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Research paper

Novel method for the selection of time hopping codes for UWB communication systems

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Abstract

This work investigates the BER performance of existing code families of Frequency Hopping (FH) codes as Time Hopping (TH) codes in multiuser UWB communication environment and provides a novel method for the selection of TH codes. The performance of codes has been validated in AWGN channel for single user and further validated over multiuser environment. A significant improvement in performance has been observed over random codes. It is validated that selection of better TH codes reduces the MUI and improves the overall performance of the communication system and FH codes with better correlation properties can be used as TH codes in multiuser UWB communication system.

Keywords: *Auto correlation; BER; BPSK; Cross correlation; Frequency Hopping (FH) codes; Time Hopping (TH) codes; Ultra Wide Band; UWB.*

1. Introduction

Ultra Wide Band (UWB) systems have been used for military communications, radio, radar and considered for Wireless Personal Area Network (WPAN) in the past three decades. Initially it was considered for radar application as impulse radio because of its see through walls capabilities. Due to its low power, low cost, high data rates and very low interference capabilities UWB became quite popular among researches for communication based applications. The Federal Communications Commission (FCC) guidelines issued in Feb 2002 explains that UWB could be used for data communication, Radar and safety applications. As per FCC definition "A signal is defined as UWB signal, if its fractional bandwidth is larger than 20% or its bandwidth is larger than 500 MHz" [1]. Frequency band from 3.1 to 10.6 GHz was allocated for UWB Communication system which provides a significantly large bandwidth of 7.5 GHz [1][2]. This allocation of very large bandwidth was approved with the restriction of very low power levels (below -41.3 dBm/MHz or 0.556 mW/MHz) [3]. Thus, UWB can co-exist without interference with already existing narrowband services like S-Band Satcom, GPS and wireless local area networks (WLANs), operating in similar frequency bands [3][4].

UWB is also called a RF free modulation system in which very narrow pulses of the order of nanoseconds are directly transmitted over the channel using BPSK or PPM methods. Time Hopping (TH) multiple access along with Binary Phase Shift Keying (BPSK) called TH-BPSK are used in UWB multiuser communication systems [3][4][5]. Time Hopping codes cannot be used in conventional narrowband communication system that's why major design issues of TH codes are still unresolved for UWB communication systems. Time hopping schemes of transmission asks for very large bandwidth. Conventional communication systems are band limited systems and use frequency domain schemes of transmissions. Hence, there is not much work reported for the realization of better TH codes usable for UWB Systems. In UWB systems normally random codes sequences are used for TH multiple access, these random codes possesses poor correlation properties [3 - 5]. Literature also reports that TH codes with better correlation properties can be designed with better error rate performance for UWB systems [4 - 6].

Time Hopping codes are integer codes and are similar in construction with Frequency Hopping Codes. The correlation properties of TH codes are also explained in the similar manner as that of FH codes [6 - 8]. However, the correlation properties of FH codes are described in terms of number frequency shifts, whereas for TH codes it is the number of time shifts [4][8]. As frequency hopping is very popular in Spread Spectrum communication and used for defence communication systems, a good amount of literature and large number of FH code families are available and still new dimensions are being investigated in FH Codes [9 - 11]. A very rich literature is also available for FH codes to define new bounds and finding accurate measure of correlation performance [8]. Literature also establishes the bounds over the correlation values of TH codes in terms of that of in FH Codes for performance acceptance [12].

BER analysis of a communication system may provide you a quality measure to choose the best system among all options keeping system constraints same for each option [13]. The present work investigates the error rate performance of QC and LC code families of FH codes as TH codes over random codes in Multiuser environment to establish the suitability of these code families for the reduction of Multiuser Interference (MUI) in UWB Systems.

The different sections of the paper are as follows: Time Hopping schemes for multiuser UWB communication system is described in Section 2. Correlation measures for FH and TH codes are given in Section 3. System model for MUI analysis is defined in Section 4. Construction of Frequency hopping codes is given in Section 5. BER performance analysis and plots are provided in Section 6. At the end, Section 7 provides the conclusion.

2. Multiple access scheme

In multiuser TH UWB communication system sequence of N_s short pulses $w(t)$ denotes a symbol of duration T_s sec [4]. Each symbol time is divided into N_s frames of duration $T_f = T_s/N_s$ sec and in each frame one pulse per user is placed. The frame is divided into N_h chips, each of duration $T_c = T_f/N_h$ sec and a pseudo-random TH code/user is used to place a pulse of respective user in one of the chips [2][4]. TH code can be viewed as a sequence of code vectors of N_s elements (one for each transmitted symbol per user), thus we denote the n^{th} element of the k^{th} code vector by $\{c_n^k\}$, n = 0,1, ..., $N_s - 1$, where $c_n^k \in \{0,1,\ldots,N_h - 1\}$, specifies the chip where the n^{th} pulse of the k^{th} user is to be placed [4][12].
PPM modulated UWB signal for k_{th} user is denoted as [4][12]

$$s_k(t) = \sum_n \sqrt{E_w} w(t - nT_f - c_n^k T_c - \delta a^k_{[n/N_s]}) \quad (1)$$

And with BPSK, it can be written as[4][12]

$$s_k(t) = \sum_n a_n^k \sqrt{E_w} w(t - nT_f - c_n^k T_c) \quad (2)$$

Where, $a_k \in \{-1,1\}$ changes the phase of the UWB pulse as per the information bits.
Where,
$w(t)$ = the pulse to be transmitted
E_w = the energy transmitted for each pulse
T_f = the frame duration (seconds)
c_n^k = the TH code value for k^{th} user
T_c = the chip duration asggined for pulse transmission (seconds)
a_n = the n^{th}information symbol
δ = the PPM time shift for modulating the symbol
N_s = the number of pulses per symbol.
The symbol rate or data rateR_s (per second) is [4][12]

$$R_s = \frac{1}{T_s} = \frac{1}{N_s T_f} \quad (3)$$

value '1', otherwise it gives '0' [12]. The Hamming function provides total number of coincidence between pair of codes, and it does not provide the Hamming distance between the pair of codes. Thus, the Hamming correlation value can be given as number of coincidences between the code sequences for some relative time delay τ [4][11] [12].
Hamming function is called Hamming Autocorrelation function, when both the code sequences are same i.e., $H_{rr}(\tau)$. The maximum value of maximum Hamming cross-correlation value H_{cmax} and the maximum Hamming autocorrelation side lobe, H_{amax} provides maximum correlation value between any two code sequences, i.e., $H_{max} = \max\{H_{cmax}, H_{amax}\}$, H_{cmax} and H_{amax} are given as below respectively, [11 - 13]

$$H_{cmax} = \max\{H_{rs}(\tau) | c^r, c^s \in C, r \neq s, \tau = 0,1,\ldots,N_s - 1\} \quad (6)$$

and

$$H_{amax} = \max\{H_{rr}(\tau) | c^r \in C, \tau = 1,2,\ldots,N_s - 1\} \quad (7)$$

3.2. TH code correlation measures

The correlation function of TH codes is given by [12][13],

$$C_{m,n}(\tau) = \sum_{j=0}^{N_s-1} h[jN_h + c^m_{[j+x]_{N_s}}, jN_h + c_j^n + y] + \sum_{j=0}^{N_s-1} h[(j+1)N_h + c^m_{[j+x+1]_{N_s}}, jN_h + c_j^n + y], \quad (8)$$

We can see that correlation function of TH codes also uses Hamming function$h[r,s]$ but in a different manner.In this case the relative time delay is given as $\tau = xN_h + y$, where x is the complete number of time frames within the delay duration, and y is the fraction of complete frame in remaining number of the chip durations [8][12]. The correlation function $C_{m,n}(\tau)$ provides the correlation between the delayed versions of the TH sequence in terms of number of coincidence [4]. TH codes correlation function involves modular function so, it may be seen in equation (8) that the collisions with the neighboring bits also occurs due to periodic nature of the correlation measure in TH codes. The first summation out of the two completely disjointed terms in (8) represent the case when $c_j^n + y < N_h$ (h_1 in Fig. 1), and the second summation represents the case when $c_j^n + y \geq N_h$ (h_2 in Fig. 1) [4][12]. Time Hopping autocorrelation function $C_{m,m}(\tau)$can be derived from (8) when, $m = n$. The maximum correlation value between any two TH codes can be given by the maximum value of TH autocorrelation side lobe, S_{max} and maximum values of TH cross-correlation valueC_{max}, i.e.,$C_{MAX} = max\{S_{max}, C_{max}\}$, $C_{max} and S_{max}$ can be defined as below:, [4][12]

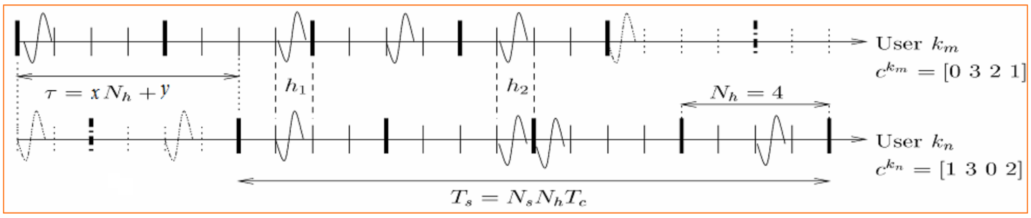

Fig. 1: TH UWB Transmission (x=1, y=2, Nh=4, Ns=4)

$$C_{max} = max\{C_{m,n}(\tau) | c^m, c^n \in C, m \neq n, \tau = 0,1,\ldots,N_s N_h - 1\} \quad (9)$$

And

$$S_{max} = max\{C_{m,m}(\tau) | c^m \in C, \tau = 1,2,\ldots,N_s N_h - 1\} \quad (10)$$

It was proven in [12] that the Lower bound on the value of correlation Measures of TH codes are:

$$S_{max} \geq H_{amax} \quad (11)$$

3. Correlation measures for codes

3.1. FH code correlation measures

Hamming Correlation function measures the quality of frequency hopping (FH) code sequences [11] [12]. Let $\{c_n^r\}$ and $\{c_n^s\}$ are FH code sequences of period N_s; the periodic Hamming cross-correlation function can be written as (4):

$$H_{r,s}(\tau) = \sum_{j=0}^{N_s-1} h[c_j^r, c^s_{[j+\tau]_{N_s}}] \quad (4)$$

Where,Hamming function is,

$$h[c_j^r, c_{j+\tau}^s] = \begin{cases} 0, & \text{if}(c_j^r \neq c_{j+\tau}^s) \\ 1, & \text{if}(c_j^r = c_{j+\tau}^s) \end{cases} \quad (5)$$

$h[r,s]$ in (5) is the Hamming function, it measures the number of coincidence between user r and s [11] [12]. Coincidence gives the and

$$C_{max} \geq H_{cmax} \tag{12}$$

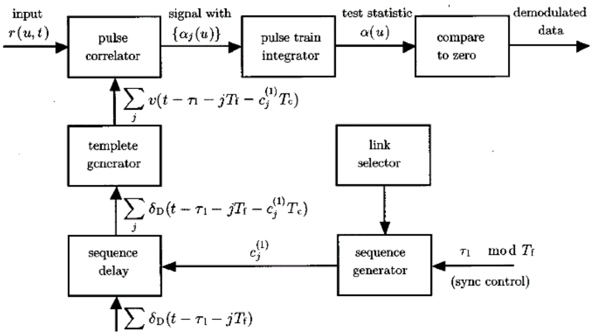

Fig. 2: Receiver Architecture for the Reception of the First User in TH PPM. Clock Pulses are Denoted by $\delta(.)$ Dirac Delta Functions [2].

4. System model: MUI analysis

An TH-BPSK UWB signal can be expressed as [2][4]:

$$s_k(t) = \sum_{n=-\infty}^{\infty} a_{\lfloor n/N_s \rfloor}^{k} \sqrt{E_w} w(t - nT_f - c_n^k T_c) \tag{13}$$

Where, $s_k(t)$ is a random process modeling the signal transmitted by the K^{th} user, and $w(t)$ is the reference pulse, normalized such that $\int_{-\infty}^{\infty} [w(t)]^2 = 1$, and with autocorrelation function $R_w(t)$. The energy transmitted for each pulse is E_w. The TH code c_n^k , $0 \leq c_n^k \leq N_h - 1$, $\forall k$, provides an additional shift (in multiples of chip time), to reduce collision effects in multiple access environment using PPM technique. As the system is asynchronous, hence use of orthogonal hopping patterns does not guarantee collision-free transmission and reception.
The frame duration is assumed to be an integer multiple of the chip duration, that is $T_f = N_h T_c$.
The received signal with N_u users transmitting simultaneously with the assumption of AWGN channel, and perfect power control is given by

$$r(t) = s_1(t - \tau_1) + \sum_{k=2}^{N_u} s_k(t - \tau_k) + n(t) \tag{14}$$

Where and $n(t)$ is a white Gaussian noise process with two-sided power spectral density $N_0/2$andτ_k, for $= 1, \ldots, N_u$, is the delay associated with k^{th} user.
The receiver is assumed to be a correlator single-user receiver that adopts $v(t) = w(t)$ as correlation waveform. User 1 is the "useful" user to be received, and a perfect knowledge of its TH pattern $\{c_j^1\}$, with an ideal synchronism between receiver and transmitter, is assumed. The receiver output, when a_0^1 is transmitted, can be given as

$$\beta_0^1 = \sum_{j=0}^{N_s-1} \int_{\tau_1 + jT_f}^{\tau_1 + (j+1)T_f} r(t) v\left(t - \tau_1 - jT_f - c_j^1 T_c\right) dt \tag{15}$$

The rule of decesion for the receiver can be given as:

$$"decide\ a_0^1 = 0" \Leftrightarrow \beta_0^1 > 0 \tag{16}$$

Fig. 2 provides the details of the signal processing corresponding to the decision rule given in (16). This decision rule is for single user and suboptimal when other users are present. The optimal detection in a multiuser environment needs more complex receiver designs [2]. The above decision rule is theoretically simple and also suggests implementations, so it has been used as a simple means of making decisions [2] [4].

We can express (13) as:

$$\beta_0^1 = s_0^1 + n_{MUI,0} + n_G \tag{17}$$

Where ,

$$n_{MUI,0} = \sqrt{E_x} \sum_{k=2}^{N_u} n_{MUI,0}^k \tag{18}$$

$$n_{MUI,0}^k = \sum_{j=0}^{N_s-1} \int_{\tau_1 + jT_f}^{\tau_1 + (j+1)T_f} v(t - \tau_1 - jT_f - c_j^1 T_c) A_k s^k (t - \tau_k) dt \tag{19}$$

(18) can be written as:

$$n_{MUI,0}^{(k)} = \sum_{j=0}^{N_s-1} R_w([c_j^1 - c_j^k] T_c + (\tau_1 - \tau_k)) \tag{20}$$

Where, $R_w(t) = \frac{1}{T_c} \int w(t + \tau) v(t) dt$. In this analysis it is assumed that chip synchronism between different users' signals exists, which yields a worst case performance bound [4]. Thus, $(\tau_1 - \tau_k) = nT_c$. Since $n = (\tau_1 - \tau_k)/T_c$ is a uniformly distributed random variable over $[0, N_h]$, (20) can be expressed as:

$$n_{MUI,0}^{(k)} = \sum_{j=0}^{N_s-1} R_w([c_j^{(1)} - c_j(k)] T_c + nT_c) \tag{21}$$

Further chip level synchronism assumption leads to only two valuse for $R_w(t)$:

$$R_w(T) = 1; when [T]_{N_h} = 0$$

$$= 0; Otherwise. \tag{22}$$

By seeing (21), it can be seen that n_{MUI} is a function of cross-correlation value of the TH codes.
The output SNR of receiver is defined as [2]:

$$SNR_{out}(N_u) \triangleq \frac{(A_1 s^{(1)})^2}{\sigma_{rec}^2 + \mathbb{E}\{|n_{MUI,0}|^2\}} \tag{23}$$

Where,

$$\mathbb{E}\{|n_{MUI,0}|^2\} \triangleq N_s \sigma_a^2 \sum_{k=2}^{N_u} A_k^2 \tag{24}$$

where Appendix VIEqn.(79) of [2] gives that:

$$\mathbb{E}\{|n_{MUI,0}^k|^2\} \triangleq \sigma_a^2 \tag{25}$$

The above analysis clearly shows that in UWB system the Multiuser Interference (MUI) depends on the cross-correlation properties of TH codes. It has been seen that cross-correlation properties of TH codes depends on the code construction. By observing (23) it is apparent that the SNR can be improved by minimizing the interference with other users. Thus, by using codes with good correlation properties MUI can be improved.
To check and analyze the effect of code construction on error rate (BER) performance, the MUI term $n_{MUI,0}^k$ is required to be characterized, while s^1 and n_G are the effective contribution to the decision variable β_0^1 coming from user 1's signal and thermal noise. Probability of error is obtained by conditioning on MUI:

$$P_{(e)} = \mathbb{E}_{n_{MUI,0}} \left[\frac{1}{2} erfc \left(\frac{s^1 + n_{MUI,0}}{\sqrt{2} \sigma_{n_G}} \right) \right] \tag{26}$$

The probability distribution functio of MUI is required for the exact computation of (26). Whereas, the closed form computation of the pdf of MUI is not available for the fixed code constructions [6].

Hence, we have numerically computed the BER for both the code constructionsusing MATLAB.

5. Code construction: QCC and LCC

The current work uses two well established families of FH code sequences with very good correlation properties. The selected code families are Quadratic Hopping Codes (QCC) and Linear Congruence codes (LCC). The construction of codes is as follows:

5.1. Linear congruence codes(LC codes)

In a finite field $GF(p)$, a Linear Congurance codes family per set C is described as [4] [11] [12]

$$C = \{c^{(f)}\}, f = i; c^{(f)} = \{c_n^{(i)}\};$$

$$c_n^{(i)} = in \bmod p, 1 \leq i \leq p - 1 \qquad (27)$$

Where, p is length of the FH code andfor TH code $N_u = p - 1, N_h = N_s = p$; and $H_{am} = 0; H_{cm} = 1$.

5.2. Quadratic hopping codes (QC codes)

In a finite field $GF(p)$, a quadratic hopping codes family per set C is describedas[4][11][12]

$$C = \{c^{(f)}\}, f = i; c^{(f)} = \{c_n^{(i)}\};$$

$$c_n^{(i)} = i^2 n \bmod p, 1 \leq i \leq p - 1 \qquad (28)$$

Where, p is length of the FH code and for TH code $N_u = p - 1, N_h = N_s = p$;and $H_{am} = 1; H_{cm} = 2$.

Table 1: Comparison of Correlation Properties of QC Codes

Correlations Values asTH codes		Correlations Values asFH codes	
S_{max}	C_{max}	H_{amax}	H_{cmax}
2	4	1	2

Table 2: Comparison of Correlation Properties of LC Codes

Correlations values as TH codes		Correlations Values asFH codes	
S_{max}	C_{max}	H_{amax}	H_{cmax}
p-1	2	0	1

Values calculated in Tables 1 and 2 confirms the lower bound concept shown in (11) and (12). It may be seen that although LC codes are better than QC codes for FH communication as correlation values are lesser. But QC codes show the better correlation values for TH codes as it is not dependent on code length [4]. The BER analysis in the next section would further clarify about the suitable code family.

6. BER performance comparison of codes for suitability

In this section, BER Performance comparison of Random codes, QC Codes and LC codes is presented in multiuser environment under AWGN Channel using MATLAB software.

Fig. 3 shows the BER vs. SNR performance of randomly selected integer codes under Multiuser UWB system. Theoretical BER performance for BPSK single user system is following the calculated BER performance for single user in AWGN Channel. On increase in number of user effect of MUI becomes prominent and performance of receiver deteriorates. The system performance for 5, 10 and 25 users are compared in Fig. 3.

Similar performance has been plotted for LC codes and QC Codes in Fig. 4 and Fig. 5, respectively. Fig. 6 shows the performance comparison Random, LC and QC codes for 25 users.

The BER performance of LC Codes and QC codes is better as compared Random codes. It is also seen that QC codes are performing better than LC codes in UWB Multiuser Environment.

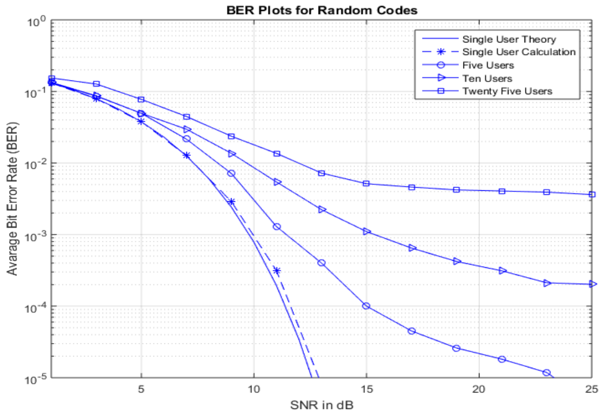

Fig. 3: BER Performance of Random Codes in Multiuser UWB System.

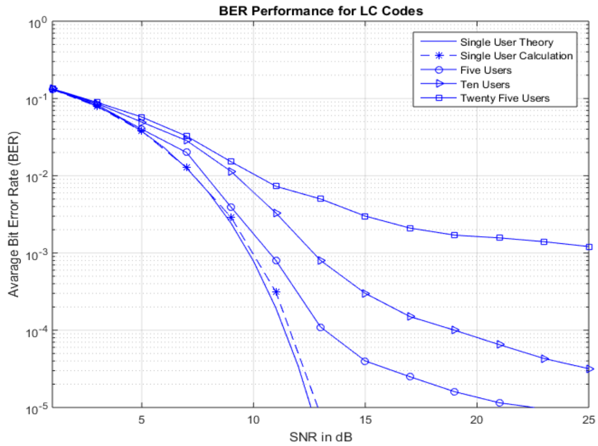

Fig. 4: BER Performance of LC Codes in Multiuser UWB System.

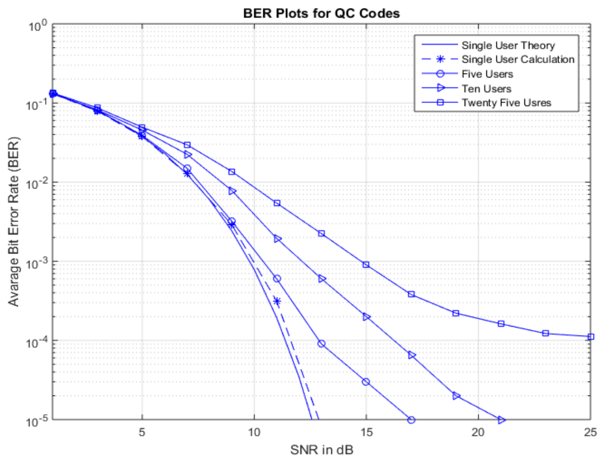

Fig. 5: BER Performance of QC Codes in Multiuser UWB System.

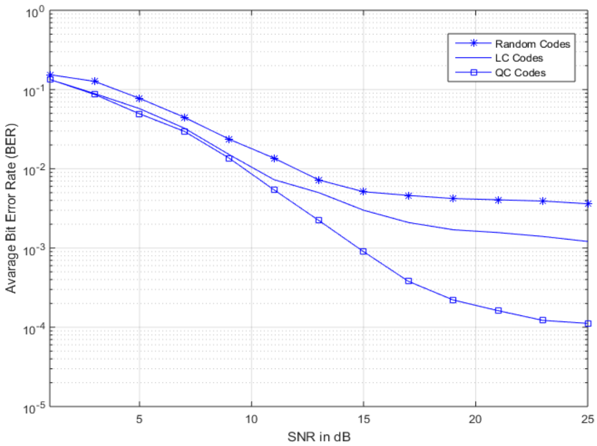

Fig. 6: BER Performance Comparison of All Three for 25 Users.

7. Conclusion

This work investigates the BER performance of existing code families of Frequency Hopping (FH) codes as Time Hopping (TH) codes to provide a method for the selection of better TH codes to improve MUI performance in multiuser UWB communication environment. BER performance comparison for AWGN channel of LC codes and QC codes with reference to random codes have been conducted. The performance of codes has been validated for single user and further validated over multiuser for 5, 10 & 25 users. A significant improvement in performance has been observed over random codes. It is also found that QC codes are better as compared to LC codes when used as TH codes in UWB communication system. It is validated that selection of better TH codes reduces the MUI and improves the overall performance of the communication system and Frequency hopping codes with better TH correlation properties can be used as Time hopping codes in multiuser UWB communication system.

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