IEEE International Conference on UWB, Zurich, Switzerland, pp. 302-307, September 5-8, 2005

Lower bounds for ranging accuracy with Multi Band OFDM and Direct Sequence UWB signals

R. Cardinali, L. De Nardis, P. Lombardo, M.-G. Di Benedetto
University of Rome La Sapienza,
Rome, Italy
r.cardinali@infocom.uniroma1.it, lucadn@newyork.ing.uniroma1.it, pier@infocom.uniroma1.it, gaby@acts.ing.uniroma1.it

Abstract — **The definition of Ultra Wide Band (UWB) signals set by the Federal Communications Commissions (FCC) opened the way to both impulse and non-impulse UWB signal formats. This is reflected within the IEEE 802.15.3a TG, aiming at the definition of a standard for UWB-based high bit rate WPANs. The two main proposals considered in this group are in fact 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 we analyze the ranging capabilities of the two proposals by first determining the Cramer-Rao Lower Bound (CRLB) for the error in distance estimation using both an ideal channel model and a real channel model taking into account the effect of multipath. Next, we investigate the impact of receiver structure and synchronization sequences adopted in the two proposals on the ranging accuracy. Results show that synchronization sequences play a key role in determining the ranging accuracy. Although the DS-UWB signal is in general best suited for ranging, thanks to its larger bandwidth and its higher frequencies of operation, specific synchronization sequences may in fact lead to better ranging accuracy for the MB-OFDM signal.**

Index Terms—**UWB, ranging, localization, Cramer–Rao Lower Bound**

I. Introduction

ULTRA Wide Band (UWB) radio has gained popularity world-wide thanks to its promise of providing very high bit rates at low cost. The interest toward this transmission technique led, yet in 2001, to the creation of the IEEE 802.15.3a Study Group, aiming at the definition of a novel 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 release of the first world-wide official UWB emission masks by the US Federal Communication Commission (FCC) in February 2002 [1]. The release of emission masks officially opened the way, at least in the US where the masks apply, to the development of commercial UWB products. The strong limitations set by the FCC naturally defined the application scenarios suitable for UWB communications, 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 are the main objective of the IEEE 802.15.4TG.

The several different UWB PHY proposals originally submitted to the 802.15.3a Task Group converged into two main 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.

The work carried out within the IEEE 802.15.3a Task Group focused on the main priority of achieving a high bit rate. As a consequence, final standard specifications do not include any requirement on one of the most appealing features of UWB radio: the capability of estimating distance between terminals with high accuracy, enabling 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 order to comply with the UWB definition given by the FCC, and can thus potentially provide high ranging accuracy.

In this work we will determine and compare 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-Rao Lower Bound (CRLB) in presence of an ideal channel. The CRLB defines in fact the lower bound on the ranging accuracy as a function of signal bandwidth and energy. Next, we will introduce a real channel model that takes into account multipath as well as frequency selectivity, and evaluate its impact on the ranging accuracy that can be obtained with the two proposals. Finally, we will investigate the impact of the receiver structure on the ranging accuracy.

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 analyzes the impact of receiver structure on ranging accuracy, while conclusions are drawn in Section VII.

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 that are modulated at N frequency carriers f_m (m = 0, …, N-1). All sub-carriers f_m are equally spaced by Δf. The binary sequence is usually mapped on a QPSK constellation, and each QPSK symbol ($c_m = a_m + jb_m$) modulates a different sub-carrier f_m.

The frequency carriers (f_p) used in the 802.15.3a MB-OFDM format [2] occupy the frequency interval between 3.1 GHz and 10.6 GHz, that is in the frequency interval where the FCC has allocated a transmission power of -41.3 dBm/MHz [1].

In the 802.15.3a MB-OFDM format, the available frequency interval is divided into 13 frequency intervals. Each interval corresponds to one band of the MB-OFDM, and is 528 MHz wide. The center frequency of each band and the band number are related according to the following rule:

$$\text{Center frequency for band } n_b = \begin{cases} 2904 + 528 \times n_b & n_b = 1 \ldots 4 \\ 3168 + 528 \times n_b & n_b = 5 \ldots 13 \end{cases} \quad (MHz) \tag{1}$$

The MB-OFDM proposal foresees two different modes of transmission: a mandatory Mode 1 and an optional Mode 2. Mode 1 uses three bands of operation: Band 1 [3.168 GHz, 3.696 GHz], Band 2 [3.696 GHz, 4.224 GHz], and Band 3 [4.224 GHz, 4.752 GHz].

Mode 2 considers seven bands: Band 1, 2, 3 (same as Mode 1), Band 6 [6.072 GHz, 6.60 GHz], Band 7 [6.60 GHz, 7.128 GHz], Band 8 [7.128 GHz, 7.656 GHz], and Band 9 [7.656 GHz, 8.184 GHz]. The four unmentioned bands have been reserved for future use. Table I introduces the key signal parameters in the MB-OFDM proposal, such as the number of subcarriers, the duration of the waveform, the period of the FFT. Additional parameters include a guard interval, which is introduced to mitigate Inter-Symbol Interference ISI and the number of pilot carriers, used for channel estimation.

Symbol duration T_{SYM} is divided into three parts: the useful signal, of duration 242.4 ns (T_{FFT}), the cyclic prefix, of duration 60.61 ns (T_{CP}), and the guard interval, of duration 9.47 ns (T_{GI}), for an overall symbol duration of 312.5 ns ($T_{SYM}=T_{FFT}+T_{CP}+T_{GI}$). 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 $g_T(t)$ is the impulse response of the pulse shaper and ϕ is the phase at t=0.

TABLE I
MAIN PARAMETERS OF THE MB-OFDM PROPOSAL

Parameter	Value
N_{SD}: Number of data subcarriers	100
N_{SDP}: Number of 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	242.42 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})

B. Direct Sequence UWB (DS-UWB)

A DS-UWB signal consists in the transmission of a binary sequence coded with a pseudorandom sequence, and which modulates the amplitudes of a train of short pulses. The bandwidth of such a signal depends on the width of the pulse. The adoption of a pseudorandom sequence guarantees a close to flat Power Spectral Density (PSD).

The transmitter is composed of four main blocks: a repeater, a transmission coder, a Pulse Amplitude Modulation (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 shorter 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.

Similarly to the case of the MB-OFDM transmission, the frequency interval occupied by the transmission signal is between 3.1 GHz and 10.6 GHz, where a transmission power of -41.3 dBm/MHz is allowed [1].

The DS-UWB proposal uses two different carrier frequencies for transmission located around 4 GHz (Low

Band) and 8 GHz (High Band). For the low (high) frequency band the filter cutoff frequency (-3 dB point) is about 684 MHz (1368 MHz) leading to a chip duration of 1/57 μs (1/114 μs).

III. CRAMER-RAO LOWER BOUND (CRLB)

The CRLB is a fundamental concept in estimation theory and, as such, it is widely addressed in literature. In this paragraph a brief description of how the CRLB can be derived and applied to UWB signals is presented. An extensive analysis of the CRLB can be found in [4] and [5].

The CRLB estimates the achievable performance using an ideal unbiased estimator, defined as the minimal achievable error variance for an unbiased estimator σ_t^2. Although this performance is not attainable using a real estimator, the Cramer-Rao lower bound is instrumental in evaluating the potentials of UWB-based ranging.

In order to individuate the characteristics of an UWB signal that minimize CRLB, let us consider a received signal $r(t)=s(t\,;\{a_k\})+w(t)$ obtained as the sum of a signal $s(t\,;\{a_k\})$, function of the time t and of a set of unknown parameters $\{a_k\}$, and of thermal noise $w(t)$. The overall frequency occupation of the signal being B, the power of thermal noise can be defined as follows:

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

At the receiver the signal is sampled at frequency $f_s=1/T_s=B$. The sequence of useful signal samples is $s_n = s(nT_s;\ \{a_k\})$, while the corresponding noise and received signal samples are $w_n = w(nT_s)$ and $r_n = s_n + w_n$ respectively.

The Cramer-Rao theorem indicates 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, in our case, as follows:

$$F_n = -E\left\{\left(\frac{\partial}{\partial t}\ln\left(p_s(t;\{a_k\})\right)\right)^2\right\} = -E\left\{\left(\frac{\partial^2}{\partial t^2}\ln\left(p_s(t;\{a_k\})\right)\right)\right\} \tag{6}$$

where $p_s(t;\{a_k\})$ is the probability density function with respect to parameter t. After some calculations one obtains that the minimal achievable variance for any unbiased estimator (CRLB) is given by:

$$\sigma_t^2 = \frac{1}{F_n} = \frac{N_0}{4\int \dot{s}^2(t;\{a_k\})\,dt} = \frac{1}{2\left(\frac{2E}{N_0}\right)\beta^2} \tag{7}$$

where:

$$\beta^2 = \frac{\int \dot{s}^2(t;\{a_k\})dt}{\int s^2(t;\{a_k\})dt} = -4\pi^2\frac{\int f^2 S^2(f;\{a_k\})df}{\int S^2(f;\{a_k\})df} \tag{8}$$

In the next section we will determine the CRLB for the MB-OFDM and DS-UWB signal formats by selecting $S^2(f)$ accordingly to the definitions provided in Section II.

IV. CRLB WITH AN IDEAL CHANNEL

The first step is the comparison between the two proposals under the hypothesis of an ideal channel, introducing an attenuation proportional to the square of the distance D between transmitter and receiver. In this case, the CRLB is:

$$\sigma_t^2 = \frac{N_0 \cdot D^2}{16\pi^2 T\int f^2 PSD(f)\,df} \tag{9}$$

For a given $PSD(f)$, eq. (9) shows that σ_t^2 depends on D^2 and T, where D is the distance between transmitter and receiver, and T is the observation interval. In the following, we will analyze the accuracy in terms of distance estimation. Variances of time estimation error (σ_t^2) is in fact related to the distance estimation error (σ_x^2) as follows:

$$\sigma_x^2 = c^2 \cdot \sigma_t^2 \tag{10}$$

where c is the propagation speed of the signal.

Figure 1 plots σ_x for the three bands used by MB-OFDM Mode 1 and for the two bands used by DS-UWB as a function of D^2/T. Figure 1 shows that all signal choices lead to a similar trend, although different degrees of accuracy are achieved by different signals. The performance differences are due to two factors: the difference in the width of occupied frequencies and in the value of the center frequency. The High Band of DS-UWB has the best ranging performance, thanks to the large bandwidth (1.3 GHz vs. 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 a ranging error that is almost one degree of magnitude larger, with, as expected, a slightly better performance for Band 3 of MB-OFDM thanks to its higher carrier frequency.

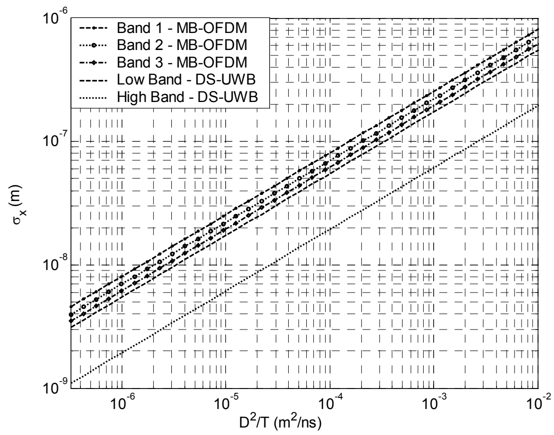

Figure 1 - Standard deviation of distance estimation error in logarithmic scale for MB-OFDM and DS-UWB signals.

V. CRLB WITH A REAL CHANNEL

In the following we will adopt the channel model proposed in Batra et al. [2] within the IEEE 802.15.3a Channel Model subcommittee. This model hypothesizes the presence of strong multipath, which causes several overlapped replicas of a transmitted signal. The model assumes that all channel parameters are random variables with specific, well defined, distributions.

The channel model introduces N replicas of the signal that are equally spaced in time and with amplitudes depending on both distance and delay. The channel impulse response can be expressed as follows:

$$h(t) = \sum_{n=1}^{N} \alpha_n (D, \tau_n) \delta(t - \tau_n) \quad (11)$$

$$\alpha_n (D, \tau_n) = k \cdot \frac{e^{-D}}{D} e^{-\frac{\tau_n}{\tau_0}} \quad (12)$$

In order to compare the ranging performance of the two proposals in presence of multipath, we will consider different realizations of the channel impulse response obtained using the above model, and evaluate the corresponding CRLB. The selected realizations are reported in Table II.

TABLE II
CHANNEL PARAMETERS CONSIDERED IN SECTION V

Scenario Identification	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 2 shows CRLB for both ideal channel and scenario A for MB-OFDM and DS-UWB as a function of D^2/T.

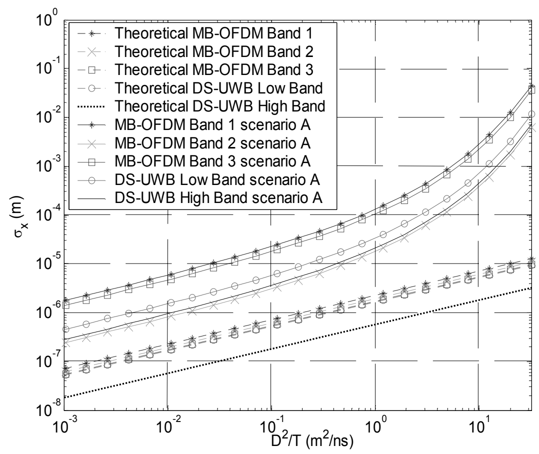

Figure 2 - Standard deviation of distance estimation error in logarithmic scale for different signals: MB-OFDM and DS-UWB for a non ideal channel (scenario A of Table II)

Note that for low distances, losses are contained, while they dramatically increase for higher distances. Also note that performance depends exponentially upon distance, since α_n depends on distance as e^{-D}. Figure 2 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. A similar result is obtained for both bands used in the DS-UWB proposal. These results are due to the particular transfer function of the channel considered in scenario A.

A different choice of the parameters defining the channel will lead to different results, as shown in Figure 3, presenting the CRLB for the MB-OFDM using Band 2 in the six scenarios defined in Table II and in the ideal case.

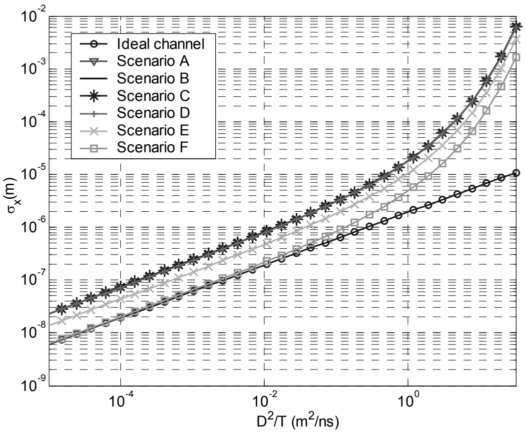

Figure 3 - CRLB obtained for the MB-OFDM signal using Band 2 in scenarios defined in Table II.

VI. ACCURACY USING CORRELATION FILTER

In this section we will evaluate the variance of the ranging error taking into account the structure of the receiver, formed of a correlation filter combined with a Delay Lock Loop based on an Early-Late Gate structure, as presented in Figure 4, , where *s(t)* is the transmitted signal and *w(t)* is the noise.

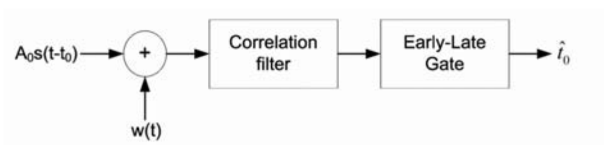

Figure 4 – Flow chart of an Early-Late Gate estimator.

The Early-Late Gate finds the null of the derivative of the input signal $x(t) = A_0 s(t - t_0) + w(t)$, solving the following equation:

$$\frac{|x(\hat{t}_0 + \Delta)|^2 - |x(\hat{t}_0 - \Delta)|^2}{2\Delta} = 0 \quad (13)$$

where A_0 is the amplitude of the signal in correspondence of the input of the Early-Late Gate, $\hat{t}_0$ is the estimation of the time of arrival, and Δ is the width of the Early-Late Gate.

The error of the estimation of the time of arrival is:

$$\delta t = \hat{t}_0 - t_0 \quad (14)$$

where t_0 is the true value.

In order to evaluate the estimation error it is necessary to write the equation of the Early-Late Gate as a function of the estimation error as follows:

$$\left|x(\hat{t}_0+\Delta)\right|^2 = A_0^2\left|s(\delta t+\Delta)\right|^2 + \\ +\left|w(\hat{t}_0+\Delta)\right|^2 + 2A_0\,\mathrm{Re}\left\{s(\delta t+\Delta)w^*(\hat{t}_0+\Delta)\right\} \quad (15)$$

By developing the previous expression in Taylor series at the first order and ignoring the second order terms of the noise and the cross term $\delta t\ w(t)$, one has:

$$\left|x(\hat{t}_0+\Delta)\right|^2 = A_0^2\left|s(\Delta)\right|^2 + A_0^2\left|\frac{\partial s(t)}{\partial t}\right|^2\Bigg|_{t=\Delta}\partial t + 2A_0\left|s(\Delta)\right|w_R(\hat{t}_0+\Delta) \quad (16)$$

where $w_R(t)$ is the real part of the noise. Thanks to the symmetry of the signal $x(t)$, eq. (13) can be written as:

$$2A_0^2\left|\frac{\partial s(t)}{\partial t}\right|^2\Bigg|_{t=\Delta}\delta t + 2A_0\left|s(\Delta)\right|\left[w_R(\hat{t}_0+\Delta) - w_R(\hat{t}_0-\Delta)\right] = 0 \quad (17)$$

leading to an estimation error given by:

$$\delta t = \frac{2A_0\left|s(\Delta)\right|\left[w_R(\hat{t}_0-\Delta) - w_R(\hat{t}_0+\Delta)\right]}{2A_0^2\left|\frac{\partial s(t)}{\partial t}\right|^2\Bigg|_{t=\Delta}} \quad (18)$$

By applying the mean value operator to the square of both sides of eq. (18) and knowing that the noise autocorrelation $R_{ww}(\tau)$ and its real part, $R_{w_R w_R}(\tau)$, satisfy the relation $R_{ww}(\tau) = 2R_{w_R w_R}(\tau)$, one obtains:

$$\sigma_t^2 = \frac{1-\rho_w(2\Delta)}{4SNR\left(\frac{\partial\left|s(t)\right|}{\partial t}\Bigg|_{t=\Delta}\right)^2} \quad (19)$$

where $\rho_w(\tau) = \frac{R_{ww}(\tau)}{\sigma_w^2}$ is the correlation function of filter, and SNR is the Signal to Noise Ratio at the input of the receiver. Note that σ_t^2 depends on the characteristics of both the signal waveform $s(t)$, through its derivative, and the synchronization sequence, through its autocorrelation function. We will use eq. (19) to evaluate the variance of error obtained using the correlation filter for both MB-OFDM and DS-UWB signals.

A. MB-OFDM synchronization sequences

The MB-OFDM proposal foresees a frequency and clock synchronization performed in every frame. The synchronization includes two phases: acquisition, which corresponds to a rough estimation, and tracking, which refines the estimation obtained during the acquisition. The synchronization algorithm uses a pilot symbol, known to both transmitter and receiver.

The MB-OFDM proposal defines four different pilot symbols, named preambles, specifically designed to operate in four different environments [2]: preamble 1 for Line Of Sight (0-4 m), 2 for Not Line Of Sight (NLOS) (0-4 m), 3 for NLOS (4-10 m), and 4 for Extreme Not Line Of Sight.

Figure 5 shows the autocorrelation functions of the four preambles, differing in the positions and the gain of the sidelobes of the autocorrelation.

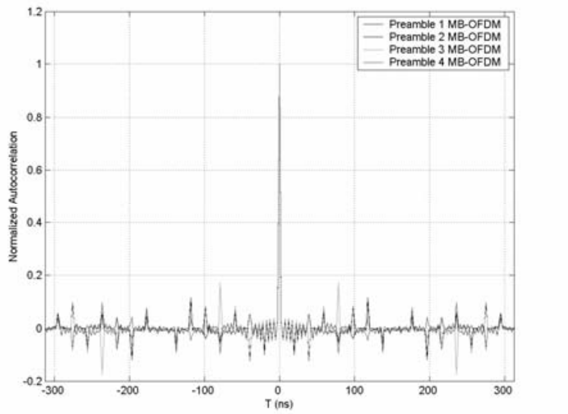

Figure 5 - Autocorrelation functions for the four preambles defined in the MB-OFDM proposal.

B. DS-UWB synchronization sequences

The DS-UWB proposal foresees three types of preamble for each of the two operation bands. The preambles, referred to as short, medium and long are designed for good, nominal and bad channel scenarios, respectively. We will refer in the following to the medium preamble, since it is the only one available in the proposal description [3].

The medium preamble has a time duration of about 15 µs for both Low Band and High Band. The time duration of each bit is about 1/55 µs and about 1/110 µs in Low Band and High Band respectively, so that the number of symbols forming the preamble in the High Band is twice the number of symbols used in the Low Band (1730 vs. 865).

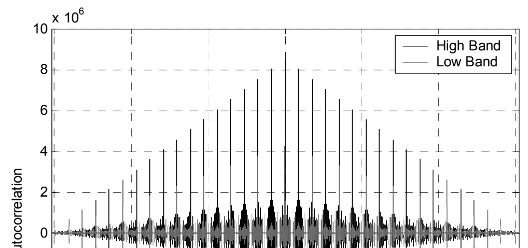

Figure 6 - Autocorrelation functions of the medium preamble of DS-UWB for both Low Band and High Band.

Figure 6 shows the autocorrelation for the two preambles, characterized by the presence of periodic peaks due to the periodicity of the preamble, allowing the synchronization of the receiver with the transmitter. Note, also, the different autocorrelation period for the Low Band and the High Band, due to the different symbol rates.

Figure 7 shows a zoom of autocorrelation, showing the different levels of the peak of the two autocorrelations.

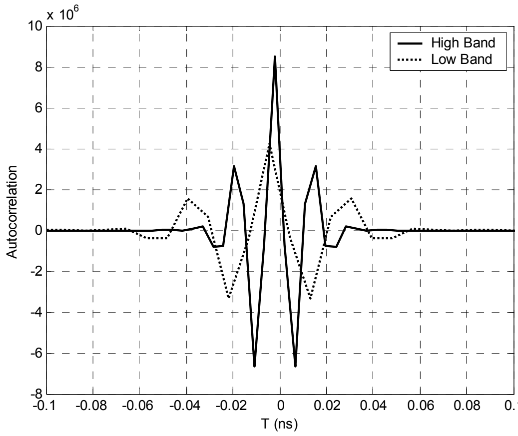

Figure 7 - Zoom of the peak of autocorrelation function of the medium preamble of DS-UWB for both Low Band and High Band.

C. *Performance comparison*

In this section we will compare the accuracy of the correlation filter with the CRLB for an ideal channel. Figure 8 shows the accuracy vs. D^2/T and the CRLB vs. D^2/T for Band 1 of Mode 1 of the MB-OFDM and for the DS-UWB in both Low Band and High Band. Although for both signals the accuracy in distance estimation obtained with the correlation receiver is almost a order of magnitude worse than the CRLB, it shows the same variation law with the D^2/T parameter. This is due to the fact that, under the assumption of ideal channel, SNR decreases as the inverse of the square of D, showing the same dependence on distance derived for the CRLB in eq. (9).

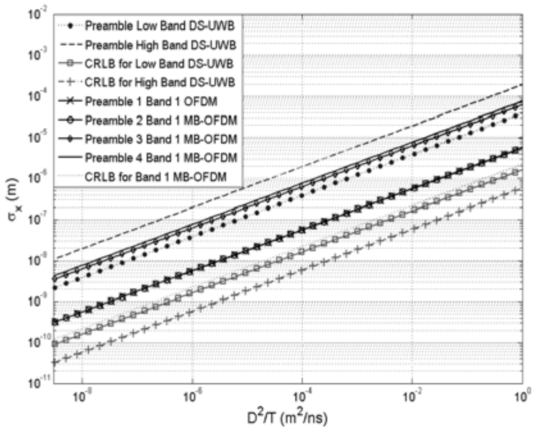

Figure 8 – Comparison of the accuracy obtained using the preambles of the MB-OFDM signal for the band 1 and the medium preambles defined for the DS-UWB for both Low and High Bands vs. the CRLB for the band 1 for MB-OFDM and for both Low and High Bands for DS-UWB.

In Figure 8, we can see that the synchronization sequence has a strong impact on ranging accuracy: in two cases (preambles 1 and 2) the MB-OFDM achieves better performance than DS-UWB, despite the smaller signal bandwidth, thanks to the properties of the synchronization sequences. Among the MB-OFDM preambles, we observe different accuracy levels due to the different autocorrelation of each preamble. In particular we can see that preamble 1 obtains the best results, thanks to its narrower autocorrelation, while preambles 3 and 4 lead to the worst performance.

As far as DS-UWB is regarded, the High Band preamble achieves better performances, thanks to the larger signal bandwidth.

VII. CONCLUSION

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 and the standard deviation for distance evaluation based on the output of the correlation filter 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 is potentially the best solution to perform ranging, thanks to its larger bandwidth and higher operative frequencies. Next, the CRLB was evaluated in presence of a real channel model with multipath. The results showed that DS-UWB and MB-OFDM are affected differently by the channel, and that the degree of multipath dramatically changes the ranging accuracy of the two signals. Finally, the ranging accuracy achievable using the correlation filter was analyzed, showing that the ranging performance of both signals is strictly related to the selected synchronization sequence, so that the advantage of DS-UWB signal in terms of bandwidth may be compensated in some cases by the characteristics of the synchronization sequences adopted for the MB-OFDM signal.

ACKNOWLEDGMENT

This work was partially supported by the European IP project N. 511766 LIAISON (LocatIon bAsed servIceS for the enhancement of wOrking enviroNment).

REFERENCES

[1] Federal Communication Commission, “Revision of Part 15 of the Commission’s rules Regarding Ultra-Wideband Transmission System: First order and report,” Technical Report FCC 02-48, (April 2002).

[2] Batra A., et al, Multi-band OFDM Physical Layer Proposal for IEEE.802.15 Task Group 3a. Available at: http://www.multibandofdm.org/papers/MultiBand_OFDM_Physical_Layer_Proposal_for_IEEE_802.15.3a_Sept_04.pdf, (September 2004).

[3] Fisher, R., R. Kohno, H. Ogawa, H. Zhang, K. Takizawa, M. Mc Laughlin and M. Welborn, “DS-UWB Physical Layer Submission to 802.15 Task Group 3a,” Available at: ftp://ieee:wireless@ftp.802wirelessworld.com/15/04/15-04-0137-03-003a-merger2-proposal-ds-uwb-update (July 2004).

[4] H. Urkowitz, “Signal theory and random processes,” Artech House, 1983.

[5] Cardinali R., L. De Nardis, P. Lombardo and M.-G. Di Benedetto, “Theoretical bounds for ranging with Multi Band OFDM and Direct Sequence UWB signals”, 14th IST Mobile & Wireless Communications Summit 2005, Dresden June 19-23 2005.