Active Interference Cancellation Technique for MB-OFDM Cognitive Radio

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ABSTRACT — **Ultra Wideband transmit power (in-band) is regulated to be -41.25 dBm/MHz (in the United States), but in the future, it may be flexibly relaxed subject to the cognitive-radio spectrum policy. However, in close proximity of a protected radio service, transmission at the relaxed power might inflict an excessive degradation on the service quality. Applying the general analog or digital notch filter in the UWB transmitter (baseband) is the simplest but not a favorable approach due to the increased cost and the power consumption of the device. In OFDM, turning off the interfering tones has been studied as the alternative solution, but the inter-carrier interference may limit the notch depth to 5-10 dB. This paper discusses a new approach that enables the accurate notch bandwidth and depth control for the general OFDM transmitter. The technique demonstrates the fundamental advantage of the OFDM-based UWB solution[1] for the future cognitive ratio.**

I. INTRODUCTION

Ultra Wideband technology provides a new paradigm for utilizing the limited frequency resource. Sharing the same frequencies in close proximity to current and future radio services, however, remains to be a challenging problem. For the out-of-band (below 3.1 GHz mostly) interference, the use of a band-limiting filter would lower the UWB spillover radiation 10 to 20 dB below the operative noise level. For the in-band (between 3.1 and 10.6 GH) interference which we examine in this paper, the use of narrow-band (notch) filters, or an equivalent mechanism is surmised to be essential, or at least necessary. Such mechanism may be required in case the upper limit of the UWB transmission power is relaxed within the vicinity of a susceptible radio receiver. The case directly relates with the future introduction of the cognitive radio[2].

Because UWB is a ubiquitous radio, we expect it to incorporate a coexistence mechanism, which should include both detection of a nearby victim radio (or compliance to the regulatory rules) and reducing the interference below the sensitivity threshold; in this paper, we focus on the latter technology. Because the UWB transmitter is a power-limited radiator, nullifying the transmission over an unnecessarily wide bandwidth hurts the throughput; thus for the victim radio, defining the tightest notch is essential. In the general filter design, a rigid band discrimination filter requires a very high sampling rate or a long taps (well over 100 signal samples) together with the filter coefficients quantized in 4 bits or more. For example, when the signal bandwidth is 1.5 GHz (impulse or DS-type UWB) and the notch bandwidth is 7 MHz, the digital filter would consume over 600 mW, even in the next-generation 90 nm CMOS (and this estimate is very optimistic).

We are interested in investigating if the Multi-band OFDM[1] UWB system, which performs the fundamental signal processing in the frequency domain would suffer from the similar problem. One aspect of OFDM which is often pointed out is that the constituent tones can be turned off at the interfering frequencies, creating a spectrum null. In MB-OFDM, each tone occupies 4.125 MHz, and this bandwidth is reasonably fine-grained to craft a notch without excessively sacrificing the system throughput (See Fig.1 for the baseband MB-OFDM spectrum).

In OFDM, tones are placed at a regular frequency interval to avoid the inter-carrier interference [5],[6](orthogonality). The inter-carrier interference becomes large in-between the tones, and is generated by all the non-zero tones following the sinc-function interpolation. Due to this property, turning off a single tone does not create a spectral null within its 4.125 MHz band, and its residual in-band power is determined by the neighboring non-zero tones. For a single tone, the notch bottom level (the inter-carrier interference power) is typically 5 dB to 10 dB below the average signal power. This may be insufficient (subject to the conditions of bandwidth, distance and sensitivity of the victim system). In OFDM, a deeper notch is achieved by turning off a larger number of tones. An example is shown for the case of 4 and 16 tones in Fig.2.

We will discuss a different solution in the next section.

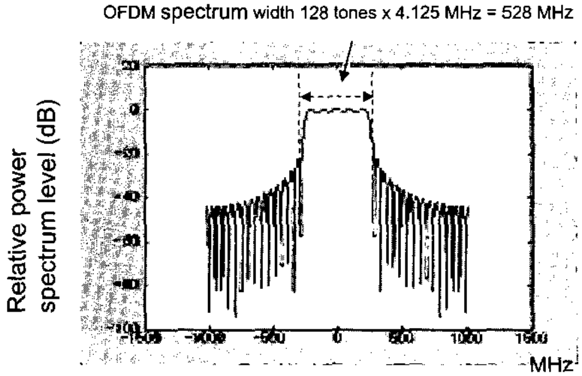


Fig. 1 MB-OFDM baseband spectrum

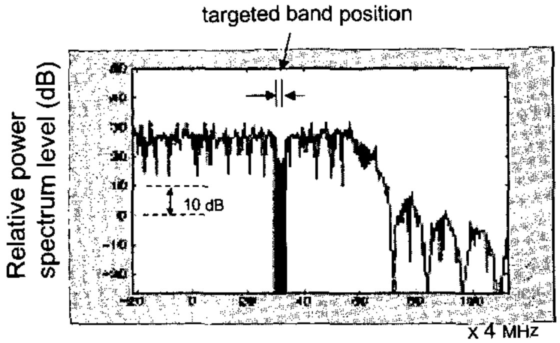


Fig. 2 (a) Turning off 4 tones creates 8 dB notch

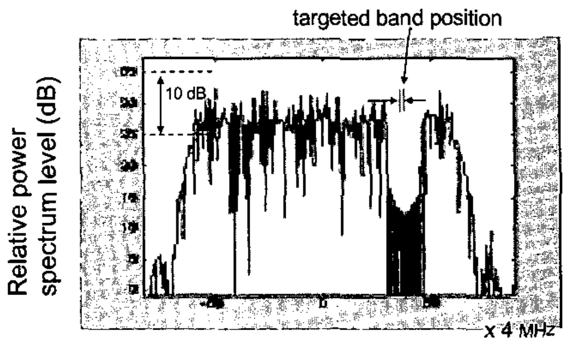


Fig. 2(b) Turning off 16 tones creates 15 dB notch

II. ACTIVE INTERFERENCE CANCELLATION

In this and the following sections, we discuss the UWB system based on Multi-Band OFDM[3]. MB-OFDM is an extension of OFDM to the 7.5 GHz-wide UWB band by defining five band-groups, each of which consists of three (the highest band uses two) OFDM symbols of 128 tones, and applying the time-frequency interleaving based on the time-frequency code (TFC). In the analysis, we treat the interference in the equivalent baseband OFDM signal.

When the information data is denoted by $X(k)$ k=0,...,127, the transmitted OFDM signal is given by

$$x(n)=\sum_{k=0}^{127}X(k)\exp(j2\pi\frac{nk}{128}) \quad (1).$$

In order to evaluate the interference in-between the tone frequencies, we up-sample (we apply four-times up-sampling here) the corresponding spectrum, which is given by $Y(l)$ (l=0,...4*128-1),

$$Y(l)=\frac{1}{128}\sum_{n=0}^{127}x(n)\exp(-j2\pi\frac{n}{128}\frac{l}{4}) \quad (2).$$

Combining these two equations, we obtain as the relation between X and Y

$$\begin{aligned}Y(l)&=\frac{1}{128}\sum_{n=0}^{127}(\sum_{k=0}^{127}X(k)\exp(j2\pi\frac{n}{128}(k-\frac{l}{4}))\\&=\frac{1}{128}\sum_{k=0}^{127}X(k)P(l,k)\end{aligned} \quad (3)$$

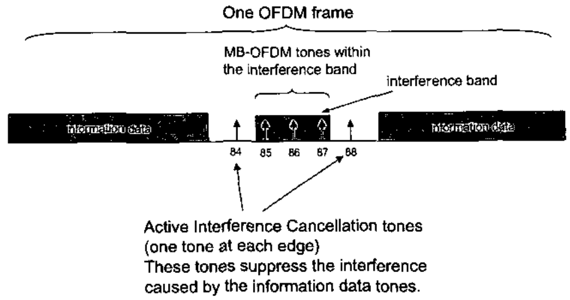


Fig.3 Definition of the AIC tone position

where $P(n, l)$ is the transform kernel.

Instead of turning off a large number of tones, we define two special tones at the edge of the interference band as shown above, and would prove that these two tones can sufficiently cancel the interference in the band. The tone values can be arbitrarily determined without affecting the information tones due to the orthogonality relationship. We call these special tones Active Interference Cancellation (AIC) tones. We discuss below how to compute the AIC tones, and how to create the notch using the minimum number of tones, or, equivalently, how to maxime the spectrum efficiency.

Following the definition of the interfering band position, OFDM tones within the band, and the position of the AIC tones shown in Fig.3, we take up a specific example of the (in-band) UWB interference to the Radio Astronomy service of 3260-3267MHz. The tones #85, 86 and 87 of the MB-OFDM Band#1 co-locate with this band as shown in the figure. The MB-OFDM interference to this band is evaluated at four-times (or higher) finer frequencies denoted by a vector d_l. $d_l(1)$, $d_l(4)$ and $d_l(8)$ correspond to the MB-OFDM tones #85, 86, 87. We then add two tones on the edge outside these three tones, and try to cancel the interference inside the interference band using the total of five tones. It will be shown later that the AIC tones play the dominant role and three 'in-band' tones can be simply 'turned off'. It has been found that increasing the number of the AIC tones does not significantly improve the cancellation performance, thus the current solution seems to be near optimum.

The vector d_l is given by

$$d_1=Pg \quad (4),$$

where P is the kernel defined by (3) and g is the vector of the information data tones with $X(84)$ to $X(88)$ turned off (zeroed).

In order to cancel the interference within the band, we need to generate the negative of the interference signal using the tones $X(84)$ to $X(88)$. Again using the relation (3) above, setting all the X to zero except for $X(84)$ to $X(88)$, the equation to be solved is given by

$$P_1h=-d_1 \quad (5)$$

where h is the column vector of $(X(84), ...,X(88))$ and P_l is the small kernel derived from P by limiting the index according to h and d_I. Thus P_I is a 9 x 5 matrix.

Here, h is our desired tone values. However, (5) cannot be solved in the straightforward way because the matrix P_I is not invertible. Hence, instead, we seek the minimization of

$$e^2 = \|P_I h + d_I\|^2 \quad (6),$$

which leads to

$$h = -(P_I^T P_I)^{-1} P_I^T d_I = -W_I d_I \quad (7).$$

This minimum mean-squared solution is also known as the Moore-Penrose generalized inverse[4]. It is noted that the resultant inverse 5 x 9 matrix W_I is pre-computable because the interference band location is pre-defined (by the regulatory rules. Also it can be broadcast by means of the inter-device communication).

Now combining (4) and (7), h is given by

$$h = -W_I P g = -W_2 g \quad (8),$$

where W_2 is also a pre-computable 5 x 128 matrix.

III. AIC Performance

For the targeted (Radio Astronomy) 7-MHz band, we compare two approaches, both of which use 5 tones for the notch implementation. By turning off all the five tones, the notch depth is limited to be around 13 dB as shown in Fig.4 (a). Using AIC, a much deeper notch of over 60 dB results. It can be further shown that the notch depth is determined by the quantization accuracy of the AIC coefficients. Here, it can be also shown that the optimum tone values are near zero for the three middle tones (#85, 86 and 87). Taking this simplification, we only have to compute the two AIC tones. Fig. 5 shows the notch depth achieved by quantizing the AIC tones to 2, 3 and 4 bits. The notch depth varies in the range of 30 to 40 dB. Hence, in the case a -80 dBm/MHz notch is desired, 4-bit quantization is required for the AIC tones (-41.25 dBm/MHz - 40dB = -81.25 dBm/MHz). Fig.6 shows an example of such a notch created by the 2-bit AIC tones.

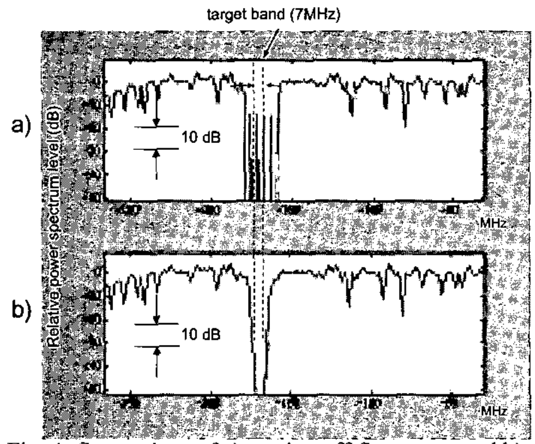


Fig. 4 Comparison of a) turning off five tones, and b) cancellation by AIC

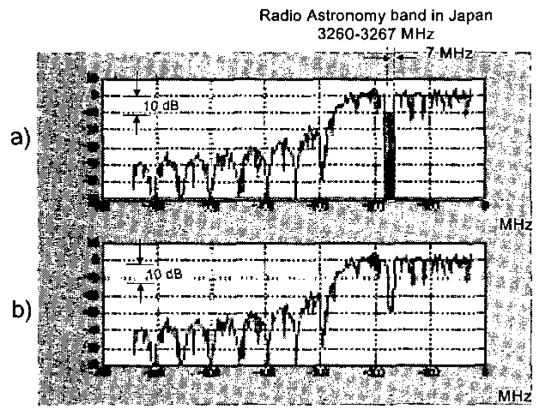


Fig. 6 Creating 7-MHz notch by a) turning off five tones, and b) 2-bit AIC tones

Here, we are interested to compare AIC with the legacy digital filter technique and this is briefly discussed below.

Under the same bandwidth constraint, FIR digital filters can be easily synthesized ignoring the coefficient quantization. For the Radio Astronomy bandwidth of 7 MHz and the transient bandwidth of 4 MHz, it can be shown that a 308-tap FIR filter can create a -63 dB

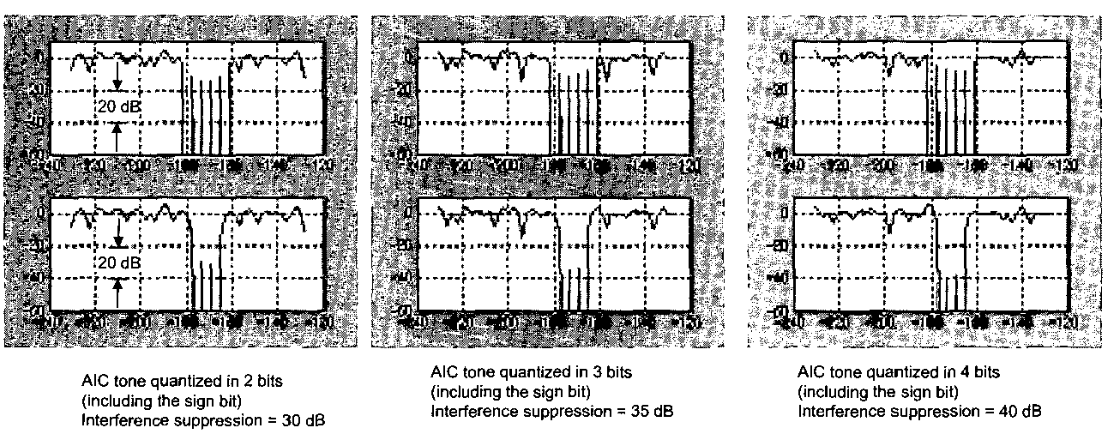
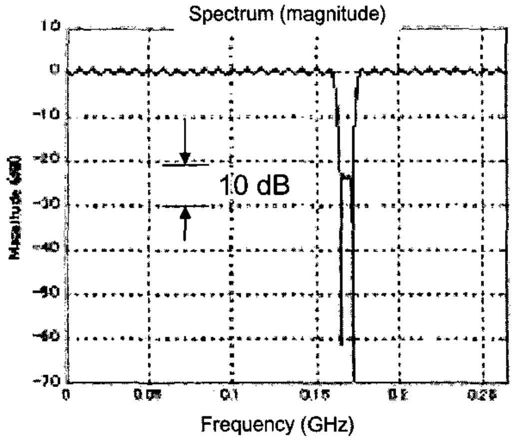


Fig. 5 Quantization of the AIC coefficients and the depth of the created notch. The case of simply turning off five tones is shown in the upper half for the reference sake.

notch. For the notch depth of 24 dB (6 dB worse than the 2-bit AIC in Fig.5), the required minimum filter tap-length is 128. The filter characteristic is shown below.



Five-tone equivalent equi-ripple 128-tap FIR (suppression depth –24 dB). Ripple is +-0.6 dB over the entire tones

Fig. 7 FIR filter characteristic realized by 128-tap 4-bit coefficients. The pass-band and transient bandwidth is equivalent to the cases shown in Fig. 4, 5 and 6.

The filter entails a ripple of 0.6 dB in the pass-band and this problem becomes more pronounced for the shorter filters. Assuming the four-bit quantization for the filter coefficients (optimistic assumption) and taking into the symmetry of the general FIR filter structure, the power consumption of this digital filter (when it is applied to the base-band signal of the bandwidth 528 MHz) is estimated to be around 300 mW, (0.13 um CMOS) while all that is required for the AIC computation is less than 2 mW. This directly comes from the advantage of the frequency-space signal processing.

For the 7-MHz notch, the total number of the tones discussed in the current paper was five. In practical applications, the associated tone reassignment would be either pre-defined according to the regulatory rules, or flexibly determined through the inter-device communication. In MB-OFDM, a notch of up to >30 MHz (4.125 x 8 = 34 MHz) bandwidth can be created without a serious throughput penalty.

Finally, Fig.8 shows an example of the wider (24-MHz) notch. The AIC tones are quantized to two bits here. The AIC concept can be easily extended to meet other notch requirements including multiple notches.

In light of the ubiquitous radio device that is destined to coexist with the current and future radio services and operate in low power (less than 200 mW), the implementation of the interference suppression mechanism in low power is an essential feature. This leads to our belief that OFDM-based UWB is the key to the future ubiquitous radio, and the key to open the new technology called the cognitive radio[2].

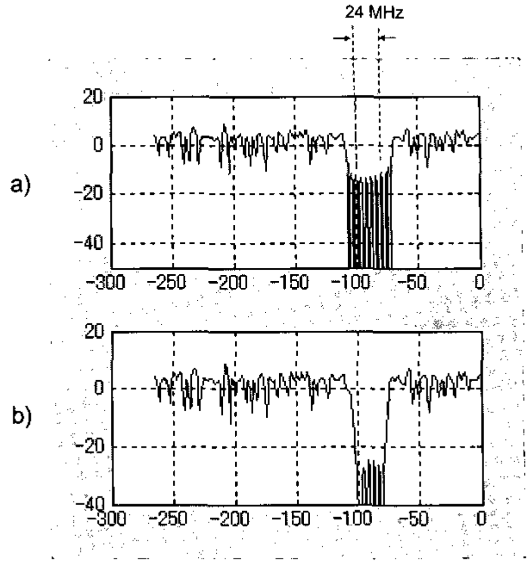


Fig.8 24-MHz notch. In a) nine tones are turned off and b) by AIC

IV. Conclusion

UWB is a new paradigm of the ubiquitous radio, but at the same time, the problem of the interference to the current and future radio services must also be addressed.

The AIC technique presented here is based on the benefits of the frequency-domain signal processing, proposed as MB-OFDM as the worldwide UWB standard. The frequency-domain signal processing is the way to go when we consider the performance and coexistence with the other radio services. MB-OFDM is a solution that achieves both goals.

Acknowledgement

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