UWB Ranging Accuracy for Applications within IEEE 802.15.3a

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***Abstract*—The definition of Ultra Wide Band (UWB) signals released by the Federal Communications Commissions (FCC) opened the way to both impulse and non-impulse UWB signal formats, as reflected within the IEEE 802.15.3a TG, devoted to the definition of a standard for UWB-based high bit rate WPANs. The two main proposals considered in this group are a Multi Band OFDM approach, based on the transmission of non-impulse OFDM signals combined with Frequency Hopping (FH), and the Direct-Sequence (DS) UWB approach, based on impulse radio transmission of UWB DS-coded pulses. In this paper, the ranging capabilities of the two proposals are investigated by determining the Cramer-Rào Lower Bound (CRLB) for the distance estimation error. The CRLB is evaluated with both ideal and real, multipath-affected, channel models and the impact of multipath on ranging accuracy is quantified. Results show that DS-UWB is, in general, best suited for ranging, thanks to its larger bandwidth and its higher frequencies of operation, although multipath may affect in a different way DS-UWB and MB-OFDM signals.**

***Index Terms*—UWB, ranging, IEEE 802.15.3a, Cramer–Rào Lower Bound**

I. Introduction

ULTRA Wide Band (UWB) radio is world-wide popular thanks to its promise of providing very high bit rates at low cost. The interest towards this transmission technique led, yet in 2001, to the creation of the IEEE 802.15.3a Study Group, aiming at the definition of a standard for Wireless Personal Area Networks (WPANs) based on a UWB physical layer capable of bit rates in the order of 500 Mb/s.

The activity of the IEEE Group (now referred to as IEEE 802.15.3aTG) further intensified after the first world-wide official UWB emission masks were released by the US Federal Communication Commission (FCC) in February 2002 [1], opening the way to the development of commercial UWB products. The application scenarios suitable for UWB communications naturally emerged from the strong emitted power limits set by the FCC, that is either high bit rates over short ranges, dealt with in the IEEE 802.15.3aTG, or low bit rates over medium-to-long ranges, that is the typical framework of the IEEE 802.15.4TG for sensor networks.

The selection process of the UWB PHY proposals originally submitted to the 802.15.3a Task Group led to two merged proposals: the Multi Band OFDM solution, based on the transmission of non-impulse OFDM signals combined with Frequency Hopping (FH) over instantaneous frequency bandwidths of 528 MHz, and the Direct-Sequence (DS) UWB proposal, based on impulse radio transmission of UWB DS-coded pulses.

Technical discussions and evaluation of such proposals focused on the priority of the IEEE 802.15.3a Task Group, that is the achievement of a high bit rate. As a consequence, proposals did not address one of the most appealing features of UWB radio: the capability of estimating distance between terminals with high accuracy, providing thus joint communications and ranging. The UWB ranging capability is particularly attractive as a support for location-aware applications in ad-hoc and sensor networks, that is the focus of the IEEE 802.15.4a Working Group, specifically aimed at low bit rate networks with location and tracking.

Although not specifically designed for ranging support, both MB-OFDM and DS-UWB proposals adopt UWB emissions with bandwidths exceeding 500 MHz, in compliance with the UWB definition given by the FCC, and can thus potentially provide high ranging accuracy.

The goal of this work is to determine and compare the ranging accuracy of MB-OFDM and DS-UWB proposals in an indoor environment. We will first carry out the analysis in an ideal case by determining the Cramer-Rào Lower Bound (CRLB) in presence of an ideal channel. The CRLB establishes in fact the lower bound on the ranging accuracy achievable by a signal characterized by a given bandwidth and energy. Next, we will introduce a real channel model taking into account multipath as well as frequency selectivity, and evaluate its impact on the ranging accuracy that can be obtained with the two IEEE 802.15.3a signal formats.

The paper is organized as follows. Section II presents the signal definition for both 802.15.3a proposals, while Section III reviews and fixes the notation for the CRLB. In Sections IV and V the CRLB is derived for the impulse vs. non-impulse UWB 802.15.3a proposals, for an ideal vs. a real channel. Section VI draws conclusions.

II. Signal definitions

Notations for the two UWB signal formats under discussion within the IEEE 802.15.3a Task Group are given in this section.

A. Multi Band Orthogonal Frequency Division Multiplexing (MB-OFDM)

An OFDM modulated signal consists in the parallel transmission of N signals modulating N frequency sub-carriers f_m (m=0,…,N-1). All sub-carriers f_m are spaced by a constant

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shift Δf. The modulating signal is usually obtained by mapping the binary sequence on a QPSK constellation, each QPSK symbol ($c_m = a_m + jb_m$) modulating a different sub-carrier f_m.

The frequency carriers used in the 802.15.3a MB-OFDM format [2] fall within the frequency interval between 3.1 GHz and 10.6 GHz, where a radiated power of -41.25 dBm/MHz is allowed by the FCC rules [1].

TABLE I
MAIN PARAMETERS OF THE MB-OFDM PROPOSAL

Parameter	Value
N_{SD}: Number of data subcarriers	100
N_{SDP}: Number of defined pilot subcarriers	12
N_{SG}: Number of guard carriers	10
N_{ST}: Total number of subcarriers	122 (=N_{SD}+N_{SDP}+N_{SG})
Δf: Subcarrier frequency spacing	4.125 MHz (=528MHz/128)
T_{FFT}: IFFT/FFT period	242.2 ns (1/ Δf)
T_{CP}: Cyclic prefix duration	60.61 ns (=32/528MHz)
T_{GI}: Guard interval duration	9.47 ns (=5/528MHz)
T_{SYM}: Symbol interval	312.5 ns (=T_{CP}+T_{FFT}+T_{GI})

In the 802.15.3a MB-OFDM format, the [3.1–10.6] GHz interval is divided into 13 sub-intervals. Each sub-interval corresponds to one band of the MB-OFDM, and is 528 MHz wide. The center frequency of each band n_b is determined by the following rule:

$$\text{Center frequency for band } n_b = \begin{cases} 2904 + 528 \times n_b & n_b \quad 1\ldots4 \\ 3168 + 528 \times n_b & n_b \quad 5\ldots13 \end{cases} \quad (MHz) \tag{1}$$

The MB-OFDM proposal foresees two different Modes of operation: a mandatory Mode 1 and an optional Mode 2. Mode 1 uses three bands of operation: Band 1 ([3.168–3.696] GHz), Band 2 ([3.696–4.224] GHz), and Band 3 ([4.224–4.752] GHz). Mode 2 uses seven bands: Bands 1, 2, 3 (as in Mode 1), Band 6 ([6.072–6.60] GHz), Band 7 ([6.60–7.128] GHz), Band 8 ([7.128–7.656] GHz), and Band 9 ([7.656–8.184] GHz). The four unmentioned bands have been reserved for future use. Table I reports values for the main parameters of the MB-OFDM signal, such as the number of the sub-carriers, the duration of the waveform and the time of the FFT. The set of parameters also includes the guard interval, which is introduced to mitigate Inter-Symbol Interference ISI, and the number of pilot carriers used for channel estimation.

Each symbol time is divided into two parts: the useful signal, of duration 242.4 ns (T_{FFT}), and the cyclic prefix, of duration 70.1 ns (T_{GI}), for an overall duration of 312.5 ns (T_{SYM}=T_{FFT}+T_{GI}). The cyclic prefix, located at the onset of the transmitted signal, is a replica of the final interval of the transmitted signal, and it is used for synchronization and for channel estimation purposes.

Under the above conditions the transmitted signal can be written as follows:

$$x(t) = g_T(t) \cdot \sum_{m=0}^{N-1} \left(a_m \cos\left(2\pi \left(f_p + f_m\right) t + \phi\right) - b_m \sin\left(2\pi \left(f_p + f_m\right) t + \phi\right) \right) \tag{2}$$

where f_p is the center frequency of the Band, $g_T(t)$ is the impulse response of the pulse shaper and ϕ is the phase at t=0.

B. Direct Sequence UWB (DS-UWB)

A DS-UWB signal consists in the transmission of a binary sequence coded with a pseudorandom sequence modulating the amplitudes of a train of short pulses. The bandwidth of such a signal depends on the width of the pulses, while the adoption of a pseudorandom sequence guarantees a close to flat PSD.

The transmitter is composed of four main blocks: a repeater, a transmission coder, a PAM modulator, and a pulse shaper.

Each bit of the binary sequence is repeated N_s times, so that the output of the repeater is a sequence of N_sN_b bits, where N_b is the number of bits of the input sequence. The repeater introduces thus redundancy in the transmitted sequence.

The transmission coder applies a binary code of period N_p to the output sequence of the repeater. Most commonly, N_p is a multiple of N_s.

The output sequence of the transmission coder enters the PAM modulator, which generates a train of Dirac pulses, located at multiples of T_s.

The output of the PAM modulator enters the pulse shaper filter with impulse response *p(t)*. The impulse response is a pulse with duration smaller than T_s.

The output signal of the transmission cascade is expressed as follows:

$$s(t) = \sum_{j=-\infty}^{+\infty} d_j p\left(t - jT_s\right) \tag{3}$$

where the symbols d_j are the symbols of the output sequence of the PAM modulator.

The DS-UWB proposal foresees two different carrier frequencies, located at 4.104 GHz (Low Band) and 8.208 GHz (High Band) respectively. For the low (high) frequency band the filter cutoff frequency (-3 dB point) is 684 MHz (1368 MHz) leading to a bit duration of 1/57 ms (1/114 ms).

III. CRAMER-RAO LOWER BOUND (CRLB)

The CRLB defines the best estimation performance, defined as the minimum achievable error variance σ_t^2, that can be achieved by using an ideal unbiased estimator. It constitutes thus a valuable tool in evaluating the potentials of UWB signals for distance estimation.

In this section we will derive the expression of the CRLB for distance estimation error that will be applied to the IEEE 802.15.3a signals in the next section.

Let us consider a signal $s(t;\{a_k\})$ arriving at the receiver through a wireless channel, and depending on time t and a set of unknown parameters $\{a_k\}$. At the receiver thermal noise $w(t)$ sums up to the signal; if the overall frequency occupation is B, the power of thermal noise can be defined as follows:

$$\sigma_w^2 = F\,kTB/2 \tag{4}$$

where F is the noise figure of the receiver and T is the temperature.

The received signal is thus given by $r(t) = s(t;\{a_k\}) + w(t)$. Such signal is sampled with a sampling period $T_s = 1/B$. The sequence of samples of the useful signal is $s_n = s(nT_s;\{a_k\})$, while the corresponding noise and received signal samples are $w_n = w(nT_s)$ and $w_n = s_n + w_n$, respectively.

The Cramer-Rao theorem states that for any unbiased estimator, the minimal achievable error variance σ_t^2 is:

$$\sigma_t^2 \geq F_n^{-1} \tag{5}$$

where F_n is the Fisher information matrix, defined as follows:

$$F_n = -E\left\{\left(\frac{\partial}{\partial\theta}\ell(X;\theta)\right)^2\right\} = -E\left\{\left(\frac{\partial^2}{\partial\theta^2}\ell(X;\theta)\right)\right\} \tag{6}$$

$\ell(X;\theta)$ in eq. (6) is the log likelihood function with respect to parameter θ. In the case we are considering, the log likelihood function is the logarithm of the probability of the estimation error conditioned to the knowledge of the delay τ and of $\{a_k\}$:

$$p(r \mid \tau;\{a_k\}) = \frac{1}{(2\pi)^{N/2}}\exp\left\{-\frac{\sum_n\left[r_n - s(nT_s-\tau;\{a_k\})\right]^2}{\sigma_w^2}\right\} \tag{7}$$

In order to evaluate the CRLB we need the second derivative of the log likelihood function, that is:

$$-\frac{\partial^2}{\partial\tau^2}\ln\left[p(r \mid \tau;\{a_k\})\right] = \frac{2}{\sigma_w^2}\sum_n\left\{\dot{s}^2(nT_s-\tau;\{a_k\}) - \left[r_n - s(nT_s-\tau;\{a_k\})\right]\ddot{s}(nT_s-\tau;\{a_k\})\right\} \tag{8}$$

The average value of eq. (8) corresponds to the Fisher information matrix:

$$F_n = \frac{4}{N_0}\int \dot{s}^2(t;\{a_k\})\,dt \tag{9}$$

The minimal achievable variance for any unbiased estimator (CRLB) is thus:

$$\sigma_t^2 = \frac{1}{F_n} = \frac{N_0}{4\int \dot{s}^2(t;\{a_k\})\,dt} = \frac{1}{2\left(\frac{2E}{N_0}\right)\beta^2} \tag{10}$$

where:

$$\beta^2 = \frac{\int \dot{s}^2(t;\{a_k\})\,dt}{\int s^2(t;\{a_k\})\,dt} = -4\pi^2\frac{\int f^2 S^2(f;\{a_k\})\,df}{\int S^2(f;\{a_k\})\,df} \tag{11}$$

The maximum theoretical ranging accuracy achievable with the proposed UWB signal formats can be obtained by considering the corresponding $s(t)$, taking into account the characteristics of the transmitted signal and of the channel.

IV. CRLB WITH AN IDEAL CHANNEL

In this section we will compare the IEEE 802.15.3a proposals under the hypothesis of an ideal channel. In this case, the CRLB is:

$$\sigma_t^2 = \frac{N_0 \cdot D^2}{16\pi^2 T\int f^2 PSD(f)\,\partial f} \tag{12}$$

For a given $PSD(f)$, eq. (12) provides σ_t^2 as a function of D^2 and T, where D is the distance between transmitter and receiver, and T is the observation interval. Distance estimation error (σ_x^2) can be obtained from the time estimation error as:

$$\sigma_x^2 = c^2 \cdot \sigma_t^2 \tag{13}$$

where c is the propagation speed of the signal.

Figure 1 plots σ_x as a function of D^2/T for Bands 1-3 used by MB-OFDM Mode 1 and for the two bands used by DS-UWB.

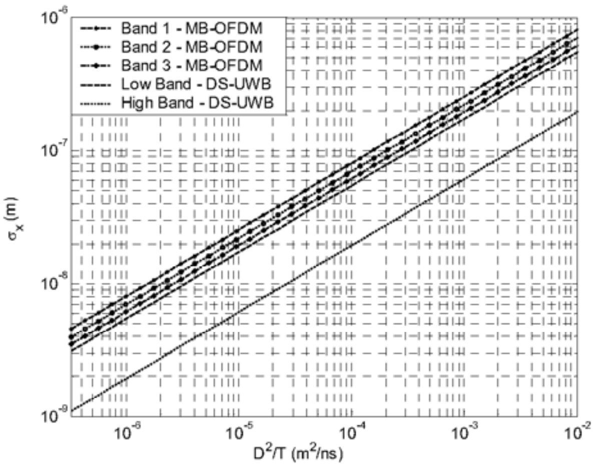

Figure 1 - Standard deviation of distance estimation error in logarithmic scale for MB-OFDM and DS-UWB signals

The High Band of DS-UWB has best ranging performance, thanks to the large bandwidth (about 1.3 GHz vs. about 600 MHz of the Low Band) and the higher frequency carrier. As an example, at D = 1 m, with an observation time T = 312.5 ns, the expected σ_x is about 10^{-7} m. The other signals lead to an error that is almost one degree of magnitude larger, with a slightly better performance for Band 3 of MB-OFDM.

Note that the ranging capability of the MB-OFDM signal could be further improved by adopting multiple bands at the same time, increasing thus the instantaneous signal bandwidth. We investigated this option by considering two additional signals using Bands 1-3 and Bands 6-9 of the MB-OFDM proposal, respectively. The results obtained are presented in Figure 2, where the two signals are identified as Mode 1 and Mode 2 MB-OFDM, respectively. The CRLB for the High Band of DS-UWB is also presented in Figure 2 as a reference.

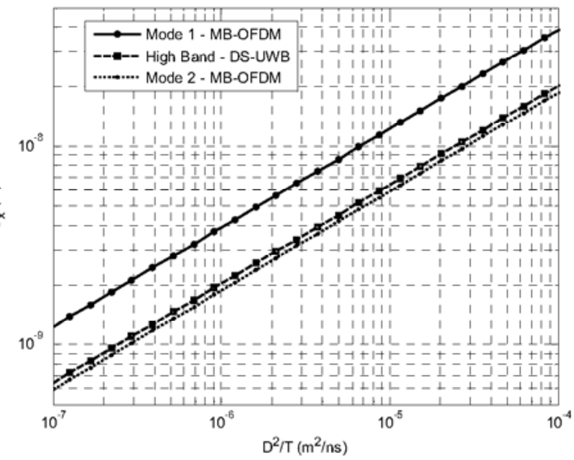

Figure 2 - Standard deviation of distance estimation error in logarithmic scale for MB-OFDM signals using multiple bands (Mode 1: Bands 1-3, Mode 2: Bands 6-9) vs. High Band of DS-UWB for an ideal channel.

Figure 2 shows that the use of Bands 1-3 only marginally improves the accuracy of MB-OFDM signals, while the use of the four Higher bands leads to the best accuracy, thus confirming the key role of carrier frequency in ranging accuracy.

It should be noted however that the better ranging performance obtained for High Band of the DS-UWB proposal and of Mode 2 of MB-OFDM is obtained at the price of a shorter communication range, due to the higher propagation loss at high frequencies.

V. CRLB WITH A REAL CHANNEL

In order to analyze the impact of a real indoor channel on ranging accuracy we adopted the channel model proposed within the IEEE 802.15.3a Channel Model subcommittee [2]. This model takes into account the presence of multipath by introducing N replicas of the signal, equally spaced in time and with amplitudes depending on both distance and delay. The channel impulse response can be expressed as follows:

$$h(t) = \sum_{n=1}^{N} \alpha_n(D, \tau_n)\, \delta(t - \tau_n) \quad (15)$$

$$\alpha_n(D, \tau_n) = k \cdot \frac{e^{-D}}{D} e^{-\frac{\tau_n}{\tau_0}} \quad (16)$$

We considered a set of realizations of the channel impulse response, represented by the six channel scenarios presented in Table II. We focused in particular on the effect of the variations of parameters N and τ_n, representing the delay between two consecutive replicas of the signal. Note that the values of τ_n and N were selected as to keep constant the duration of channel impulse response.

TABLE II

CHANNEL PARAMETERS CONSIDERED IN SECTION V

Scenario	τ_n *(ns)*	N	k	τ_0 *(ns)*
A	From 0 to 50 ns spaced 1 ns	50	0.1	15
B	From 0 to 50 ns spaced 1.25 ns	40	0.1	15
C	From 0 to 50 ns spaced 1.67 ns	30	0.1	15
D	From 0 to 50 ns spaced 2.5 ns	20	0.1	15
E	From 0 to 50 ns spaced 5 ns	10	0.1	15
F	From 0 to 50 ns spaced 50 ns	2	0.1	15

Figure 3 shows CRLB for both ideal channel and scenario A in Table II for MB-OFDM and DS-UWB as a function of D^2/T.

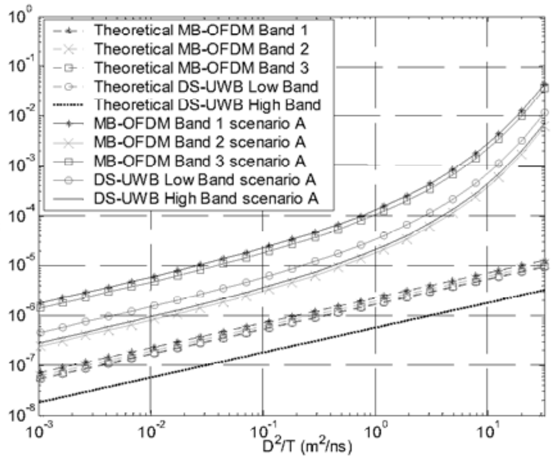

Figure 3 - Standard deviation of distance estimation error in logarithmic scale for MB-OFDM and DS-UWB signals in an ideal channel and in a real channel (scenario A in Table II)

Figure 3 shows that in scenario A the MB-OFDM in Band 2 leads to the lowest estimation error with a variance of the estimation error that, for low distances, is close to the CRLB achievable with the ideal channel, while it dramatically increases for higher distances. A similar result can be observed for both bands used in the DS-UWB proposal.

The better performance of Band 2 is highly related to the channel transfer function defined in scenario A, determined by the choice of the channel parameters. As a consequence, the CRLB for MB-OFDM and DS-UWB in the different bands will vary in a different way as a function of such parameters.

In order to evaluate the effect of the parameters of the channel model on the achievable performance, let us consider a test case, in particular the MB-OFDM using Band 2, in order to analyze the effect of different channel realizations on the corresponding CRLB. Note that considerations made in the remaining part of this section apply to the DS-UWB case as well.

Figure 4 shows the CRLB for the MB-OFDM using Band 2 in the six scenarios of Table II and in the ideal case considered in section IV. It can be observed that, by increasing the delay between two replicas, moving from scenario A to F, the CRLB obtained approaches the CRLB obtained using an ideal channel.

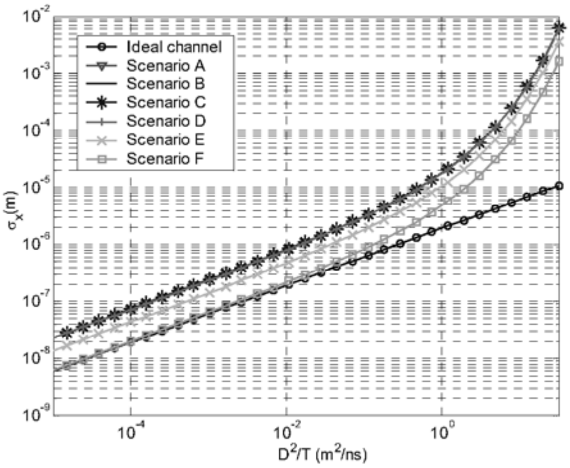

Figure 4 - CRLB obtained for the MB-OFDM signal using Band 2 in scenarios defined in Table II

This effect can be explained by considering the effect of the delay τ_n on the channel transfer function, presented in Figure 5. Figure 5 shows in fact that, as τ_n increases, the multipath effect decreases and the channel transfer function resembles the transfer function of an ideal channel. Note that the value of τ_n affects the positions and the number of the peaks in the transfer function. The two limit cases are the presence of only two replicas of signal (Scenario F) and the presence of 50 replicas (Scenario A). The transfer function of the Scenario F is almost flat, while the Scenario A has a big peak in correspondence of Band 2 used in the MB-OFDM, and thus explains the better performance achieved for the signal working in this band presented in Figure 3.

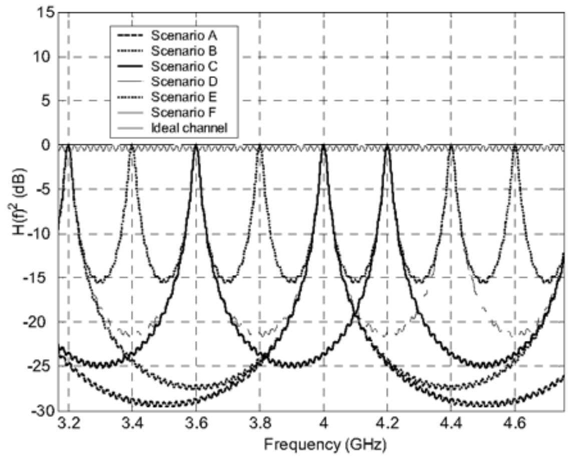

Figure 5 - Transfer function of the different realizations of channel H(f) reported in Table II for the MB-OFDM signal using Band 2

VI. CONCLUSIONS

In this paper, we analyzed the ranging capabilities of the two UWB signal formats proposed within the IEEE 802.15.3a TG, that is the impulsive DS-UWB and the non-impulsive MB-OFDM. The analysis was carried out by evaluating the Cramer-Rao Lower Bound for the two proposed UWB signals, taking into account the emission limits set by the FCC for indoor UWB emissions. The CRLB was first evaluated considering an ideal channel, and the results highlighted that the DS-UWB signal using the High Band has the best ranging accuracy, thanks to its larger bandwidth and higher operative frequency, and that the same accuracy is only achievable by MB-OFDM signals if multiple bands are used at the same time. The CRLB was then evaluated in presence of a real channel model with multipath, showing that DS-UWB and MB-OFDM are differently affected by the channel. The effect of channel was analyzed in detail in the case of the MB-OFDM signal operating in Band 2, highlighting that strong multipath significantly reduces the ranging accuracy, and suggesting that a channel-aware selection of the transmission band can significantly improve ranging performance.

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