Sardar Muhammad GULFAM[1], Ayesha Maryam SIDDIQUI[1], Ali KHAQAN[1], Abrar AHMED[1], Azhar YASIN[1], Mohsin JAMIL[3], Sharjeel RIAZ[1], Mehmood QURESHI[1], Samar Naseem ABBASI[1], Raja Ali RIAZ[1,2]

Department of Electrical Engineering, COMSATS Institute of Information Technology, Islamabad (1), School of ECS, University of Southampton (2), National University of Science and Technology, Islamabad (3)

The Q-Best Spreading Sequences for Low-Complexity DS-CDMA IEEE 802.15 UltraWideBand Systems in Dense Multipath Channels

Abstract. *This paper presents an analysis for the selection of Q-Best spreading sequences of the synchronous Direct Sequence Code Division Multiple Access (DS-CDMA) UltraWideBand (UWB) system on the uplink using joint detection. It is shown that the time-domain cross correlation function between the spreading sequences is a prime interference measure for the synchronous DS-CDMA UWB users. Therefore auto and cross correlation funcitons of the spreading sequences, along with UWB IEEE 802.15 channel characteristics are amalgamated to obtain minimum Bit Error Rate (BER), using low complexity correlation joint detection scheme. Some well known classes of length Q sequences, such as m, Gold, Walsh and Random sequences are evaluated with respect to the aforementioned basic criteria. Explicitly, the performance of each sequence with length Q is shown in high Inter-Symbol Interference (ISI) and Multiple Access Interference (MAI) environment produced by dense multipath and multiuser.*

Streszczenie. *W artykule przedstawiono analizę metod rozpraszania widma z wykorzystaniem detekcji połączeń, dla metody dostępowej DS-CDMA w połączeniu z satelitą w systemie UltraWideBand. Wykazano, że wyznaczenie funkcji korelacji przejścia dziedziny czasu między sekwencjami rozpraszania powinno stanowić główny czynnik pomiarowy dla użytkowników systemu DS-CDMA UWB. W badaniach wykorzystano najlepiej znane klasy o długości sekwencji Q (Gold, Walsh, Random, m). Ich działanie sprawdzono w środowisku ISI oraz MAI stworzonym przez gęsty zbiór wielu ścieżek i wielu użytkowników.* ***(Sekwencja rozpraszania Q-Best w systemie DS-CDMA UWB IEEE 802.15 w kanałach wielościeżkowych)***

Keywords: Spreading Sequences, DS CDMA, UWB, Dense Multipath
Słowa kluczowe: sekwencja rozpraszania, DS-CDMA, UWB, spójna wielodrożność.

Introduction

The Federal Communications Commission's (FCC) ruling released the band spanning from 3.1 to 10.6 GHz in the USA for UltraWideBand UWB forms the basis of the current era of UWB. The received UWB signal is constituted by a high number of multipath components [1] owing to its wide bandwidth. Furthermore high bandwidth results in a fine time domain received signal resolution, leading to accurate position sensing. These are few of the other attractions created research community interest in UWB. In [2], UWB communications were proposed for both Wireless Sensor Networks (WSN) and Personal Area Networks (PAN). The IEEE 802.15.3a standardazition task group has ratified a standardrized channel model to be used for the evaluation of PAN physical layer protocols [3].

Heavy digital imaging and multimedia applications result in the requirements of high data rate wireless links. UWB has the capacity to fulfil the requirements of low cost and high speed digital indoor networks. The DS-CDMA has been used for the implementation of UWB system. Multiple chips with the chip duration equal to the basic time-domain signal are used to transmit data bits. Furthermore multiple access capability is enhanced by employing the conventional CDMA technology [4].

The role of Spreading Sequences in DS-CDMA UWB system is very important. The facility of extra bandwidth compared to narrowband systems gives the leisure of getting diversity through resolving large number of multipath components. In this scenario, the auto and cross correlation of the spreading sequences play a pivotal role to get better performance.The sequence which has better properties of time-domain autocorrelation is more suited to mitigate the Inter-Symbol interference (ISI) of the multiusers. The Multiple Access Interference (MAI) is directly related to the time-domain cross-correlation of the corresponding sequences. Therefore it is mandatory for UWB systems that the sequence which has the best time-domain correlation properties should be selected for specific scenarios [5].

The novelty and rationale of the paper can be summarised as follows:

1. *An analytical approach is taken to illustrate the effect of the main characteristics such as code length Q, auto-correlation and cross-correlation of some important PN and orthogonal sequences on system performance of DS-CDMA UWB system.*
2. *The selection criteria for best Q length spreading sequence in IEEE 802.15 dense multipath channel enviornment is suggested. Furthermore system performance is enhanced for the lowest complexity correlation detection scheme through UWB characteristics along with time-domain correlation properties of spreading sequences.*

The rest of this paper is organised as follows. In first Section we introduce our system model, followed by the Section, where the m, Gold and Walsh codes are explained, Third Section covers UWB transmitter and receiver, followed by our results discussion and finally conclusions are drawn.

System Model

Figure 1 shows the discrete-time baseband model of the synchronous DS-CDMA UWB system on the uplink using joint detection for different Q length Spreading Sequences $\mathbf{s}^{(u)}$. Each user transmits a data symbol sequence $\mathbf{m}^{(u)}$ consisting of N elements at symbol intervals T_s. Each data symbol $\mathbf{m}_n^{(u)}$ of user u is repeated Q times and the resultant Q-dimensional vector is multiplied by the Q chips of the specific signature sequence $\mathbf{s}^{(u)}$, having a period of Q. Each of the U channels is described by the UWB Channel Impulse Response (CIR) $\mathbf{h}^{(u)}$ consisting of W samples during the chip interval $T_c = \frac{T_s}{Q}$.

As shown in Figure 1, the received complex-valued symbols are first detected by the Correlation (Corr) detector in order to produce the corresponding estimated data bits $\hat{\mathbf{m}}$, which are fed into the BPSK demodulator and finally for UWB pulse demodulation. In this contribution, the Q length spreading vector $\mathbf{s}^{(u)}$ takes on values for m, Gold, Walsh and random sequences. These sequences are explained in the follwoing section.

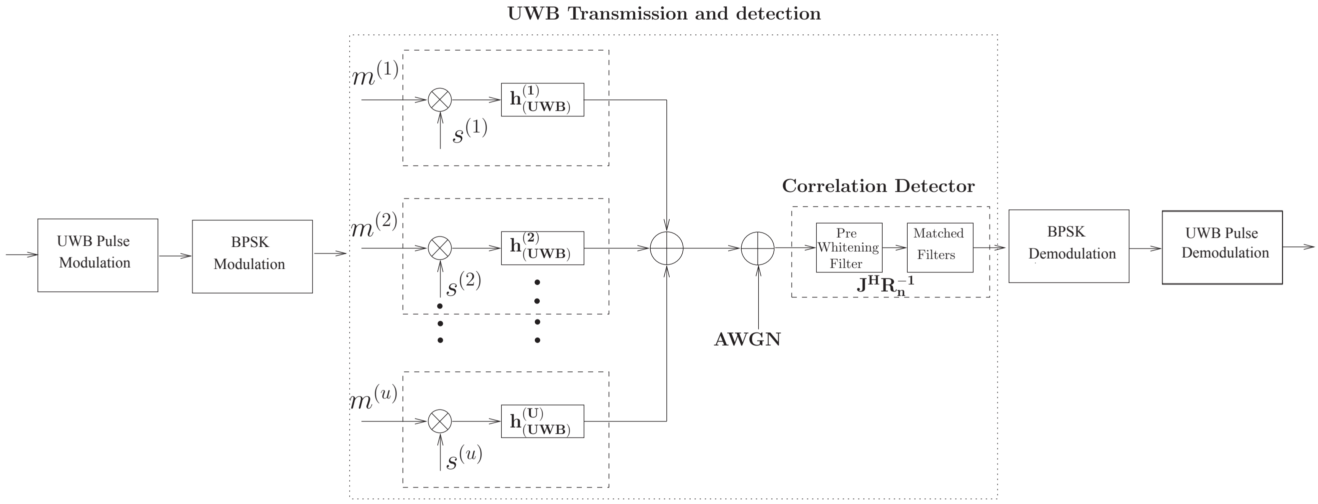

Figure 1. Discrete System Model of a synchronous DS-CDMA UWB on the uplink using joint detection for different Q length Spreading Sequences $\mathbf{s}^{(u)}$.

Spreading Sequences

m-Sequences

The m-Sequences (Maximal-Length Sequences) are the largest codes that can be generated by a given delay element D of a given length in Linear Feedback Shift Register (LFSR). The finite recurrence relation of m-sequence can be expressed as a ratio of finite ploynomials as [6]

$$\mathbf{C}(\mathbf{D}) \triangleq \frac{\mathbf{P_g}(\mathbf{D})}{\mathbf{P_c}(\mathbf{D})} = \frac{\sum_{k=1}^{n} w_k D^k \left(e_{-k}D^{-k} + ... + e_{-1}D^{-1}\right)}{1 + \sum_{k=1}^{n} w_k D^k}. \quad (1)$$

where $\mathbf{P_c}(\mathbf{D})$ is called the characteristic ploynomial of the LFSR sequence generator, depends solely on the connection vector $w_1, ..., w_n$ and determines the main characteristics of the generated sequence. The polynomial $\mathbf{P_g}(\mathbf{D})$ depends on the initial condition vector $e_{-n}, e_{-(n-1)}, ..., e_{-1}$ and determines the phase shift of the sequence. The connection vector w and sequence vector e are related by

$$e_i = w_1 e_{i-1} + w_2 e_{i-2} + ... + w_n e_{i-n} = \sum_{k=1}^{n} w_k e_{i-k}. \quad (2)$$

The period of the sequence generated by aforesaid configuration will be $Q = 2^n - 1$. The Auto-CorreLation (ACL) of m-Sequence can be calculated as

$$\mathbf{R_{kk}}(\mathbf{0}) = Q \quad (3)$$

$$\mathbf{R_{kk}}(\mathbf{q}) = -1 \qquad for \quad q \neq 0 \quad (4)$$

These ACL properties are near-ideal for code acquisition or synchronization, where the perfectly aligned condition of $q = 0$ between the received and locally stored sequences has to be detected as shown in Figure 2a. As an additional constraint, in multiuser communication a large set of spreading sequences exhibiting low Cross-CorreLation (CCL) values are needed. The m-Sequence does not staisfy this requirement since some m-Sequence pairs have large CCL values [7].

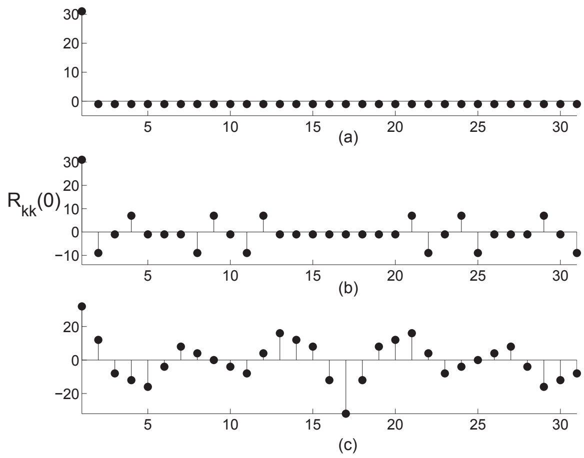

Figure 2. The ACLs of m, Gold and Walsh Spreading Sequences of length $Q = 31$.

Gold Sequences

The Gold Sequences are constructed from preferred pairs of m-Sequences. The attribute of Gold Sequences is the large number of codes they can supply. The CCL between the codes is uniform and bounded over a set of codes available from a given generator. The family size of a Gold Sequence set having a period of Q is $K = Q + 2$. The CCLs and out of phase ACLs of Gold Sequences have only three possible values which are given by [7]

$$\mathbf{R_{kk}}(q) = \begin{cases} Q & \text{for } q = 0 \\ \{-1, -t(m), t(m) - 2\} & \text{for } q \neq 0 \end{cases} \quad (5)$$

$$\mathbf{R_{jk}}(q) = \{-1, -t(m), t(m) - 2\} \quad \forall q, j \neq k \ . \quad (6)$$

where

$$t(m) = \begin{cases} 2^{\frac{(m+1)}{2}} + 1 & m \text{ is odd} \\ 2^{\frac{(m+1)}{2}} + 1 & m \text{ is even} \end{cases} \quad (7)$$

Figure 2b, schematically presents Equations (5) and (7).

Walsh Sequences

Walsh Sequences are generated by mapping codeword rows of square matrices called Hadamard matrices. These matrices contain one row of all zeros, and the remaining rows

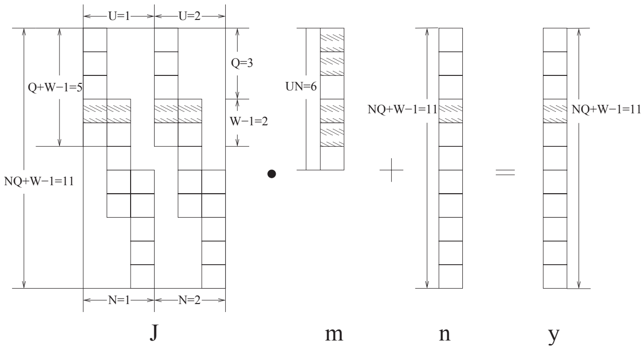

Figure 3. Stylized structure of the matrix equation $\mathbf{y} = \mathbf{Jm} + \mathbf{n}$ for a $U = 2$-user system. Each user transmits $N = 3$ symbols per transmission brust, and each symbol is spread with a signature sequence of $Q = 3$ chips. The channel for each user has a dispersion length of $W = 3$ chips. © Hanzo $et.\ al.$ [7].

each have equal numbers of ones and zeros. Walsh functions can be constructed for block length $Q = 2^n$. The genral form of Hadamard matrices is

$$H_{2Q} = \begin{bmatrix} H_Q & H_Q \\ H_Q & \overline{H_Q} \end{bmatrix} \tag{8}$$

where Q is a power of 2 and the bar denotes the binary complement of the bits in the matrix. The ACLs of Walsh Sequences are not very effective as depicted in Figure 2c but the cross correlation is zero for synchronous sequences and can be expressed as

$$\mathbf{R_{jk}}(q) = \ 0 \quad \forall q, j \neq k \tag{9}$$

Next section details UWB transmitter and receiver.

UWB Transmission and Detection

DS-UWB Baseband Signal

In direct sequence UWB systems, which are analogous to conventional direct sequence spread spectrum (DS-SS) systems [8], the signalling pulse transmissions are controlled by a pseudo random noise code, obeying an appropriate finite bandwidth chip waveform generating an UWB signal. The v^{th} data bit of user u can be transmitted using binary pulse amplitude modulation (BPAM) and the transmitted signal $g^{(u)}(t)$ is formulated as:

$$g^{(u)}(t) = \sum_{v=0}^{\infty} \sum_{q=0}^{Q-1} \psi(t - vT_s - qT_c) s_q^{(u)} m_v^{(u)}, \tag{10}$$

where $\psi(t)$ is the chip waveform representing the UWB pulse, which controls the bandwidth of the UWB signal, $m_v^{(u)}$ corresponds to the data information of user u, T_c is the chip duration and $s_q^{(u)}$ is the q^{th} chip of the spreading code of user u. We assume that a block of data consisting of M bits is transmitted within the block duration of $0 < t \leq MT_b = T_s$, where T_b is the bit duration. The DS-SS waveform $s^{(u)}(t)$ of user u consists of periodic aforementioned sequences having a length of Q chips, which can be expressed as $s^{(u)}(t) = \sum_{q=0}^{Q-1} s_q^{(u)} \psi(t - qT_c)$, where $s_q^{(u)}$ assumes a value of +1 or -1.

Channel Model

The complex valued low-pass multipath CIR can be expressed as [9]

$$h(t) = \sum_{x=0}^{\infty} \sum_{z=0}^{\infty} \alpha_{zx} e^{j\phi_{zx}} \delta(t - T_x - \tau_{zx}), \tag{11}$$

where the gain of the z^{th} ray of the x^{th} cluster is α_{zx} and its phase is ϕ_{zx}, while T_x is the x^{th} cluster's arrival time and τ_{zx} is the z^{th} ray of the x^{th} cluster's arrival time. Furthermore, ϕ_{zx} represents a statistically independent uniformly distributed random variable spanning over $[0, 2\pi)$ and α_{zx} is a statistically independent positive random variable having a Rayleigh probability density function (PDF) given by $p(\alpha_{zx}) = (\frac{2\alpha_{zx}}{\overline{\alpha_{zx}^2}}) e^{(\frac{-\alpha_{zx}^2}{\overline{\alpha_{zx}^2}})}$. The mean square values $\overline{\alpha_{zx}^2}$ are monotonically decreasing functions of T_x and τ_{zx} given by $\overline{\alpha_{zx}^2} = \overline{\alpha^2(T_x, \tau_{zx})} = \overline{\alpha^2(0,0)} e^{\frac{-T_x}{\Gamma}} e^{\frac{-\tau_{zx}}{\gamma}}$, where $\overline{\alpha^2(0,0)}$ = $\overline{\alpha_{00}^2}$ is the average power gain of the first ray of the first cluster. Furthermore, the variables Γ and γ represent the power decay time constants for the clusters and rays respectively.

Receiver Model

The composite transmitted data sequence of the U users can be written as $\mathbf{m} = [\mathbf{m}^{(1)T}, \mathbf{m}^{(2)T}, ..., \mathbf{m}^{(U)T}]^T$, where $m_j = m_n^{(u)}$ for $j = n + N(u-1)$, $u = 1, 2, ..., U$ and $n = 1, 2...., N$. The overall system matrix $\mathbf{J}$ can be interpreted as

$$[\mathbf{J}]_{ij} = \begin{cases} b_n^{(u)}(l) & u = 1, 2, ..., U; \\ & n = 1, 2, ..., N \\ & l = 1, 2, ..., Q + W - 1 \\ 0 & \text{otherwise}, \end{cases} \tag{12}$$

where $i = 1, ..., NQ + W - 1$, $j = 1, ..., UN$. The structure of the system matrix considered is highlighted in Figure 3. In Equation (12) the combined impulse response, $\mathbf{b}_n^{(u)}$ is given by:

$$\mathbf{b}_n^{(u)} \ = \ \left[b_n^{(u)}(1), b_n^{(u)}(2), ..., b_n^{(u)}(l), ..., b_n^{(u)}(Q + W - 1)\right]^T,$$

$$\mathbf{b}_n^{(u)} = \mathbf{s}^{(u)} * \mathbf{h}_n^{(u)}$$

where $u = 1, 2, ..., U$, $n = 1, 2...., N$, $l = 1, 2, ..., Q + W - 1$. Furthermore, $\mathbf{s}^{(u)}$ and $\mathbf{h}_n^{(u)}$ are the corresponding Q-chip spreading sequence vector and the W-chip CIR vector encountered at the chip rate of $\frac{1}{T_c}$, which are defined as $\mathbf{s}^{(u)} = \left[s_1^{(u)}, s_2^{(u)}, .., s_q^{(u)}, ..., s_Q^{(u)}\right]^T$ and $\mathbf{h}_n^{(u)} = \left[h_n^{(u)}(1), h_n^{(u)}(2), .., h_n^{(u)}(w), ..., h_n^{(u)}(W)\right]^T$, where we have $u = 1, ..., U$, $q = 1, ..., Q$, $w = 1, ..., W$ and $n = 1, ..., N$. The discretised composite received signal can be expressed as

$$\mathbf{y} = \mathbf{Jm} + \mathbf{n}, \tag{13}$$

where we have $\mathbf{y} = [y_1, y_2, ..., y_{NQ+W-1}]^T$ and $\mathbf{n} = [n_1, n_2, ..., n_{NQ+W-1}]^T$ with $\mathbf{n}$ representing the noise sequence, which has a covariance matrix of $\mathbf{R}_n = E[nn^H]$. In what follows we will discuss the operation of the correlation detector.

Correlation Detector

The correlation detector is constituted by two filtering stages. The pre-whitening filter [7] is followed by the matched filter, as depicted in Figure. 1. The Cholesky decomposition of the noise covariance matrix $\mathbf{R}_n$ is given by

$$\mathbf{R}_n = \mathbf{LL^H}, \tag{14}$$

where $\mathbf{L}$ is a lower triangular matrix having real-valued elements on its main diagonal. The z-domain transfer function of the pre-whitening filter is $\mathbf{L}^{-1}$. The output of the pre-whitening filter can be expressed as

$$\mathbf{y}' = \mathbf{L}^{-1}\mathbf{y} = \mathbf{L}^{-1}\mathbf{J}\mathbf{m} + \mathbf{L}^{-1}\mathbf{n}. \tag{15}$$

The discrete transfer function $\mathbf{T_{Mf}}$ of the matched filter may be formulated as [12]:

$$\mathbf{T_{Mf}} = (\mathbf{L}^{-1}\mathbf{J})^{\mathbf{H}} = \mathbf{J}^{\mathbf{H}}(\mathbf{L}^{-1})^{\mathbf{H}}. \tag{16}$$

Finally, combining Equations (15) and (16) provides joint estimates of the data symbols for the correlation detector expressed as:

$$\hat{\mathbf{m}}_{\mathbf{Corr}} = \mathbf{y}'' = \mathbf{T_{MF}}\mathbf{y}' = \mathbf{J}^{\mathbf{H}}\mathbf{R}_{\mathbf{n}}^{-1}\mathbf{y}. \tag{17}$$

Equation (17) can be expanded into the Multiple Access Interference (MAI) and InterSymbol Interference (ISI) as follows:

$$\hat{\mathbf{m}}_{\mathbf{Corr}} = \underbrace{diag(\mathbf{J}^{\mathbf{H}}\mathbf{R}_{\mathbf{n}}^{-1}\mathbf{J})\mathbf{m}}_{symbols} + \underbrace{\overline{diag}(\mathbf{J}^{\mathbf{H}}\mathbf{R}_{\mathbf{n}}^{-1}\mathbf{J})\mathbf{m}}_{ISI,MAI} + \underbrace{\mathbf{J}^{\mathbf{H}}\mathbf{R}_{\mathbf{n}}^{-1}\mathbf{n}}_{noise}, \tag{18}$$

It becomes clear from Equations (17) and (18) that the correlation detector is the best detector to exploit the ACLs and CCLs of the Spreading Sequences being used. The system overall performance is heavily dependent upon better ACLs and CCLs of the Spreading Sequences being used.

Table 1. System Parameters

Spreading Factor	$Q = 31$
Spreading Sequences	m, Gold, Walsh, Random
No. of Users	$U = 5, 10, 31$
Data Burst Length Per User	$N = 1, 10$
Channels	AWGN, UWB IEEE 802.15
Resolvable Multipath Components	$W = 1, 30, 40, 50$
$\Lambda\left[\frac{1}{nsec}\right]$(Cluster Arrival Rate)	0.0233
$\lambda\left[\frac{1}{nsec}\right]$(Ray Arrival Rate)	2.5
Γ(Cluster Decay Factor)	7.1
γ(Ray Decay Factor)	4.2
Detector	Correlation

Results and Discussion

In this section we present our system performance results. The system considered in this section obeys the schematic of Figure 1 and employs the parameters outlined in Table I for transmission over the IEEE 802.15.3a channel model [3].

Figure 4 present the Bit Error Rate (BER) for the system shown in Figure 1 with users $U = 31$ and AWGN channel, while employing the system parameters outlined in Table I. This graph truly depicts the CCLs of the Spreading Sequences being used. As there is no ISI and UWB channel fading effects since data brust $N = 1$ and AWGN, so the performance is schematic presentation of the CCLs of $Q = 31$ length Spreading Sequences. There is only MAI so the Walsh Sequences (WS) has the best performance which is the AWGN performance for the system as discussed in Section II. The Gold Sequence (GS) and m-Sequence has almost equal performance. The Random Sequence (RN), which are use for comparison, has the worst performance having no CCLs among the sequences.

Figure 5 present the BER for the system with specifications detailed in Table I, specifically $N = 10$, $U = 5$, $W = 30$ using UWB IEEE 802.15 dense multipath channel. There will be a significant factor of ISI along with multipath

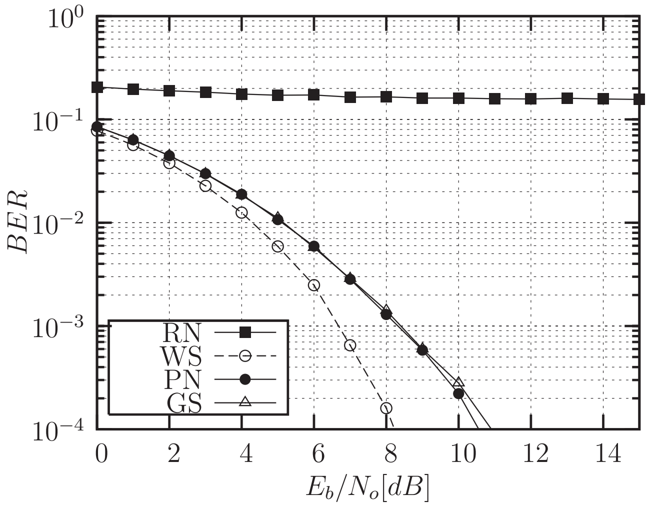

Figure 4. BER versus $\frac{E_b}{N_o}$ for AWGN channel while employing the system parameters outlined in Table I with $N = 1$ and $U = 31$.

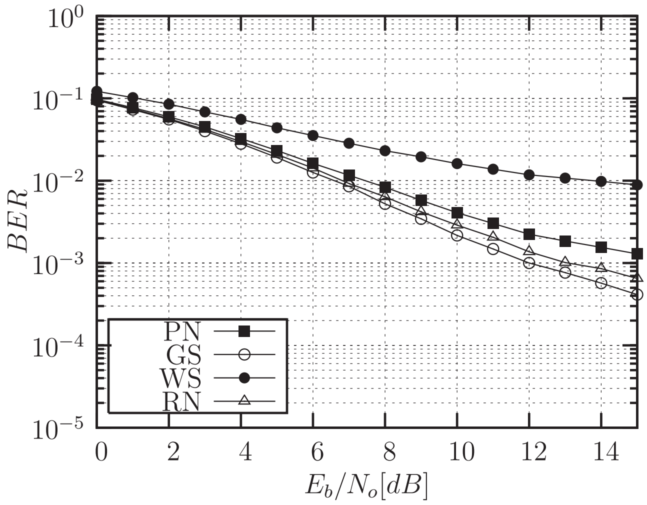

Figure 5. BER versus $\frac{E_b}{N_o}$ for IEEE 802.15 UWB channel while employing the system parameters outlined in Table I with $N = 10$, $U = 5$ and $W = 30$.

fading in multuser scenario. Though we are able to resolve lot of multipaths as it's UWB model but it will also increase ISI. In this enviornment the ACLs of the $Q = 31$ length Spreading Sequences play an important role to mitigate ISI. Since it's not high multiuser scenario so CCLs of Spreading Sequences have little effect. As the trends of BER curves in Figure 5 the best performance is shown by GS which is elaborative from Equations (5) and (6).

Figure 6 the simulation has more stringent conditions for MAI as number of users has been increased to $U = 10$ with resolvable multipath components increased to $W = 40$ using UWB IEEE 802.15 dense multipath channel. In this MAI and ISI conditions, the performance of all $Q = 31$ length Spreading Sequences are same.

Finally fully-loaded system with $U = 31$, $W = 50$, and $N = 10$ using UWB IEEE 802.15 dense multipath channel, we get a perfect floor for CORR detector. Still in this fully loaded synchronous system WS has much better performance than other sequences which is schematic presentation of the property detailed in Equation (9).

Conclusion

In this contribution we presented the performance study of Q-length Spreading Sequences in a synchronous DS-CDMA UWB system communicating over the IEEE 802.15

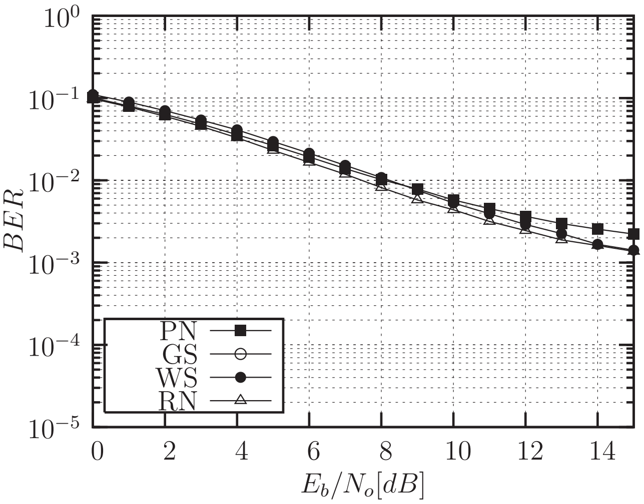

Figure 6. BER versus $\frac{E_b}{N_o}$ for IEEE 802.15 UWB channel while employing the system parameters outlined in Table I with $N = 10$, $U = 10$ and $W = 40$.

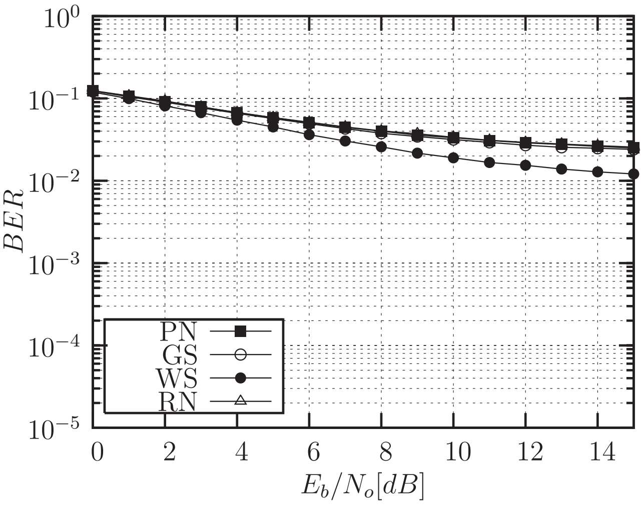

Figure 7. BER versus $\frac{E_b}{N_o}$ for IEEE 802.15 UWB channel while employing the system parameters outlined in Table I with $N = 10$, $U = 31$ and $W = 50$.

UWB channel.The system stated the performance of the Sequences in different scenarios combined with low complexity Correlation detector. We have explicitly stated, which sequence is best in multipath and multiuser UWB transmission on the basis of their time-domain ACLs and CCLs characteristics.

REFERENCES

[1] Liuqing Yang and Giannakis, G. B.: Ultra-wideband communications: an idea whose time has come, IEEE Signal Processing Magazine, pp. 26–54, 2004.

[2] Hamalainen, M. and Hovinen, V. and Tesi, R. and Iinatti, J. H. J. and Latva-aho, M.: On the UWB system coexistence with GSM900, UMTS/WCDMA, and GPS, IEEE Journal on Selected Areas in Communications, pp. 1712–1721, 2002.

[3] Molisch, A. F. and Foerster, J. R. and Pendergrass, M.: Channel models for ultrawideband personal area networks, IEEE Wireless Communications, pp. 4–21, 2003.

[4] Foerster, J. R.: The performance of a direct-sequence spread ultrawideband system in the presence of multipath, narrowband interference, and multiuser interference, IEEE Conference on Ultra Wideband Systems and Technologies, pp. 87–91, 2002.

[5] L. Hanzo and L-L. Yang and E-L. Kuan and K. Yen: OFDM and MC-CDMA for broadband multi-user communications, WLANs and broadcasting, John Wiley and Sons, England, 2003.

[6] Solomon W. Golomb: Shift Register Sequences, Aegean Park Press, 1992.

[7] L. Hanzo and L-L. Yang and E-L. Kuan and K. Yen: Single and Multi-Carrier DS-CDMA: Multi-user Detection, Space-Time Spreading, Synchronisation, Networking and Standards, John Wiley and Sons, Ltd and IEEE Press, NY, USA, 2003.

[8] Hara, S. and Prasad, R.: Overview of multicarrier CDMA, IEEE Communications Magazine, pp. 126–133, 1997.

[9] Saleh, A. and Valenzuela, R.: A Statistical Model for Indoor Multipath Propagation, IEEE Journal on Selected Areas in Communications, pp. 128–137, 1987.

[10] Chia-Chin Chong and Su Khiong Yong: A Generic Statistical-Based UWB Channel Model for High-Rise Apartments, IEEE Transactions on Antennas and Propagation, pp. 2389–2399, 2005.

[11] L. Hanzo and L-L. Yang and E-L. Kuan and K. Yen: Single- and Multi-Carrier DS-CDMA: Multi-User Detection, Space-Time Spreading, Synchronisation, Networking and Standards, John Wiley and Sons, England, 2003.

[12] Klein, A. and Kaleh, G. K. and Baier, P. W.: Zero forcing and minimum mean-square-error equalization formultiuser detection in code-division multiple-access channels, IEEE Transactions on Vehicular Technology, pp. 276–287, 1996.

***Authors**: Sardar Muhammad Gulfam (MS, Finland)and Abrar Ahmed (MS, UK), Associate Prof. Raja A. Riaz (Ph. D.), Electrical Engineering Department, COMSATS Institute of Information Technology (http://ciitisb.edu.pk), Park Road, Chak Shehzad Campus, 44000, Islamabad, Pakistan, email: rajaali@comsats.edu.pk*