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Filter Bank Based Notch Filter for Interference Cancellation in UWB Systems

Saurabh Srivastava and O.P. Sahu***

ABSTRACT

The primary concern of any communication engineer is the bandwidth of the transmitted or received signal and the noise encountered during the transmission reception process. We analyze the effects of narrowband interference in Multicarrier UWB systems such as short distance IEEE 802.11a system. It is known that the process of narrowband interference cancellation is quite complex especially for ultra-wideband systems due to their power spectral density as low as -41dBm/MHz recommendations by the FCC. We review the model for narrow band interference and use the statistical property of correlation to determine the interference power spectral density. We review the sub band processing of UWB signals and apply notch filtering after measuring the threshold to eliminate the interference. We propose a novel mechanism for generation of the required notch filter using the sub band signals generated after the sub band decomposition of the UWB signal using filter banks. The proposed mechanism may be applied in conjunction with the other filter bank based multicarrier systems that have the advantage of better side-band attenuation of signals than commonly used OFDM system.

Keywords *Multicarrier; Filter Bank; Orthogonal Frequency Division Multiplexing (OFDM); Wireless-Local Area Network (WLAN); Sub-Band Decomposition; Narrowband Interference; Modeling; Cancellation; Adaptation.*

1.0 Introduction

The primary concern of any communication engineer is the bandwidth of the transmitted or received signal and the noise encountered in the channel during the transmission reception process. The focus area of modern communication systems is towards utilizing multicarrier (MC) techniques for transmission and reception, and towards minimizing the noise and interference encountered during the communication process.

In wideband multi carrier communications, the channel bandwidth is split into various bins of smaller bandwidth referred to as sub-carriers or sub-channels. The signal to be transmitted is then modulated with the subcarrier frequency using digital modulation methods such as Quadrature Phase Shift Keying (QPSK), Quadrature Amplitude Modulation (QAM) etc. as in Orthogonal Frequency Division Multiplexing (OFDM). To avoid interference between the neighboring subcarriers, the subcarriers are made orthogonal by introducing guard interval [1]. The ultra-wideband (UWB) is referred by the frequency band of 3.1 Hz to 10.6 GHz by the Federal Communications Commission (FCC). It coexists with the other licensed and unlicensed communication systems operating in the same spectrum but with a very low power spectral density (PSD)[2]. It is known that the process of removal of narrowband interference (NBI) is quite complex for wideband and ultra-wideband systems owing to their low PSD. Also, the interference occupies a much narrower frequency band but has a higher-power spectral density than the large bandwidth information. On the other hand, the UWB systems are carrier less systems. So, Gaussian pulses and its derivatives are employed to generate the baseband UWB signal [3]. Wideband signal usually has autocorrelation properties quite similar to those of AWGN (Adaptive Wide Gaussian Noise), so filtering in the frequency domain is possible [4].

In this paper, we show that correlation between the received samples in an UWB-OFDM based Wireless-Local Area Network (WLAN)

**Corresponding Author: Department of Electronics & Communication Engineering, Teerthanker Mahaveer University, Moradabad, India (E-mail: saurabh_nitk@yahoo.com)*
***Department of Electronics & Communication Engineering, NIT Kurukshetra, Kurukshetra, India*

802.11a or High Performance Radio LAN (HiperLAN) type 2 systems may be used for determination of NBI PSD. The HiperLAN type 2 system also has similar PHY layer parameters as 802.11a and the error performance of both the ultra-wideband mechanisms is the same [5].

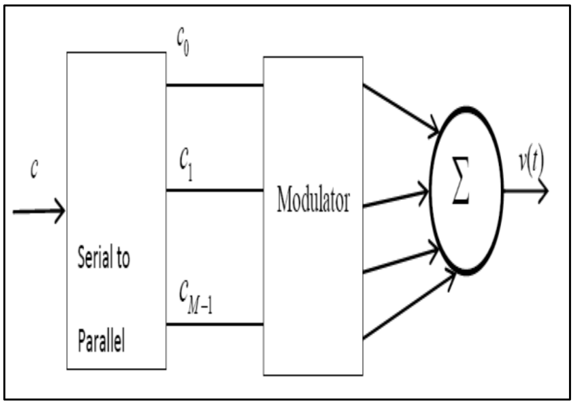
Hence, in this paper we would focus on IEEE 802.11a systems. We consider the narrowband interference as either a single tone interference signal or a narrow bandwidth interference signal. The issue of NBI suppression in multicarrier wideband systems is of primary importance in such systems and has been studied extensively in the last few years. Two main types of approach are generally adopted. The first involves various frequency excision methods, where the corrupted frequency bins of the multicarrier symbols are excised or their usage avoided. The second approach or the cancellation techniques aim at eliminating or mitigating the effect of the NBI on the received multicarrier signal [6-10]. We choose the method for detection of the NBI using the correlation of the received signals, and then apply filter banks to derive the notch filter that is further used for the mitigation of the NBI.

The paper is organized as follows first we review the multicarrier communication, Filter Bank sub band decomposition, OFDM and the UWB IEEE 802.11a standard. Next we describe the NBI detection and mitigation techniques. We also use the single tone and narrowband noise models in deriving at the correlation properties of the received ultra-wideband OFDM signal. The simulation model for NBI suppression in UWB systems is described in next section. In next section we present the simulation results for NBI suppression in UWB channels and multicarrier systems. Finally, Section concludes the paper giving future direction and suggesting possible application scenarios of the research work.

2.0 Review of Multicarrier Systems

In multicarrier (MC) communication systems, the data is transmitted over many frequencies instead of a single carrier frequency. This is done by dividing the wideband channel into several sub-bands with mild fading. This has the advantage of better channel estimation and equalization. Also, MC symbol is longer in duration than single carrier (SC) symbol which helps reduce synchronization complexity of MC system. A general representation of MC modulation scheme is shown in fig 1.

Fig 1: Multicarrier Modulation Scheme



Here, the serial input c is split into M parallel streams $c_0, c_1, c_2, ..., c_{N-1}$ in the Serial to Parallel Convertor. Then, the input bitrate R is reduced to R/M in each of the M parallel sequences. The discrete symbols c_i are modulated by shifting to desired frequency. The center frequency of the n^{th} sub-channel is given by

$$\omega_n = \omega_0 + \frac{2\pi}{T}n, \quad n = 0,1,2,...,M-1, \qquad (1)$$

Where ω_0 the center frequency of is the lowest sub-channel and M is the total number of sub-channels.

The transmitted signal is given by

$$v(t) = \sum_{n=0}^{M-1}\sum_{l=-\infty}^{\infty} c_n(l) g_n(t-lT)\exp(-j\omega_n t), \quad n = 0,1,2,...,M-1 \ (2)$$

In OFDM, the bandwidth is split into M sub-bands. Each sub-band is used by one sinusoidal sub-carrier. The baseband signal in OFDM is represented as

$$x(t) = \frac{1}{\sqrt{M}}\sum_{k=-\infty}^{k=\infty}\sum_{i=0}^{M-1} A_i(k) h(t-kT)\exp(ji\frac{2\pi}{T}t), \ (3)$$

Where $h(t)$ is a rectangular pulse of duration T, and $A_i(k)$ are QAM or QPSK symbols. The OFDM symbol duration is T. Each of the M sub-carriers is centered at frequency $f_i = \frac{i}{T}, \quad i = 0,1,2,...,M-1$.

The spectrum of the sub-carriers is obtained by the convolution of the Fourier transform of exponential signal with the Fourier transform of the rectangular pulse. Hence the spectrum of each sub-carrier is a sinc function centered

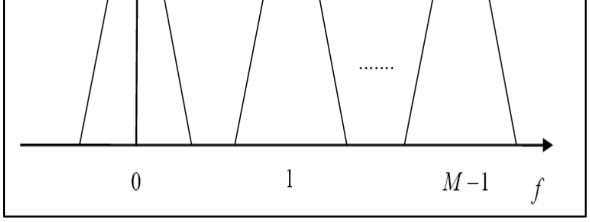
$$\text{at } f_i = \frac{i}{T}, \quad i = 0, 1, 2, \ldots, M-1.$$

OFDM based 802.11a system has a channel spacing of 20 MHz, FFT size of 64, with subcarrier modulation scheme of Binary Phase Shift Keying (BPSK), QPSK, 16-QAM or 64-QAM, the useful symbol length of 3.2 μs, and sub-carrier spacing of 312.5 KHz. Using the 5 GHz band gives 802.11a a significant advantage, since the 2.4 GHz band is heavily used to the point of being crowded. Degradation caused by such conflicts can cause frequent dropped connections and degradation of service. OFDM has fundamental propagation advantages when in a high multipath environment, such as an indoor office, and the higher frequencies enable the building of smaller antennas with higher RF system gain which counteract the disadvantage of a higher band of operation. OFDM is the regarded as natural choice for high speed reliable Multicarrier communications for short range systems.

The division of channel into sub-bands is as shown in the figure 2.

As shown in fig.2, the entire channel bandwidth is divided into *M* uniform sub-bands (sub-channels in OFDM). This may be done by using a simple lowpass filtering of the channel with a prototype filter (as shown for sub-channel 0), and repeating till sub-channel. *M*-1 Clearly, all sub-channels except sub-channel 0 are the modulated (shifted) copies obtained with the bandpass versions of the prototype filter.

Fig 2: Sub-Band Splitting of Channel



2.1 Sub band splitting using filter banks

A filter bank is basically a group of filters performing a specialized task. In many communication applications, it is often required to split a wideband signal into smaller bandwidth components or sub-bands for effective transmission of data. The natural way to perform this is using filters. For multicarrier communication systems, this is performed easily using analysis- synthesis filter bank structures that divide the received signal into several sub channels (analysis part), and reconstruct the original signal

Fig 3: Uniform Decimating M-Channel (Analysis) Filter Bank

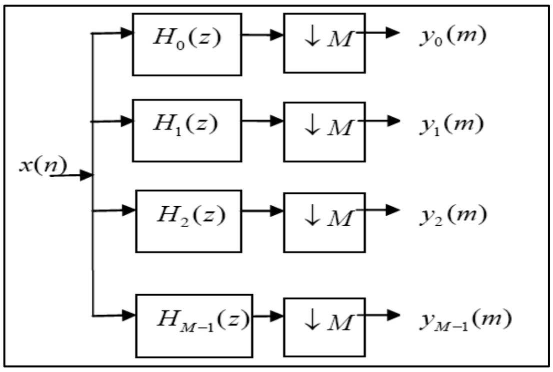
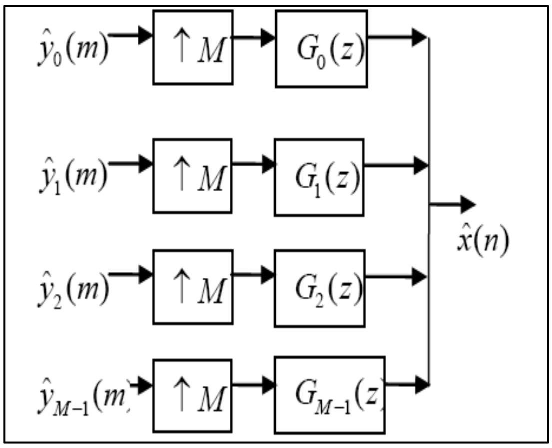


Fig 4: Interpolating M-channel (Synthesis) Filter Bank



from the sub channels (synthesis part), after some optional processing.

In signal processing, uniform decimation Filter Bank has the above property of sub-carrier division and is shown in figure 3. Such a filter bank makes the system efficient by lowering the input sampling frequency by M . This is followed by the optional sub-band processing of the output signals.

The reverse operation, i.e. sub-band signal combining is carrier out using interpolation filter bank or synthesis bank, as shown in figure 4.

Here, $\hat{y}_i(m),\quad i = 0,1,2,..M-1$ are the estimated values of sub-band that are passed to a bank of upsamplers. The upsamplers increase the sampling frequency exactly in the inverse ratio of decimation.

The upsampled signals are then given to a set of filters that synthesize the initial wideband signal from its sub-bands, and provide an estimated value of it, represented by $\hat{x}(n)$.

2.2 WLAN 802.11a

The IEEE 802.11 group of standards popularly called as Wi-Fi, has its subset as the 802.11a standard. This standard works in the 5 GHz unlicensed ISM band, that lies within the UWB spectrum.

The 802.11a has 12 overlapping channels, 8 dedicated to indoor and 4 for point to point communication.

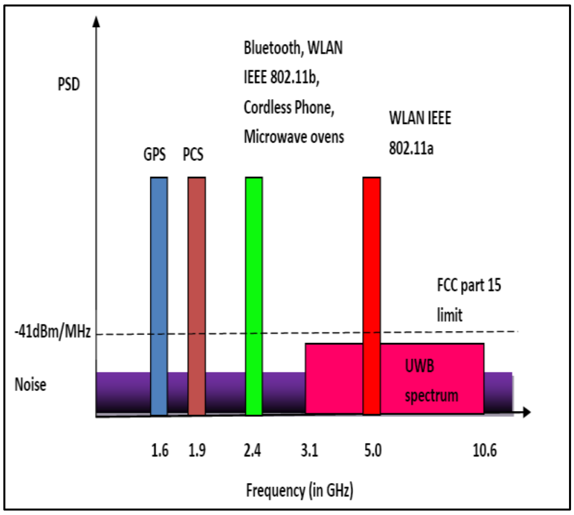
It finds application in short distance wireless communication within a range of about 30m. It uses OFDM and has a channel width of 20MHz. The 802.11a RF signal consists of 52 OFDM subcarriers. Of these 48 are used for the data transmission and four are used as pilot subcarriers. The separation between the individual subcarriers is 0.3125 MHz .

This results from the fact that the 20 MHz bandwidth is divided by 64. Although only 52 subcarriers are used, occupying a total of 16.6 MHz, the remaining space is used as a guard band between the different channels.

As with many data transmission systems, the generation of the signal is performed using digital signal processing techniques and a baseband signal is generated.

This is then upconverted to the final frequency. Similarly for signal reception, the incoming 802.11a signal is converted down to baseband and converted to its digital format after which it is processed digitally.

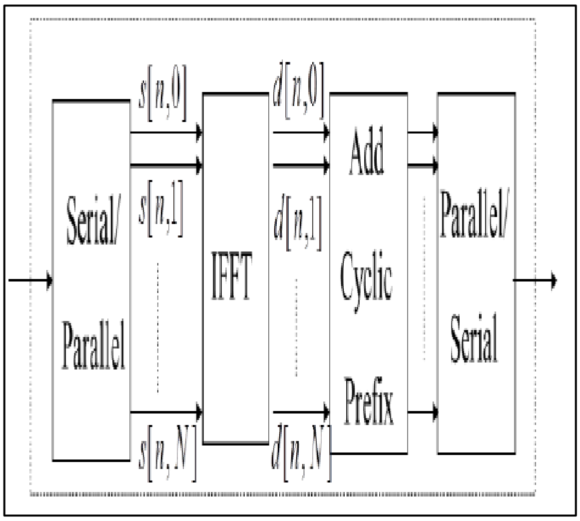
Fig 5: Spectrum Crossover of Narrowband Interferes in UWB Systems [15]



2.3 OFDM system

OFDM is the most widely used MC modulation technique presently. The basic OFDM transmitter system based upon fig.1, is shown as in fig. 6

Fig 6: OFDM Transmitter [12]



As shown in fig. 6, the S/P convertor acts as a Time/Frequency mapper. The input data *s* [*nk*] is fed into the IFFT block that generates the required time domain waveform

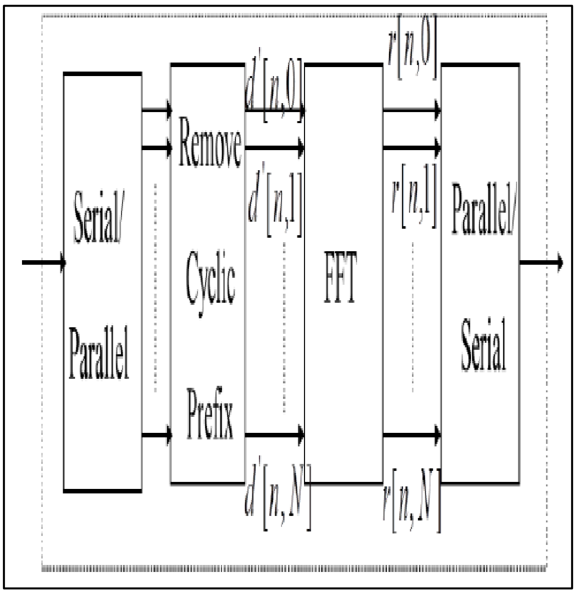
$$d[n,i] = \frac{1}{\sqrt{N}} \sum_{k=0}^{N} s[n,k] e^{j2\pi i \frac{k}{N}}, \quad i = 0,1,\ldots,N$$

To the output from IFFT block, Cyclic Prefix (CP) is added. The Cyclic Prefix acts like guard interval and makes equalization easy. The data is again converted into serial form and transmitted. The reverse operations occur in OFDM receiver section as shown in fig. 7.

In the receiver section, CP is discarded after the conversion from serial data to parallel data. This is followed by FFT block that generates the required frequency domain signal. Finally, The P/S convertor acts as a frequency/time mapper.

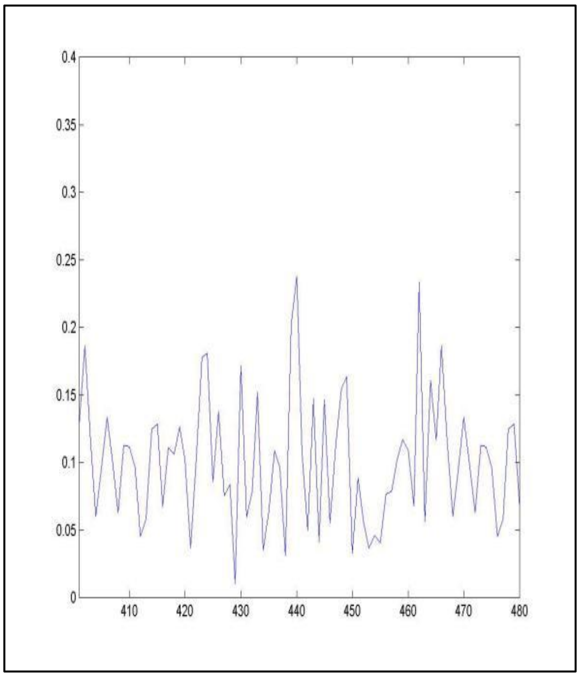
To ensure orthogonality between the sub-carriers, the sub-carrier spacing is made the inverse of OFDM symbol duration. For N point IFFT (or FFT), the total bandwidth becomes N times of subcarrier-spacing. Also after the CP insertion, the symbol duration increases.

Fig 7: OFDM Receiver [12]



The usage of large CP ensures no delay spread in received OFDM waveform. In OFDM the equalization employed at the receiver side, and is Time Domain Equalization (TDE) before removal of CP and Frequency Domain Equalization (FDE) after the FFT operation. The application of FDE provides almost flat fading at the sub-carrier level, which creeps in as ICI terms in frequency domain. The ICI is reduced practically by reducing OFDM symbol duration (i.e. increasing sub-carrier width) or by transmit pulse shaping. For 802.11a, the OFDM transmitted waveform is shown in fig. 8.

Fig 8: The Transmitted OFDM Waveform



A filter bank multicarrier system can be implemented using the analysis and synthesis filter bank is as shown in fig. 9.

The transmitted signal $x[n]$ is found to be

$$x[n] = \sum_{l} \sum_{k=0}^{M-1} s_{k,l}\, g_k[n - lL_s] \qquad (4)$$

Where M is the no. of subcarriers, $s_{k,l}$ is the l[th] symbol in k[th] subcarrier, L_s is the no. of symbols per transmit symbol spacing, and $g_k[n]$ is the synthesis filter for the k[th] subcarrier. At the receiver part, the estimated l[th] symbol in k[th] subcarrier, $\hat{s}_{k,l}$ is given as

$$\hat{s}_{k,l} = (y[n] * h_k[n])_{n=lLs} \quad (5)$$

Where $y[n]$ is the received signal and $h_k[n]$ is the impulse response of the analysis filters for the k[th] subcarrier. Defining L , where $L \geq M$, as no. of samples per symbol duration .

For OFDM, $s_{k,l}$ are QAM symbols and $L_s = L$. The synthesis and analysis filters are defined as

$$g_k[n] = h_k[n] = p[n]W_L^{-kn} \quad (6)$$

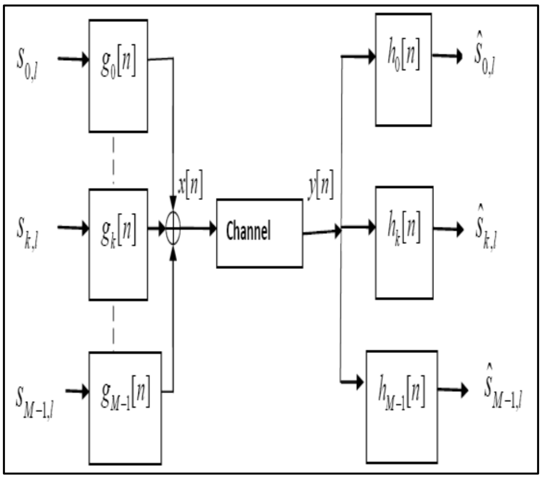
Where the prototype filter $p[n] = \frac{1}{\sqrt{L}}$ for n=0, 1,..,L-1

and 0 elsewhere is of length L_p , and

$$W_L = e^{-j2\pi/L} \quad (7)$$

We have chosen FBMC against OFDM system, as FBMC system provides more out of band power rejection than OFDM. Moreover, FBMC is more bandwidth efficient than OFDM. The increased complexity by using FBMC against OFDM can be justified by the spectral characteristics of the FBMC sub-carriers in providing significantly high suppression to out of band radiation and to excellently partition the wideband spectrum. Moreover, as the adaptive systems need time to adapt to the input data, so it is beneficial to split the input signal and apply the adaptive interference cancellation logic in parallel over each sub-carrier. It is expected that a fair improvement in the system performance shall be observed with parallel operation of adaptive section on the sub-carriers.

Fig 9: General FBMC System [13]

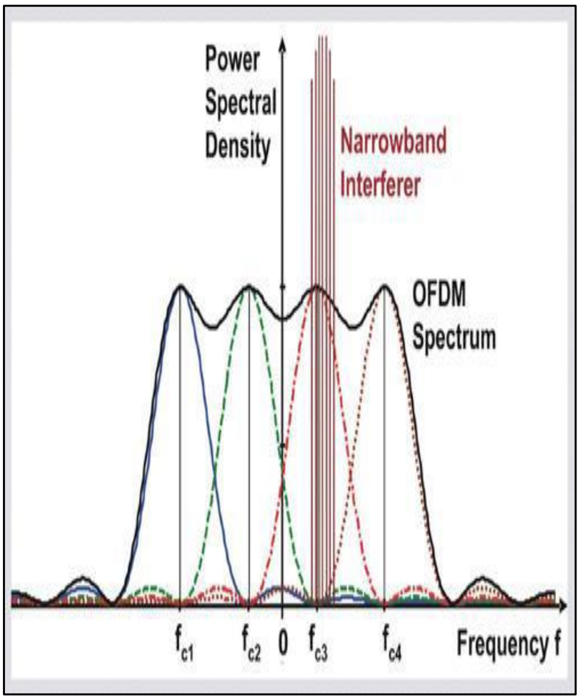


3.0 NBI Detection and Mitigation Techniques

The issue of NBI suppression in wideband OFDM systems is of primary importance in such systems and has been studied extensively in the last few years. Two main types of approach are generally adopted. The first involves various frequency excision methods, whereby the affected frequency bins of the OFDM symbol are excised or their usage avoided. The second approach is related to “cancellation techniques” which are aimed at eliminating or mitigating the effect of the NBI on the received signal. In this paper, a method for NBI cancellation based on adaptive complex digital filtering, using the Least Mean Squares (LMS) algorithm to adapt to the central frequency of the NBI is presented and the method is compared to other mitigation techniques. The proposed method offers considerable benefits, including low computational complexity.

The NBI arises due to narrowband systems operating in the UWB frequency band itself, and have predetermined center frequencies and bandwidths. The most probable interferes include Fixed satellite systems and WLAN 802.11a. The effect of NBI is shown in fig. 10.

Fig 10: Narrowband Interference Corrupting OFDM Signal of WLAN 802.11a [16]



The most prominent source of NBI is the IEEE 802.11A WLAN system with frequency allocations as shown in fig. 5, and table I.

Table 1. Frequency Allocations for WLAN 802.11a [14]

Band (GHz)	Channel No.	Centre Frequency (MHz)	Max. power output (with upto 6dBi antenna gain)
UNII lower band (5.15-5.25)	36 40 44 48	5180 5200 5220 5240	40 mW (2.5 mW/MHz)
UNII middle band (5.25-5.35)	52 56 60 64	5260 5280 5300 5320	200 mW (12.5 mW/MHz)
UNII upper band (5.725-5.825)	149 153 157 161	5745 5765 5785 5805	800 mW (50 mW/MHz)

The main factors characterizing the interference are its model, the center frequency and its bandwidth. There may be various scenarios depending upon values of these factors. Nevertheless, the main objective here is to mitigate the interference from the interferer.

We assume that the NBI is a single tone signal given by

$$i(t) = A\sqrt{2P_i}\cos(2\pi f_c t + \varphi_i) \tag{8}$$

Where A is the channel gain, P_i is the average power, f_c is the frequency and φ_i is the phase of the interfering sinusoid. For the case where the interference has a narrow bandwidth, we assume it as a zero mean Gaussian random process and its PSD can then by defined as

$$S_i(f) = \begin{cases} P_{\text{int}}, & f_c - B/2 \le f \le f_c + B/2 \\ 0, & otherwise \end{cases} \tag{9}$$

Here B is the bandwidth of the interferer, f_c is the center frequency of the interferer and P_{int} is the interference power spectral density included in bandwidth B.

The received signal can be shown as

$$r(t) = w(t) + i(t) + n(t) \tag{10}$$

Where $w(t)$ is the transmitted ultra-wideband signal, $i(t)$ is the NBI and $n(t)$ is the AWGN with PSD of N_0. The correlation characteristics of transmitted ultra-wideband signal are very much similar to that of AWGN. Hence, $w(t)$ can be assumed to be a part of $n(t)$. Also, assuming that the interference is not correlated to the AWGN and AWGN has impulsive autocorrelation. This gives the correlation between the received samples for single tone NBI as

$$R_i(\tau) = P_i|A|^2\cos(2\pi f_c \tau) + N_0\delta(\tau) \tag{11}$$

Where τ is the duration between received samples.

For the band limited interferer case, the autocorrelation between received signal samples is given as

$$R_i(\tau) = 2P_{\text{int}}B\cos(2\pi f_c \tau)\,\text{sinc}(B\tau) + N_0\delta(\tau) \tag{12}$$

First we consider the scenario where the interference is a single tone signal with known frequency f_c, in order to determine the average power of the interferer, the correlation between the received signals is computed. Choosing a value of τ approximately but not equal to zero serves our purpose. For this we take minute increments in τ between 0+ and 500ns. Using (4) and from the obtained correlation values, a decision can be made about NBI and P_{int} can be determined. Another scenario consists of interference being band limited signal and f_c is known. Considering the fact that the bandwidth of WLAN 802.11a system is 20 MHz and τ has a maximum value of 500 ns, $B\tau \le 1$. Hence, $\text{sinc}(B\tau) \approx 1$, Now , using the correlation values of received signals the existence of NBI can be verified and P_{int} determined.

Another scenario is when the center frequency is not known but the spectral nature of interference is known. The correlation values indicate the presence of NBI, but it would be difficult to determine interference PSD. In this case, if the center frequency of band limited interferer is confined to a certain region (within 20 MHz), and τ is made very small, then $R_i(\tau)$ can be computed again, and P_{int} can be determined. If uncertainty of f_c increases, i.e. if f_c lies in-between UNII lower band and middle band (5180-5320 MHz), then f_c has uncertainty of 140 MHz. In this case, determined. If uncertainty of f_c increases, i.e. if f_c lies in-between UNII lower band and middle band (5180-5320 MHz), then f_c has uncertainty of 140 MHz. In this case, τ has to be smaller than 1 ns. This high sampling rate of received signal is impractical due to current hardware limitations. Observing that the received signal autocorrelation has a sinusoidal nature, hence this suggests repeating values of τ to exist for same correlation value. Considering the two sided maximum shift in center frequency as δf, and the periodicity of the cosine term in equation (12), we can write

$$\cos(2\pi(f_c \pm \frac{\delta f}{2})\tau) = \cos(2\pi(f_c \pm \frac{\delta f}{2})(\tau + \frac{k}{f_c \pm \frac{\delta f}{2}})) \quad (13)$$

Where k is any integer. Hence, by increasing τ a practical value can be determined for sampling of correlation values, provided $\frac{1}{f_c \pm \frac{\delta f}{2}}$ is an integer. In our WLAN 208.11a case, as δf is always less than 625 MHz, and f_c takes specific integer values in between 5180 and 5805 MHz, $f_c \pm \frac{\delta f}{2}$ is always an integer, thereby justifying (12). For the OFDM based 802.11a system, the NBI interference cancellation can be done by designing suitable notch filter at the location of the interference.

Fig 11: A Basic Gaussian Pulse

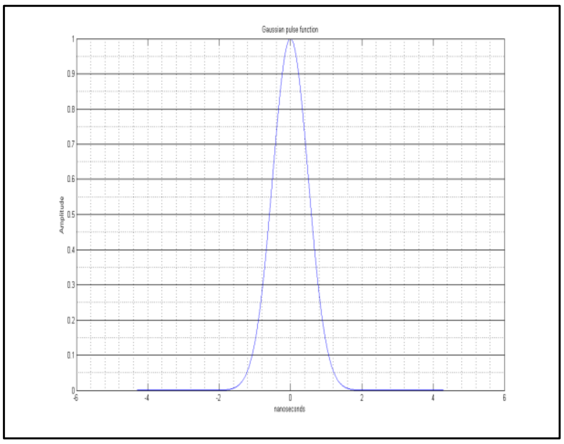
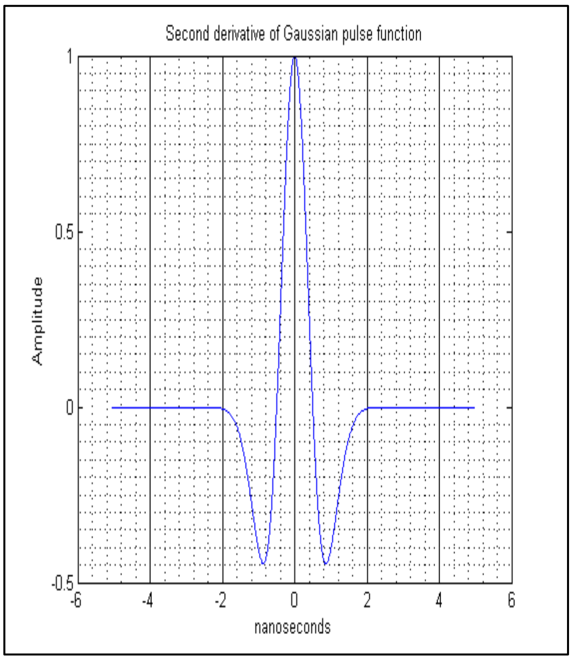
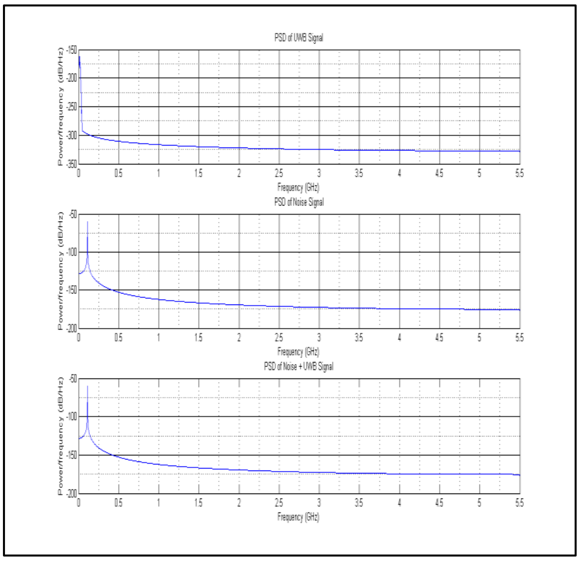


Figure 11 shows the basic Gaussian mono pulse used in the simulation for generation of UWB pulse with a pulse width of 0.5 ns. The second derivative of the monopulse was used to generate the UWB pulse for simulation purpose as shown in figure 12.

Fig 12. Second Derivative of Gaussian Pulse Used for UWB Signal Generation



Next, the PSD of the transmitted UWB signal, the noise signal and the composite signal is shown in fig. 13.



4.0 Notch Filtering Scheme Using Sub–Band Decomposition

Knowing the expected f_c of the single tone interference, the idea is to design a notch filter centered at f_c. The steps for such a design may be given as :

Step 1: Identify the interference frequency f_c.

Step 2: Partition the UWB interference band into two bands – lower band and upper band.

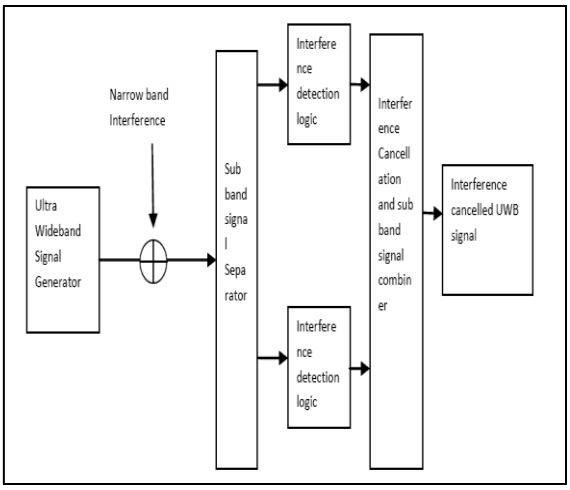
Step 3: In each band generate two sub-pulses $s_1(t)$ and $s_2(t)$, by adjusting the cut-off frequencies of the two bands, and the pulse amplitudes and keeping in mind the characteristics of complying with the FCC mask, and $S_1(f_c) = -S_2(f_c)$, (13)

Step 4: Superpose the two sub-pulses to generate the desired UWB pulse, which clearly has a notch at f_c.

Step 5 Transform the generated UWB pulse into frequency domain. This gives the required notch filter.

The simulation model for the proposed noise cancellation system can be described using following fig. 14

Fig 14: The Proposed System for Narrowband Interference Detection and Cancellation Logic

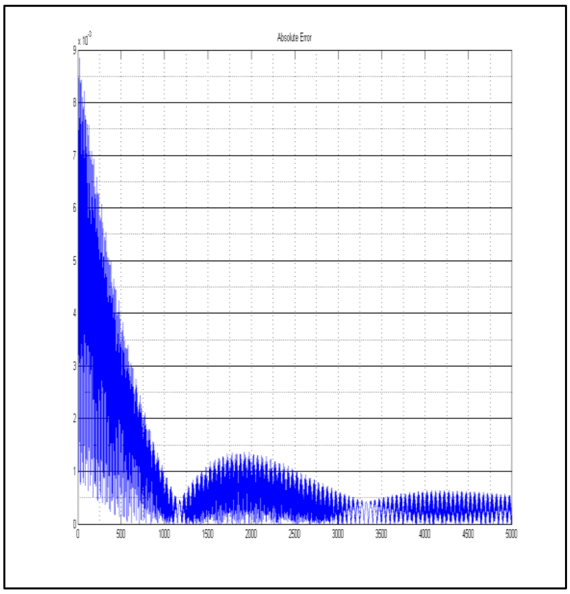


As shown in the above figure, the transmitter consists of an ultra-wideband signal generator, which passes the generated UWB signal to filter bank based sub-band signal separator that splits the wideband signal into two sub-bands. At the input of the sub-band signal separator stage, consists of a correlation receiver that receives the input samples and determines the correlation between received samples. Based upon these correlation values, the interferer frequency and power can be determined (approximately in case of the band limited interference. For the reconstruction of the ultra-wideband data, two sub-pulses are generated for both the sub-bands, by adjusting cut-off frequency of the bands under the FCC constraints as given in equation (13). As the generated sub-pulses have transforms

as $S_1(f_c) = -S_2(f_c)$, clearly at the interference frequency f_c, $S(f) = S_1(f_c) + S_2(f_c) = 0$. Hence a perfect notch would be obtained at f_c, with the frequency response of the designed notch filter as $S(f)$.

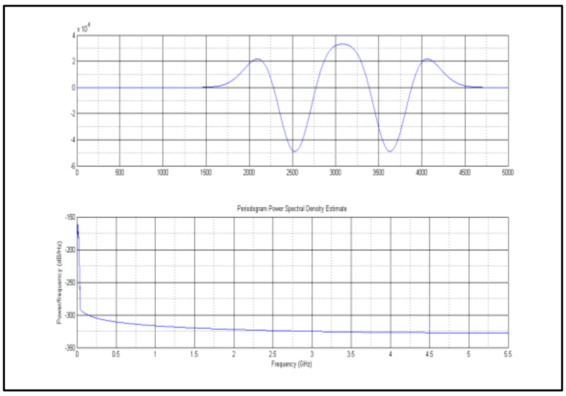
The above algorithm was simulated with MATLAB and the results verified a very low absolute error of the order of 0.1%, in the interference cancelled UWB signal as observed from figure 15.

Fig 15: Absolute Error in the Reconstruction of UWB Signal



Finally, the reconstructed UWB signal is shown in fig. 16 with corresponding periodogram. It can be verified that this matches with the periodogram of the UWB transmitted signal.

Fig 16: Recovered UWB Signal and Its Periodogram



The parameters used in the simulation are as follows

UWB pulse width = 0.5 ns, a second derivative of Gaussian pulse was used as an UWB signal. To ensure that the spectrum occupancy of the signal matches with the FCC recommendations (-41dBm/MHz), a bandpass equiripple filter was designed using MATLAB, and the UWB pulse was shaped properly using the filter. A composite signal was formed by the addition of UWB pulse and Narrowband Interference signal in accordance with equation (9). Using the autocorrelation values of the received signal samples, the interferer frequency was determined. The sub-band decomposition of the received signal was done with filter banks generating sub-pulses of desired characteristics for each sub-band. Superposition of the sub-pulses was performed resulting in the required notch filter. Once the required notch filter is generated, the received UWB signal is notch filtered with the generated filter to produce the interference cancelled UWB signal.

5.0 Results

Based on the simulation setup and results obtained we can say that the notch filtering proposed for narrowband interference cancellation in UWB systems using the sub band decomposition of the signal has the definite advantage of being of an automatic nature. Further, the notch is exactly at the interferer frequency which is a clear advantage over adaptive filtering solution of the same. Thirdly, the proposed method describes a decent application of sub-band filters in interference cancellation in UWB spectrum.

Moreover, advantages of using filter bank are numerous. Some of them include, more spectrally efficient waveform generation, suitability for MC communications.

6.0 Future Direction

Further research includes the application of the proposed structure in conjunction with other filter bank based structures and probable modifications at the physical layer of such a system. A typical example could include FBMC-SMT systems to incorporate the proposed notch filter section and analyze the performance of the system.

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