Abstract—In this paper, we analyze the achievable location accuracy of a wireless localization system using pulse arrival time measurements of ultra-wideband (UWB) pulses. We briefly review the limits on the ranging accuracy given the regulatory constraints of UWB emissions and the parameters of the UWB transceiver hardware used for the localization system. We show that the accuracy of the arrival time measurements does not depend on the pulse spectrum in a very small measurement interval equal to half the inverse of the pulse center frequency. For measuring the arrival time outside this (usually tiny) measurement interval, we show that the measurement accuracy declines considerably and that it furthermore depends on the pulse bandwidth. We also show why short transmit pulses are necessary in a multi-path free radio frequency channel to maintain an acceptable accuracy of the pulse arrival time.

I. INTRODUCTION

An application utilizing the radio frequency (RF) channel is commonly called ultra wide-band (UWB), if the covered bandwidth is >0.5GHz or >20% of the center frequency. Until recently, only niche applications like radar or military communications deserved to be called UWB. This is different today, where numerous companies and universities investigate applications utilizing the radio frequency band from 3.1GHz to 10.6GHz, whose usage has passed standardization through the Federal Communications Commission (FCC) [1] in the U.S.A. and is soon expected to be standardized by the European Telecommunications Standards Institute (ETSI) [2] in Europe.

Besides the established companies with know how in UWB technology such as TimeDomain [3], the majority of commercial market players in this area currently focuses on short-range medium- to high-rate communication applications for so-called wireless personal area networks (WPAN). A number of companies already offer chip sets for the high data-rate WPAN standard IEEE802.15.3a [4] implementing the multi-band orthogonal frequency division multiplex (M-OFDM) approach such as [5-8]. Impulse radio (IR) utilizing pulse position modulation (PPM) or chirp spread spectrum (CSS) modulation are two methods for UWB communication, which have been approved as candidates for the low data-rate WPAN standard IEEE802.15.4a [9]. The potential of location and tracking applications has been discussed by this task group as well, since in particular the IR approach allows to measure the arrival time of the transmitted pulses precisely. This information is the basis for calculating the time-of-flight of the transmitted pulse by utilizing one-way or two-way ranging algorithms. Finally, the time-of-flight information allows to locate the devices sending and receiving the UWB pulses [10].

We currently study integrated circuit (IC) designs in complementary metal oxide semiconductor (CMOS) technology at our institute, which implement an UWB transceiver for transmitting UWB pulses and measuring the arrival time of UWB pulses with high precision. This IC is part of a tag, which is subject to precise localization in indoor and/or outdoor environments. We show analytically and via simulations that the IC can measure the arrival time of UWB pulses with an accuracy that is comparable to or even better than that of current state-of-the-art technology. The system can be adapted to comply with the FCC or ETSI regulations for UWB emissions. It can cope with signal interference of narrow-band communication services in the 3.1-10.6GHz band such as the wireless local area network (WLAN) standard IEEE802.11a. The fully digital architecture also promises low power consumption and flexibility.

In preliminary work [11], we analyzed the localization system in a multi-path-free environment to study how the imperfect hardware (time jitter in the samplers, sample quantization, unsynchronized clocks) affects the accuracy of the arrival-time measurements. It turned out that neither of these hardware issues significantly deteriorates this accuracy. In this paper, we draw our attention on the multi-path nature of the radio channel indoors (residential and office environment) and outdoors. Unfortunately, the measurement errors increase significantly in such an environment, even when there is a clear open path between the UWB pulse transmitter and receiver. This scenario is referred to as the line-of-sight (LOS) condition. We show that the reason for these measurement errors is that the pulse arrival time estimator in the receiver cannot discriminate the received UWB pulse from its replica added in the multi-path RF channel. We also show that if the so-called LOS component of the received pulse can be identified, the achieved measurement accuracy is close to that in a multi-path-free RF channel. Reasons for the obtained results and possible remedies will be discussed.

The next section continues with the description of the application for which we develop the UWB transceiver IC. Section III derives theoretical limits of the time measurement
accuracy using the proposed IC design given a multi-path RF channel. These limits are compared to simulation results in Section IV. The paper concludes with Section V.

II. LOCALIZATION SYSTEM DESCRIPTION

Consider the wireless localization system depicted in Figure 1. A (large) number of small tags transmit a sequence of UWB pulses to a set of base stations, which report the measured arrival time of the pulse train to a processing hub. The hub calculates the tag coordinates using these arrival times. There exist numerous approaches to convert pulse arrival times into the tag coordinates. See for example [12] and [10].

In this paper, we do not elaborate on the reservation scheme governing the pulse emissions of the tags and the base station-to-tag and tag-to-tag communication. We focus on the achievable accuracy of the pulse arrival time measurements in the base stations.

However, to be able to compare our transceiver proposal with existing localization systems, we need to relate the achieved time measurement accuracy to an achievable ranging accuracy. We define the ranging accuracy of a localization system as the standard deviation \( \sigma_R \) of the error

\[
e_R = \sqrt{(\hat{x} - x)^2 + (\hat{y} - y)^2 + (\hat{z} - z)^2}
\]

between the true coordinates \((x,y,z)\) of a tag and its estimate. Commercially available wireless localization systems achieve an accuracy \( \sigma_R \) down to 10-15cm under LOS conditions in a 50m working range [13] or \( \sigma_R = 30cm \) under LOS conditions in a working range of 100m [14]. For the applications we have in mind, a significantly improved accuracy in the cm range under LOS conditions indoors is required. The desired working range is at least 20m. Our goal is to determine the ranging accuracy \( \sigma_R \) for our system depending on the RF channel characteristics (multi-path distribution, path loss, noise). Note that there are numerous other parameters affecting \( \sigma_R \) such as the antenna (geometry, aperture, gain, reference point) and the transceiver circuitry (noise figure, amplifier bandwidth, sampling rate, sampling time jitter, clock stability). These circuitry-level parameters as well as some system-level issues (base station clock synchronization, algorithm for coordinate calculation, pulse repetition rate, ...) are considered in [11].

In the sequel, we obtain lower bounds and simulation results on the standard deviation \( \sigma_T \) of the time measurement errors

\[
e_{T,i} = \hat{T}_i - T_i
\]

occurring independently in each base station, where \( T_i \) is the time-of-flight of the UWB pulse transmitted by the tag and received at base station \( i \). To calculate the ranging accuracy \( \sigma_R \) from \( \sigma_T \), we apply for simplicity the relationship

\[
\sigma_R \geq 2.5 \cdot c \cdot \sigma_T
\]

taken from [12] (p. 183), where \( c \) is the speed of light. This formula holds for small \( \sigma_T \) by directly calculating the tag coordinate \((x,y,z)\) from the time-of-flight measurements. Similar studies on \( \sigma_R \) have been conducted in [15-17], but without incorporating the UWB regulatory constraints and the effects of a multi-path RF channel.

![Figure 1: A wireless localization system.](image)

III. ANALYSIS OF THE TIME MEASUREMENT ACCURACY

Consider the architecture of the transceiver IC depicted in Figure 2, which is part of the tags as well as the base stations in the wireless localization system depicted in Figure 1. The tags transmit a series of the pulse \( s_{TX}(t) \), which at the \( i \)-th base station becomes a series of received pulses given by

\[
s_R(t) = \sqrt{G_{path}} \cdot \left( s_f(t - T_i) + \sum_{k=1}^{N_{tag}} a_k \cdot s_f(t - T_i - \tau_k) \right),
\]

where \( G_{path} \) is the path loss, \( s_f(t) \) is the effective transmit pulse including the impulse responses of the TX and RX antenna, respectively, and \( a_k \) is the coefficient of the \( k \)-th multi-path component of the transmitted pulse arriving at the base station with delay \( \tau_k \) relative to the LOS component. We apply a modified Saleh-Valenzuela channel model [18] to describe the RF channel, i.e., the distribution of the parameters \( a_k \) and \( \tau_k \). Figure 3 depicts some channel realizations (channel impulse responses, CIRs) for this model, which were taken from [9]. For zero gain TX and RX antennas, the path loss \( G_{path} \) is approximately given by

\[
G_{path} = \left( \frac{c}{4\pi f_c g} \right)^2 \cdot d^{-2},
\]

where \( f_c \) is the geometric center frequency of the pulse and \( d \) is the distance between the antennas [11].

The received pulse \( s_R(t) \) is amplified with a CMOS wide-band low noise amplifier (LNA). State-of-the-art CMOS LNAs for the frequency band from 3.1GHz to 10.6GHz such as that proposed in [19] achieve an average power gain \( G_{LNA} \) of 9dB and an average noise figure \( k_{nf} \) of 5.2dB in that band. The total noise power is \( k_{nf} N_0 B_R \), where \( B_R \) is the receiver bandwidth.

![Figure 2: Building blocks of the UWB transceiver IC.](image)
and $N_0=-174\text{dBm/Hz}$.

![Figure 3: Channel impulse responses of UWB RF channels (CM1: LOS, residential; CM3: LOS, office; CM5: LOS, outdoors) taken from the IEEE802.15.4a task group database at [9] (documents 04/688r0, 04/662r0, 04/714r0, and 04/671r0).](image)

A bank of $S$ parallel samplers in the receiver is driven via a delay lock loop (DLL) from a clock with period $T_{clk}$, i.e., the effective sampling time is $T_s=T_{clk}/S$. The samplers yield 1Bit-quantized samples given by

$$s_n = q\left(\sqrt{G_{\text{ins}} G_{\text{path}}} \cdot s_G(n T_s + j_n) + w_n\right)$$

where $q(x)=+1$ if $x\geq0$ and $q(x)=-1$ if $x<0$, $j_n$ is a Gaussian-distributed sample time jitter independent over the index $n$ with zero mean and standard deviation $\sigma_j$, and $w_n$ is a Gaussian-distributed noise sample with zero mean and variance $\sigma_w^2$. We set the jitter parameter $\sigma_j$ to $10\text{ps}$ for the chosen IC technology [11] and the noise variance $\sigma_w^2$ to $k_{B}T_{\text{amb}}(2T_s)$, i.e., the receiver bandwidth $B_R$ is $1/(2T_s)$.

Assume now that the transmitter generates a series of $P$ pulses $s_{j}(t)$, which are spaced apart by the pulse repetition period $T_p$.

The samples $s_n$ are accumulated in the $R=T_p/T_s$ registers $r_k$ of the correlator, whose contents are given by

$$r_k = \sum_{n=0}^{N} s_{k+nR}.$$  

The registers are red out for further processing if $|r_k|$ for some $k$ exceeds a predefined threshold. In this case, the base station assumes that a pulse has been received.

The smallest possible standard deviation $\sigma_T$ of the time measurement error given the data set $\{r_k\}$ with any type of signal processing is determined by the Cramer-Rao bound

$$\sigma_T \geq \sqrt{I_F^{-1}},$$

where $I_F$ is the Fisher information [20]. The analysis in [11] shows that this bound evaluates as follows for transmission over a multi-path-free RF channel, i.e., all $a_k$ are zero:

**no quantization, no sample time jitter:**

$$\sigma_T > \frac{d}{\sqrt{P}} \cdot \sqrt{\frac{2}{c^2} \cdot \frac{k_{B}T_{\text{amb}}}{G_{\text{ins}}} \cdot E_T},$$

**no quantization, with sample time jitter:**

$$\sigma_T > \frac{d}{\sqrt{P}} \cdot \sqrt{\frac{2}{c^2} \cdot \frac{k_{B}T_{\text{amb}}}{G_{\text{ins}}} \cdot E_T + \frac{\sigma_j^2}{Z}},$$

**1Bit quantization, with sample time jitter:**

$$\sigma_T > \frac{d}{\sqrt{P}} \cdot \sqrt{\frac{\pi}{2} \cdot \frac{2}{c^2} \cdot \frac{k_{B}T_{\text{amb}}}{G_{\text{ins}}} \cdot E_T + \frac{\sigma_j^2}{Z}},$$

where $E_T$ is the energy of $s_{j}(t)$, i.e.,

$$E_T = \int_{-\infty}^{+\infty} s_{j}(t)^2 dt$$

and $Z$ is the number of samples in which the transmit pulse $s_{j}(t)$ is non-zero. The time measurement accuracy does not depend on the actual pulse shape nor the pulse center frequency or the pulse bandwidth. It is a function of the available signal-to-noise ratio (SNR) $E_T/N_{0}$, the receiver parameters $k_{B}T_{\text{amb}}$ and $G_{\text{ins}}$, and the distance $d$ between the TX and the RX antenna, only. This result seems to contradict the “rule-of-the-thumb” in high resolution RADAR applications that $\sigma_T$ declines proportionally to the pulse bandwidth [20]. This rule holds of course as well for the wireless localization system considered here, but the decline $\sigma_T$ due to an increasing pulse bandwidth (exact: quadratic center frequency of the pulse spectrum [11]) is compensated for by a rise due to the path loss $G_{\text{path}}$, which declines proportionally to the square of the pulse bandwidth (exact: geometric center frequency of the pulse spectrum [11]). Thus, the pulse arrival time measurement accuracy of the wireless localization system is determined by the regulatory limit on the allowed transmit pulse energy $E_T$ and some receiver circuit parameters, only.

Figure 4 depicts lower bounds on the standard deviation $\sigma_T$ of the time measurement error for the three receiver circuit models defined above (with or without sampling time jitter and 1Bit quantization). The bounds are shown as function of the distance $d$ between the TX and RX antenna.

The FCC regulation on UWB emissions [1] restricts the effective isotropically radiated power (EIRP) via the power spectral densities -34dBm/MHz (peak) and -41.3dBm/MHz (average), which correspond to a transmit power of 3mW (peak) and 0.56mW (average) when the entire spectrum from 3.1 to 10.6GHz is covered up to the EIRP limit. The chosen peak power of 0.8mW in Figure 4 attains 92% of the peak power limit at -34dBm/MHz.

From Figure 4 follows that a localization system using our transceiver IC can achieve a ranging error standard deviation
of at most $2.5 \cdot 0.5 \cdot 0.4 = 0.5 \text{mm}$ distance between the RX and the TX antenna. This accuracy is by far sufficient for most application scenarios we have in mind (we require a cm accuracy) and it is most likely that other system aspects such as the synchronization between the base stations and the relative antenna position cause much larger systematic ranging errors. Obviously, the time jitter and the 1-Bit quantization affect $\sigma_T$ very little for the chosen IC parameters.

The results of Figure 4 should be interpreted carefully. Consider Figure 5, which depicts how the example transmit pulse $s_T(t)$ from Figure 4 arrives at the RX antenna at time $T_i$. The Cramer-Rao analysis on the standard deviation $\sigma_T$ of the time measurement error while measuring the arrival time of UWB pulses transmitted over a multi-path-free RF channel. The analysis takes into account. The parameters of the transmit pulse $s_T(t)$ are:

- **Pulse shape**: Gaussian, modulated with a cosine wave at frequency $f_c=4\text{GHz}$, pulse bandwidth: $B=2\text{GHz}$, peak transmit power: $0.8\text{mW}$, pulses per burst: $P=500$, pulse repetition time: $T_p=200\text{ns}$, transmit burst length: $P_{T_i}=100\mu\text{s}$, circuit parameters: $k_{\text{ef}}=3.3$, $T_{\text{cs}}=1\text{GHz}$, $S=10$, $G_{\text{in}}=8$, and $\alpha_i=10\text{ps}$.

Thus, as shown in Figure 5, the smaller $f_{\text{cq,eq}}$ the wider the transmit pulse becomes and the harder it is to measure the arrival time $T_i$ outside the interval $[0,1/(2f_c)]$. For the example pulse in Figure 4, we find that $f_{\text{eq}}=4.02\text{GHz}$, $f_{\text{eq}}=3.86\text{GHz}$, and $f_{\text{eq}}=503\text{MHz}$ holds [11]. It follows that the standard deviation $\sigma_T$ of measuring $T_i$ outside the interval $[0,1/(2f_c)]$ is $f_{\text{eq}}f_{\text{eq}}=8$ times the standard deviation $\sigma_T$ of measuring $T_i$ inside the interval $[0,1/(2f_c)]$. As depicted in Figure 4, this results in a ranging error standard deviation $\sigma_T$ of at most $2.5 \cdot 0.5 \cdot 0.4 = 0.5 \text{mm}$ at $d=50\text{m}$ distance between the RX and TX antenna (considering time jitter and 1-Bit quantization). Thus, the wireless localization system should use a transmit pulse $s_T(t)$ with large bandwidth to improve the accuracy of measuring the pulse arrival time in the receiver. Finally, we also have to take the multi-path effects of the RF channel into account. The effects of multi-path propagation on the accuracy of time of arrival (TOA) measurements were analyzed in [21;22]. They also derive algorithms for estimating the channel impulse response (CIR) to improve the measurement accuracy, which is in our setup a function of the coefficients $a_i$ and the delays $\tau_i$. We attempt to estimate the arrival time of the transmitted pulse $s_T(t)$ by considering the LOS component $s_T(t-T_i)$, only. As shown in Figure 3, the received signal contains many multi-path copies of $s_T(t-T_i)$ delayed by $\tau_i$ and attenuated by $a_i$, which are possibly stronger than the LOS path $s_T(t-T_i)$. Using an appropriate threshold on the register contents $|r_k|$ of the correlator in the receiver IC, we aim to discriminate the LOS path $s_T(t-T_i)$ from the multi-path components. Clearly, a small threshold yields a large probability of detecting the LOS path, but this increases as well the probability of false alarm, i.e., some noisy samples $r_i$ of the correlator are mistaken as received pulse.

At the end of this section, we state a final argument for choosing a short UWB pulse as transmit pulse $s_T(t)$ in the wireless localization system. The longer $s_T(t)$ becomes in time (with or without having a large bandwidth), the more likely it
is that $s_f(t-T)$ mixes with its multi-path versions $a_i s_f(t-T_i-\tau)$. It follows that with the same data set $\{\tau_k\}$, many more variables than just $T_i$ have to be estimated (coefficients $a_i$ and delays $\tau_i$). Clearly, a third Cramer-Rao analysis on the standard deviation $\sigma^2_{\tau}$ of the error of measuring $T_i$ is required given that the delays $\tau_i$ and the coefficients $a_i$ must be estimated as well. From the Cramer-Rao lower bound on the estimation error standard deviation for a vector of parameters [20] follows that $\sigma^2_{\tau}$ increases sharply compared to $\sigma^2_\tau$ if the data set $\{\tau_k\}$ cannot be split into subsets of samples depending on $T_i$, or $\tau_i$, respectively. This split is possible only if the LOS path $s_f(t-T)$ is separated in time from the multi-path versions $a_i s_f(t-T_i-\tau)$. 

IV. RESULTS

From Figure 4 and the analysis in the previous section followed that a wireless localization system achieves a ranging error standard deviation $\sigma_0$ of at most $2.5 \cdot c \cdot \sigma^2 \cdot 8.5ps = 3mm$ at the distance $d=50m$ between the TX and RX antenna given the system and pulse parameters defined in Figure 4 and a multi-path free RF channel. This bound can be compared to the simulation results in Figure 6. For determining the arrival time $T_i$, maximum likelihood estimation was applied [20]. To synchronize the tag and the base station clock, the tags transmit an initial synchronization sequence, which is used by the base station to reduce the clock skew (chosen uniformly distributed in the range $\pm 20ppm$) down to $<1ppm$. The simulation results show that the time measurement error standard deviation is very close to the bound $\sigma^2_\tau$ in a working range of up to $d=20m$. For example, from Figure 4 and the ratio $f_{\text{ch}} = 8$ follows that $\sigma^2 = 8 \cdot 0.4ps = 3.2ps$ holds, which coincides with the simulation result in Figure 6. For larger distances $d$, our synchronization procedure starts to become unreliable causing large estimation errors. Ongoing work includes improving the synchronization algorithm applied so far in order that the working range of the system (which strongly depends on the number $P$ of transmitted pulses) increases. The slight increase of the error for small distances $d$ in Figure 6 is due to the applied 1Bit quantization, since the arrival time estimation algorithm requires a very low SNR to work properly. This does not hold for small distances $d$.

The simulation results in Figure 7 were obtained in a residential indoor environment. Even though the corresponding channel model CM1 taken from [9] is defined for the distance range $0<d<4m$, we applied it for $0<d<20m$ in order that the simulation results focus on the dependency of the decaying SNR with increasing $d$. Given this multi-path RF channel model, the increase in the measurement error is tremendous. The ranging error standard deviation at $d=20m$ is now in the meter range, since $\sigma_0 = 2.5 \cdot c \cdot 12ns = 9m$ holds. However, a closer look at the histograms of the estimation error $e_{\text{T},i}$ reveals that the loss in measurement accuracy is because the LOS component has been missed by the estimator for some particular channel realizations. In Figure 8 are shown only those measurements from Figure 7 for which the LOS component in the received pulse could be found correctly. In this case, the ranging error standard deviation $\sigma_0 = 2.5 \cdot c \cdot 8.5ps = 6.4mm$ at the distance $d=20m$ is again close to the Cramer-Rao bound of $2.5 \cdot c \cdot 8.0ps = 2.4mm$.

**Figure 6:** Time measurement error standard deviation for determining the arrival time of UWB pulses transmitted over a multi-path-free RF channel, including sampling time jitter and 1-Bit quantization in the receiver circuit. Also shown is the actual histogram of the measurement error $e_{\text{T},i}$ over 100 measurements for some distances $d$.

**V. CONCLUSIONS**

The achievable time measurement accuracy of our UWB transceiver design is much lower than that of commercially available localization systems [13;14] or that obtained in related work on UWB localization systems [21;22]. However, we focused on the accuracy of a single pulse transmission experiment and did not include other system aspects such as the synchronization of the base station's time bases into the error analysis. We showed that the achievable arrival time measurement accuracy does not depend on the pulse center frequency $f_c$ or bandwidth $B$ in a measurement interval equal to $[0,1/(2f_c)]$, which corresponds to a few cm if the considered UWB pulses have their $f_c$ in the UWB frequency band from 3.1 to 10.6GHz. In the measurement interval $[0,\infty)$, the time measurement accuracy declines approximately by the ratio of the pulse bandwidth $B$ and the center frequency $f_c$. In order to keep this decline short, a pulse with large bandwidth $B$ must be used. We also showed why short transmit pulses are necessary in a multi-path RF channel to maintain the arrival time measurement accuracy. Our simulation results revealed the problem of determining the LOS component of the received UWB pulse in a multi-path RF channel. Ongoing work should therefore focus on how to improve the probability that the LOS components of the UWB pulses transmitted by the tags can be detected. This is hard to achieve with a minimal configuration of tags and base stations, i.e., the localization system must offer redundant base stations to obtain further measurement information, e.g., through a sensor network of tags, which are able to transmit and receive UWB pulses.
Figure 7: Time measurement error standard deviation for determining the arrival time of UWB pulses transmitted over a multi-path RF channel. The chosen channel model is the CM1 model (LOS, residential environment) from [9] (document 04/688r0). Also shown is the actual histogram of the measurement error $e_{T,i}$ over 100 measurements for some distances $d$.

Figure 8: Time measurement error standard deviation for determining the arrival time of UWB pulses transmitted over a multi-path RF channel. The chosen channel model is the CM1 model (LOS, residential environment) from [9] (document 04/688r0). Compared to Figure 7, the standard deviation $\sigma_T$ was calculated by considering the measurements in the main peak of the histograms in Figure 7, only. The width of this peak is 100ps.

VI. REFERENCES


