Paper

On the Effects of Code Cardinality for TH-PPM Ultra Wideband Systems

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Abstract—This paper demonstrates the effects of code cardinality at transmitter section on bit error rate (BER) performance of time hopping pulse position modulation (TH-PPM) based ultra wideband (UWB) indoor radio communication. In the transmitter, different code cardinality values have been chosen and correspondingly the effects on BER of the system have been investigated. The recently accepted IEEE 802.15.3a model of the UWB channel has been used as the propagation channel model in indoor environment. Results show that the system BER performance is significantly dependent on the code cardinality value of time hopping code. For such higher code cardinality values as in the range from 30 to 50, the BER performance degrades severely. Finally, code cardinality in the range from 10 to 15 has been recommended for TH-PPM system in UWB indoor communications providing better BER performance for the same system data rate requirement.

Keywords—code cardinality, multiple-user interference, TH-PPM, ultra wideband.

1. Introduction

Ultra wideband (UWB) transmission systems are seen as very promising solutions for many wireless indoor and short-range communication environments such as ad hoc, home, personal and body area networks, since they can exploit the 3–10 GHz unlicensed spectrum [1]. Impulse radio UWB (IR-UWB) systems are one of the two main streams of UWB technology. In IR-UWB systems, subnanosecond pulses are transmitted in the wireless medium. For time hopping (TH) UWB radio, it is indicated that both modulation method and TH code influence the bit error rate (BER) performance of the system [2]. However, the effect of TH code properties directly on the BER performance still lacks enough research attention. Code cardinality is an important characteristic in case of TH code used for time hopping pulse position modulation (TH-PPM) systems. This is why the effect of code cardinality on BER is a significant investigation in this field. Time hopping is a popular multiple access scheme used especially with pulse position modulation (PPM). For a typical time hopping format employed by an energy normalized impulse radio signal, the output signal of the kth transmitter can be expressed as

$$s_{tr}^{(k)}\left(t^{(k)}\right) = \sum_{j=-\infty}^{\infty} w_{tr}\left(t^{(k)} - jT_f - c_j^{(k)}T_c - \delta d_{\lfloor j/N_s \rfloor}^{(k)}\right), \quad (1)$$

where $c_j^{(k)}$ is the distinct time hopping sequence, t is the transmitter clock time, w_{tr} is the transmitted monocycle waveform, T_f is the pulse repetition time or the frame time, T_c is the chip duration, δ is the modulation index used to distinguish between pulses carrying the bit 0 and the bit 1 for PPM scheme and d_j is the information symbol [3].

To eliminate catastrophic collisions due to multiple access, each user (indexed by k) is assigned a distinctive time shift pattern called a time hopping code. This provides an additional time shift of $c_i^{(k)}T_c$ seconds to jth monocycle in the pulse train. The modulation index δ can be chosen to optimize system performance. For performance prediction purposes, the data sequence $\left\{d_j^{(k)}\right\}_{j=-\infty}^{\infty}$ is modeled as a wide-sense stationary random process composed of equally likely symbols. In TH multiple access scheme, the "pulse repetition time" or "frame time" between two consecutive pulses is divided into a number of smaller time slots, the length of each slot being called as "chip duration". Code cardinality, denoted as N_h, is the total number of such time slots within each frame time. Moreover, each information bit is transmitted using N_S consecutive pulses, leading to (N_S, 1) repetition code. The resulting information bit rate is thus $R_b = \left(N_S T_f\right)^{-1}$. In this paper, the effect of code cardinality on BER performance of the system has been investigated and corresponding results have been presented. The effect of pulse repetition rate, N_S for different code cardinality values is also shown. The simulations have been performed for a typical 16.6 Mbit/s indoor UWB system, however, the nature of how the system performance would deviate in case of increased data rate requirements is also indicated by showing results for 50 Mbit/s and 100 Mbit/s TH-PPM systems.

The paper is organized as follows: Section 2 provides a brief description of the specific pulse shape used. The discussion is followed by Section 3 describing briefly the system model. Results obtained in this investigation have been presented in Section 4. Finally, Section 5 concludes the paper.

2. Ultra Wideband Pulse Shape

The selection of the most appropriate pulse shape for UWB transmission requires that it match the Federal Communications Commission (FCC) regulated power spectral density (PSD) mask in a reasonably good manner and at the same time increases signal bandwidth. Considering the nth derivative of Gaussian pulse as the transmitted pulse of UWB transmission, where $A_{\max}$ is the peak power spectral density that has been set as limit by the FCC in USA, the PSD of the transmitted signal can be expressed as [4]

$$|P_t(f)| \equiv A_{\max}|P_n(f)| = \frac{A_{\max}(2\pi f\sigma)^{2n} e^{\{-(2\pi f\sigma)^2\}}}{n^n e^{(-n)}}. \quad (2)$$

Based on normalized PSD of nth order Gaussian derivative pulse, applying bisection method as shown in [4], the fourth order derivative of Gaussian pulse with pulse shaping factor of 0.168 ns has been chosen in our simulations. This is because as shown in Fig. 1 this specific

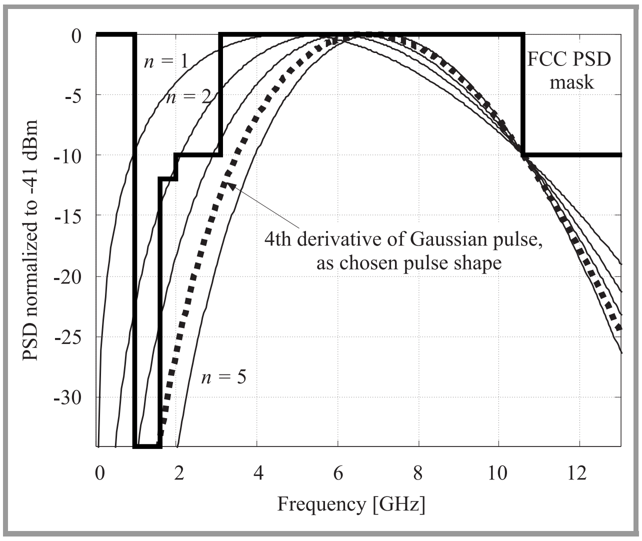

Fig. 1. PSD of 4th order derivative of Gaussian pulse fulfilling indoor UWB PSD requirement for indoor systems.

condition fulfills the FCC regulated PSD mask in the most appropriate manner. Figure 1 also presents the effect of higher order Gaussian derivative pulses on FCC regulated PSD mask for UWB indoor communications. The basic fourth order derivative of Gaussian pulse has been illustrated in Fig. 2.

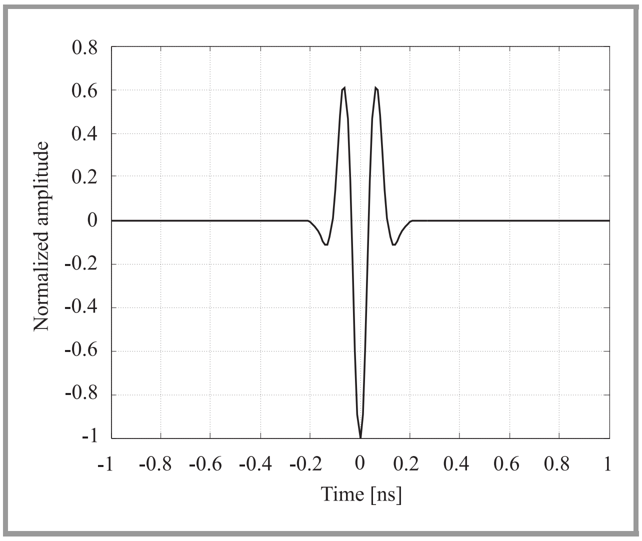

Fig. 2. Fourth order derivative of Gaussian pulse.

3. System Model

In this paper, the effects of different code cardinality values on bit error rate have been studied with the most recent IEEE 802.15.3a [5] UWB channel model. The overall system model is shown in Fig. 3 and is described in detail in the following.

3.1. Transmitter Section

Time hopping multiple access has been used along with PPM modulation scheme in the transmitter. The transmitter specifications along with the remaining parameters used in simulation of the complete system have been presented in Table 1. The fourth derivative of Gaussian pulse with a power decay factor of 0.168 ns best satisfies the FCC regulated PSD mask and so it has been used in this paper.

Table 1
Parameters used in simulation of the complete system

Parameter	Value used in simulation
Source data rate	16.6 Mbit/s
Processing gain	20.79 dB
Average transmitter power	–30 dBm
Sampling frequency	30 GHz
No. of pulse per bit	1, 2, 4, 8
Frame time	60.1 ns
Periodicity of the TH code	2000
Chip time	1 ns
Multi-user interference	Single user and multiple user scenarios
Receiver	Selective RAKE, 8 arms
Channel model	IEEE 802.15.3a, CM-3: 4–10 m, NLOS
Modulation scheme	PPM
Multiple access	TH
Time shift for PPM	0.5 ns
Pulse shape	Gaussian 4th derivative
Pulse width	0.5 ns
Pulse decay factor	0.168 ns
Code cardinality	5, 10, 15, 20, 30, 50

3.2. IEEE 802.15.3a UWB Channel Model

In IEEE 802.15.3a UWB multipath channel model, a modified Saleh-Valenzuela model has been adopted on the basis of observed clustering phenomenon in several channel measurements. Log-normal distribution rather than a Rayleigh distribution for the multipath gain magnitude has been recommended. In addition, independent fading is assumed for each cluster as well as each ray within the cluster. There-

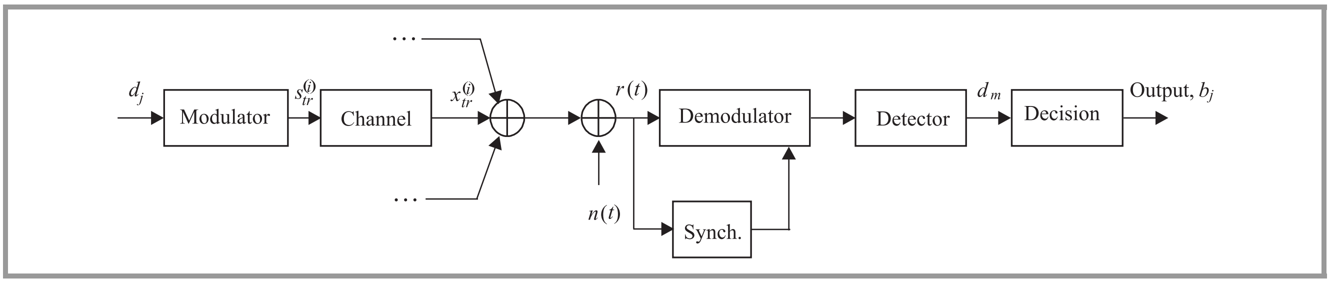

Fig. 3. The system model.

fore, the discrete-time impulse response of the multipath channel model can be described as [6]

$$h_i(t) = X_i \sum_{l=0}^{L} \sum_{k=0}^{K} \alpha_{k,l}^{i} \delta\left(t - T_l^i - \tau_{k,l}^{i}\right), \tag{3}$$

where $\{\alpha_{k,l}^i\}$ are the multipath gain coefficients, $\{T_l^i\}$ is the delay of the lth cluster, $\{\tau_{k,l}^i\}$ is the delay of the kth multipath component relative to the lth cluster arrival time (T_l^i), $\{X_i\}$ represents the log-normal shadowing and i refers to the ith realization.

So, according to the model, T_l represents the arrival time of the first path (ray) of the lth cluster; $\tau_{k,l}$ is the delay of the kth path (ray) within the lth cluster relative to the first path arrival time, T_l. The IEEE 802.15.3a channel model has been already explained in several available literature, e.g., in [6], for four special cases depending on transmitter to receiver distance and the availability of line of sight (LOS) path between them. In this paper, CM-3 (4–10 m, NLOS) condition of the channel has been used because CM-3 represents a typical indoor environment in the transmitter-receiver distance of 4–10 m. The corresponding channel parameters are shown in Table 2.

Table 2
Model parameters in IEEE 802.15.3a UWB channel [6]

Model parameters	CM-3 NLOS at 4–10 m
Cluster arrival rate, Λ [1/ns]	0.0667
Ray arrival rate, λ [1/ns]	2.1
Cluster decay factor, Γ	14
Ray decay factor, γ	7.9
Std. dev. of cluster log-normal fading, σ_1 [dB]	3.3941
Std. dev. of ray log-normal fading, σ_2 [dB]	3.3941
Std. dev. of total multipath log-normal fading, σ_x [dB]	3

3.3. Receiver Section

In the receiver section, selective RAKE receiver has been used. The received signal is the sum of replicas of the transmitted signals. The received signal is, therefore, expressed as

$$r(t) = X \sum_{l=1}^{L} \sum_{k=1}^{K} \alpha_{k,l}\, s_{tr}(t - T_l - \tau_{k,l}) + (n(t) + n_f(t)), \tag{4}$$

where $s_{tr}(t)$ is the transmitted signal which suffers from attenuation and time delay in multipath propagation, $n(t)$ is zero mean AWGN (additive white Gaussian noise) and $n_f(t)$ is the multiple user interference signal. The remaining symbols are as described in Subsection 3.2.

For simulation of this study RAKE receiver with 8 arms has been chosen. This is because in our simulation 8 RAKE arms have shown to give better results providing a trade-off between number of RAKE arms and desired BER of the system. First arm is locked to the first multipath component, m_1. Multipath component, m_2 arrives τ_1 time units later than m_1 and is captured and so on. All decision statistics are weighted by a weighting factor, α to form overall decision statistics. The signals are then integrated over the entire period. The integrated signal is then compared with the appropriate threshold value to receive the better estimate of the transmitted signal. Hard decision detection (HDD) has been chosen at the receiver section because in our simulation results HDD has been found to be more efficient than soft decision detection (SDD) for TH-PPM UWB systems.

4. Results

Code cardinality (N_h) has a significant effect on the system bit error rate in case of TH-PPM UWB system using IEEE 802.15.3a UWB channel model. Code cardinality influences BER performance at the receiver quite significantly if its value is as large as in the range from 30 to 50. As shown in Fig. 4 the system BER performance is almost unchanged when code cardinality value is low, e.g., in the range from 5 to 20. In this range BER performance is almost independent of the code cardinality for up to an E_b/N_o value of 12 dB, but beyond that point the BER performance degrades for higher code cardinality values. For instance, the condition of $N_h = 20$ gives comparatively worse performance compared to that of N_h in the range from 5 to 15. On the other hand, our simulation results show that when code cardinality value (N_h) is set at 30, the BER performance degrades significantly. Also, if code cardinality is

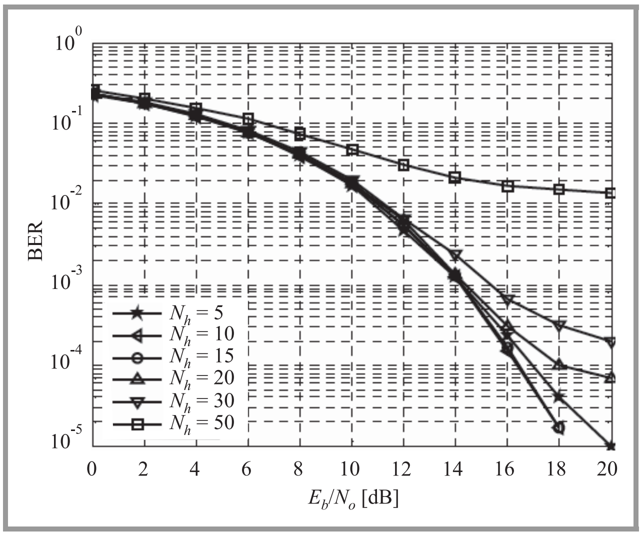

Fig. 4. BER performance for various code cardinality values, at a distance between transmitter and receiver of 5 m, with 8 selective RAKE arms, one pulse per information bit, $N_S = 1$, no multiple user interference.

again increased to 50 the performance is the worst of all. It is important to note that all of the above cases have been simulated for a TH-PPM system of a data rate capacity of 16.6 Mbit/s with the number of pulses to represent one bit (N_S) set as $N_S = 1$. For our study, the frame time (T_S) of the TH-PPM transmitter has been chosen as 60.1 ns, which makes the overall data rate 16.6 Mbit/s. The chosen values of N_S and T_S pair determine and limit the maximum number of elements in the code cardinality vector, i.e., the value of code cardinality (N_h) in TH-PPM transmitter section. In view of the above discussions it is evident that the effect of code repetition rate (N_S) and the frame time (T_S) should also be investigated along with the effects of code cardinality on BER performance of TH-PPM system.

Figure 5 shows the effect of code repetition rate (N_S) of TH-PPM transmitter on overall system BER performance. Again, the system is considered as a 16.6 Mbit/s TH-PPM system with a constant value of code cardinality set at $N_h = 5$. In order to keep the data rate constant all through, the chosen values of (N_S, T_S) pair as used to generate the results in Fig. 5 have been illustrated in Table 3.

Table 3
Chosen values of (N_S, T_S) pair for Fig. 5

Code repetiition rate, N_S	Frame time, T_S [ns]	Data rate = $1/(N_S T_S)$ [Mbit/s]
1	60.1	16.6
2	30	16.6
4	15	16.6
8	7.5	16.6

As presented in Fig. 5 at a code cardinality value of $N_h = 5$ for a 16.6 Mbit/s TH-PPM UWB system, higher code repetition rates result in severe performance degradation. For example, for a desired BER of $2 \cdot 10^{-2}$, one pulse per information bit condition (i.e., $N_S = 1$) provides E_b/N_o gains of 5 dB, 6.5 dB and 7.5 dB over the performances of $N_S = 2$, $N_S = 4$ and $N_S = 8$ cases, respectively. However, this is also important to note that these results are not the results for the effects of data rate on BER of TH-PPM system, which is usually done by varying any or both of code repetition rate, N_S and frame time, T_S.

As mentioned earlier, the results presented so far have been obtained from simulations based on a 16.6 Mbit/s TH-PPM UWB system. However, the effect of higher system data rate requirements on BER performance has also been shown in Fig. 6. It is clearly illustrated in Fig. 6 that if the system data rate requirement is increased from 16.6 Mbit/s to 50 Mbit/s or 100 Mbit/s, the BER performance degrades

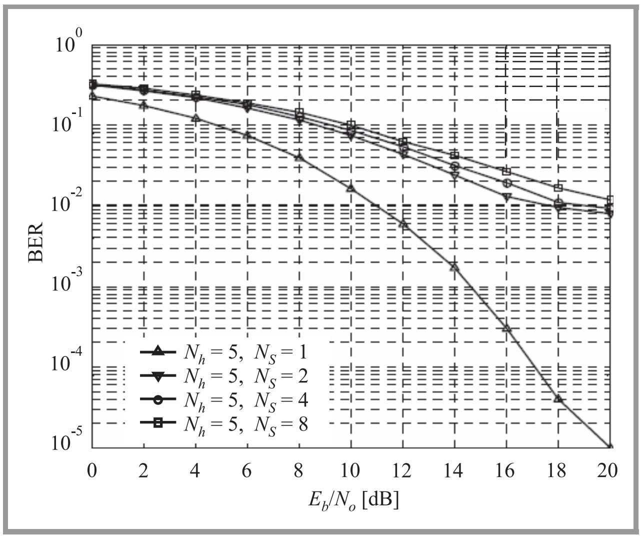

Fig. 5. BER performance for different code repetition rates at distance between transmitter and receiver of 5 m, 8 selective RAKE receiver arms, code cardinality, $N_h = 5$, no multiple user interference.

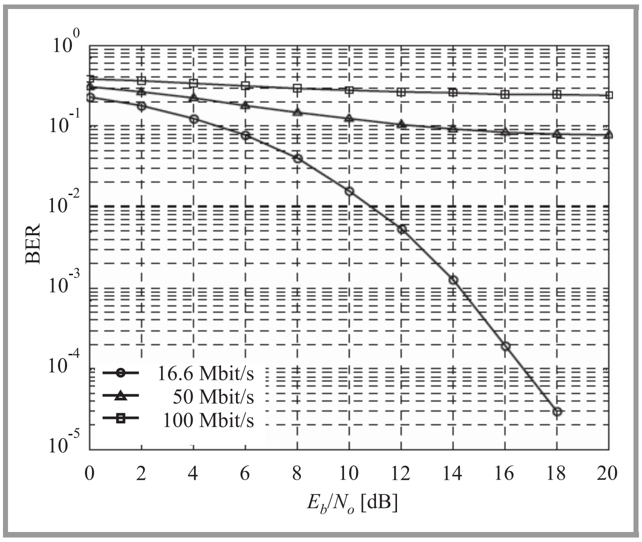

Fig. 6. BER performance of TH-PPM UWB system at different system data rate requirements, at distance between transmitter and receiver of 5 m, 8 selective RAKE receiver arms, no multiple user interference.

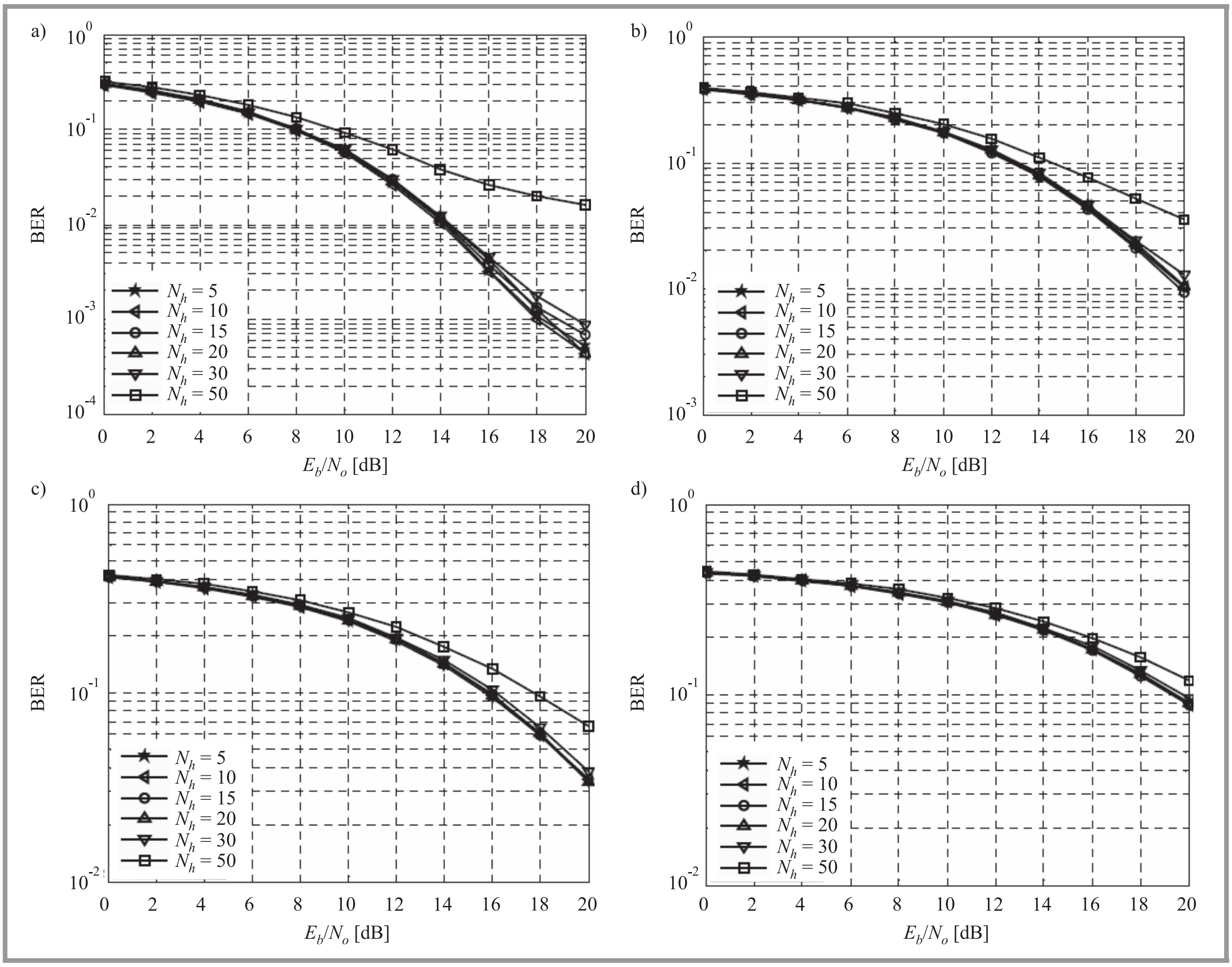

Fig. 7. BER performance of TH-PPM UWB systems with: (a) 1; (b) 5; (c) 10; (d) 20 interfering users for various code cardinality values, at a distance between transmitter and receiver of 5 m, with 8 selective RAKE arms, one pulse per information bit, $N_S = 1$.

enormously. In view of the simulation results so far obtained in our work, a code cardinality value of 10 to 15 is recommended for a 16.6 Mbit/s TH-PPM UWB system with no multiple user interference, because such a condition provides the best BER performance for TH-PPM UWB indoor communication system.

Moreover, system BER performance for different multiple user scenarios of 1, 5, 10 and 20 interfering users has also been shown in Fig. 7. Results in Fig. 7 suggest that BER performance is almost the same for all code cardinality values unless it is as high as $N_h = 50$. As a result, a code cardinality value of 10 to 15 can also suit well for TH-PPM UWB systems with multiple user interference. It is also noted that TH-PPM UWB system suffers serious performance degradations in the presence of multiple user interference.

5. Conclusions

In this paper, the effect of code cardinality on the BER performance of TH-PPM UWB communication system has been presented. TH-PPM scheme has been chosen to investigate into this effect because TH-PPM is the most widely used scheme for impulse radio systems. The simulations in this study considered both single and multiple user scenarios. Separate results have also shown the effect of pulse repetition rates along with those of code cardinality. This is because in simulating the effect of code cardinality only one pulse per bit transmitted has been used and so investigation into multiple pulses per bit transmitted is worth-considering in TH-PPM UWB systems. Another important implication of investigating into code cardinality in case of TH-PPM UWB systems is that the PSD of the TH-PPM transmitter signal is related to code cardinality. That is why an appropriate analysis of code cardinality and its influence on BER of the system needs much research attention.

This paper concludes that a code cardinality value in the range from 10 to15 can be recommended as the most appropriate code cardinality value for 16.6 Mbit/s TH-PPM UWB systems with both single and multiple user scenarios, especially in view of BER performance. However, for other systems the code cardinality value must be chosen giving much attention to code repetition rate and frame time as well as to the data rate requirement of the system.

References

[1] N. Laurenti, T. Erseghe, and V. Cellini, "On the performance of TH-PPM and TH-PAM as transmission formats for UWB communications", in *Proc. IEEE Veh. Technol. Conf. VTC – Spring*, Milan, Italy, 2004.

[2] J. Zhang, R. A. Kennedy, and T. D. Abhayapala, "Conditions and performance of ideal RAKE reception for UWB signals in lognormal fading channels", *Int. J. Wirel. Inform. Netw*., vol. 10, no. 4, pp. 193–200, 2003.

[3] M. Z. Win and R. A. Scholtz, "Impulse radio: how it works", *IEEE Commun. Lett*., vol. 2, no. 2, pp. 36–38, 1998.

[4] H. Sheng, P. Orlik, A. M. Haimovich, L. J. Cimini Jr., and J. Zhang, "On the spectral and power requirements for ultra-wideband transmission", in *Proc. Int. Conf. Commun. ICC*, Anchorage, Alaska, USA, 2003, pp. 738–742.

[5] "IEEE Standard for information technology – Telecommunications and information exchange between systems – Local and metropolitan area networks – Specific requirements". Part 15.3: "Wireless Medium Access Control (MAC) and Physical Layer (PHY) Specifications for High Rate Wireless Personal Area Networks (WPANs)", IEEE Std 802.15.3TM-2003.

[6] J. R. Foerster, M. Pendergrass, and A. F. Molisch, "A channel model for ultrawideband indoor communication", in *Proc. Wirel. Pers. Multimed. Commun. WPMC-03*, Kanagawa, Japan, 2003, vol. 2, pp. 116–120.

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