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COMPARATIVE PERFORMANCE STUDIES OF INTERFERED LOW DATA RATE ULTRA WIDEBAND SYSTEMS IN MULTIPATH CHANNEL

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ABSTRACT

This paper studies the performance differences of three low data rate ultra wideband (UWB) systems in interfered AWGN and multipath channels. The studied systems are based on ultra wideband frequency modulation (UWB-FM), direct sequence UWB (DS-UWB) and multiband orthogonal frequency division multiplexing (MB-OFDM). The systems are studied in very high and ultra high frequency bands (VHF/UHF), i.e. 230 – 390 MHz, and 6.336 – 7.920 GHz. The VHF/UHF channel model is based on the measurements carried out in typical Finnish forest, whereas channel model for 6.336 – 7.920 GHz band is based on the modified Saleh-Valenzuela model. The intentional interference locates at the centre of the studied band having a 20 MHz bandwidth. In the literature, the comparison of the different low data rate UWB systems is rather insignificant. Therefore, the results of this paper are filling up this evident gap. The same spectral allocation and data rate are used as a starting point for a study. In the lower band, DS-UWB seems to tolerate more interference than UWB-FM in AWGN and multipath channels. The interference power can be higher for UWB-FM than MB-OFDM without performance degradation in AWGN channel in the upper band. The system performance starts to decrease with the same interference power in the case of MB-OFDM and UWB-FM in the interfered multipath channels in the upper band.

I. INTRODUCTION

The UWB regulation made progress in the European Union (EU) when the Commission of the European Communities published its decision on 21 February 2007 [1]. The decision describes UWB to be a technology that spreads the transmitted radio-frequency energy wider than 50 MHz. The UWB systems can operate in the frequency band 6.0 – 8.5 GHz without any requirement for mitigation technique. The maximum power spectral density (PSD) in this frequency band is fixed to -41.3 dBm/MHz [1]. The decision also allows the use of band between 3.4 – 4.8 GHz with the same PSD limit if low duty cycle restrictions are applied. Otherwise, the maximum PSD is limited to -70 dBm/MHz.

The Federal Communications Commission (FCC) [2] and the Commission of the European Communities do not specify a particular air interface technique or modulation scheme for UWB. Hence, the UWB system can be design in many ways. The UWB systems can be divided into two categories: singleband and multiband techniques. DS-UWB presents the traditional singleband, impulse radio solution [3], whereas UWB-FM is the latest innovation in the field of singleband UWB [4]. The dominant multiband approach is MB-OFDM, known as a WiMedia [5]. These systems are introduced in Section 2 in more details.

The very low transmission power and extremely wide bandwidth of the UWB signal make it very difficult to detect for unwanted parties. UWB provides low probability of interception and detection (LPI/LPD) features that are essential in military applications. In the frequency regulations, there are specific frequency bands allocated for military applications in VHF/UHF band. Therefore, it is also feasible to study the performances of UWB systems that are operating at this band.

The literature survey indicates that the comparative studies between different UWB systems are rather unsubstantial, especially in the low data rate applications. The performance differences between different high data rate UWB concepts are studied and compared, e.g., in [6,7].

In our study, the main assumptions are that the systems use the same frequency band and they have similar data rates. In addition, the channel model and interference are similar in different cases. The performances of the systems are studied in VHF/UHF band, i.e. 230 – 390 MHz, and also in a band between 6.336 and 7.920 GHz. In addition, the behaviour of the systems under interference is investigated.

This paper is organized as follows; Section 2 introduces the system models. In addition, it presents the interference and channel models. In Section 3, the simulation parameters are introduced and justified. The results are given and discussed in Section 4. The paper is concluded in Section 5.

II. SYSTEM MODELS

This section describes the simulation models for UWB systems, radio channels models and interference model in more details.

A. UWB-FM

In the case of UWB-FM, information signal is spread twice in the frequency domain [4]. At first, a low-modulation index digital frequency shift keying (FSK) is applied. In FSK, two subcarrier waveforms can be chosen: sinusoidal or triangular. After a high-modulation index analog FM, sinusoidal subcarrier waveform generates flat spectrum with very steep roll-off. However, the flatter spectrum can be achieved utilizing triangular waveform with the cost of less steeper roll-off than sinusoidal waveform. The transmitted signal modulated by a sinusoidal signal can be expressed as [4]

$$s(t) = A\sin\left(\omega_c t - \beta\cos(\omega_m t) + \varphi_0\right). \tag{1}$$

In (1), A, β, t, ω_c and ω_m are amplitude, modulation index, time and angle frequencies of the carrier and modulating

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signal, respectively, and φ_0 is an arbitrary but time-independent constant phase. The modulation index describes how much signal's carrier frequency varies around its unmodulated level. The modulation index is defined by [4]

$$\beta = \frac{\Delta f}{f_\mathrm{m}} = \frac{\Delta\omega}{\omega_\mathrm{m}}. \qquad (2)$$

In (2), Δf is the frequency deviation, $\Delta\omega$ is the corresponding angle frequency and f_m is the frequency of the modulating signal.

The receiver applies a delay-line FM demodulator [4]. In addition, the FSK demodulation is done by using the mathematical demodulator presented in [8].

B. DS-UWB

In direct sequence UWB, the pulse repetition is applied by using a pseudo random code to spread the symbol energy over multiple chips like in conventional direct sequence spread spectrum systems [9]. In UWB case, the chip waveform inherently generates ultra wideband spectrum. The transmitted signal using binary pulse amplitude modulation (BPAM) can be given as [3]

$$s(t) = \sum_{k=-\infty}^{\infty}\sum_{j=0}^{N-1} w\left(t - kT_\mathrm{d} - jT_\mathrm{f}\right)\left(c_\mathrm{p}\right)_j d_k. \qquad (3)$$

In (3), T_d and T_f are data and frame length, respectively, and $(c_\mathrm{p})_j$ is a code phase out of N possible code phases. Pulse waveform and data bit are depicted with $w(\cdot)$ and d_k, respectively. Polarity of the transmitted pulse is defined by the chip polarity and data bit [3].

C. MB-OFDM

The formerly presented physical layer solutions, UWB-FM and DS-UWB, utilize primarily singleband approach that could be more than GHz wide, whereas MB-OFDM applies 528 MHz fractions of the total allocated band, and the transmission could hop the between different subbands in the frequency domain. Totally 110 subcarriers are used per each subband to transmit information; 100 carriers for data and 10 guard carriers. In addition, a coherent detection needs additional 12 subcarriers [5].

The information is modulated to the orthogonal frequencies by using inverse fast Fourier transform (IFFT). In addition, quaternary phase shift keying (QPSK) or dual carrier modulation (DCM) are applied as data modulation techniques. The transmitted signal is presented as [5]

$$s(t) = \mathrm{Re}\left\{\sum_{n=0}^{N_\mathrm{p}-1} s_n\left(t - nT_\mathrm{SYM}\right)\exp\left(j2\pi f_\mathrm{c}(q(n))t\right)\right\}. \qquad (4)$$

In (4), $\mathrm{Re}(\cdot)$ presents the real part of the signal, N_p is the number of symbols per packet, $f_\mathrm{c}(m)$ is the center frequency for the mth frequency band, $q(n)$ is a function that maps the nth symbol to the appropriate frequency band, and $s_n(t)$ is the complex baseband signal representation for the nth symbol. $s_\mathrm{n}(t)$ must satisfy the following property: $s_\mathrm{n}(t) = 0$ for $t \notin [0, T_\mathrm{SYM})$ [5].

D. IEEE 802.15.4a Channel Model

Based on the measurements, the IEEE 802.15.4a task group has defined low data rate UWB channel models [10]. The models are based on the Saleh-Valenzuela (SV) model [11]. The complex baseband impulse response for SV model is given as [11]

$$h_\mathrm{discr}(t) = \sum_{l=0}^{L-1}\sum_{k=0}^{K-1} a_{k,l}\exp\left(j\varphi_{k,l}\right)\delta\left(t - T_l - \tau_{k,l}\right). \qquad (5)$$

In (5), $a_{k,l}$ is the tap weight of the kth component in the lth cluster, T_l is the delay of the lth cluster, $\tau_{k,l}$ is the delay of the kth multipath component relative to the lth cluster arrival time T_l, $\varphi_{k,l}$ is the uniformly distributed phase and $\delta(t)$ is Dirac's delta function.

In this paper, four channel types are applied. Residential environment covers the range from 7 m to 20 m in the frequency band of 2 – 10 GHz. Indoor office environment covers the range from 3 m to 38 m in the frequency band of 2 – 8 GHz. The residential line-of-sight (LOS) and non-LOS (NLOS) channels are referred as channel model 1 (CM1) and channel model 2 (CM2), respectively. The acronyms CM3 and CM4 are reserved to indoor office LOS and NLOS channels, respectively [10].

E. 230 – 390 MHz Models

The channel models presented in [12] are applied in our studies at VHF/UHF frequencies, i.e., from 230 MHz to 390 MHz. The models are based on the measurements in typical Finnish forest using long link distances, i.e. 0.5 – 5.6 km.

Overall, seven channel models are presented in [12]. From these models, two types of model are utilized here, and are referred as Experimental 1 (E1) and Experimental 2 (E2), respectively. E1 model has strong first component and the other multipath components are highly attenuated, whereas E2 has strong multipath components coming about 0.07 µs after the first component. Link distances for models E1 and E2 are 2.5 km and 3.1 km, respectively. The channel E1 is slightly more obstructed than E2. Root mean square (RMS) delays for E1 and E2 are shown to be 0.15 µs and 0.21 µs, respectively. By using the Kolmogorov-Smirnov goodness-of-fit test [13], it was found that the amplitude distribution of the paths fits best to Rice distribution. In Figure 1 and Figure 2, the tapped delay line models for channels E1 and E2 are illustrated, respectively [12].

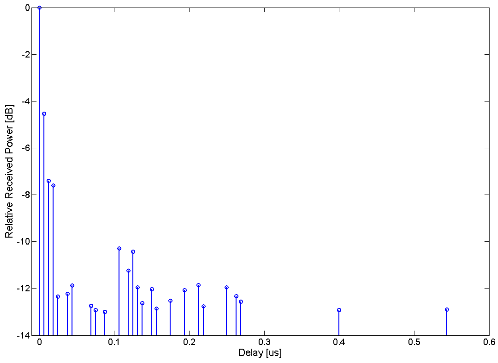

Figure 1. The tapped delay line model for E1.

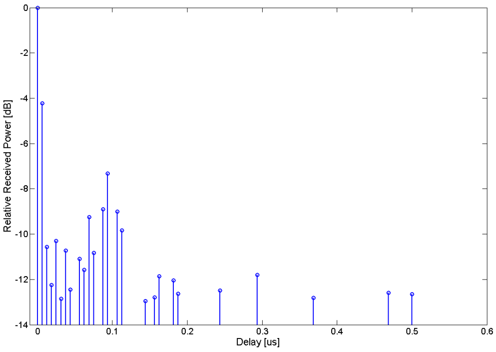

Figure 2. The tapped delay line model for E2.

F. Interference

For the sake of simplicity, the interference is modelled as coloured Gaussian noise (CGN) that is a band-limited version of white Gaussian noise [14]. The intentional interference locates in the centre of the studied bands, i.e., 310 MHz and 7.128 GHz, and has 20 MHz bandwidth, which is the bandwidth of, e.g., IEEE802.11a or GPS. Corresponding comparative studies for high data rate UWB systems have been carried out using 20 MHz interference bandwidth, which justifies its use also in this context.

III. SIMULATION CONFIGURATIONS

The software simulators were developed in Matlab© in order to evaluate the performances of selected UWB systems. This section presents and justifies the simulating parameters for the studied systems. The simulations for DS-UWB were carried out by using the simulator that is introduced in [15]. The UWB-FM simulator was embedded in this singleband simulator. The functionality of UWB-FM was verified against the results from [4] by using similar system parameters. Respectively, the MB-OFDM simulator implementation is discussed in [16].

The systems are studied at two different frequency bands; 230 – 390 MHz and 6.336 – 7.920 GHz. The data rates used are R_d = 64 kbps and R_d = 1 Mbps. The lower band (230 – 390 MHz) is chosen to study the UWB suitability for military applications operating at the military dedicated VHF/UHF band. The upper frequency band is fixed according to the Group 3 of MB-OFDM specification, i.e., 6.336 – 7.920 GHz [5].

In the lower band, UWB-FM and DS-UWB system performances are compared. In UWB-FM, modulation index for FSK is set to 1 following the studies from [4]. The carrier frequency and frequency deviation for FM are 310 MHz and 80 MHz, respectively, in order to occupy the whole lower band. To have maximum spectral overlapping with UWB-FM, DS-UWB applies the fifth derivative of the Gaussian monocycle and pulse width of 7.5 ns, thus having a center frequency of 301.5 MHz and -10 dB bandwidth of 296 MHz. According to the data rates, processing gains for DS-UWB are fixed to 33.2 dB for 64 kbps and 21.2 dB for 1 Mbps, respectively. In addition, DS-UWB utilizes BPAM. The earlier reported results from [12] showed that BPAM is reasonable choice for binary data modulation. In multipath channels, eight finger selective rake receiver with maximum ratio combining is applied for DS-UWB. Neither systems uses error control coding.

Correspondingly, the performances of UWB-FM and MB-OFDM are studied at the upper band. In the UWB-FM case, the FSK modulation index is kept one. The carrier frequency and frequency deviation for FM are 7.128 GHz and 792 MHz, respectively. At the same time, MB-OFDM exploits QPSK and DCM data modulation schemes. It has been shown that in multipath environment MB-OFDM needs error control coding for reliable detection [16]. Therefore, convolutional coding having a rate of 1/3 and constraint length of 7 is applied. At the receiver, Viterbi decoding with soft decision is applied.

Using these assumptions, the UWB systems are spectrally occupying the same band and have approximately the same data rate. This makes it possible to compare the inherent performances of these systems under similar interference and channel state.

As was discussed in Section 2, the interference is modelled as CGN. The intentional interference locates at the centre of the studied band, i.e., at 310 MHz or 7.128 GHz. The bandwidth of the interference is chosen to be 20 MHz. In interference simulations, bit energy-to-noise power density ratio (E_b/N_0) are chosen so that the bit error rate (BER) level of 10^{-4} is obtained. The fixed E_b/N_0 values for the lower and the upper band are tabulated in Table 1 and Table 2, respectively.

Table 1. E_b/N_0 values used in the simulations in lower band to get BER = 10^{-4}

Simulated Concept		data rate [kbps]	Required E_b/N_0 in AWGN [dB]	Required E_b/N_0 in E2 [dB]
UWB-FM	Triangular	64	16	22
		1000	13	30
	Sinusoidal	64	15	-
		1000	12	-
DS-UWB		64	8	10
		1000	8	10

Table 2. E_b/N_0 values used in the simulation in the upper band to get BER = 10^{-4}

Simulated Concept		data rate [kbps]	Required E_b/N_0 in AWGN [dB]	Required E_b/N_0 in E2 [dB]
UWB-FM	Triangular	64	28	33
		1000	25	33
	Sinusoidal	64	27	-
		1000	23	-
MB-OFDM	QPSK	64	8	13
		1000	8	13
	DCM	64	11	15
		1000	11	15

IV. RESULTS

In Figure 3 and Figure 4, the BER performances of the systems without interference are presented in AWGN channel in the lower and the upper bands, respectively. In the case of UWB-FM, the sinusoidal subcarrier waveform gives approximately 1 dB better performance at the BER level of 10^{-4} than triangular waveform with both data rates and bands.

In addition, the performance improves when the data rate increases. In UWB-FM, the ratio between RF and subcarrier bandwidths can be consider as a spreading gain of conventional spread spectrum system. When the RF bandwidth is fixed and the modulation index for FSK is set to one, the lower is data rate the higher is the spreading gain. By taking into account the spreading gain in the decision, the minimum spreading gain gives the best result.

The effect of interference to system's performances in AWGN in the lower and the upper band are depicted in Figure 5 and Figure 6, respectively. In the lower band, the degradation of performance of UWB-FM with data rate R_d = 1 Mbps can be seen when interference-to-signal power ratio (ISR) is more than -5 dB. When the ISR is less than 0 dB, DS-UWB does not suffer from the performance degradation under interference. In the upper band, MB-OFDM seems to tolerate only low interference power. By using R_d = 64 kbps, the interference starts to decrease the performance of MB-OFDM when ISR is more than -25 dB. At the same time, ISR should be less than this in the case of R_d = 1 Mbps to obtain the unchanged level of performance. Similarly, the performance of UWB-FM decreases when ISR is more than -10 dB with both data rates.

Figure 7 and Figure 8 present the results from the system simulations in multipath channels in the lower and the upper band, respectively. In the lower band, E1 and E2 channel models are applied, whereas CM3 channel model is utilized in the upper band. In the case of UWB-FM, 1 Mbps data rate suffers from the multipath propagation in the lower band. By using triangular waveform in E2 channel, the BER level of 10^{-4} can be achieved with 1 Mbps data rate.

In the upper band, simulation results show that UWB-FM behaves similar as in E1 channel with R_d = 1 Mbps in CM1, CM2 and CM4 channels. On the other hand, MB-OFDM has approximately same behaviour in CM1, CM2 and CM4 channel than it has in CM3 channel.

Simulation results point out that DS-UWB and UWB-FM can tolerate ISR of 0 dB and -12 dB without performance degradation with R_d = 1 Mbps in the E2 channel in the lower band, respectively. In the upper band, the ISR threshold of performance degradation is -15 dB for both systems with R_d = 1 Mbps in the CM3 channel.

V. CONCLUSION

In this paper, low data rate UWB systems were studied in interfered AWGN and multipath channels. Results indicated that UWB-FM and DS-UWB with R_d = 1 Mbps can tolerate ISR less than -5 dB and 0 dB without performance degradation in AWGN channel in the lower band, respectively. In the studied multipath channel in the lower band, e.g. E2, the effect of interference can be seen when ISR is more than -12 dB or 0 dB in the cases of UWB-FM and DS-UWB with R_d = 1 Mbps, respectively.

In the upper band, the ISR thresholds of performance degradation for MB-OFDM and UWB-FM were -25 dB and -10 dB in AWGN channel in the case of R_d = 1 Mbps, respectively. In addition, simulation results showed that the performances of MB-OFDM and UWB-FM systems having R_d = 1 Mbps decreased when ISR is more than -15 dB in the CM3 channel.

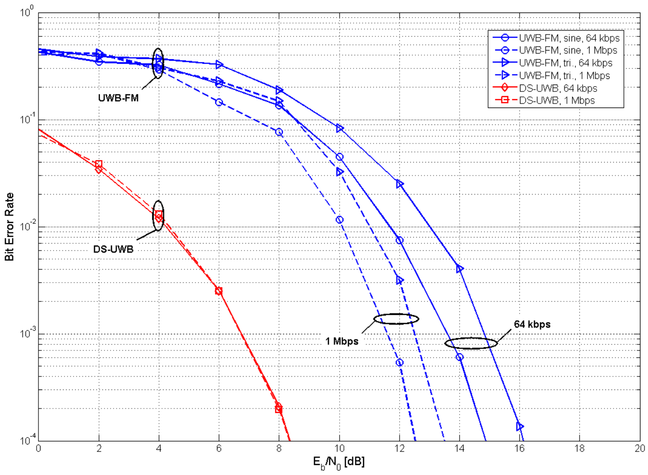

Figure 3. BER as a function of E_b/N_0 in lower band in AWGN channel.

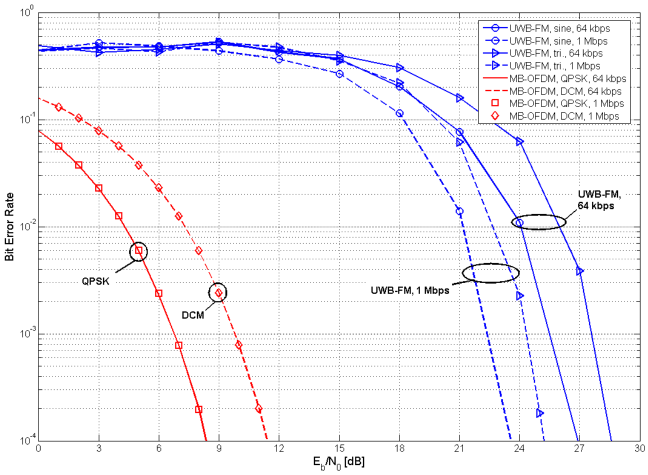

Figure 4. BER as a function of E_b/N_0 in the upper band in AWGN channel.

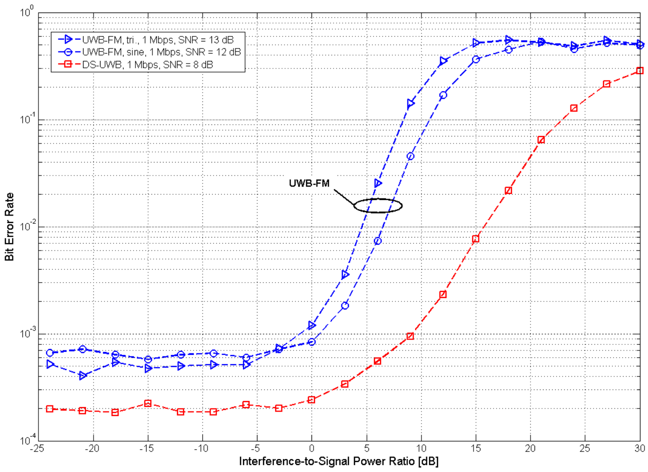

Figure 5. BER as function of ISR in the lower band in AWGN channel.

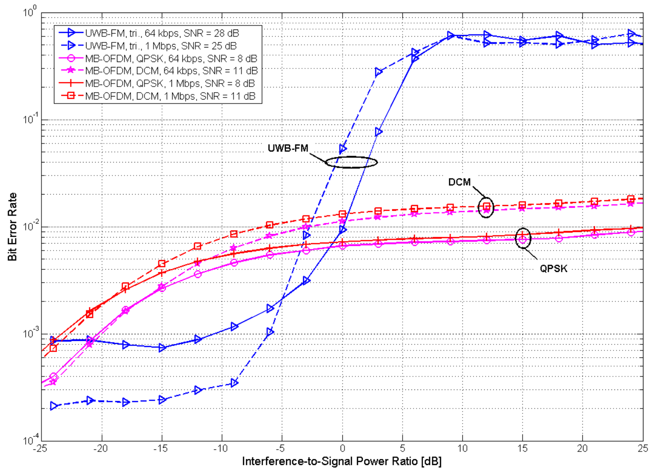

Figure 6. BER as a function of ISR in the upper band in AWGN channel.

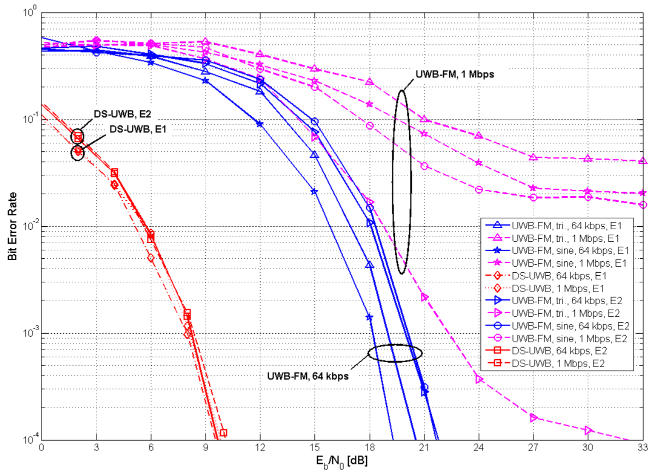

Figure 7. BER as a function of E_b/N_0 in the lower band in E1 and E2 channels.

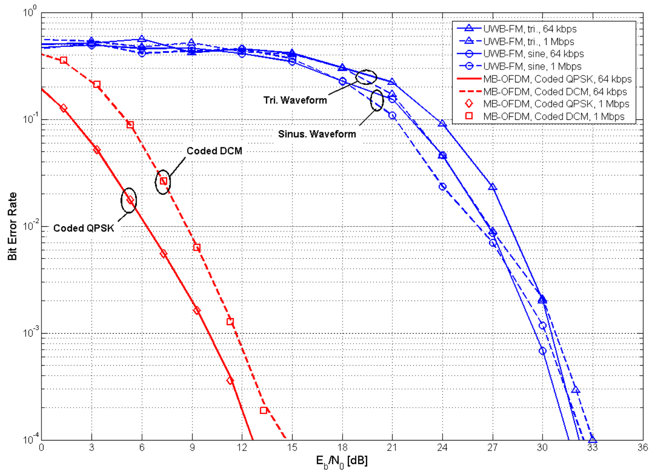

Figure 8. BER as a function of E_b/N_0 in the upper band in CM3 channel.

VI. ACKNOWLEDGEMENT

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REFERENCES

[1] Commission of the European Communities, "Commission Decision of 21/II/2007 on Allowing the Use of the Radio Spectrum for Equipment Using Ultra-Wideband Technology in a Harmonised Manner in the Community, " Feb. 21, 2007.

[2] Federal Communications Commission, "Revision of Part 15 of the Commission's rules regarding ultra-wideband transmission systems," First Report and Order, ET Docket 98-153, 2002.

[3] M. Hämäläinen, *Singleband UWB Systems. Analysis and Measurements of Coexistence with Selected Existing Radio Systems*, Doctoral Thesis, Acta C240, University of Oulu, Oulu, Finland, 2006, 99 p.

[4] J.F.M. Gerrits et al, "Principles and Limitations of Ultra-Wideband FM Communications Systems," *EURASIP Journal on Applied Signal Processing*, vol. 2005, issue 3, pp. 382-396, 2005.

[5] Ecma International, "High Rate Ultra Wideband PHY and MAC Standard," Standard ECMA-368, 2005.

[6] H. Viittala, M. Hämäläinen. and J. Iinatti, "Comparative Studies of MB-OFDM and DS-UWB with co-existing Systems in AWGN Channel," in *Proc. IEEE International Symposium on Personal, Indoor and Mobile Radio Communications*, 2006.

[7] H. Viittala, M. Hämäläinen. and J. Iinatti, "Performance Comparison between MB-OFDM and DS-UWB in interfered multipath channel," in *Proc. IEEE Military Communication Conference*, 2006.

[8] M.H.L. Kouwenhoven, *High-Performance Frequency-Demodulation Systems*, Doctoral Thesis, Delft University Press, Delft, the Netherlands, 1998, 363 p.

[9] S. Hara and R. Prasad, "Overview of multicarrier CDMA," *IEEE Communications Magazine*, vol. 35, pp. 126-133, Feb. 1997.

[10] A.F. Molisch et al., "IEEE 802.15.4a Channel Model – Final Report. Submitted to IEEE 802.15 WPAN Low Rate Alternative PHY Task Group 4a (TG4a)," doc: IEEE 802.15.04-0662-01-004a, Nov. 2004.

[11] A. Saleh and R. Valenzuela, "A Statistical Model for Indoor Multipath Propagation," *IEEE Journal on Selected Areas in Communications*, vol. 5, pp. 128-137, Feb.1987.

[12] N. Laine, *Ultra Wideband Channel Modelling and Communication System Performance in Outdoor Environment*, Master's Thesis, Department of Electrical and Information Engineering, University of Oulu, Oulu, Finland, 2004, 92 p.

[13] A. Papoulis and S. Unnikrishna Pillai, *Probability, Random Variables and Stochastic Processes*, 4th ed., Boston, USA: McGraw-Hill Inc., 2002, 852 p.

[14] J.G. Proakis, *Digital Communications*, 4th ed., Boston, USA: McGraw-Hill Inc., 2001, 1002 p.

[15] R. Tesi, *Ultra Wideband System Performance in the Presence of Interference*, Licentiate Thesis, Department of Electrical and Information Engineering, University of Oulu, Oulu, Finland, 2004, 97 p.

[16] H. Viittala, *Comparative Study on the Impact of Interference on MB-OFDM and DS-UWB System Performance*, Master's Thesis, Department of Electrical and Information Engineering, University of Oulu, Oulu, Finland, 2006, 76 p.