Performance of Hybrid Direct-Sequence Time-Hopping Ultrawide Bandwidth Systems over Nakagami-m Fading Channels

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***Abstract*— This paper investigates and compares the performance of various ultrawide bandwidth (UWB) systems when communicating over Nakagami-m fading channels. Specifically, the direct-sequence (DS), time-hopping (TH) and hybrid direct-sequence time-hopping (DS-TH) UWB systems are considered. The performance of these UWB systems is studied associated with employing the conventional single-user correlation detector or minimum mean-square error (MMSE) multiuser detector. Our simulation results show that the hybrid DS-TH UWB system may outperform a corresponding pure TH-UWB or pure DS-UWB system in terms of the achievable error performance. Given the total spreading gain of the hybrid DS-TH UWB system, there is an optimal setting of the TH spreading factor and DS spreading factor, which results in the best error performance.**

I. INTRODUCTION

In recent years the UWB techniques have received wide interest in both the research and industry communities. This is because UWB techniques are capable of providing high data rate, accurate position and ranging, immunisation to multipath fading, covert communications due to low transmission power, coexistence with other communication systems because of the low power spectral density (PSD), material penetration capabilities, etc [1]. The study has shown that UWB is one of the alternative techniques that are well suitable for short-range communications, such as for wireless sensor networks (WSN) and personal area networks (PAN) [1]–[3].

Initially, UWB has been implemented with the aid of time-hopping pulse-position modulation (TH-PPM) techniques without carrier modulation [2], [4]. In the carrier-less or baseband UWB systems information is transmitted with the assistance of trains of time-shifted pulses through pulse position modulation. In the TH-PPM UWB multiple pulses are usually used to transmit a single symbol for the sake of enhancing the transmission performance. Recently, the direct-sequence spread spectrum (DS-SS) technique has also been proposed for implementation of UWB communications [5]. In DS-UWB a data bit is transmitted associated with multiple chips and the chip-duration is usually equal to the width of the basic time-domain signal. In DS-UWB the conventional CDMA related techniques may be applied for improving the multiple-access capability [5].

Explicitly, both the TH-UWB and DS-UWB have their advantages and disadvantages. Due to using low-duty baseband pulses and supporting low rate, TH-UWB is more desirable when long battery life becomes important [6]. TH-UWB systems also have the capability to mitigate the multipath interference. It has been demonstrated in [3] that the performance of the TH-UWB is slightly better than that of the DS-UWB in the presence of interference, when communicating over AWGN channels.

By contrast, the performance of the DS-UWB systems degrade due to inter-chip interference (ICI) and inter-symbol interference (ISI) [5] when single-user correlation detector is considered. In [5] it has been shown that the DS-UWB system is capable of mitigating the multiuser interference. However, it experiences severe narrowband interference. It can be shown that, when the energy per bit is constant in both the DS-UWB and TH-UWB systems, the energy per pulse in the TH-UWB is higher than that in the DS-UWB. Consequently, the peak-to-average-power and the power-spectral density (PSD) is lower in DS-UWB in comparison with the TH-UWB. Furthermore, it has been shown in [3] that the DS-UWB usually causes less in-band interference on the other types of systems operated in the same frequency band of the UWB systems.

In this contribution we propose and investigate a novel UWB system, namely the hybrid DS-TH UWB system, which employs both DS spreading and TH. It can be shown that the hybrid DS-TH UWB system is capable of inheriting the advantages of both the DS-UWB and TH-UWB, while avoiding their disadvantages. Furthermore, it can be shown that the hybrid DS-TH UWB is capable of providing more degrees-of-freedom for system design and reconfigurations than either the pure DS-UWB or the pure TH-UWB. In this contribution we compare the performance of the hybrid DS-TH UWB systems with that of the pure DS-UWB or pure TH-UWB, when the conventional single-user correlation detector or conventional minimum mean-square error (MMSE) multiuser detector is employed. The performance of the above-mention three types of UWB systems is investigated and compared, when communicating over typical UWB channels experiencing Nakagami-m fading. Our study and simulation results show that there exists a tradeoff between the DS and TH spreading factors. Given the channel conditions, signal-to-noise ratio (SNR) and the total spreading factor equalling to the product of the DS and TH spreading spreading factors, there exist optimum DS and TH spreading factors, which result in the lowest achievable bit-error rate (BER).

The rest of this paper is organised as follows. Section II describes the system model for the hybrid DS-TH UWB system which includes the transmitted signal, channel model and the receiver structure. Detection schemes considered in our simulations are presented in Section III. In Section IV we provide our simulation results, while in Section V, conclusions are summarised.

II. Description of the Hybrid DS-TH UWB System

A. Transmitted Signal

The block diagram for considered hybrid DS-TH UWB system is shown in Fig.1. In hybrid DS-TH UWB systems each bit is first spread by invoking the principles of DS spreading and then the location of the transmitted pulses are determined according to the TH code as detailed in our forthcoming discourses. In this contribution we assume binary phase-shift keying (BPSK) baseband modulation. Consequently, the transmitted signal $s^{(k)}(t)$ by the kth user can be expressed as

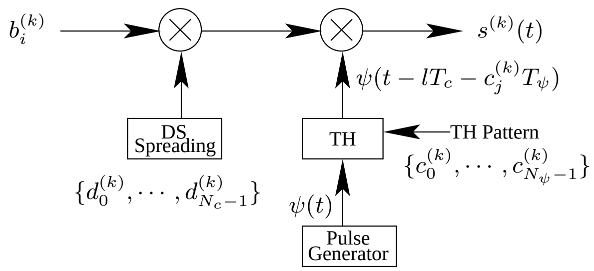

Fig. 1. Transmitter model of hybrid direct-sequence time-hopping ultrawide bandwidth (DS-TH UWB) systems.

$$
\begin{aligned}
s^{(k)}(t) &= \sqrt{\frac{E_b}{N_c T_\psi}} \sum_{j=0}^{\infty} b^{(k)}_{\lfloor \frac{j}{N_c} \rfloor} d_j^{(k)} \\
&\times \psi\left[t - \left(j - \left\lfloor \frac{j}{N_c} \right\rfloor\right) T_c - c_j^{(k)} T_\psi\right] \qquad (1)
\end{aligned}
$$

where $b_i^{(k)} \in \{+1, -1\}$ represents the ith data bit transmitted by user k. Let us assume that the bit-duration is T_b. In the DS-TH UWB system, a bit-duration of T_b is first divided into N_c chips having a duration of T_c. Then, each chip-duration of T_c is further divided into N_ψ time-slots with a duration T_ψ, where T_ψ is the width of a basic time-domain pulse $\psi(t)$. Therefore, we have the relationship of $T_b = N_c T_c = N_c N_\psi T_\psi$. In (1), $\lfloor x \rfloor$ represents the floor function which returns the largest integer less than or equal to x, $\{d_i^{(k)}\}$, where $d_i^{(k)} \in \{+1, -1\}$, represents the binary DS spreading sequence assigned to the kth user, while $\psi(t)$ represents the basic time-domain pulse, which determines the bandwidth occupied by the UWB system. As shown in (1), each chip transmits a pulse and the position of the pulse within a chip is determined by the TH sequence $\{c_j^{(k)}\}$, where $c_j^{(k)}$ takes a value in $\{0, 1, 2, \cdots, N_\psi - 1\}$ with equal probability.

From the above description it can be observed that if $N_\psi = 1$, T_ψ and T_c are equal and in this case the hybrid DS-TH UWB is reduced to the pure DS-UWB. By contrast, the hybrid DS-TH UWB with $N_c = 1$ is reduced to the pure TH-UWB. Note that, the processing gain of the hybrid DS-TH UWB system is $N = N_c N_\psi$.

The principles of the hybrid DS-TH UWB can be understood with referring to Fig. 2. As shown in Fig. 2, the $(V-2)$th bit duration is divided into N_c chips of duration T_c. Each chip is further divided into N_ψ time-slots of duration T_ψ, and the pulse is transmitted in the first time-slot of the second chip.

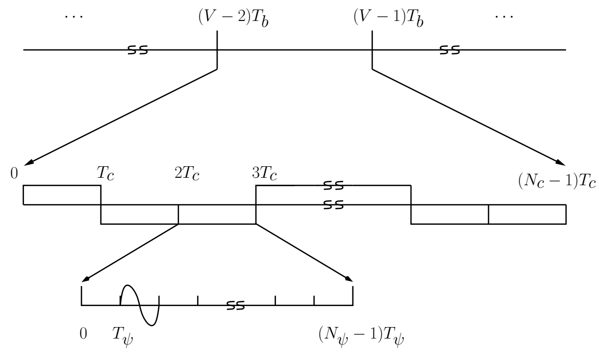

Fig. 2. Illustration of the signalling in the hybrid DS-TH UWB systems.

B. Channel Model

An UWB channel model has been proposed in the standard of IEEE 802.15.3a in the context of high data rate communications from 110 to 480 Mbps over a range of less than 10 meters for WPAN [7]. The spectrum considered in IEEE 802.15.3 is between 3.1 GHz and 10.6 GHz. The multipath channel model considered in IEEE 802.15.3 can be expressed as [7]

$$h(t) = \sum_{l=0}^{L-1} h_l \delta(t - T_0 - lT_\psi) \qquad (2)$$

where L represents the number of resolvable multipaths, $h_l = |h_l|e^{j\phi}$ represents the gain of the lth resolvable multipath component, T_0 is the transmission delay of the line-of-sight (LOS) signal from the transmitter to the receiver, while lT_ψ represents the excess delay of the lth resolvable path.

In order to make the channel model sufficiently general, firstly, we assume that the delay spread spans g data bits, yielding $(g-1)N_c N_\psi \leq (L-1) < gN_c N_\psi$. Secondly, we assume that among the L number of resolvable paths there are L_s strong multipath components, which convey the majority of the transmitted power. Furthermore, we assume that the L_s number of significant multipath components are randomly distributed over the L number of resolvable paths, but they are the same for each data block. As shown in [1], the measured data shows that the UWB channels usually follow lognormal or Nakagami distribution, which has been validated by using the Kolmogorov-Smirnov testing with a significance level of 1%. In this contribution the performance of the hybrid DS-TH UWB systems is investigated when Nakagami-m fading is assumed, since the Nakagami-m distribution employs the following characteristics:

1) Lognormal distribution can be well approximated by the Nakagami-m distribution associated with a high value of the fading parameter m [1];

2) Rayleigh distribution is valid in some communications environments even when the resolvable bin size is very small [1]. It can be shown that the Nakagami-m distribution is reduced to the Rayleigh distribution when the fading parameter m is set to one, i.e, when $m = 1$;
3) Nakagami-m distribution is a generalised distribution, which often gives the best fit to land-mobile and indoor-mobile multipath propagation environments, as well as to scintillating ionospheric radio links [8]. Different propagation scenarios can be modelled by the Nakagami-m distribution by simply changing the value of m in the Nakagami-m distribution. Furthermore, the Nakagami-m distribution offers features of analytical convenience [8].

In our analysis we assume that the amplitude of the fading gain obeys the independent Nakagami-m distribution with a probability density function (PDF) given by [9]

$$P_{|h_l|}(r) = \frac{2m_l^{m_l} r^{2m_l-1}}{\Gamma(m_l)\Omega_l^{m_l}} \exp(-m_l/\Omega_l)r^2, \qquad r > 0 \tag{3}$$

where $\Gamma(\cdot)$ is the gamma function, m_l is the fading parameter corresponding to the lth multipath component and the parameter Ω_l is given by $\Omega_l = E[|h_l|^2]$ [9]. Furthermore, we assume that the phase rotation due to fading channel is uniformly distributed in $[0, 2\pi]$. Let us now consider the receiver structure.

C. Receiver Structure

Let assume that the hybrid DS-TH UWB system supports K users and when the DS-TH UWB signal as shown in (1) is transmitted over the Nakagami-m fading channels with the channel impulse response (CIR) as in (2), the received signal can be expressed as

$$\begin{aligned} r(t) &= \sqrt{\frac{E_b}{N_c T_\psi}} \sum_{k=1}^{K} \sum_{l=0}^{L-1} \sum_{j=0}^{MN_c} h_l^{(k)} b_{\left\lfloor \frac{j}{N_c} \right\rfloor}^{(k)} d_j^{(k)} \\ &\times \psi_{rec}\left[t - \left(j - \left\lfloor \frac{j}{N_\psi} \right\rfloor\right) T_c - c_j^{(k)} T_\psi \right. \\ &- \left. T_0 - lT_\psi - \tau_k \right] + n(t) \end{aligned} \tag{4}$$

where $n(t)$ represents the additive white Gaussian noise (AWGN) with zero-mean and single-sided power spectrum density of N_0 per dimension, τ_k takes into account the lack of synchronisation among the users, while $\psi_{rec}(t)$ represents the time-domain pulse received, which is usually the second derivative of the transmitted pulse $\psi(t)$ [10].

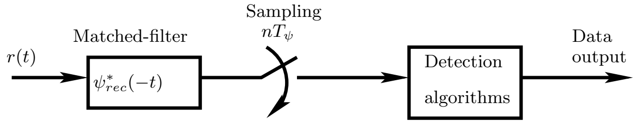

Fig. 3. Receiver block diagram for detecting the hybrid DS-TH UWB signals.

The receiver structure for detection of the DS-TH UWB signal is shown in Fig. 3. The received signal is first passed through a matched-filter (MF) having the impulse response $\psi^*_{rec}(-t)$. The output of the MF is then sampled at a rate of $1/T_\psi$. Therefore, if M number of bits are detected, the detector can collect a total $(MN_cN_\psi + L - 1)$ number of samples, where $(L-1)$ is due to the L number of resolvable multipaths. In more detail, the λth sample can be obtained by sampling MF's output at the time instant $t = T_0 + (\lambda + 1)T_\psi$, which can be expressed as

$$y_\lambda = \left(\sqrt{\frac{E_b T_\psi}{N_c}}\right)^{-1} \int_{T_0+\lambda T_\psi}^{T_0+(\lambda+1)T_\psi} r(t)\psi^*_{rec}(t)dt \tag{5}$$

Let define

$$\boldsymbol{y} = [y_0, y_1, \cdots, y_{MN_cN_\psi+L-2}]^T \tag{6}$$

$$\boldsymbol{n} = [n_0, n_1, \cdots, n_{MN_cN_\psi+L-2}]^T \tag{7}$$

Then, according to (5), it can be shown that the element n_λ in $\boldsymbol{n}$ can be represented as

$$n_\lambda = \left(\sqrt{\frac{E_b T_\psi}{N_c}}\right)^{-1} \int_{T_0+\lambda T_\psi}^{T_0+(\lambda+1)T_\psi} n(t)\psi^*_{rec}(t)dt \tag{8}$$

which is a Gaussian random variable with mean zero and a variance of $\sigma^2 = N_0/2E_b$ per dimension. Furthermore, upon substituting the received signal in the form of (4) into (5), it can be shown that, after some simplifications, $\boldsymbol{y}$ can be expressed as

$$\boldsymbol{y} = \boldsymbol{C}\boldsymbol{H}\boldsymbol{b} + \boldsymbol{n} = \sum_{k=1}^{K} \boldsymbol{C}_k \boldsymbol{H}_k \boldsymbol{b}_k + \boldsymbol{n} \tag{9}$$

where $\boldsymbol{b}_k = [b_0^{(k)}, b_1^{(k)}, \cdots, b_{M-1}^{(k)}]^T$ contains the M number of data bits transmitted by the kth user, the channel matrix of the kth user, $\boldsymbol{H}_k$ is given by

$$\boldsymbol{H}_k = \text{diag}\,\{\boldsymbol{h}_k, \boldsymbol{h}_k, \ldots, \boldsymbol{h}_k\} \tag{10}$$

which is a $(ML \times M)$-dimensional matrix with $\boldsymbol{h}_k$ given by the CIR of user k as

$$\boldsymbol{h}_k = \left[h_0^{(k)}, h_1^{(k)}, \ldots, h_{L-1}^{(k)}\right]^T \tag{11}$$

The spreading matrix $\boldsymbol{C}_k$ of the kth user is a $[(MN_cN_\psi + L - 1) \times ML]$-dimensional matrix which can be expressed as

$$\boldsymbol{C}_k = \left[\begin{array}{|c|c|c|c|} \hline \boldsymbol{C}_1^{(k)} & \mathbf{0} & \mathbf{0} & \mathbf{0} \\ & \boldsymbol{C}_2^{(k)} & \mathbf{0} & \mathbf{0} \\ \hline \mathbf{0} & & \ddots & \mathbf{0} \\ \mathbf{0} & \mathbf{0} & & \boldsymbol{C}_M^{(k)} \\ \mathbf{0} & \mathbf{0} & \mathbf{0} & \\ \hline \end{array}\right] \tag{12}$$

where

$$\boldsymbol{C}_i^{(k)} = \tag{13}$$

$$\begin{bmatrix} c_{(i-1)N_cN_\psi}^{(k)} & 0 & \cdots & 0 \\ c_{(i-1)N_cN_\psi+1}^{(k)} & c_{(i-1)N_cN_\psi}^{(k)} & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ c_{(i-1)N_cN_\psi+L-1}^{(k)} & c_{(i-1)N_cN_\psi+L-2}^{(k)} & \cdots & c_{(i-1)N_cN_\psi}^{(k)} \\ \vdots & \vdots & \ddots & \vdots \\ c_{iN_cN_\psi-1}^{(k)} & c_{iN_cN_\psi-2}^{(k)} & \cdots & c_{iN_cN_\psi-L}^{(k)} \\ 0 & c_{iN_cN_\psi-1}^{(k)} & \cdots & c_{iN_cN_\psi-L+1}^{(k)} \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & c_{iN_cN_\psi-1}^{(k)} \end{bmatrix}$$

and $\mathbf{0}$ in (12) has dimensionality of $(N_c N_\psi \times L)$ respectively. Let us now consider the detection of the hybrid DS-TH UWB signals in the next section.

III. Detection of Hybrid DS-TH UWB Signals

The hybrid DS-TH UWB is detected with the aid of low-complexity linear detectors. In this contribution it is assumed that the receiver has perfect channel knowledge and both the DS and TH codes for the desired user are known to the receiver. Both the conventional single-user correlation detector and the conventional MMSE multiuser detector are considered.

A. Correlation Detector

The correlation detector is also referred to as the MF detector. The correlation detector does not possess the ability to mitigate the multiuser interference (MUI), ICI and ISI. Therefore, as shown in Section IV the performance of the correlation detector degrades as the number of users increases or as the number of multipath components increases. In the context of the single-user correlation detector, the estimate to $\boldsymbol{b}_k$ of the kth user is given by

$$\hat{\boldsymbol{b}}_k = \boldsymbol{H}_k^H \boldsymbol{C}_k^T \boldsymbol{y} = \boldsymbol{H}_k^H \boldsymbol{C}_k^T \{\boldsymbol{C}\boldsymbol{H}\boldsymbol{b} + \boldsymbol{n}\} \qquad (14)$$

B. Minimum Mean Square Error (MMSE) Detector

The MMSE detector is a linear multiuser detector [11]. The MMSE detector is usually preferred over the decorrelating detector as it can be implemented adaptively [11], it takes into account the background noise in detection and furthermore, it utilises the knowledge of the received power for enhancing the detection performance.

For the linear MMSE detector, the estimate to $\boldsymbol{b}_k$ can be expressed as

$$\hat{\boldsymbol{b}}_k = \boldsymbol{W}_k^H \boldsymbol{y} \qquad (15)$$

where $\boldsymbol{W}_k = \boldsymbol{R}_y^{-1} \boldsymbol{C}_k \boldsymbol{H}_k$ and $\boldsymbol{R}_y$ represents the autocorrelation matrix of $\boldsymbol{y}$, which is given by

$$\boldsymbol{R}_y = E[\boldsymbol{y}\boldsymbol{y}^H] = \sum_{k=1}^{K} \boldsymbol{C}_k \boldsymbol{H}_k \boldsymbol{H}_k^H \boldsymbol{C}_k^T + 2\sigma^2 \boldsymbol{I} \qquad (16)$$

where $\boldsymbol{I}$ is an identity matrix. Note that R_y can usually be estimated at the receiver without requiring the knowledge about the other users.

IV. Simulation Results and Discussion

In this section BER versus SNR performance of the hybrid DS-TH UWB system, pure DS-UWB and pure TH-UWB is investigated, when either the correlation or MMSE detector is considered. The performance of the DS-TH UWB is compared with that of the pure DS-UWB and TH-UWB systems. In our simulations the number of multipaths are assumed to be 15. Out of these 15 paths there are 5 significant paths conveying 85% of the total transmitted power. The total spreading factor is constant, and $N_c N_\psi = 128$. It is worth mentioning again that the hybrid DS-TH UWB system is reduced to the pure DS-UWB system with $N_c = 128$ when $N_\psi = 1$, while reduced to the pure TH-UWB system with $N_\psi = 128$ when $N_c = 1$.

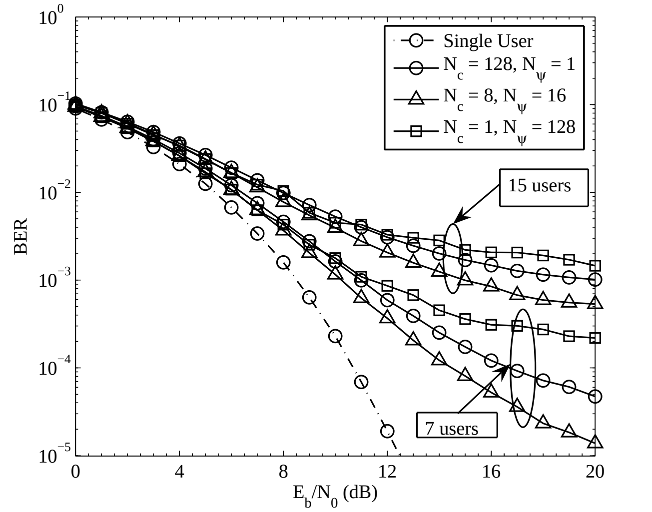

Fig. 4. BER versus SNR performance of the hybrid DS-TH UWB system using correlation receiver in Rayleigh fading channels. The total spreading factor is $N_c N_\psi = 128$, there are a total of 15 multipaths, 5 out of which 5 convey 85% of the transmitted power.

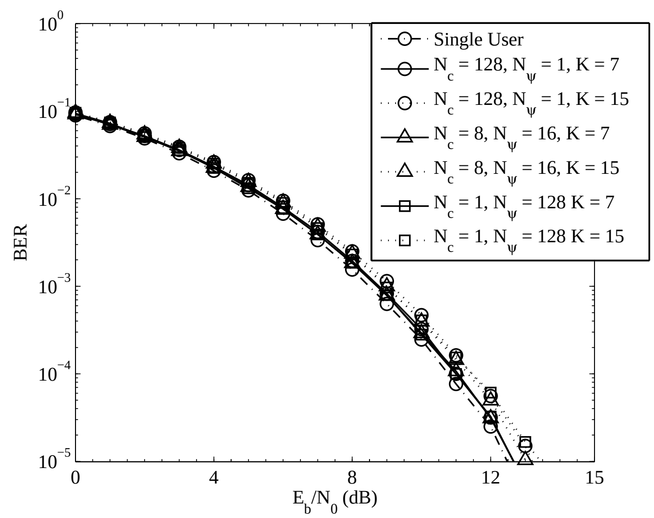

Fig. 5. BER versus SNR performance of the hybrid DS-TH UWB system using MMSE receiver in Rayleigh fading channels. The total spreading factor is $N_c N_\psi = 128$, there are a total of 15 multipaths, 5 out of which convey 85% of the transmitted power.

Fig. 4 depicts the performance of the hybrid DS-TH UWB system using correlation detection, when communicating over Rayleigh Fading channels. It can be easily observed that hybrid DS-TH UWB system outperforms the pure DS-UWB and the pure TH-UWB systems. As shown in Fig. 4, as the number of users increases the performance of the UWB systems using the correlation receiver becomes worse.

Fig. 5 shows the performance of the hybrid DS-TH UWB system using MMSE receiver. Since the MMSE receiver is capable of mitigating the MUI, ICI and ISI, the performance achieved by the hybrid DS-TH UWB system is close to the single-user performance bound for the scenarios considered. The hybrid DS-TH UWB, pure DS-UWB and the pure TH-UWB all achieve a similar BER performance. As shown in Fig. 5, when 15 users are supported, the performance of the hybrid DS-TH UWB system is slightly better than that of the other two UWB schemes.

Fig. 6 shows the performance of the hybrid DS-TH UWB systems associated with different settings. As shown in Fig. 6 there is a trade-off between the DS spreading factor and the TH spreading factor. Given the value of $N_c N_\psi = 128$, there is an optimum combinations of (N_c, N_ψ) which yields the lowest achievable BER. It can be observed from the Fig. 6 that the best performance is achieved when $N_c = 8$ and $N_\psi = 16$.

Finally, in Fig. 7 the performance of the hybrid DS-TH UWB systems using correlation and MMSE receivers is investigated when communicating over Nakagami-m fading channels associated with different m values. Since the channel quality improves as the m value increases, the performance of the hybrid DS-TH UWB system becomes better when the value of m increases. It can also be observed that the MMSE receiver significantly outperforms the correlation receiver, at the cost of a relatively higher complexity.

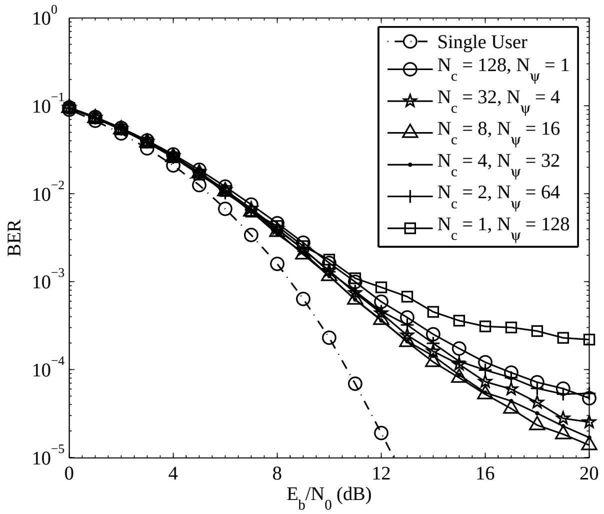

Fig. 6. BER versus SNR per bit performance of the hybrid DS-TH UWB system using correlation receiver and supporting 7 users when communicating over Rayleigh fading channels. The total spreading factor is $N_c N_\psi = 128$, there are a total of 15 multipaths, 5 out of which convey 85% of the transmitted power.

V. Conclusion

From our study we can conclude that in a hybrid DS-TH UWB system there is a tradeoff between the DS and TH spreading factors, especially, when the single-user correlation detector is employed. It can be shown that the best performance of the hybrid DS-TH UWB system may be obtained by appropriately choosing the DS and TH spreading factors. Furthermore, in the hybrid DS-TH UWB systems supporting multiple users, the MMSE multiuser detector may be employed for enhancing the BER performance. Our future research will concentrate on the low-complexity high-efficiency multiuser detectors for the hybrid DS-TH UWB systems.

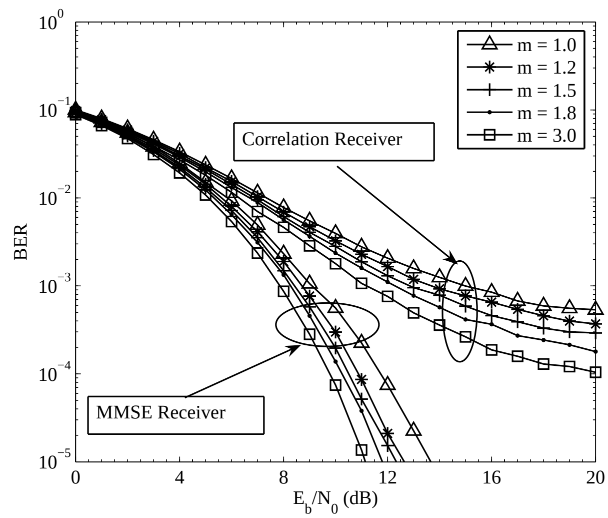

Fig. 7. BER versus SNR per bit performance of the hybrid DS-TH UWB system using correlation and MMSE receiver when supporting 15 users and communicating over Nakagami-m fading channels. The total spreading factor is $N_c N_\psi = 128$, the DS spreading factor is $N_c = 8$ and the TH spreading factor is $N_\psi = 16$. The total number of resolvable multipaths are 15, 5 of which convey 85% of the transmitted power.

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