}_t$ is determined by the coefficient α. In order to have a stable IIR filter α has to be larger than 0 and smaller than 1. The larger α, the more important the new measurement is, and the faster the position of the blindfolded node is tracked. If α is chosen smaller (*e.g.*, α < 0,3), the node's representation in the GUI will follow the real position much slower. From now on, instead of working with x_t, we use $\hat{x}_t$ to determine a position.

IV. Test Results

A. *Distribution of TOA measurements*

In the work of Patwari [7], it is claimed that the TOA measurements distribution deviates from the standard normal distribution. This statement can be confirmed by evaluating our own test results, retrieved from measurements in an anechoic chamber, in which the blindfolded node and a reference node are positioned with an inter-node distance of 4 m. An anechoic chamber was chosen as test environment in order to eliminate the side-effects introduced by reflections.

Fig. 5 shows a QQ[4]-plot of these test results retrieved by processing the data with a mathematical packet. The tails indicate that the distribution deviates from the standard normal distribution. The non-parametric Kolmogorov-Smirnov[5] test affirms this conclusion [11].

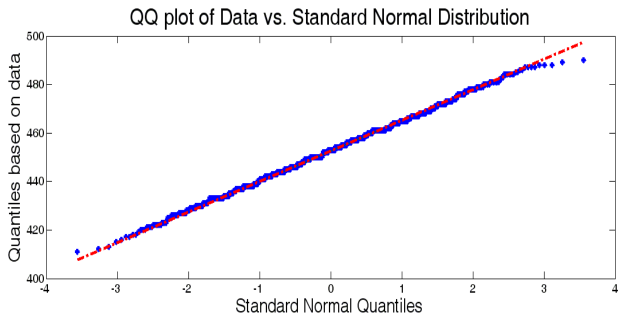

Fig. 5 QQ plot of test results in anechoic chamber. TOA measurements do not follow the standard normal distribution.

[4] QQ-plot: Q stands for Quantiles. 'Data Quantiles' are compared to 'Normal Theoretical Quantiles'

[5] The Kolmogorov-Smirnov test is used to test if a data set has a standard normal distribution.

B. Non-Line-Of-Sight (NLOS) situations

It is stated in section II and [7] that TOA measurements perform worse in NLOS situations. The NLOS signal arrives at the receiving node after reflection(s) to objects, walls, etc. and introduces corresponding time delays. NLOS situations are very likely in indoor environments, especially in areas with moving objects, for example people walking around in an office.

Fig. 6 sketches the TOA difference between LOS and NLOS signals. It is clear that the NLOS signal reaches the receiver later in time due to reflections. When the LOS signal is blocked, the receiver detects the NLOS signal first. When using this delayed signal for calculating the inter-node distance, measurement errors are introduced.

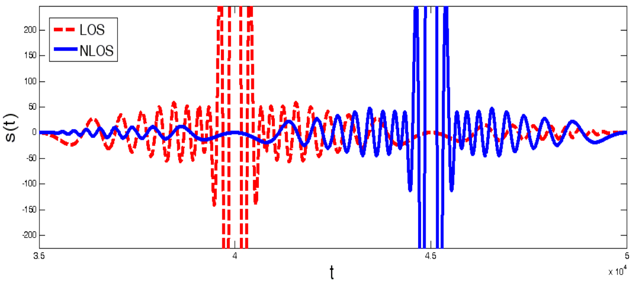

Fig. 6 When the direct path signal is blocked, the reflected signal (NLOS – full line) will be used instead of direct path signal (LOS – dashed line). This introduced time delay leads to miscalculations of the inter-node distance.

To find out in what way the performance gets worse in realistic environments, which frequently suffer from NLOS situations, some test setup is built [8]:

- LOS configuration:

For this alignment we positioned the blindfolded node in the centre of the 4 reference nodes. No objects are placed in the middle of this rectangle to ensure perfect Line-Of-Sight. For each reference node the estimated/measured distances to the blindfolded node are stored. The retrieved test results are averaged and the standard deviation to the exact distance is calculated. The results are shown in Table I A.

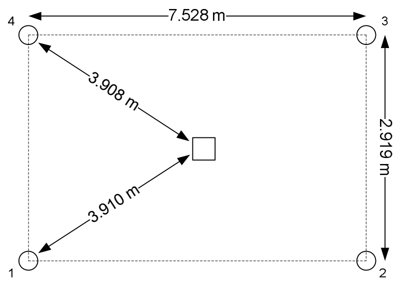

Fig. 7 LOS situation. The blindfolded node is placed in the centre of the reference nodes.

- NLOS configuration:

Again the blindfolded node is positioned in the centre of the 4 reference nodes. To realize NLOS, the blindfolded node is covered by a box made of gypsum. The same measurements are performed and the test results are stored. The results are represented in Table I B.

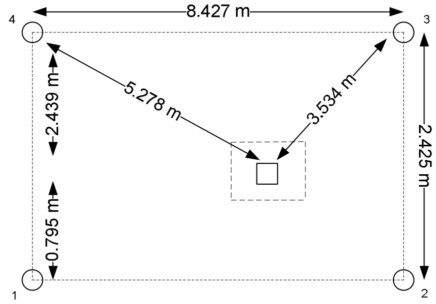

Fig. 8 NLOS situation. The blindfolded node is covered by a box and is placed in the centre of the 4 reference nodes.

TABLE I

A. LOS SITUATION

Reference Node	Average [m]	Standard Deviation [m]
1	3.9645	0.1503
2	3.9731	0.1974
3	3.7528	0.1629
4	3.6710	0.1522

B. NLOS SITUATION

Reference Node	Average [m]	Standard Deviation [m]
1	8.777	0.5798
2	5.0208	0.4231
3	6.1979	0.4948
4	7.5071	0.4631

If we compare the standard deviation of LOS and NLOS, it is clear that NLOS, with deviations of approximately 0.5 m or 7 % to 8 % of the total distance, performs much worse than the LOS-case with deviations of 15 cm to 20 cm or 4 % to 5 % of the total distance. This corresponds with the expected results.

C. Effect of moving objects

In real office environments people and objects are moving around, this obviously will influence the test results. Due to occasionally NLOS situations, TOA measurements will perform differently in an "empty office" – nobody is present – and in a "used office" – people are working and crossing the room. These tests were performed during the day and overnight in a class room. Students are crossing the room frequently during the day and thus block LOS signals. Thousands of measurements were processed and, after calculation with a mathematical packet, led to the histograms and a QQ plots of the inter-node distance measurements between the blindfolded node and one of the reference nodes as depicted in Fig. 9 (empty office) and Fig. 10 (used office).

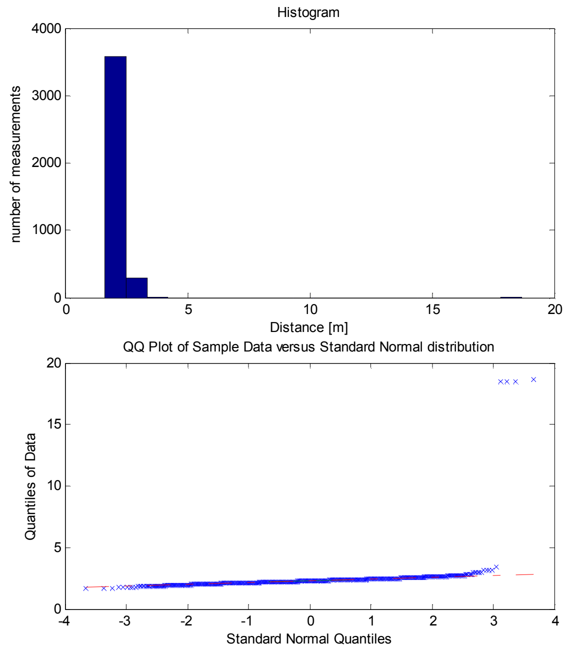

Fig. 9 – Histogram and QQ plot of measurements in empty office.

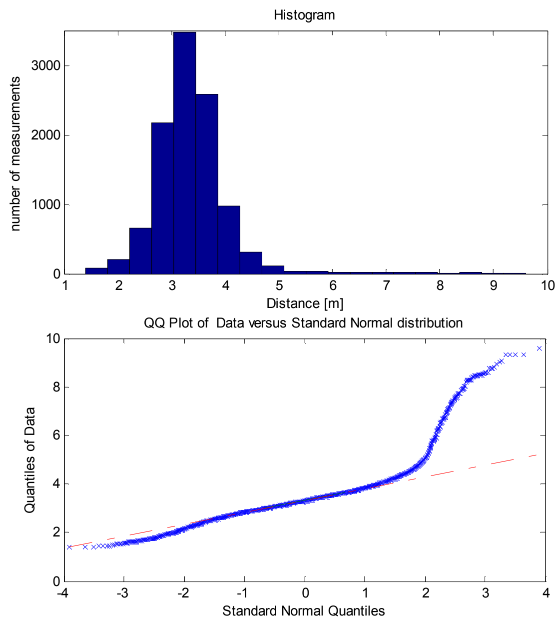

Fig. 10 Histogram and QQ plot of measurements in a used office. People cross the office and influence the measurements. Due to occurring NLOS situations, distance measurements deviate from the expected value. This is clear if both, histogram and QQ plot, are compared with fig 7.

The QQ plot of Fig. 10 shows that those measurements deviate much more from the standard normal distribution than the measurements in Fig. 9. It can be concluded that moving objects do affect the accuracy of the TOA measurements. This is due to the fact that, occasionally, NLOS situations may occur.

D. *Reflection sensitivity*

Even though the appearance of NLOS situations is a great source of erroneous results, other side effects cannot be neglected. Even when we have a perfect LOS situation measurements errors can appear due to reflections on objects and walls. In order to understand the sensitivity of this system, with respect to reflections, one should gain knowledge of which type of signals are transmitted.

The nanoLOC system introduces the combination of two types of pulses, sinc-pulses and chirp pulses. Firstly, sinc-pulses were introduced because they have the shortest possible duration at a given bandwidth B. Consequently, they have a very small bandwidth-time product (BT=1). These sinc-pulses are generated relatively easy and can be detected with a simple amplitude discriminator. Therefore, they are used in the transceivers. Formula (3) represents the sinc distribution S(t) in the RF band.

$$S(t) = S_0 \frac{\sin(\pi Bt)}{\pi Bt} \cos(\omega_0 t + \varphi) \quad (3)$$

Due to the small BT-product, sinc-pulses are very sensitive to disturbances during transmission and thus unsuitable. To overcome this disadvantage, a second type of pulse is used to transmit the information, namely linear frequency modulated chirp pulses [9]. Because of its large bandwidth-time product it is very robust against disturbances during transmission. The chirp pulse P(t) is represented in formula (4).

$$P(t) = \frac{P_0}{\sqrt{B}} \cos(\omega_0 t + \frac{pt^2}{2} + \varphi) \quad (4)$$

A large benefit is that sinc-pulses can be converted into a chirp pulse and vice versa by the use of a dispersive delay line (DLL), for example a SAW[6] filter. This filter performs a cross correlation of the received chirp signal (delayed in time) and the original signal and leads to the detection of a sinc-pulse [10]. This technique was included in the IEEE 802.15.4a standard and is represented in Fig. 11.

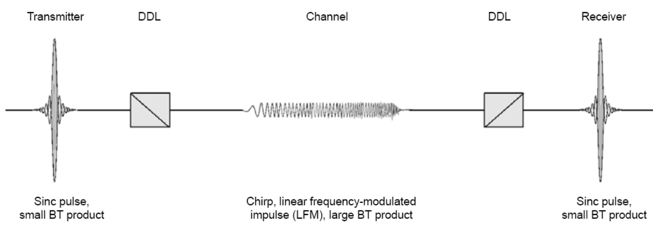

Fig. 11 The sinc-pulse used inside the transceivers is converted into the more robust chirp pulses to be transmitted. This is performed by a DDL which performs a cross correlation.

Knowing the nature of the signals used, we can now perform tests on their reflections. These tests pointed out that measurements performed indoor are less accurate than those performed outdoor. This is caused by reflections which are more likely to occur indoor than outdoor. Even though there exists a LOS path, the presence of reflected signals is a major source of miscalculations, especially in the TOA technology. Each reflected signal travels a time t_d [ns] longer than the direct path signal. Since both signals will reach the receiver, both should be taken into account.

Since the moment the receiver picks up both the direct signal and the reflected signal shortly after each other, it is not able to distinguish between them. This leads to an error in the detection of the highest peak of the sinc-pulse of the

[6] SAW filter = Surface Acoustic Wave filter

direct path signal and introduces a time measurement error Δt_m [ns]. Fig. 12 depicts the theoretical relationship between Δt_m, the time measurement error, and t_d , the extra time a reflected signal travels in comparison to the direct path signal. The amplitude of both signals is important in constructing this figure. The amplitude of the direct path and the reflected signal were chosen to be equal.

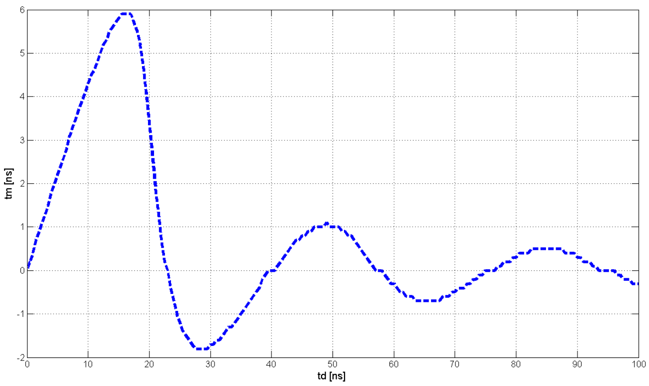

Fig. 12 Theoretical travel time measurement error due to reflected signals. For t_d [0..10 ns] a linear relationship can be found. The detected peak is in the middle of both arrival times. For t_d>15 ns the head lobe of the LOS signal will overlap with the side lobes of the reflected signals. For t_d>>, t_m decreases, the receiver is able to distinguish both signals.

If we analyze Fig. 12, it is clear that if the difference in arrival time between the direct path and reflected path becomes larger (towards 100 ns), the measurement error at the receiver decreases. This is the result of the receiver accuracy, which is able to distinguish both signals, and thus can detect the peak of the direct path. We can draw the attention to the first part of the figure: t_d [0..10 ns]. As long as the amplitude of the reflected signal and the amplitude of the LOS signal are more or less the same. An approximation of Δt_m is described by formula (5):

$$\Delta t_m \approx \frac{1}{2} t_d \qquad (5)$$

As long as t_d is small enough, the head lobes have a certain overlap and lead to a positive error. The top of the peak will be situated in the middle of both arrival times. So the measurement error will be half of the difference in arrival time.

When t_d becomes larger (t_d> 15 ns), the overlap of the head lobes is no longer important. From now on the head lobe of the LOS signal can overlap with the side lobes of the reflected signal. This can introduce positive and negative errors.

V. CONCLUSION

This paper has introduced the technology TOA, based on chirp pulses according the IEEE 802.15.4a standard, as a means to perform localization in Wireless Sensor Networks at 2.4 GHz. First, a general overview of TOA characteristics is sketched. Second, practical test situations were set up to approve these properties.

It is demonstrated that TOA performs well in LOS situations. Unfortunately, NLOS situations are more difficult to tackle by this technology. The disadvantage that nodes need to be synchronized to perform TOA is handled by the introduction of the related technology SDS-TWR as it is used in the IEEE 802.15.4a standard. Tests have pointed out that TOA measurements have a distribution, deviating from the standard normal distribution. Due to the incapability of TOA in NLOS situations, the achieved results for this technique are vulnerable for moving objects. At last it is also confirmed by a theoretic and practical study that reflection is a major source of miscalculations in the inter-node distance.

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