Dummy Tone Insertion for Spectral Sculpting of the Multi-Band OFDM UWB System

Jaiganesh Balakrishnan
Wireless Connectivity Solutions
Texas Instruments
Bangalore, India
jai@ti.com

***Abstract*—As the UWB regulations have not been finalized in many parts of the world, spectral flexibility is a key requirement for an UWB system to win in the global marketplace. The unlicensed nature of the UWB spectrum makes it imperative for these devices to have the capability to coexist with existing services. The multi-band OFDM UWB communication system, standardized by ECMA for high-speed WPAN, has the ability to satisfy these requirements. This paper describes a time-domain windowing technique and a dummy tone insertion mechanism that enable spectral sculpting of a multi-band OFDM UWB communication system. The protection offered to radio astronomy bands in Japan is used as an example to illustrate the advantages of these techniques.**

Keywords- UWB, Multi-band OFDM, Co-existence, Global Compliance, Spectral Scuplting, Windowing

I. Introduction

In early 2002, the Federal Communications Commission (FCC) issued its landmark Report & Order which allocated 7,500 MHz of spectrum (from 3.1 GHz to 10.6 GHz) for use by Ultra Wide-band (UWB devices [1]. The emissions limit for UWB devices is illustrated in Figure 1. The Report & Order created several new opportunities for innovation and technical advancement within the industry as well as the academia.

The UWB spectrum makes it possible to develop a new wireless personal area networking (WPAN) technology and achieve high-speed wireless communications at low power and low cost. In fact, UWB promises to deliver data rates that can scale from 110 Mb/s at a distance of 10 meters up to 480 Mb/s at a distance of two meters in realistic multi-path environments. Indeed, UWB is the only technology expected in the near future to address the consumer's insatiable need for higher data rates, while still being an affordable, low-power solution.

The use of extremely large bandwidths implies that UWB devices will occupy the same frequencies that have already been allocated to other services. Therefore, designers of UWB systems will have to pay careful attention to coexistence with other services, both in terms of radiating energy into other devices and in terms of being able to tolerate interference from other services.

In fact, the ability of UWB devices to co-exist with other devices will most likely determine the success of the technology. Those devices that can co-exist with other services without additional complexity will eventually win in the marketplace, while those devices that are unable to co-exist or require additional complexity to co-exist are likely to fail in the marketplace.

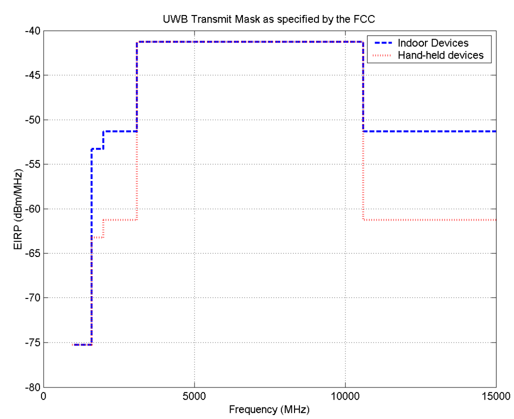

Figure 1. UWB emission limit for indoor and hand-held Devices

The multi-band OFDM system [2], [3], [4], originally proposed by Texas Instruments, has been promoted and standardized by the WiMedia alliance [5], a global non-profit organization, comprising of over 350 leading companies in the consumer electronics, personal computing, home entertainment, mobile phone, semiconductor and digital imaging market segments. This proposal has been approved as a standard by ECMA [6]. The multi-band OFDM UWB technology has been selected for Wireless UWB and next generation Bluetooth.

Multi-band OFDM system has been designed to have sufficient flexibility in its ability to co-exist with other services and comply with various international regulations [7]. In this article, we describe techniques that enable the global compliance and co-existence capabilities of the Multi-band

OFDM system. Techniques to spectral sculpt the multi-band OFDM system, a mechanism that enables the multi-band OFDM UWB system to be a cognitive radio solution, are presented in this article.

This paper is organized as follows: Section II describes the challenges associated with Global compliance of a UWB System. Various techniques for sculpting the spectrum of the multi-band OFDM UWB system and the associated trade-offs are presented in Section III and Section IV concludes.

II. Global Compliance

A key challenge in UWB system design is that the regulations and spectrum allocation are currently only available in the United States. Other areas of the world – for example, Europe, Japan, Korea and China – are currently exploring the possibility of allocating spectrum for UWB devices. Regulations in other parts of the world have not been finalized, and the exact frequency allocation and emission limits may differ from those specified in the United States. Therefore, it is important to design a system with sufficient spectral flexibility so that a *single* solution (chip and reference design) can be shipped throughout the world, with only software changes required. Hence, the capability to sculpt the spectrum is a key requirement for any UWB system.

A. Japanese Radio Astrnomy Bands

To illustrate the need for spectral flexibility, we consider the example of radio astronomy bands in Japan. The Japanese regulatory authority appears to be strongly committed towards protecting the radio astronomy bands. They propose that the emissions from UWB devices within these frequencies be limited to -64.3 dBm/MHz, which corresponds to a reduction in transmit energy of 23 dB over the emission level of -41.3 dBm/MHz specified by the FCC. TABLE I. lists the radio astronomy bands that overlap with the UWB spectrum in the frequency range of 3.1 to 10.6 GHz [8]

TABLE I. Japanese Radio Astronomy Bands

Designation	Frequency Range (MHz)
S-band	3260 – 3267
S-band	3332 – 3339
S-band	3345.8 – 3352.5
C-band	4800 – 4990
C-band	4990 – 5000
C-band	6650 – 6675.2

Naturally, UWB devices that have the ability to dynamically sculpt their spectrum can introduce notches into the transmitted spectrum thereby protecting the radio astronomy bands. By introducing notches, UWB proponents can remove any fears and doubts that radio-astronomers may have about interference from UWB devices, and thereby speed adoption and allocation of UWB spectrum in Japan.

The UWB devices effectively sacrifice bandwidth in order to protect the radio astronomy bands. Therefore, it is imperative to minimize the loss in bandwidth as this would affect performance. Ideally, the notches ought to have a sufficiently narrow bandwidth, so as to null out only the particular radio astronomy band, and have a depth of at least 23 dB.

In summary, to ensure coexistence with other services, the ideal UWB device should have the ability to sculpt the spectrum while satisfying the following key criterion:

- Reduce power spectral density in the band of interest. For example, in the radio astronomy band, this reduction should be 23 dB, corresponding to an emission level of -64.3 dBm/MHz.
- Minimize the loss in usable bandwidth, and hence performance, needed to protect the radio astronomy bands.
- Require minimal increase in transmitter complexity/hardware and no increase in receiver hardware.

III. Spectral Sculpting for the Multi-Band OFDM Systems

In a multi-band OFDM system, the information is transmitted instantaneously on a single band whose bandwidth is 528 MHz. The information is further interleaved across three consecutive frequency bands. For example, the first OFDM symbol could be transmitted in sub-band #1, the second OFDM symbol on sub-band #3, the third OFDM symbol on sub-band #2, and so forth. Within a single band, the information is transmitted on multiple tones, where the frequency spacing between two adjacent tones is 4.125 MHz. Hence a single 7 MHz wide radio astronomy band would overlap with at most three tones of the multi-band OFDM system. An advantage of the multi-band OFDM system is that the signal is constructed in the frequency domain; therefore it is easier, both mathematically and computationally, to shape the spectrum of the transmitted signal.

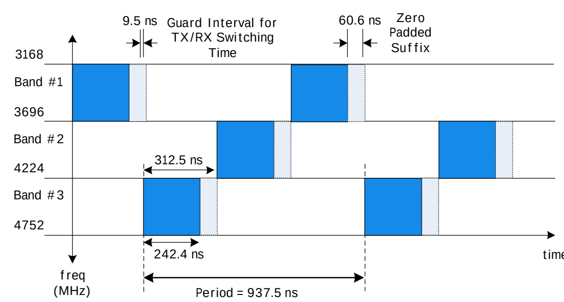

Figure 2. Illustration of Multi-band OFDM Signal Transmission.

In addition to having a resolution of 4.125 MHz, the multi-band OFDM system has the ability to turn on and off sub-bands within the system. This ability provides a resolution of 528 MHz. Therefore, it is possible to shape the spectrum at a very fine level as well as at a very coarse level. In this article, the focus is on creating notches using the fine resolution of the tones within a band. It is fairly obvious how to use the coarse resolution of a band and therefore, this technique will not be discussed in this article

A. *Tone Nulling*

The most common technique for creating a notch in the frequency domain is to zero out tones that overlap with the radio astronomy band. The advantage of this technique is that there is no increase in complexity at the transmitter. Additionally, the receiver does not require any prior knowledge of the notch. At the receiver, tones carrying no information will look similar to a deep fade in the channel. Since the receiver is not able to differentiate between these two phenomena, no prior information needs to be communicated to the receiver in order to compensate for the tones carrying no information.

The transmitted OFDM signal is constructed using an inverse discrete Fourier transform (IDFT). As a rectangular window is applied to the data, each tone has a wider than expected spectrum, where the spectrum has the shape of a sinc function. Although, the sinc function has zero crossings at each of the tone locations, zeroing out only a few tones results in a shallow notch. For example, to obtain a notch with a depth of 23 dB for the radio astronomy band, a total of 29 tones need to be zeroed out. This corresponds to a total loss of 120 MHz of bandwidth, i.e., nearly eight percent of the spectrum for a three-band system. Using any fewer tones does not produce the desired notch depth. This is illustrated in Figure 3. where a total of 11 tones (~45 MHz of spectrum) are zeroed out to obtain just 15 dB of suppression.

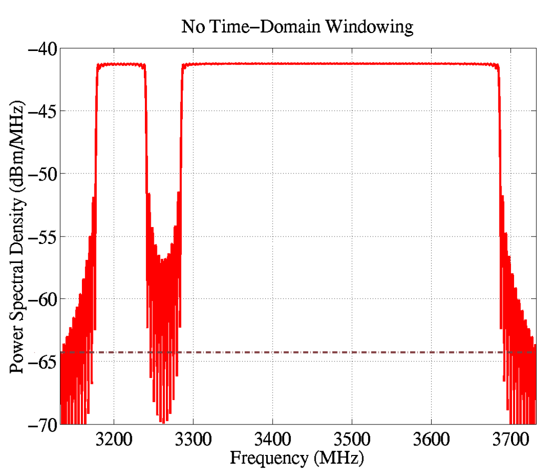

Figure 3. Tone Nulling for Spectral Sculpting of Multi-Band OFDM System.

B. *Time-Domain Windowing*

As the tone nulling technique is limited by the decay rate of the side-lobes of the sinc-spectrum, we propose a time-domain windowing mechanism to reduce the side-lobe level. In a multi-band OFDM System, a zero-padded suffix [4] is inserted after each OFDM symbol instead of a cyclic prefix. This is done to ensure a flat emission spectrum and maximize the transmitted power while still complying with the FCC emissions mask.

Alternately, if a cyclic post-fix (or a suffix) where to be added, in which the initial few samples of the OFDM symbol are copied to the end of the OFDM symbol, it allows us to employ a time-domain windowing to improve the spectral leakage of the OFDM sub-carrier. The operation of adding a cyclic post-fix followed by multiplication with a time-domain windowing function is illustrated in Figure 4.

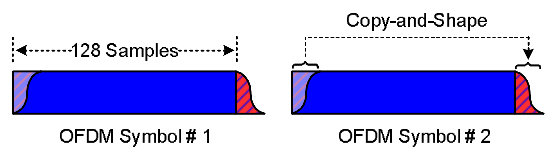

Figure 4. Time Domain Windowing of Multi-band OFDM Signal.

The output of the IFFT with the cyclic post-fix for the l^{th} symbol can be mathematically represented as,

$$s_l(n) = \begin{cases} \frac{1}{\sqrt{N}} \sum_{k=0}^{N-1} C_{l,k} \exp\left(\frac{j2pkn}{N}\right) & \text{for } k = 0, 1, \ldots, N + L_p - 1 \\ 0 & \text{otherwise} \end{cases} \quad (1)$$

where $s_l(n)$ is the time-domain sequence for the l^{th} OFDM symbol prior to windowing, $C_{l,k}$ is the information (data/pilot/null) mapped on to tone k and L_p is the chosen post-fix length. The transmitted base-band signal $y(n)$ after time-domain windowing is represented as

$$y(n) = \sum_{l=0}^{N_{symb}-1} W(n - lT_{symb}) s_l(n - lT_{symb}) \quad (2)$$

where N_{symb} is the total number of OFDM symbols, T_{symb} is the no. of samples in each OFDM symbol including the cyclic suffix, remainder of the zero suffix and guard interval (165 samples @ 528 MHz) and $W(k)$ is the time-domain windowing function.

This time-domain windowing operation of the zero-padded (i.e., addition of a zero-padded suffix) multi-band OFDM signal preserves the cyclic convolution property [4] of the multi-path channel under the following conditions:

- The sum of the delay spread length and the cyclic postfix length is less than 60.6 ns (32 samples @ 528 MHz)

- The receiver retains the over-lap-and-add structure introduced at the IFFT input for zero-padded suffix OFDM system, and
- The windowing function has a property $W(k)+W(N_{fft}+k) = 1$, where $N_{fft} = 128$.

The time-domain windowing technique increases the spectral domain ripple of the multi-band OFDM signal. For spectral emission compliance the time-domain windowed signal needs to be backed-off by the level of ripple. For instance, the ripple for a raised-cosine windowed multi-band OFDM signal with a L_p=16 samples (30.3 ns) is ~0.15 dB.

The advantage of preserving the cyclic convolution property is the fact that the application of a time-domain windowing does not have to be explicitly communicated to the receiver, as there no change is required in the receiver processing. A few sample time-domain windowing functions that preserve the cyclic convolution property of the channel impulse response are the raised cosine windowing function

$$W(k)=\begin{cases}\frac{1}{2}\left[1+\cos\left\{\frac{\pi(2L_p-2k-1)}{2L_p}\right\}\right] & k=0,\ldots,L_p-1 \\ 1 & k=L_p,\ldots,N-1 \\ \frac{1}{2}\left[1+\cos\left\{\frac{\pi(2k-2N+1)}{2L_p}\right\}\right] & k=N,\ldots,N+L_p-1 \\ 0 & \text{otherwise}\end{cases} \quad (3)$$

and the trapezoidal windowing function

$$W(k)=\begin{cases}\frac{2k+1}{2L_p} & k=0,\ldots,L_p-1 \\ 1 & k=L_p,\ldots,N-1 \\ \frac{2N+2L_p-2k-1}{2L_p} & k=N,\ldots,N+L_p-1 \\ 0 & \text{otherwise}\end{cases} \quad (4)$$

Note that other windowing functions that satisfy the property $W(k) + W(N_{fft}+k) = 1$ (or a constant) exist.

The improved protection of the radio astronomy band (3260 – 3267 MHz) with time domain windowing is illustrated in Figure 5. A total of 11 null tones are used, i.e., 4 sub-carriers on either side of the victim band (overlap of 3 sub-carriers) are set to zero. Emissions in the radio astronomy band are met when a raised cosine windowing function is used with a roll-off length (i.e., cyclic post-fix value, L_p) of 16 samples (30.3 ns).

The trade-off between the total number of null tones and the length of the cyclic postfix (i.e., the roll-off duration of the raised cosine function) is illustrated in Figure 6. As can be seen, an increase in the value of the cyclic post-fix length allows the time-domain windowed multi-band OFDM system to comply with the 23 dB of attenuation required for the radio astronomy bands by sacrificing fewer data/pilot tones.

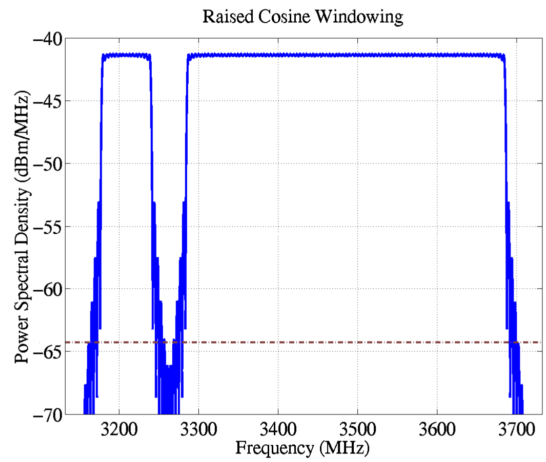

Figure 5. Multi-band OFDM Spectral Sculpting with Time-Domain Windowing and Tone Nulling.

This technique does have a penalty associated with it. Firstly, time-domain windowing decreases the multi-path robustness as the equivalent length of the zero-padded suffix (ZPS) is reduced from 60.6 ns to (60.6 – L_p/0.528) ns. The performance impact due to the reduced multi-path robustness is dependent on the channel environment and the data rate. To study the impact of reducing the effective ZPS length, the ratio of the inter-carrier-interference (ICI) to the captured signal energy is illustrated, as a function of the prefix length, in Figure 7.

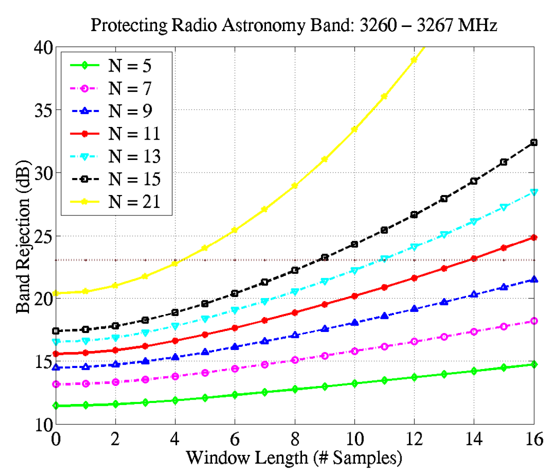

Figure 6. Windowing Length Requirements for Spectral Compliance of Radio Astronomy Bands.

For this evaluation, a non-line of sight channel model for a 4 – 10 m range (see [4] for details on UWB channel models) has been used and a data rate of 200 Mbps has been assumed. The required SNR for a BER of 10^{-5} (Sensitivity) is ~5 dB for a data rate of 200 Mbps, excluding any implementation losses. Hence, even if the effective ZPS length were to be halved to 30.3 ns, the multi-path performance hit may be acceptable.

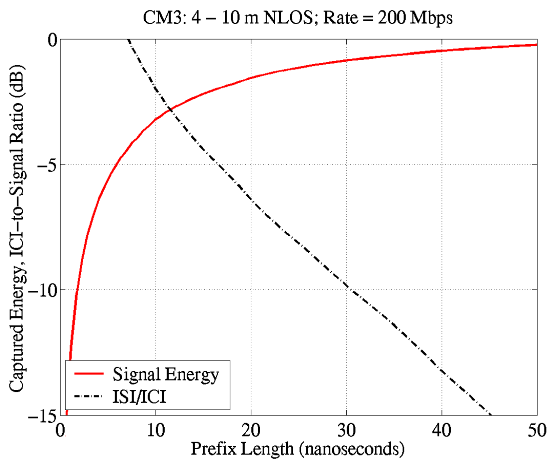

Figure 7. Loss of multi-path robustness due to time-domain windowing of multi-band OFDM.

C. Time-Domain Windowing

A deeper notch can be obtained by inserting data-specific dummy tones on either side of the victim band [9]. The spectral leakage, which is the root cause of the wider notches, is dependent on the data that is transmitted on the non-zero tones. By accounting for the contribution due to the non-zero tones, dummy tones can be introduced to minimize the spectral leakage and thereby increase the depth of the notch.

We now describe the method to determine the value of the dummy tones as a function of the information transmitted in the data tones for each OFDM symbol. The spectral leakage on each of the sub-carriers due to the application of the N-point IDFT operation is given as,

$$\Phi(f) = \frac{1}{\sqrt{N}} \sum_{n=0}^{N-1} \exp\left(\frac{-j2\pi nf}{N} \right) \tag{5}$$

Note that it would be straightforward to appropriately modify $\Phi(f)$ to account for the use of a time-domain windowing function. The frequency domain response of each transmitted OFDM symbol is

$$S(f) = \sum_{k=0}^{N-1} C(k)\Phi(f-k) \tag{6}$$

in which C(k) refers to the data/pilot information transmitted on the k^{th} sub-carrier. Let the frequency domain response be sampled at frequencies that are ¼ of the inter-carrier spacing apart. Then

$$\underline{b} = P\underline{s} \tag{7}$$

where $\underline{b}$ is a *L* x *1* vector that represents the frequency domain spectrum at frequencies within the radio astronomy band, $\underline{s}$ is a *N* x *1* vector with the data/pilot/null tones and *P* is a *L* x *N* matrix derived by picking L rows from a circulant matrix computed by sampling $\Phi(f)$. The $(l,k)^{th}$ entry of the matrix P is given below

$$P_{l,k} = \sum_{n=0}^{N-1} \exp \frac{-j2\pi n\{f(l)-k\}}{N} \tag{8}$$

where $f(l)$ corresponds to the frequency of the radio astronomy band at the l^{th} sampling point. The data specific dummy tones are then determined by minimizing the cost function,

$$\underline{\hat{x}} = \arg\min_{x} \left\| P_1 \underline{x} + \underline{b} \right\|_2^2 \tag{9}$$

where $\underline{x}$ is an *M* x *1* vector representing the data to be inserted in the *M* dummy tones and P_1 is an *L* x *M* sub-matrix derived by picking *M* columns from the matrix *P* corresponding to the dummy tone locations. The least-squares solution for the dummy tones is

$$\begin{aligned} \underline{\hat{x}} &= \left(P_1^H P_1\right)^{-1} P_1^H \underline{b} \\ &= \left(P_1^H P_1\right)^{-1} P_1^H P \underline{s} \end{aligned} \tag{10}$$

Using this method, a notch with a depth 23 dB in the frequency band of 3260 – 3267 MHz can be generated by using a total of just five tones: three zero tones, which overlap with the band of interest, and a data-specific dummy tone on each edge of the victim band. The dummy tone is loaded such that it cancels out the spectral leakage into the radio astronomy band. The resulting PSD of the transmitted signal is illustrated in Figure 8.

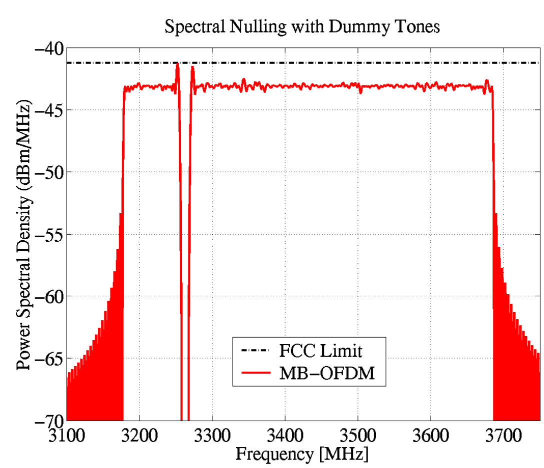

Figure 8. Spectral Nulling of a Radio Astronomy Band for a Multi-band OFDM System.

The advantage of this technique is that only a total of five tones need to be sacrificed to insert a 23 dB notch in the 3260 – 3267 band. This corresponds to a loss of about 20 MHz of spectrum, i.e., less than 1.3 percent of the spectrum for a three-band system. Note that these five tones are sufficient to introduce even deeper notches.

However, a severe limitation of this technique is that it increases the ripple in the power spectral density (PSD) and specifically causes peaking at the band edges. To meet the FCC specifications, the power spectral density of the UWB system should be below the -41.25 dBm/MHz level. The resolution bandwidth for the FCC compliance measurement for average PSD is 1 MHz and the averaging time is about 100 ms. Hence, this necessitates a transmit power back-off of nearly 1.8 dB and hence a loss in performance or equivalently range. Note that a 1.8 dB back-off in transmit power is equivalent to losing nearly a third of the usable spectrum. This is a very serious drawback of this technique

D. *Constrained Dummy Tone Insertion*

To avoid peaking in the PSD of the transmitted multi-band OFDM signal, we propose a modification to the way in which the dummy tones are derived. Although, insertion of the dummy tone reduces the spectral emissions in the band of interest (e.g., the radio astronomy band) there is no guarantee that it would not increase the emissions outside this band. Specifically, as the magnitude of the dummy tones is not constrained at frequencies outside of the radio astronomy band, it introduces peaking at the edges of the notch.

Ideally, we need to constrain the peak spectral content in the UWB frequencies in addition to minimizing the emissions in the radio astronomy band. However, introducing such a constraint makes the optimization intractable and does not result in a closed form solution. Hence, to mitigate the ripples in the power spectral density, we propose the following modification to the cost function. We add a regularization term that constrains the amount of energy placed on the dummy tones and indirectly reduce the emissions in the UWB frequencies. This is mathematically represented as,

$$\underline{\hat{x}}^C = \arg\min_x \left\{ \left\| P_1 \underline{x} + \underline{b} \right\|_2^2 + \lambda \left\| \underline{x} \right\|_2^2 \right\} \qquad (11)$$

where λ is a weighting coefficient for the regularization term. The least-squares solution then turns out to be

$$\begin{aligned} \underline{\hat{x}}^C &= \left(P_1^H P_1 + \lambda \right)^{-1} P_1^H \underline{b} \\ &= \left(P_1^H P_1 + \lambda \right)^{-1} P_1^H P \underline{s} \end{aligned} \qquad (12)$$

The efficacy of this technique is illustrated in the PSD plot of Figure 9. in which a λ value of 16 has been used.

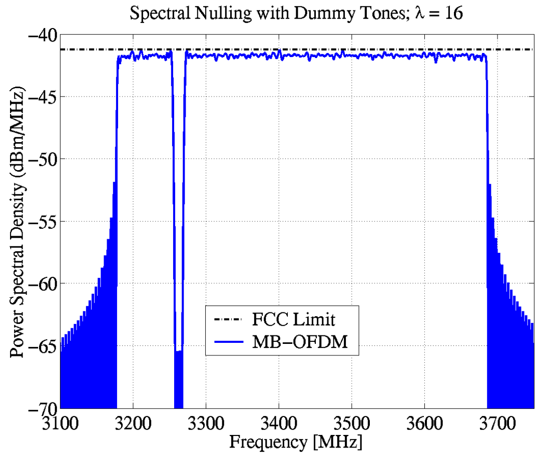

Figure 9. Constrained Dummy Tones for Spectral Sculpting of the Multi-band OFDM Signal.

We are able to introduce a 23 dB notch with minimal ripple or peaking in the pass-band (~ 0.5 dB). Additionally, the value of λ can be pre-determined and the matrix inverse and the matrix product terms can be pre-computed.

One potential draw-back of this technique is the fact that insertion of dummy tones may have to be communicated to the receiver. A work-around for this explicit communication is to null out (inserting zero tones) the dummy tone locations only during the Channel Estimation Sequence of the multi-band OFDM preamble. This is equivalent to having nulls in the channel and hence the receiver would ignore these tones.

1) *Complexity Analysis*

This technique requires the computation of only two values, which are to be loaded on to the dummy tones, for each OFDM symbol transmitted with a notch. Since the notch only exists for OFDM symbols transmitted on Band #1, this computation needs to be performed on average for only a third of the transmitted OFDM symbols, i.e., once every 0.9375 microseconds. The two dummy tones can be computed using a finite-tap frequency domain filter on the data and pilot tones. Since, the data-and-pilot tones are from a QPSK constellation, the filtering requires only addition/subtraction operations.

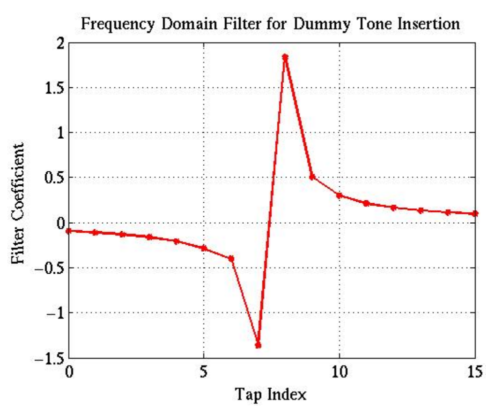

Figure 10. Signal Impulse Response of a Dummy Tone Computation Filter..

As an example, a 16-tap frequency domain filter with real coefficients can be used to compute the data specific information for the two dummy tones. In terms of computational complexity, this filtering would require a total of 68.5 Mega addition operations/second. The frequency domain filter is illustrated in Figure 10.

IV. Conclusions

In this article, we discussed the co-existence capability of the multi-band OFDM UWB system by examining its ability to dynamically sculpt the transmitted spectrum. We proposed a time-domain windowing technique that reduces the number of null tones that need to be inserted to achieve the required suppression in the Japanese radio astronomy band.

Furthermore, a dummy tone insertion technique, and a constrained optimization method to determine the required dummy tones with minimal peaking in the spectral domain, to ensure spectral compliance with even fewer tones was proposed. The proposed techniques enable the multi-band OFDM system to address potentially different world-wide regulations.

Acknowledgment

The author would like to acknowledge Anuj Batra for valuable discussions on various aspects associated with the multi-band OFDM UWB System. The author would also like to than Texas Instruments for supporting this research.

References

[1] Federal Communications Commission, “First Report and Order, Revision of Part 15 of the Commission’s Rules Regarding Ultra-Wideband Transmission Systems,” ET Docket 98-153, February 14, 2002.

[2] J. Balakrishnan, A. Batra and A. Dabak, “A Multi-band OFDM System for UWB Communication,” Proc. IEEE Conf. on Ultra Wideband Systems and Technologies, Reston, VA, pp. 354 – 358, November 2003.

[3] A. Batra, et al., “Multi-band OFDM Physical Layer Proposal,” IEEE P802.15-03/268r0-TG3a, July 2003.

[4] A. Batra, J. Balakrishnan, J. R. Foerster, R. A. Aiello and A. Dabak, “Design of a Multi-band OFDM System for Realistic UWB Channel Environments,” IEEE Transactions on Microwave Theory and Techniques, Vol. 52, No. 9, pp. 2123 - 2138, September 2004.

[5] WiMedia Alliance, http://www.wimedia.org.

[6] Standard ECMA-368, “High Rate Ultra Wideband PHY and MAC Standard,” December 2005, http://www.ecma-international.org

[7] A. Batra, J. Balakrishnan and S. Lingam, “Multi-band OFDM: The First True Cognitive Radio for UWB,” Proc. IEEE Symposium on Circuits and Systems, May 2006.

[8] Radio Astronomy Frequency Allocations, http://www.ukaranet.org.uk/basics/frequency_allocation.htm.

[9] H. Yamaguchi, “Active Interference Cancellation Technique for MB-OFDM Cognitive Radio,” European Microwave Week, Amsterdam, 2004.