Adaptive Mitigation of Multi-Narrowband Interferences in Impulse Radio UWB Systems Using A Spread Spectrum Sensing Technique

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***Abstract*— The coexistence among different systems is a fundamental issue in communications. Both coexistence analysis, i.e. measuring the mutual interference, as well as coexistence techniques, i.e. all the actions that guarantee the simultaneous use of the spectrum by different systems, have an impact on the performance of the system. This paper is focused on both these two aspects. In particular, we analyze the coexistence between ultra-wide bandwidth (UWB) and narrow bandwidth (NB) systems emphasizing the role of spectrum sensing to identify and classify the NB interferers with highest powers. Direct Sequence (DS)-Time Hopping (TH) codes are then designed to mitigate the identified NB interference where notch frequencies are created in the UWB signal spectrum at bands where NB services operate. Finally, due to the severe multipath channel of UWB systems, a scenario where spectrum is sensed every symbol-duration to apply the mitigation technique on the identified NB interferer is presented.**

***Index Terms*-coexistence, interference mitigation, spectrum sensing, cognitive radio (CR), code sequence design, impulse radio (IR), matched filter (MF), narrowband (NB) interference, spectrum shaping, spread-spectrum (SS).**

I. INTRODUCTION

The increasing demand for higher data rates in personal area networks have led to the current interest and development in UWB communications technology. UWB is a promising candidate for high speed, low power, low complexity and extensive resources short-range indoor wireless communications [1]. Although UWB was used for positioning, military communications, radar and sensing 20 years ago, it has been focused on consumer electronics and communications only very recently. In 2002, the FCC allocated a huge bandwidth of 7,500 MHz in 3.1 GHz -10.6 GHz at the noise floor, where UWB devices are allowed to operate under certain spectral masks for indoor and outdoor applications. A signal is classified as UWB if its bandwidth is larger than 500 MHz or its fractional bandwidth is larger than 20% [2]. One approach for UWB deployment is impulse radio (IR). In IR UWB systems a train of extremely narrow pulses is used for signal transmission [3]. IR UWB systems communicate with time hopping (TH) [4] or direct sequence (DS) spread spectrum (SS) or a Hybrid of both providing multiple-access (MA).

The strength of UWB systems lies the use of extremely wide transmission bandwidths, resulting in desirable capabilities, including: 1) accurate position location and ranging, and lack of significant multipath fading due to fine delay resolution; 2) multiple access due to wide transmission bandwidths; 3) covert communications due to low transmission power operation; 4) high data rates; and 5) possible easier material penetration due to low-frequency components.

Large transmission bandwidths, on the other hand, introduce new challenges where UWB have to successfully coexist with the overlapping existing NB services. In fact, most of the wireless communication systems use separate narrowband frequencies in order to avoid interference to each other. However, in order for UWB systems to avoid interference with other NB services, they have to meet the spectral mask defined in the FCC's report [3] in February 2002, which means they emit in very low power levels. The effect of NB interference on UWB remains an important topic which is investigated in [5] and [6]. In [7], [8] and [9] notch filter, non-linear prediction filter, minimum mean square-error (MMSE) rake reception where performed at the receiver as NB suppression techniques to reduce the interference effect. However these techniques are used to reduce the interference on UWB signals, the interference caused by UWB signals to licensed NB signals must be efficiently mitigated.

Spectrum shaping of UWB signals is an effective approach to suppress the mutual interference between UWB and NB systems, where notches are created at the frequencies dedicated to NB services. By transmitting low signal powers in the overlapping bands UWB reduces the interference to NB systems. On the other hand, the matched filter receiver of UWB will act as a notch filter that removes the undesired NB interference. References [10], [11] shaped the UWB spectrum through pulse shaping. Code sequence design could offer better control on UWB spectrum for mitigation of single or multiple narrowband interferers over greater dynamic signal range.

One promising and simple approach for shaping the UWB signal spectrum is by design of the DS or the TH sequence in UWB signals [12] and [13]. However they mitigated the mutual interference between NB and UWB through using one of these sequences, they lost the desired properties of SS signals.

To maintain both, mutual interference suppression and gaining SS benefits, [14] used both DS designs to minimize the interference from a single NB interferer and TH sequences to preserve the desired SS signal properties. In [15] eigenvalues and vectors were used to design DS and TH sequence by alteration for shaping UWB spectrum, two scenarios were considered wherein the first scenario DS was used for NB interference mitigation and was able to minimizing multiple interferer's powers however In the second scenario where TH sequence was used for mitigation the proposed technique was able to mitigate a single NB interferer. Since the designed TH code in [15] can mitigate a single NB interferer, however UWB signals suffer from multiple NB interferers with varying powers, which lead to a severe performance degradation.

In this paper, a proposed model shown in Figure 1 improves the performance of the system by sensing the spectrum every symbol-duration to identify and mitigate the interferer with the highest power.

The paper is organized as follows. The system model, including transmitter, NBI, channel response, and receiver are described in Section II. Section III briefly discusses the idea and algorithm of TH code design for NB interference mitigation. In Section IV, energy detection spectrum sensing for NB interferers classification and identification is discussed. Section V presents representative numerical results of system performance under various conditions. Finally, Section VI draws the conclusions.

II. SYSTEM MODEL

A. Signal flow

We consider a binary communication system with MF reception. The transmitted signal can be represented by the following model

$$S_u(t) = \sqrt{E_u}\, d_i \sum_i b(t - iT_b), \qquad d_i \in \{-1, 1\} \tag{1}$$

where

$$b(t; d_i) = \sum_{k=0}^{N_s-1} c_k^{DS} p(t - kT_f - c_k^{TH} T_c) \tag{2}$$

is a unit-energy waveform used to transmit a single information bit d_i, belonging to the set $\{-1, 1\}$, E_u the energy per transmitted bit, $T_b = 1/R_b$ is the bit duration, N_s is the number of pulses, and $p(t)$ is the signal pulse with energy $1/N_s$. The pulse repetition time (frame length) T_f and the bit duration T_b are related by $T_b = N_s T_f$. Finally c_k^{TH}, is the TH sequence, T_c is the TH chip width, and c_k^{DS} is the DS spreading sequence. The bit waveform (2) is valid for a general transmitted scheme that combines TH and DS, and results in pure TH when $c_k^{DS} = 1, \forall k$, and pure DS when $c_k^{TH} = 0, \forall k$.

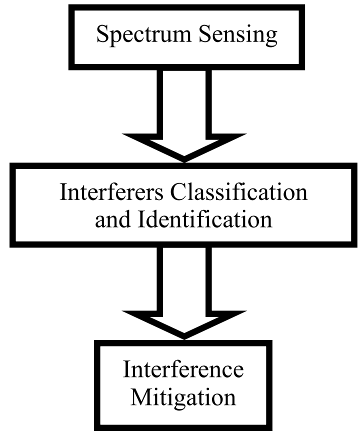

Figure 1. The proposed system model

In this paper, a combination of TH and DS is used where TH code is used for multi-user interference (MUI), DS code for NB interference mitigation and vice-versa.

NB interference can be modeled as in [5] and [6].

$$S_n(t) = \sqrt{2I_n}\cos(2\pi f_n t + \theta_n) \tag{3}$$

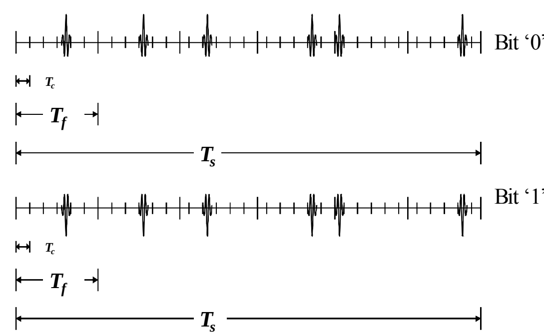

Figure 2. The transmitted DS-TH UWB signal at N_s =6 and N_h=4.

While UWB signals cover a large Bandwidth it is reasonable to assume that they experience a frequency-selective fading channel with channel impulse response,

$$h_u(t) = \sum_{l=0}^{L-1} h_{u,l}\,\delta(t - \tau_{u,l}). \tag{4}$$

NB signals, which have a small bandwidth, experience a frequency-flat fading channel with impulse response

$$h_n(t) = \alpha_n \delta(t - \tau_n). \tag{5}$$

The received signal at the UWB receiver can be expressed as in [5]

$$r(t) = \sqrt{E_u}\sum_i r_u(t - iT_b; d_i) + \sum_{n=1}^{N_n} \sqrt{I_n}\, r_n(t) \tag{6}$$

where

$$r_u(t; d_i) = b_u(t; d_i) \otimes h_u(t) = \sum_{l=0}^{L-1} h_{u,l}\, b(t - \tau_{u,l}; d_i) \tag{7}$$

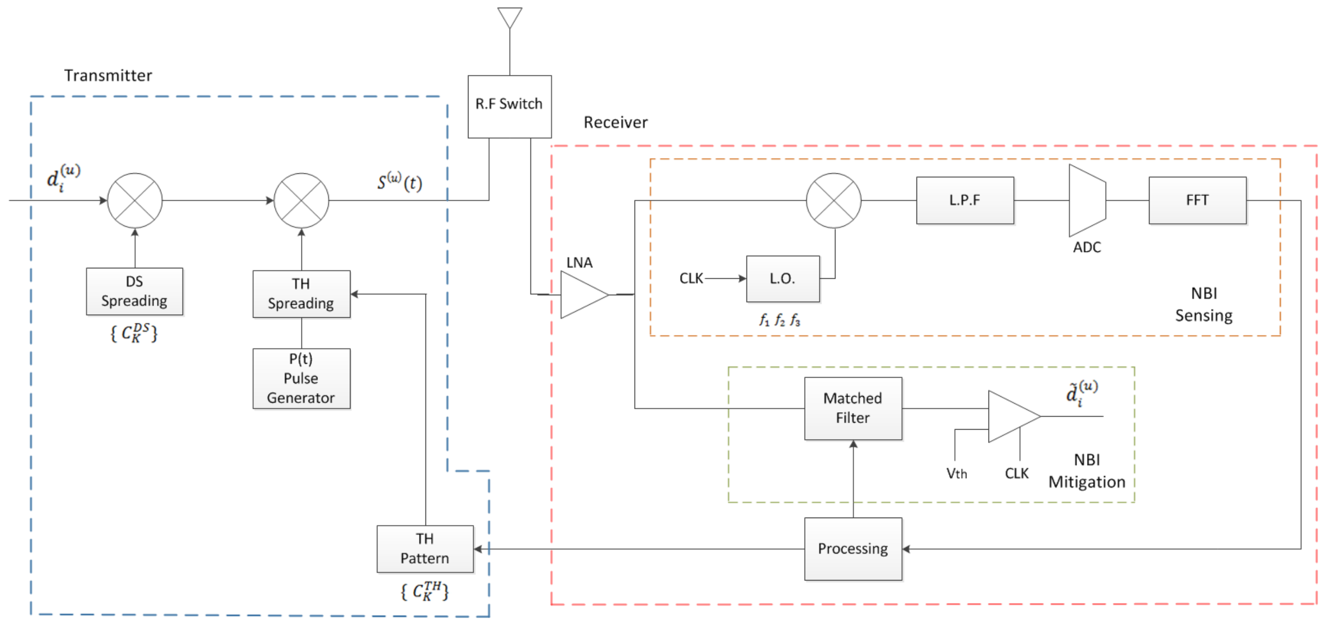

Figure 3. The proposed Adaptive mitigation UWB transceiver

$$r_n(t) = s_n(t) \otimes h_n(t) = \alpha_n s_n(t - \tau_n) \tag{8}$$

The received signal in (6) is affected by AWGN and interference. If only AWGN is present, the optimum receiver consists of a filter, matched to the difference $r_b(t;0) - r_b(t;1)$ or, equivalently, a correlator followed by a sampler. The template waveform of the correlator $\upsilon(t)$ is given by

$$\upsilon(t) = r_b(t;0) - r_b(t;1). \tag{9}$$

Assuming perfect synchronization with the desired signal, the MF output u(t) at the appropriate sampling instant t_0 be written as

$$u(t_0) = s_0 + \sum_{n=1}^{N_n} \alpha_{In} \sqrt{2I_n} \left| H(f_n) \right| \cos\phi_n + n_0 \tag{10}$$

where s_0 is the desired signal

$$s_0 = \sqrt{E_b} \int_{-\infty}^{t_0} r_b(t; d_0) \upsilon(t) dt. \tag{11}$$

H(f) is the MF transfer function and n_0 is the noise sample with zero mean and variance $\sigma^2 = (N_0/2)\int_{-\infty}^{\infty} \upsilon^2(t)dt$. The MF is matched to the received waveform, so its transfer function can be easily evaluated as (12)

$$H(f) = F\{\upsilon(t)\} = F\{r_b(t;0) - r_b(t;1)\} \tag{12}$$

where F{.} denotes the Fourier transform. Since H(f) can be written as

$$\left| H(f) \right| = \left| H_0(f) \right| \left| F\{h_u(t)\} \right| \tag{13}$$

where

$$H_0(f) = F\{b(t;0) - b(t;1)\}. \tag{14}$$

It is important to note that H(f) is composed of two factors, the first depends on the waveforms used, while the second depends on the CIR for the desired signal.

B. *Transceiver operation*

Assuming that the NB interferers locations are previously determined and the transmitter and receiver are within the coherent distance, i.e. they are experiencing the same channel response.

As stated in [15], the designed TH code can only cope with the mitigation of a single NB interferer. However UWB signals suffer from multiple NB interferers with varying powers, which lead to a severe performance degradation.

As shown in Figure 3 the proposed receiver improves the performance of the system by sensing the spectrum every symbol-duration. A tuned LNA is used over the bandwidth of the previously known interferers frequency locations. The input signal is mixed with the three frequencies generated from the local oscillator (LO) passing by a low pass filter (LPF) followed by an analog to digital converter (ADC) enabling processing on digital data. Fast Fourier Transform (FFT) is then used to generate a decision metric for each interferer. Processing is done to identify the interferer with the highest power. The frequency location of this NB interferer is then an input to the TH code design algorithm discussed next section. The designed TH code shapes the spectrum of the transmitted waveform and in turn shapes the transfer function of the MF creating notches at this frequency location.

Since the transmitter and the receiver are assumed to be experiencing the same CIR, therefore the same TH code designed at the transmitter will be generated at the receiver.

III. TH CODE DESIGN FOR NB INTERFERENCE MITIGATION

In this section a TH code is designed as to minimize the response of the matched filter at frequency locations of NB interferers.

As derived in [5] conditional SINR, conditioned on the CIR, can be expressed as

$$SINR_{con} \equiv \frac{S(h)}{\frac{N_0}{E_u} + \sum_{n=1}^{N_n} \frac{I_n}{2CT_b} \cdot \frac{|H_0(f_n)|^2 |H_u(f_n;h,t)|^2}{S(h)}} \quad (15)$$

where

$$C = E_b/T_b \quad (16)$$

and

$$S(h) = \sum_{l=0}^{L-1} h_{u,l}^2. \quad (17)$$

To maximize (15) we can only minimize the interference term in SINR which is

$$\sum_{n=1}^{N_n} I_n |H_0(f_n)|^2 \quad (18)$$

Recall that $H_0(f)$ depends on the waveforms used where,

$$|H_0(f)| = 2|p(f)| \left| \sum_{k=0}^{N_s-1} c_k^{DS} \exp(j2\pi f(kT_f + c_k^{TH} T_c)) \right|. \quad (19)$$

Spectrum is shaped by designing the appropriate TH code used in the formation of UWB waveforms such as to create notches at the frequency locations of NB interferers.

According to [15] the proposed algorithm can only cop with a single NB interferer, i.e. the objective function is to minimize $H_0(f)$ at a single frequency location f_1.

$$|H_0(f_1)|^2 = \left| \sum_{k=0}^{N_s-1} \exp(j2\pi f_1 c_k^{TH} T_c) c_k^{DS} \exp(j2\pi f_1 k T_f) \right|^2 \quad (20)$$

which can be written in the form

$$|H_0(f_1)|^2 = C_{TH,e}^* (V_{p,1} V_{p,1}^*) C_{TH,e} = C_{TH,e}^* Q_{TH} C_{TH,e} \quad (21)$$

where

$$Q_{TH} = V_{p,1} V_{p,1}^* \quad (22)$$

$$V_{p,1} = \left(p_{0,1}, \ldots, p_{N_s-1,1} \right) \quad (23)$$

$$p_{k,1} = c_k^{DS} \exp(j2\pi f_1 k T_f) \quad (24)$$

$$C_{TH,e} = (c_0^{TH,e}, \ldots, c_{N_s-1}^{TH,e}) \quad (25)$$

$$c_k^{TH,e} = \exp(j2\pi f_1 c_k^{TH} T_c) \quad (26)$$

This quadratic problem can be minimized by finding the smallest eigenvalue of the Hermitian matrix Q_{TH} and choosing its corresponding eigenvector as the TH code if it is present in $I_{TH}^{N_s}$ (the set of all possible TH codes), otherwise a simple Euclidean distance measure is done to generate the nearest TH code.

IV. ENERGY DETECTOR BASED SENSING

Energy detector based approach is the most common way of spectrum sensing because of its low computational and implementation complexities. In addition, receivers do not need any knowledge on the primary users signal. The signal is detected by comparing the output of the energy detector with a threshold, which depends on the noise floor [16]. The received signal has the following form

$$y(n) = s(n) + w(n) \quad (27)$$

where $s(n)$ is the signal to be detected, $w(n)$ is the additive white Gaussian noise (AWGN), and n is the sample index. Note that $s(n) = 0$. The decision metric for the energy detector can be written as

$$M = \sum_{n=0}^{N} |y(n)|^2, \quad (28)$$

where N is the size of the observation vector. Comparing the decision metric M to a fixed threshold λ_E gives a decision on the band conditions. This is equivalent to choosing one of two hypotheses:

$$H_0 : y(n) = w(n)$$
$$H_1 : y(n) = S(n) + w(n) \quad (29)$$

The performance of the detection algorithm can be summarized with two probabilities: probability of detection P_D and probability of false alarm P_F. P_D is the probability of detecting a signal on the considered frequency when it truly is present. Thus, a large detection probability is desired. It can be formulated as

$$P_D = P_r(M > \lambda_E | H_1) \quad (30)$$

P_F is the probability that the test incorrectly decides that the considered frequency is occupied when it actually is not, and it can be written as

$$P_F = P_r(M > \lambda_E | H_0) \quad (31)$$

P_F should be kept as small as possible in order to prevent underutilization of transmission opportunities. The decision threshold λ_E can be selected for finding an optimum balance between P_D and P_F. However, this requires knowledge of noise and detected signal powers. The noise power can be estimated, but the signal power is difficult to estimate as it changes depending on ongoing transmission characteristics and the distance between the cognitive radio and primary user. In practice, the threshold is chosen to obtain a certain false alarm rate [17]. Hence, knowledge of noise variance is sufficient for selection of a threshold. The white noise can be modeled as a zero-mean Gaussian random variable with variance σ_w^2 *i.e.* $w(n) = N(0, \sigma_w^2)$. For a simplified analysis, let us model the signal term as a zero-mean Gaussian variable as well, *i.e.* $s(n) = N(0, \sigma_s^2)$. The model for $s(n)$ is more complicated as fading should also be considered. Because of these assumptions, the decision metric (28) follows chi-square distribution with $2N$ degrees of freedom χ_{2N}^2 and hence, it can be modeled as

$$M = \begin{cases} \dfrac{\sigma_w^2}{2}\chi_{2N}^2 & H_0 \\ \dfrac{\sigma_w^2+\sigma_s^2}{2}\chi_{2N}^2 & H_1 \end{cases} \tag{32}$$

For energy detector, the probabilities P_F and P_D can be calculated as [18]

$$P_F = 1-\Gamma\left(L_f L_t, \frac{\lambda_E}{\sigma_w^2}\right), \tag{33}$$

$$P_D = 1-\Gamma\left(L_f L_t, \frac{\lambda_E}{\sigma_w^2+\sigma_s^2}\right), \tag{34}$$

where λ_E is the decision threshold, and $\Gamma(a, x)$ is the incomplete gamma function as given in [19].

The spectrum sensing task in this work is different in the sense that a sort of classification is needed to determine the interferer with highest power among all previously assumed NB interferers frequency locations. As suggested sensing will be done at each of these frequency locations and a ratio will be taken between the decision metric and the fixed threshold λ_E to classify the interferers. The interferer with the highest ratio will be mitigated at every symbol-duration.

V. NUMERICAL RESULTS

In this section, simulation results are shown to illustrate the effectiveness of the proposed adaptive NB interference mitigation receiver structure. Considering the second derivative of a Gaussian monocycle with pulse duration normalization factor τ_p=0.5ns and energy $1/\sqrt{N_S}$ given by

$$p(t) = \sqrt{\frac{8}{3N_s\tau_p}}\left[1-4\pi(t/\tau_p)^2\right]e^{-2\pi(t/\tau_p)^2} \tag{35}$$

Simulation parameters are given in TABLE I. . Pseudo random DS codes are used for multiple-access, which was randomly chosen as C_{DS} = [1, 1,−1, 1, 1,−1, −1, 1, 1, 1,−1, 1, 1,−1, 1,−1] and assumed to be known by the UWB device wherein the TH sequence design is implemented.

TABLE I. SIMULATION PARAMETERS

Parameter	Value
N_h	16
N_s	16
τ_p	0.5 ns
T_c	1 ns
T_f	T_cN_h= 16 ns
T_b	N_sT_f = 256 ns

TH codes are then designed to mitigate the effect of NB interference. We first illustrate the role of TH code design technique to mitigate interference where in Fig. 4 the normalized transfer function of the matched filter is shown to have a notch at the frequency location of the NB interferer which was assumed to be f_n=2.412GHz, therefore, the mutual interference between UWB and NB systems can be highly reduced when the designed TH sequence is applied to UWB signals.

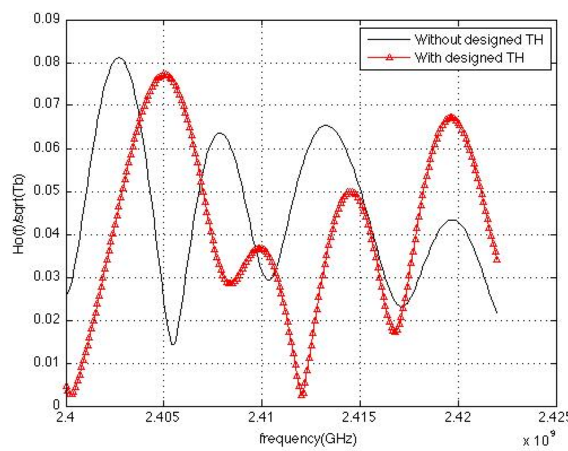

Figure 4. Normalized transfer function of the matched filter with and without the TH code design in the presence of single NB interferer at f_n=2.412GHz.

Fig. 5 shows a comparison between BER performance of three scenarios where in the first scenario a single NB interferer is present in the channel at f_n=2.402 GHz and was successfully mitigated to improve the UWB system performance. The second scenario assumes the presence of three NB interferers at frequencies f_1=2.402 GHz, f_2=2.41 GHz and f_3=2.42 GHz with time-varying amplitudes, the mitigation is done on a randomly selected NB interferer and shows a performance degradation due to the varying amplitudes of the interferers. The third scenario applies the proposed adaptive mitigation algorithm and shows a performance improvement than the second scenario. Note that, in the three scenarios SIR was set to be -10 dB.

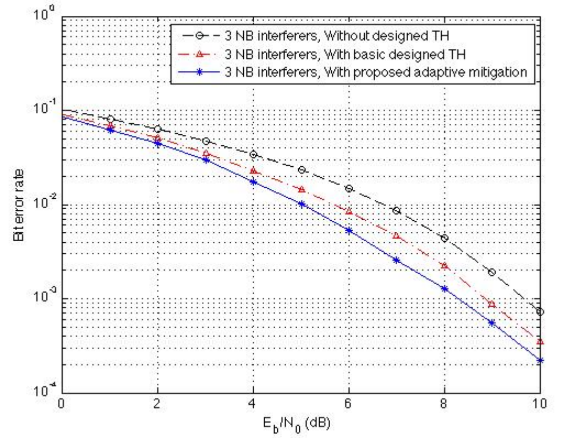

Figure 5. The BER of an UWB system with and without the designed TH sequence, in the presence of three NB interferers at f_1=2.402 GHz, f_2=2.41 GHz and f_3=2.42 GHz with time-varying amplitudes.

In Fig. 6 spectrum is sensed every symbol-duration, i.e. every 256 ns, to determine the interferer with highest power and works on mitigation it's effect. The 3-D plot of time vs. frequency vs. normalized MF transfer function shows the adaptive multi-NB interferences mitigation over 8 UWB transmitted symbols.

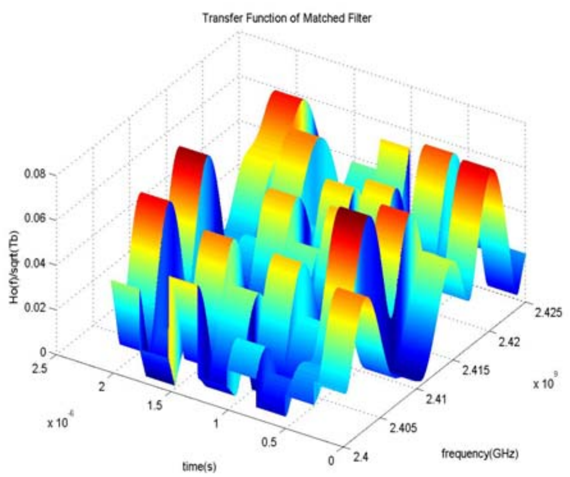

Figure 6. 3-D plot of time vs. frequency vs. normalized MF transfer function shows the adaptive multi-NB interferences mitigation.

VI. CONCLUSION

In this paper, mutual interference between UWB and NB systems was investigated. DS-TH code designs were used to mitigate the mutual interference enabling successful coexistence between both services. However the TH code design can mitigate a single NB interferer, UWB signals suffer from multiple NB interferers with varying powers, which lead to a severe performance degradation. Spectrum sensing was used at every symbol-duration to determine and classify the NB interferer with highest power. TH spreading sequence is then designed to adaptively mitigate the effect of the identified NB interference.

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