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Interference Mitigation Using Improved Spectrum Shaping TH Codes to Address Coexistence Issue in UWB Systems

Rajendra Singh[1*], B. S. Jassal[2]

[1]Defence Electronics Applications Laboratory,
[2]Department of Electronics and Communication,
Graphic Era Deemed to be University, Dehradun, Uttarakhand, India.
*Corresponding author: raj.deal@gmail.com

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Abstract
The power spectrum of UWB systems can be controlled by proper selection of any of the three entities pulse, modulation scheme and Time Hopping (TH) codes, or their combinations. This paper proposes algorithms to improve the correlation properties of these TH codes without changing their spectrum shaping property, so that system performance is not comprised. The earlier work of the authors provides algorithms to design TH codes with good correlation properties for spectrum shaping to create Null at a selected frequency, of multiuser UWB signals, to avoid interference to existing narrow band systems. These algorithms are presented in the form of three methods (Method I, Method II and Method III) to show correlation improvement in synchronous system first. The paper provides a novel and general mathematical model for improving correlation properties of spectrum shaping code using basic code construction of known FH code family, which can be used for both synchronous as well as asynchronous systems.

Keywords- Ultra Wide Band (UWB) System, Time Hopping (TH) Codes, Frequency Hopping (FH) Codes.

1. Introduction

Ultra Wide Band (UWB) wireless communication is known for supporting high data rates with low power consumption and low complexity in terms of transmission/reception operation. The technology has been used for communication, consumer appliances for smart home and military communications. The Federal Communications Commission (FCC) had assigned a bandwidth of around 7.5 GHz (3.1-10.6 GHz) with the restriction of very low power levels (below -41.3 DBm/MHz) which allows UWB technology to overlay already available services (Ghavami et al., 2007; Singh and Jassal, 2018).

The modulation schemes used by UWB systems are Binary Pulse Position Modulation (BPPM) and Binary Phase Shift Keying (BPSK). There are two commonly used Multiple Access (MA) techniques for multiuser UWB systems, namely Time Hopping (TH) and Direct Sequence (DS). TH is gaining more popularity over DS among researchers for supporting better multipath immunity and having better spectral efficiency than DS (Singh and Jassal, 2016). Due its presence from D.C. to several GHz, UWB systems and conventional narrowband systems can interfere with each other. Therefore, the coexistence problem between UWB and narrowband systems, and the effects of their mutual interference are being investigated by researchers (Singh and Jassal, 2015).

Spectrum shaping TH codes generation methods provide software based technique to create spectral null at desired frequency with control of width of the null. These methods provide easy tool to researcher to solve coexistence problem of UWB systems with conventional narrow bandwidth systems without changing system hardware or pulse shape (Wang and Tung, 2006; Chiani and Giorgetti, 2009). Authors of Piazzo and Romme (2003), introduced about the dependency of TH codes over spectrum shape and also provided spectrum nulling method with the help of code construction modification. Spectrum nulling code generation methods have been referred from the previous work of Piazzo and Romme (2003) and it does not address the problem of MUI due to multiuser communication. The code generation method described therein uses the system model for single user only which makes it impractical for use in actual system as it degrades system performance due to MUI. In Singh and Jassal (2015), authors have modified the TH nulling code generation method 1 of Piazzo and Romme (2003) for multiuser system keeping all assumption same and called it the reference method.

Further to that authors proposed algorithms to improve the correlation properties of these TH codes without changing their spectrum shaping property, so that system performance is not comprised (Guvenc and Arslan, 2004). These algorithms are presented in the form of methods (Method I, Method II and Method III) to show correlation improvement in synchronous system first in the previous work (Singh and Jassal, 2015). Authors in the previous work (Singh and Jassal, 2016; Singh and Jassal, 2018) shown that FH code with good TH correlation properties can be considered to be used as TH codes in UWB systems.

This paper provides a novel and general mathematical model for improving correlation properties of spectrum nulling code using basic code construction of FH code families (Fan and Darnell, 1996; Fan et al., 2005; Chung and Yang, 2012; Ren et al., 2013). Which can be used for both synchronous as well as asynchronous systems.

The organization of the rest of the paper is as follows. In section 2, a brief description of the UWB signal with modulation and its power spectrum is introduced. The dependency on TH code for modification of spectrum is also explained. Reference method spectrum shaping is explained in section 3. Spectrum shaping TH code with improved correlation performance are discussed in Section 4. Finally, conclusions are drawn in Section 5.

2. UWB Signal and Spectrum Shaping Method

A Time Hopping Binary Phase Shift Keying (TH-BPSK) modulation scheme has been considered for the system model.

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A binary phase shift keying modulation (TH-BPSK) scheme have been considered here. The TH-BPSK multiple access UWB signal with periodic TH Codes, for synchronous transmission, can be written as follows (Singh and Jassal, 2018):

$$s(t) = \sum_{k=0}^{N_u-1} a_k \sum_{n=0}^{N_s-1} w(t - c_n^k T_c - nT_f) \quad (1)$$

where,
a_k = Information bits modulating the pulse ; $w(t)$ = the transmitted UWB pulse
T_f = The frame duration (seconds) ; c_n^k = the Time Hopping code
T_c = The time interval when a user is active (seconds)
N_s = The number of pulses transmitted per symbol. ; N_u = The number of users.

The power spectrum of the UWB signal (1) can be computed as in (2). The spectrum shape is given by:

$$S(f) = |W(f)|^2 G(f) \quad (2)$$

where,
"*W(f)* is Fourier Transform (FT) of the pulse $w(t)$ and $G(f)$ is termed as the total code spectrum" given by Singh and Jassal (2015):

$$G(f) = \sum_{k=0}^{N_u-1} |C_k(f)|^2 \quad (3)$$

where,

$$C_k(f) = \sum_{n=0}^{N_s-1} e^{-j2\pi f (c_n^k T_c + nT_f)} \quad (4)$$

and $C_k(f)$ is the individual code spectrum.

It can be seen from (3) and (4) that the TH code can be exploited to control the system spectrum by means of the code spectrum. Some methods have been presented to create null at a selected frequency in the code spectrum. For simplicity the code spectrum can be measured by measuring the spectrum of an UWB signal constructed assuming a pulse $w(t) = \sin(\pi t/T_c)/(\pi t/T_c)$. Since the FT of the given pulse is 1 in the band *-1/(2Tc) to 1/(2Tc)* and zero otherwise, from (2) $S(f) = G(f)$ in the band of interest. To this end *s(t)* has to be sampled to get a digital sequence to evaluate effect of code sequence over the spectrum. Now after substituting $w(t) = \sin(\pi t/T_c)/(\pi t/T_c)$ in (2) the sequence of samples of *s(t)* is obtained by sampling it at $t = iT_c$. Thus, (1) can be written as Singh and Jassal (2015),

$$s_i = u(iT_c) = \sum_{k=0}^{N_u-1} a_k \sum_{n=0}^{N_s-1} \delta(i - c_n^k - nN_h) \quad (5)$$

where, $\delta(\,)$ is the Dirac delta function, defined by $\delta(k) = 0$ for $k \neq 0$ and $\delta(0) = 1$ and N_h = The number of possible users in a frame. The sample sequence s_i can be produced using Matlab simulation. The signal spectrum can be estimated by taking the Discrete Fourier Transform (DFT) of the blocks and taking square of it.

3. Spectrum Shaping for Creating Null

The spectrum shaping to create Null at desired frequency $f = 1/(KT_c)$ in multiuser UWB systems has been given in detail in the previous work of the authors in Singh and Jassal (2015). Where T_c is the max. UWB pulse duration and K is an even integer. The above mentioned work provides the *reference method* for creating spectrum null using TH codes in multiuser UWB system.

Further to that authors proposed algorithms to improve the correlation properties of these spectrum nulling TH codes without changing their spectrum shaping property, so that system performance is not comprised (Guvenc and Arslan, 2004). These algorithms are presented in the form of methods (Method I, Method II and Method III) to show correlation improvement in synchronous system first in the previous work (Singh and Jassal, 2015).

Next section provides a novel generalized method to improve the auto-correlation and cross-correlation properties of the spectrum nulling codes, using known FH codes.

4. Generalized Novel Method

It is already discussed in Singh and Jassal (2015), that the spectral nulling degrades the code sequence in terms of its correlation properties. If family of codes is represented with each code sequence as a row of a matrix, such a matrix can be said as a code matrix. The key point of the proposed method is that once a code element is generated according to the Section 3, it can be placed anywhere in the code matrix without affecting the spectrum nulling property of codes.

The method is explained as below:

i. Generate a standard code matrix A based on FH Codes (e.g., LC, QC, OCFH or HC Codes), with N_s columns, N_u rows and $x_{i,j} \in [0, N_h - 1]$. Where $x_{i,j}$ is ij^{th} element of the code matrix, as shown below.

$$A = \begin{bmatrix} a_1 & a_2 & a_3 & a_4 & a_5 & a_6 \\ b_1 & b_2 & b_3 & b_4 & b_5 & b_6 \\ c_1 & c_2 & c_3 & c_4 & c_5 & c_6 \\ d_1 & d_2 & d_3 & d_4 & d_5 & d_6 \\ e_1 & e_2 & e_3 & e_4 & e_5 & e_6 \\ f_1 & f_2 & f_3 & f_4 & f_5 & f_6 \end{bmatrix}.$$

ii. Apply Method I to A and generate matrix B, such that

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$$B = \begin{bmatrix} a_1 & a'_2 & a_3 & a'_4 & a_5 & a'_6 \\ b_1 & b'_2 & b_3 & b'_4 & b_5 & b'_6 \\ c_1 & c'_2 & c_3 & c'_4 & c_5 & c'_6 \\ d_1 & d'_2 & d_3 & d'_4 & d_5 & d'_6 \\ e_1 & e'_2 & e_3 & e'_4 & e_5 & e'_6 \\ f_1 & f'_2 & f_3 & f'_4 & f_5 & f'_6 \end{bmatrix}.$$

In the matrix *B* elements of odd columns are same as that of matrix *A* and each element of even columns is related with its previous element in the same row as:

$$[a'_2] = [a_1 - N_h - K/2] + sK \quad (6)$$

where integer s randomly in [0, S-1]. (where, S=Nh/K denotes the integer division of Nh by K). In matrix B also $x_{i,j} \in [0, N_h - 1]$.

iii. The new code set *B* has bad correlation properties as compared to the standard code matrix *A*.

iv. Now from matrices *A* and *B*, two matrices *A'* and *B'* can be extracted by only taking even elements, as given below.

$$A' = \begin{bmatrix} a_2 & a_4 & a_6 \\ b_2 & b_4 & b_6 \\ c_2 & c_4 & c_6 \\ d_2 & d_4 & d_6 \\ e_2 & e_4 & e_6 \\ f_2 & f_4 & f_6 \end{bmatrix},$$

$$B' = \begin{bmatrix} a'_2 & a'_4 & a'_6 \\ b'_2 & b'_4 & b'_6 \\ c'_2 & c'_4 & c'_6 \\ d'_2 & d'_4 & d'_6 \\ e'_2 & e'_4 & e'_6 \\ f'_2 & f'_4 & f'_6 \end{bmatrix}.$$

v. As the elements of matrices *A'* and *B'* belong to same set, some elements of matrix *B'* may have the same value as that of elements of matrix *A'*. The elements having same value may or may not be in the same positions in two matrices.

To achieve good correlation among codes, rearrange the elements of *B'* in such a way that it gets as close as possible to the matrix *A'*.

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vi. Consider a matrix *C'* of same size as of *A'* and *B'*. Now, fill *C'* with the elements of *A'*, also present in *B'*, at the same location as in *A'* and arrange rest of the elements of *B'* randomly in the remaining locations of *C'*.

vii. Assuming that all the elements of *A'* are present in *B'* except $a'_2,\ a'_6,\ b'_2,\ and\ d'_6$,. Then matrix *C'* will look like as:

$$C' = \begin{bmatrix} a_2 & a_4 & a_6 \\ b_2 & b_4 & b_6 \\ c_2 & c_4 & a'_2 \\ a'_6 & d_4 & d_6 \\ e_2 & e_4 & b'_2 \\ f_2 & d'_6 & f_6 \end{bmatrix}.$$

viii. Finally, generate a matrix *C* with odd columns from matrix *A* and even columns from matrix *C'*, as below:

$$C = \begin{bmatrix} a_1 & a_2 & a_3 & a_4 & a_5 & a_6 \\ b_1 & b_2 & b_3 & b_4 & b_5 & b_6 \\ c_1 & c_2 & c_3 & c_4 & c_5 & a'_2 \\ d_1 & a'_6 & d_3 & d_4 & d_5 & d_6 \\ e_1 & e_2 & e_3 & e_4 & e_5 & b'_2 \\ f_1 & f_2 & f_3 & d'_6 & f_5 & f_6 \end{bmatrix}.$$

Matrix *C* is the optimized code matrix. Analysis to show the correlation improvement can be done on similar steps as done in Singh and Jassal (2015).

The next section presents the analysis of correlation properties improvement of TH nulling code, generated using an FH Codes family in Matlab.

5. Analysis of TH Spectrum Nulling Codes Generated Using OCFH Codes

This section uses method described in section 4 for correlation improvement of TH nulling codes using OCFH code family of FH codes. The parameter values for the analysis have been assumed as:

$$N_h = 16,\ N_s = 16,\ N_u = 16,\ T_c = 1\,nsec., and\ K = 4.$$

This analysis plots the correlation values plots of standard OCFH codes as TH codes i.e., auto-correlation side-lobes and cross correlation. Then it generates spectrum nulling codes using OCFH code for K=4 and again draw correlation value plots. The analysis shows the degradation in the correlation values. Then using section 4 the correlation values are optimized and plotted, which indicates the improvements in the correlation values.

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In all the plots, the y-axis indicates the magnitude of correlation and the x-axis plots value of relative time delay.

Results of the analysis for TH nulling codes using OCFH codes are discussed below:

A. Autocorrelation Analysis

I. Figure 1 shows the worst case TH auto-correlation side lobe plot of OCFH codes with S_{max} as 2 and average value of auto-correlation side lobe also as 2.

II. Figure 2 shows the worst case TH auto-correlation side lobe plot after spectrum nulling of the same codes. Figure 2 clearly indicates a significant deterioration in the auto-correlation properties of codes as compare to Figure 1, where worst case value of auto-correlation side lobe became 5 and average value of the same parameter became 3.

III. Figure 3 shows the plot of TH auto-correlation side lobe for optimized nulling codes using section 4. It shows improvement in the auto-correlation side lobe values. The value of S_{max} is reduced to 4 as compare to that of Figure 2 and average value is also reduced to 2.

Table 1 summarizes the results.

Table 1. Autocorrelation side lobe analysis of OCFH codes with and without improvement

Value without Nulling	Value with Nulling	Value with optimized Nulling
2	5	4

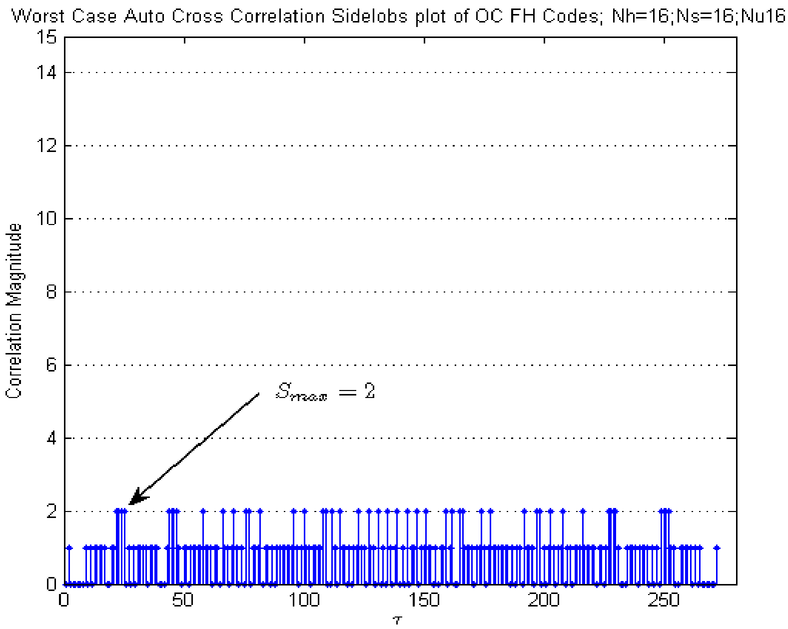

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Figure 1. Worst case TH auto correlation side lobe plot of OC FH sequence without nulling; Ns= 16; Nh=16; Nu=16

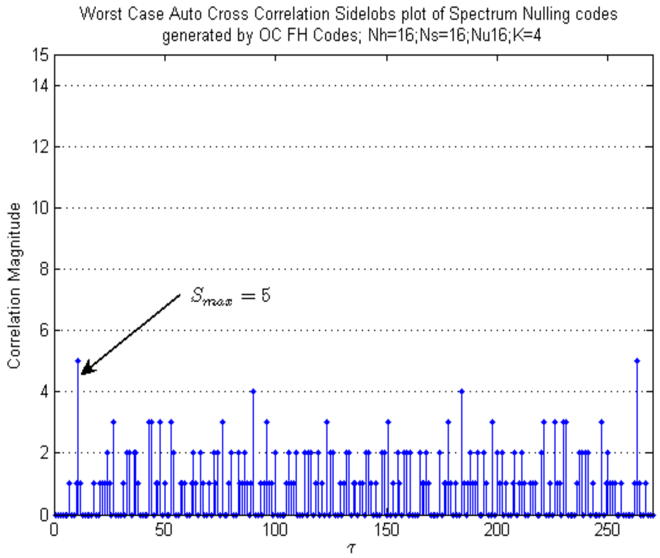

Figure 2. Worst case TH auto correlation side lobe plot of OC FH sequence after spectral nulling; Ns=16; Nh=16; Nu=16

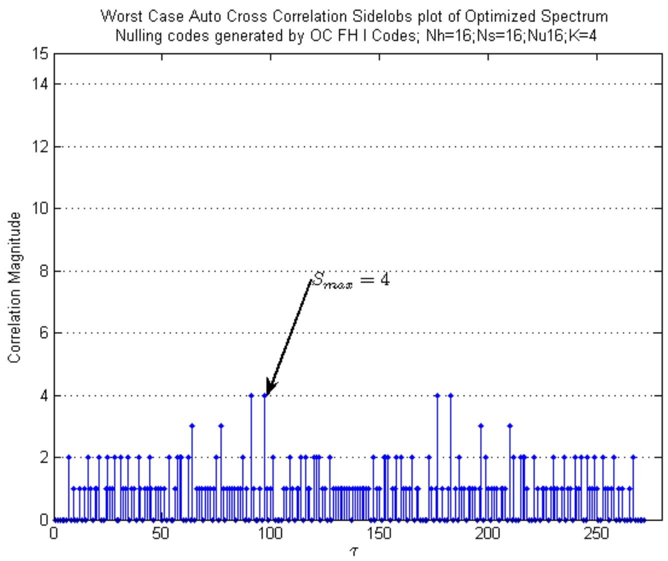

Figure 3. Worst case TH auto correlation side lobe plot of OC FH sequence after optimized spectral nulling; Ns=16; Nh=16; Nu=16

B. Cross Correlation Analysis

I. Figure 4 shows the worst case TH cross correlation plot of OCFH codes with value of C_{max} as *p-2* and its average value as 2.

II. Figure 5 plots the cross correlation value for spectrum nulling codes using same OCFH codes. The figure clearly indicates significant deterioration in the value of TH cross

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correlation value where C_{max} became 10 and its average value as 4.

III. Figure 6 shows the plots of cross correlation for optimized nulling codes generated using section 4. It shows improvement in the cross correlation values as compared to Figure 5. The value of C_{max} is reduced to 9 and average value also reduced to 3.

Table 2 summarizes the results.

Table 2. Cross correlation side lobe analysis of OCFH codes with and without improvement

Value without Nulling	Value with Nulling	Value with optimized Nulling
p-2	10	9

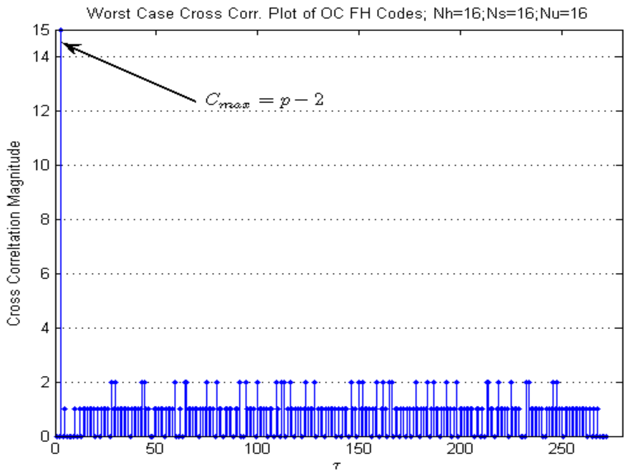

Figure 4. Worst case TH cross correlation plot of OC FH sequence without spectral nulling; Ns= 16; Nh=16; Nu=16

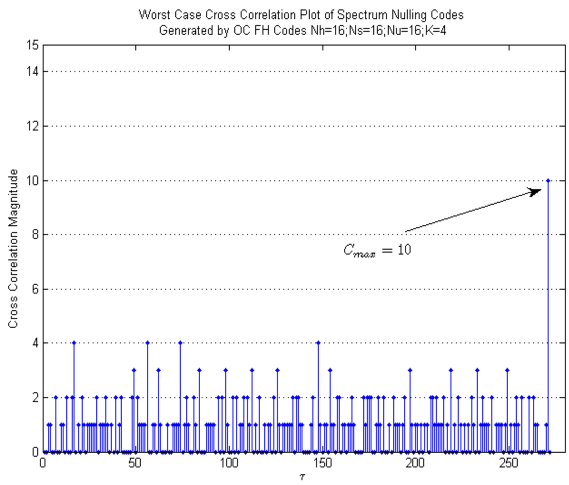

Figure 5. Worst case TH cross correlation plot of OC FH sequence after spectral nulling; Ns= 16; Nh=16; Nu=16

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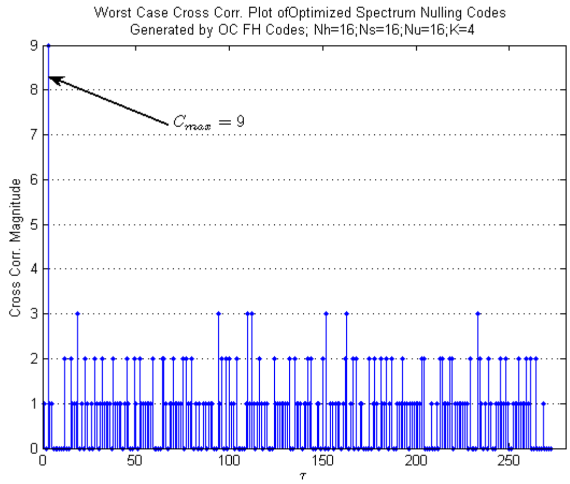

Figure 6. Worst case TH cross correlation side lobe plot of OC FH sequence after optimized spectral nulling; Ns= 16; Nh=16; Nu=16

6. Conclusion

This paper proposes algorithms to improve the system performance of TH codes without changing their spectrum shaping properties. The earlier work reported by authors (Singh and Jassal, 2015) proposes algorithms in the form of methods, for specific types of code construction, show the correlation improvement for synchronous system. The current work reported in this paper provides the novel generalized mathematical model for improving correlation properties of spectrum shaping TH codes using well known FH codes construction for practical asynchronous communication system. The analysis of the model has been done using Matlab for an FH code families OCFH codes, which indicates significant improvement in the correlation performance of spectrum shaping TH codes.

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