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Re:	[-03/138-9, -03/153-4, etc.]	
Abstract	[This joint contribution is offered in support of all monopulse candidate Alt PHY Proposals.]	
Purpose	[The purpose of this document is to provide the Task Group 3a a joint contribution on regulatory issues that supports the monopulse candidate Alt PHY Proposals.]	
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Spectral Flexibility in Designs of UWB Communication Systems

Executive Summary

Strict radio frequency power limits must be respected by ultra-wideband (UWB) devices operating in different physical environments. Worldwide outside the USA, the regulatory power limits have not yet been set but it is possible that UWB devices will be required to accommodate different spectral emission masks. Additionally, a UWB device must accept all radio frequency interference (RFI) received from both primary licensed devices and other unlicensed devices. These requirements give rise to a concept of spectral flexibility and robustness not seen in past devices operating under unlicensed regulatory regimes. Consequently, an ideal UWB device must include means for changing its power characteristics versus frequency in accordance with potentially differing geographic regulatory requirements, as well as means for effectively dealing with both static and dynamic RFI. When comparing state-of-the-art techniques for implementing UWB communication systems, one must evaluate the following considerations. First, what is the implementation complexity and corresponding system cost? Second, what is the inherent system capability to reject RFI that will degrade communication system performance? In the following text, convincing, supported facts are presented that lead to only one conclusion. That conclusion is when considering UWB communication systems based on true impulse radio, rather than systems based on pulsed sub-band techniques, impulse radio systems are significantly less costly and less complex to implement, have better overall RFI rejection and tolerance, and are more flexible with respect to accommodating different spectral emission masks.

Introduction

Spectral flexibility has been identified as a characteristic that will provide robust performance in the presence of narrowband interferers or collocation within other wireless devices (such as. 802.11a or a 5.8 GHz cordless phone), and also will allow operation in potentially different regulatory regions, since only the United States of America has regulations in place today. In the various proposals before the IEEE 802.15.3a task group, (see for example [1], [2], and [3]) "spectral flexibility" is addressed as it relates to three independent considerations. This paper seeks to address each independently to add clarity to the process. The first consideration deals strictly with how extensible the proposed implementations are at meeting differing or changing international regulations. In other words, how easily can their spectral characteristics be changed for regulatory purposes, and what are the regulatory constraints? As such, this issue has nothing to do with the receiver and everything to do with regulations and transmitters. For example, suppose that some years from now the FCC added 10.6 – 24 GHz to the spectrum allocated to UWB. Can the UWB architectures be readily extended, (i.e. without changing the MAC or giving up backward compatibility), to include the newly allocated spectrum?

The second consideration deals with the performance of the proposed implementations if it is in the presence of radio frequency interference (RFI) at its receiver. In other words, how well can it separate UWB waveforms from narrowband interference (NBI), and at what performance sacrifice? As such, this issue deals strictly with the receiver, and has nothing to do with regulations or the transmitter.

A third consideration is the ability of the UWB architectures to be co-located with other wireless devices. While all three of these considerations are driven by the UWB waveform and the hardware required to generate and receive that waveform, they are, nonetheless, independent issues that are best addressed separately.

This paper evaluates and compares approaches based on monopulse modulation with approaches based on pulsed sub-band modulation, in regard to their addressing these spectral flexibility issues. For the purposes of this paper, the term monopulse modulation refers to encoding the data in single pulses that cover entire bands, as opposed to encoding data by pulsed sub-bands. An example of monopulse modulation would be multi-band direct sequence spread spectrum (DSSS) modulation [1] where symbols made up of a coded sequence of pulses carry N-bits per symbol via m-ary bi-orthogonal keying (M-BOK)—where the M-BOK is done via different code sequences. Another example would be adaptive-band bi-phase coded pulses that use pulse position for M-BOK (PP-MBOK) [2]. The analysis shows that monopulse modulation approaches provide a better balance of spectral flexibility with low complexity and are superior in meeting these challenges.

Spectral Flexibility for Global Regulatory Compliance

The FCC has ruled to allow UWB handheld devices for communications with a uniform power spectral density in the range 3.1-10.6 GHz. It is to be hoped that the regulations set by other bodies will be harmonized with those of the FCC. Nonetheless, the means are being proposed to address potential cases where other countries adopt modified emission requirements, or where permitted bands are added in the future.

Pulsed-sub-band approaches can comply by shipping devices with preprogrammed bands turned off. This turning off of bands method, however, significantly reduces the radio performance. This conclusion is fundamentally driven by two facts. First, the tuning has coarse 500 MHz bandwidth granularity. Second, turning off bands significantly affects the modulation efficiency. The latter has to do with there being very few hop frequencies available especially considering that there are guaranteed collisions with multipath and with other overlapping piconets even if all are turned on.

Monopulse UWB (such as multi-band DSSS-UWB or adaptive-band PP-MBOK) can comply by shipping with preprogrammed waveforms that meet spectrum regulations. Waveform changes can reduce the radio performance but the architecture tends to minimize the reduction. This conclusion is fundamentally driven by the fact that the frequency-tuning can be made on a fine scale and with little impact to the modulation efficiency—particularly the efficiency in the context of the requirement to support multiple overlapping piconets in multipath.

Spectral Flexibility for Narrowband Interference Mitigation

Radio frequency interference (RFI) from narrowband sources falls into three categories: mild, moderate, and severe. In all three cases designs based on monopulse-UWB are shown to have the advantage in performance and complexity.

In mild RFI, the Signal to Interference (SIR) is within the design margin of the system. The extra processing gain across wide contiguous bands gives more design margin to DSSS-UWB and PP-MBOK.

In moderate RFI, monopulse-UWB has the advantage again. The desired solution is supposed to meet three requirements simultaneously: (1) operate 4 uncoordinated overlapping networks (one desired, others interfering); (2) operate all of these in a real multipath environment; and (3) handle an NBI like a spurious response from a cordless phone. To meet all requirements simultaneously, pulsed sub-band systems will suffer significant degradation. When NBI is encountered, one or more bands must be "turned off." But this tuning off of bands happens in the context of supporting overlapping piconets in multipath environments. Recall that the required three overlapping piconet operation guarantees collisions on three bands even without multipath. Therefore, tuning off of bands is done when a high percentage of the bands are already suffering collisions. The FEC is not robust enough to handle losing 4+ bands out of 7 or 8 bands.

As opposed to the serious performance reduction suffered by pulsed sub-band systems, digital signal processing (DSP) techniques give most monopulse-UWB approaches an additional advantage of >10dB relative to their already superior mild-interference margin, yet with essentially no performance reduction. While this DSP capability is a surprise result to some researchers in UWB communications, it is supported by a variety of well developed and understood techniques.

Severe RFI is an issue faced by all UWB systems as it saturates an unprotected receiver front-end. Nonetheless, monopulse-UWB has the advantage again. Because a notch filter can be "relatively narrow" compared to the full-band of Monopulse-UWB systems, front-end notch filters can be made with little impact on the radio performance. Because the same notch filter is not "relatively narrow" to a 500 MHz wide sub-band, the performance of the sub-band can be significantly degraded, effectively causing the sub-band to be "turned off."

Spectral Flexibility for Global Regulatory Compliance

Manufacturers must design their UWB devices so that they can operate in potentially different regulatory domains that may have different spectral emission requirements, since today, regulations only exist in the United States of America.

This requirement leads to two important conclusions:

- First, any flexibility in excess of that required to meet specific regulations at the time of manufacturing is wasted from a regulatory point of view, and is likely to reduce performance in some of the dynamic modes, as well as add unnecessary cost and/or power consumption.
- Second, the best way to provide spectral flexibility is in a way that minimizes the impact on system performance.

Technical analysis shows that these can best be accomplished by designing the system to use the widest contiguous coherent bandwidth possible. This conclusion follows from two facts. First, it is well known that the widest coherent bandwidth allows systems to enjoy the best combination of propagation and penetration effects of UWB, including minimal multipath fading with maximum time and multipath resolution. Ultimately, taking advantage of this physics leads to the most robust quality of service to users. Second, in whatever way a regulation in a particular country restricts emissions, the UWB system will maximize its performance by contiguously and coherently filling this available allocation to the fullest extent. This filling maximizes the average transmitted power and takes the most advantage of the propagation benefits of UWB—using a wide contiguous coherent bandwidth. Clearly, the lowest cost and highest performance result would occur if the regulatory standards were the same all over the world. In the absence of such harmonization, manufacturers could, for example, build devices programmed for one band (for example, the 3.1-4.9 GHz) for sale in one country, and the same devices programmed for a highly overlapping band (for example 3.1-5.1 GHz) for sale in a different country.

As another example, suppose a regulation were to provide for a wide operating band, but with a narrow notch in the middle of it to protect an existing spectrum user. In this case, the UWB system would ideally want to protect the notched band using pulse-shaping or filtering at the transmitter to minimize the lost spectrum. Doing this with minimal impact to the performance and the modulation efficiency is to use the widest contiguous band so that the notch is a very small percentage of the whole band.

As yet another example, suppose that some years from now, regulatory agencies add 10.6 – 24 GHz to the spectrum allocated for UWB. The UWB system architecture would ideally just include the newly allocated spectrum as a natural extension to what was already there without changing the MAC or giving up backward compatibility.

The proposed UWB systems that are based on monopulse-UWB do exactly these things. First, they provide fine-scale flexibility in the center frequency and bandwidths of these bands so as to precisely meet differing of changing regulations (see for example, [1] and [2). Second, as a result, they operate in widest coherent bands consistent with the regulations. This lets them maximally capture the propagation benefits of UWB.

Third, they are extensible. The frequency and bandwidth of the bands can simply be part of the "code" that is assigned to a piconet. The addition of a 10.6-24 GHz band, for example, is a simple and natural extension to the existing architecture. The MAC handles the change by simply assigning this new band to an already existing field in the MAC that already is there supporting the bands allocated today. The PHY handles this significant regulatory change by adding the required transmitter and receiver circuitry to support the additional 50% bandwidth UWB band.

Fourth, the codes that DSSS systems use can be selected to give spectral notches. While regulations forcing this additional constraint on any UWB system would not be welcome, the DSSS system provides a mechanism that allows this to happen, yet with little impact to the system performance. Figure **1** illustrates this with an over plot of eight different code spectrums. Figure 3 also shows the same effect across 32 codes. Alternative monopulse-UWB approaches to notching are given in [2].

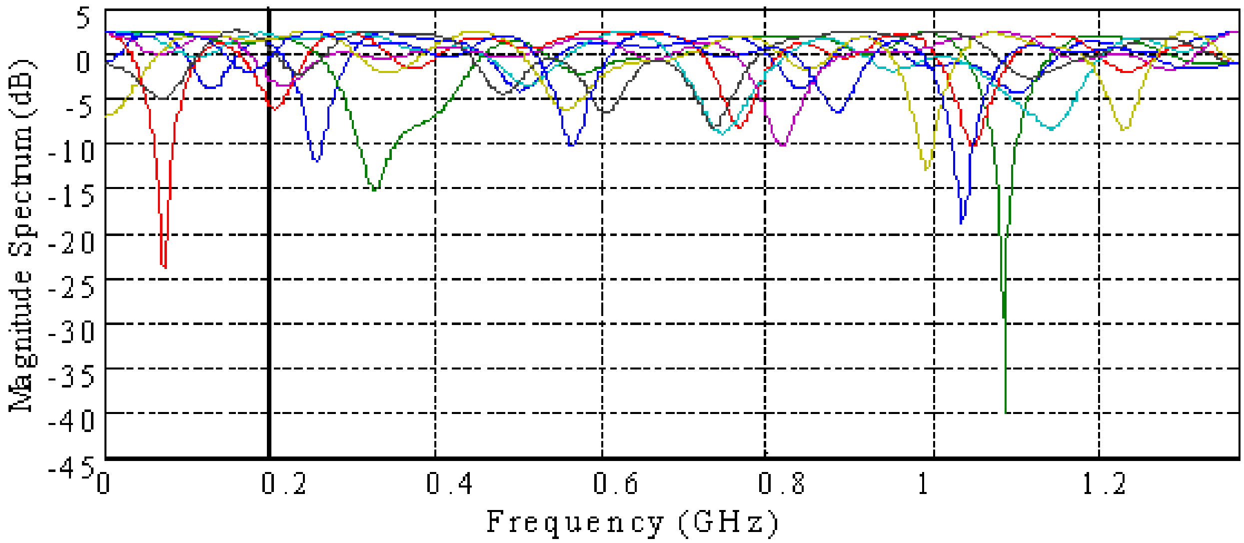

Figure 1. Plots of eight code spectrums to illustration notches in the spectrum of codes. The horizontal axis is frequency relative to the band center frequency. The vertical axis is PSD relative to average PSD.

By contrast, the proposed UWB systems that are based on pulsed sub-band frequency hop approaches, have none of the above four features. First, they have relatively coarse 500 to 700 MHz granularity in their bandwidth adjustments. Second, as a result, they cannot obtain as much bandwidth or the full bandwidth that the regulations allow. So they are less capable of capturing the propagation benefits of UWB. Third, regarding extensibility to new bands, both approaches meet this desire, assuming both add the new band as an essentially separate entity. A key issue in this regard is that the sub-band design and analysis must take into account that the antenna aperture shrinkage at higher frequencies would cause the SNR in sub-bands in the 10.6 to 24 GHz band to be drastically mismatched with the SNR in sub-bands in the 3.1-5 GHz band. Fourth, spectral notches are comprised of a missing band and are very wide “notches.” These notches drastically affect the radio performance. The performance impact happens because the modulation space or constellation (i.e. the number of available hop frequencies) is reduced. This reduction not only affects the range/data-rate metric in the clear, but also drastically affects the radio’s ability to work in multipath and to have acceptable multi-user performance. Since there are 3 guaranteed sub-band collisions from multiple users, eliminating even one more sub-band tends to be catastrophic, swamping the FEC so that it cannot recover the data. The net result is that the overlapping piconet separation distances must be significantly increased and at the same time, the data reduced.

To summarize, the FCC has issued rules to allow UWB handheld devices for communications with a uniform power spectral density in the range 3.1-10.6 GHz. It is to be hoped that the regulations set by other regions will be harmonized with those of the FCC. In case other countries modify the emission requirements, or if permitted bands change or are enlarged, it would be advantageous for the architecture to have the flexibility to easily adapt to them. Pulsed-sub-band approaches can comply by shipping devices with preprogrammed bands turned off.

This approach, however, significantly reduces the radio performance, especially since it must simultaneously support overlapping piconets in high multipath. Monopulse-UWB can comply by shipping devices with preprogrammed waveforms that meet spectrum regulations. Waveform changes with reduced spectrum can reduce the radio performance but the monopulse architectures tend to minimize the performance reduction.

Spectral Flexibility for RFI/NBI Rejection

RFI falls into three categories: mild, moderate, and severe. In mild RFI, the Signal to Interference (SIR) is within the design margin of the system. In moderate RFI, the SIR exceeds the design margin but the front-end does not saturate. Lastly, severe RFI is when interference saturates an unprotected front-end. Severe RFI is a common challenge for all UWB solutions. This has been acknowledged in both monopulse-UWB proposals (e.g. [1], [2]), and pulsed sub-band proposals (e.g. [3]). We will examine each of these cases in this section.

The analysis procedure used to compute the interference rejection of DSSS versus pulsed sub-band is illustrated in the block diagram shown in Figure 2. Here, both systems are normalized to the same PSD as measured in regulatory standards. Similarly, both systems are "jammed" by the same narrowband signal. We assume that both systems use an ideal matched filter. For the DSSS-UWB system, the matched filter includes both the code and pulse shape. To compare performance, we evaluate the RMS SIR at the output of the matched filter. The RMS SIR is computed by taking the RMS of the SIR across a uniform distribution of interference phases.3

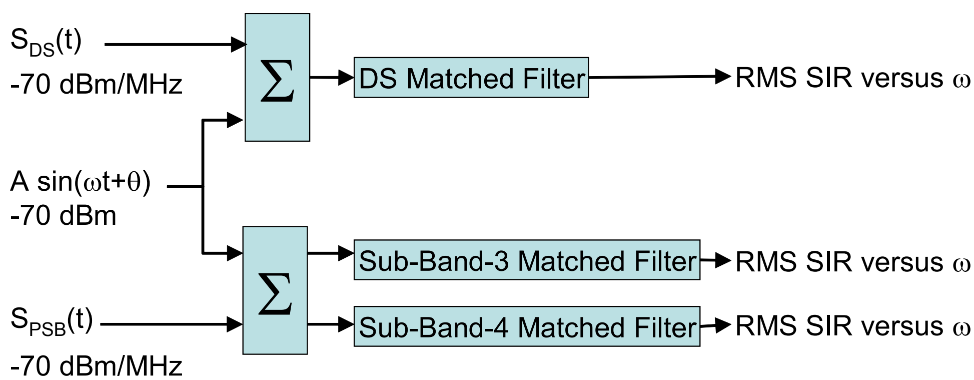

Figure 2. Methodology used to compute the interference rejection shown in Figure 3.

The DSSS-UWB system can withstand more RFI before it moves from the "Mild" category to the "Moderate" category. This result happens because DSSS-UWB starts with more code processing gain—6 dB more in the 3.1-5.1 GHz DSSS-UWB band relative to 500 MHz sub-bands, and 9 dB more in the 6-10.6 GHz DSSS-UWB band. Figure 3 shows the RMS SIR as a function of the frequency of the NBI for DSSS-UWB and pulsed sub-band approaches. The overplot of the 32 curves shows the results of the 32 24-length ternary codes proposed for DSSS-UWB. The other two curves show the same analysis for two adjacent 500 MHz pulsed sub-bands using half-sine weighting on the pulses.

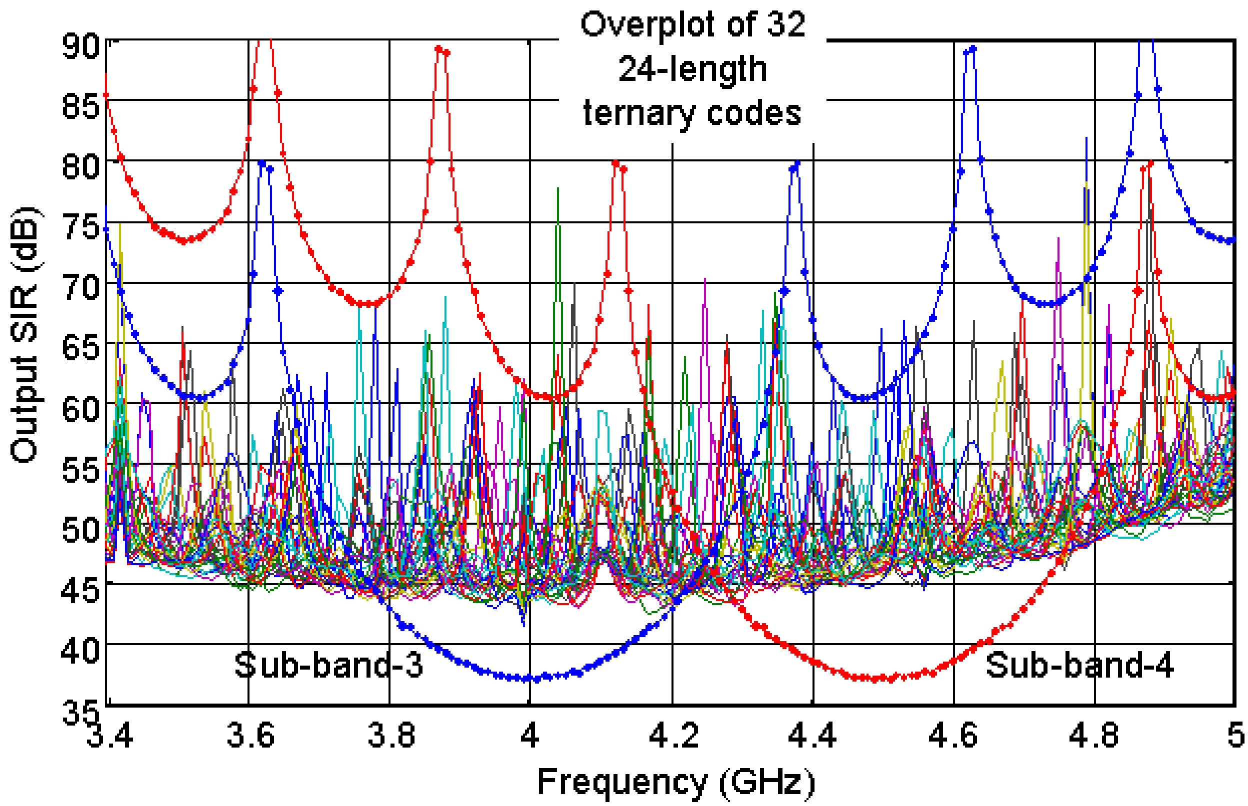

Figure 3. Interference rejection for DSSS-UWB and pulsed sub-band systems showing the combined effects of processing gain and pulse shape filtering.

For moderate RFI where the Signal to Interference (SIR) does not overload the front-end but the interference is more than the system was designed to withstand, the pulsed sub-band system simply turns off (or stops using) the band with the RFI in it. This approach diminishes every performance aspect of the pulsed sub-band radio because the modulation constellation is reduced. This reduction affects its raw data-rate capacity as well as its capability to support multi-user operations and support operations in multipath.

For RFI in the moderate category, well known DSP algorithms [4, 5, 6, 7, 8, 9, 10] can be applied to provide >10 dB of additional margin to monopulse-UWB systems. XtremeSpectrum, for example, has demonstrated >10 dB improvements in SIR using a low-complexity DSP algorithm, as shown in Figure **4**. Here without the interference, the SNR was 15 dB. The NBI reduced the eye opening to a 5 dB SIR. After removal of the NBI the SNR was back to the original 15 dB.

A key to being able to use fast DSP algorithms is to have equally spaced data samples. Bi-phase and QPSK DSSS-UWB systems and PP-MBOK systems, by virtue of their low jitter fixed rate clocks, preserve the capability to apply all fast DSP algorithms in their signal processing chain. This fact gives significant advantages to DSSS-UWB systems and is very notable because the

DSP capabilities are good for more than just NBI mitigation. The architecture lays the foundation to support DSP that can be used for a variety of improvements to extend the performance.

While most PPM solutions do not have this capability due to the randomization of the sample times, Bi-phase PP-MBOK solutions that use, for example, 20 Gsps analog to digital converters are able to apply DSP algorithms.

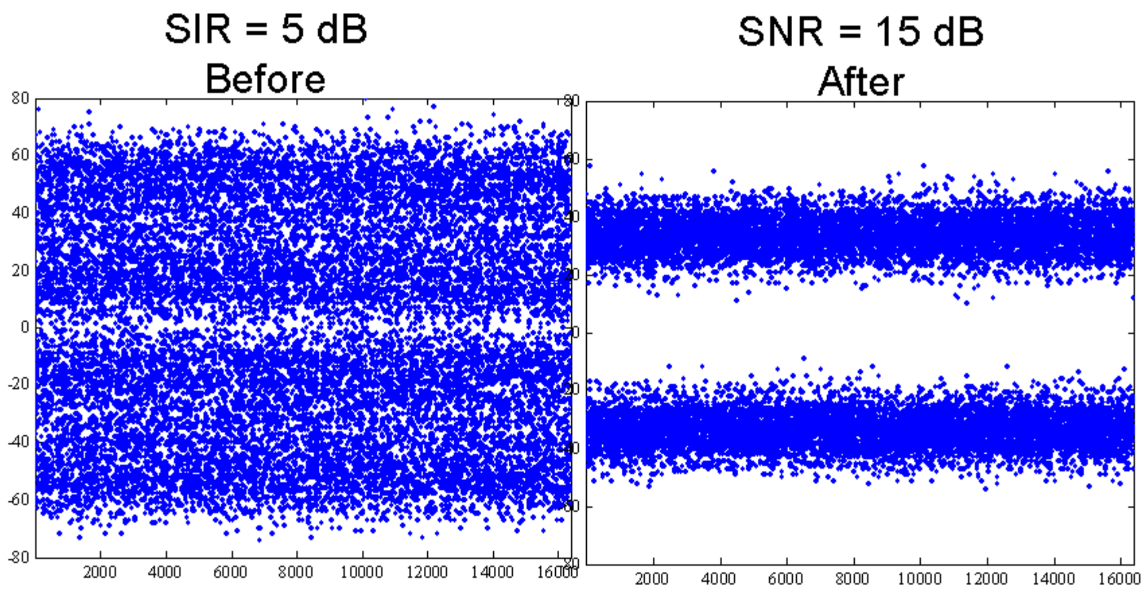

Figure 4. Eye pattern (left) of 15 dB SNR signal with NBI giving 5 dB SIR, and (right) eye pattern after DSP removal of NBI showing 15 dB SNR.

Severe RFI is a common challenge for all UWB solutions. This has been acknowledged in both monopulse-UWB proposals (e.g. [1], [2]), and pulsed sub-band proposals (e.g.[3]. Severe RFI will effectively disable the entire band for any system that uses a single wideband LNA.

For a monopulse-UWB system, an effective solution for the severe RFI problem is a low-complexity programmable notch filter. The filtering approach combined with the wide contiguous bandwidth of monopulse systems is advantageous because the ratio of the bandwidth of the UWB waveform to the bandwidth of the notch filter is large. This large ratio results in a small performance loss.

One proposal to avoid this for the pulsed sub-band system is to use a filter bank and separate LNA for each band. This approach, however, leads to a high power high complexity system with marginal effectiveness due to the conflict between having sharp filter skirts yet low time sidelobes.

A notch filter is simple relative to a sharp-skirt filter bank combined with a bank of LNAs. While it may at first seem that the notch filter would affect both monopulse-UWB and pulsed sub-band approaches equally, it does not. If the low-complexity programmable notch-filter approach were attempted within a sub-band of a pulsed-sub-band system, the ratio between the bandwidth of the sub-band to the bandwidth of the notch would be too small to continue to operate the sub-band. The pulsed sub-band solution (dropping a band) would always lose at least one full 500 MHz band. Whether one band or several are disabled, this reduction in the available hopping positions would result in a significant impact to the raw radio performance and result in a severe impact on its capability to offer multi-user capacity in the anticipated high multipath environment. Under ideal conditions, 3 in 7 bands experience collisions when 3 overlapping piconets are operating. This leaves only 4 bands operating. The FEC must be capable of coding over the errors. If even one more sub-band is dropped to account for RFI, then only 3 bands are left, making the job of the FEC even more difficult.

So for the severe interference case, monopulse-UWB approaches again have the advantage.

To summarize:

In mild RFI, the Signal to Interference (SIR) is within the design margin of the system. The extra processing gain gives more design margin to monopulse UWB. So monopulse-UWB has the advantage.

In moderate RFI, monopulse-UWB has the advantage again. Pulsed sub-band systems suffer on the radio performance and quality of service due to one or more bands being “turned off,” especially on multi-user performance. DSP gives monopulse-UWB an additional advantage of >10dB over its mild interference performance. This DSP capability is a surprise result to some researchers in UWB communications. Nonetheless, several techniques have been thoroughly developed and are well understood. DSP is a natural capability of direct sampling.

Severe RFI is an issue faced by all UWB systems as it saturates an unprotected receiver front-end. Monopulse-UWB has an advantage because its performance suffers less. Monopulse-UWB suffers less performance loss for three reasons: (1) due to the large ratio between the bandwidth of the monopulse-UWB signal and the bandwidth of a low complexity notch filter; (2) because monopulse-UWB is not forced to drop an entire 500 to 700 MHz wide band, effectively having a narrower notch; and (3) it does not suffer the coding loss of the missing band in a pulsed sub-band modulation scheme where most bands are missing due to the combination of multi-user and multipath and RFI.

Co-Location

A related concern that is a special case of severe RFI has to do with the ability of the implementation to be co-located with other wireless devices such as 802.11a or 5.8 GHz cordless phones. In this case, the interference isolation required is on the order of 70 dB. Note that this is for both transmit and receive—the LNAs of both co-located radios must be protected. This amount of isolation is far more than a pulsed-sub-band approach can achieve by simply disabling a band. For this special case of co-located applications, neither the pulsed sub-band nor monopulse-UWB approaches has any flexibility: either support for co-location is built in, or it cannot be supported.

The multi-band monopulse UWB approaches (such as [1]) inherently support being co-located on the same card (such as a compact-flash card) because they are designed from the ground up to be isolated by deep a deep stop band in the U-NII band.

The PP-MBOK approach doesn't restrict the pulse spectrum occupation by dropping specific band for co-location but uses an adaptive band approach since it is independent from the pulse shape combined with a programmable notched filter.

Again, the multi-band monopulse-UWB systems have an advantage due to the flexibility to position the deep stop-bands precisely where they are needed. On the contrary, pulse sub-band systems must fit the effect of deep stop-bands into predefined sub-bands. The result is simply that the affected bands are missing, which as discussed previously, significantly impacts system performance. All of the performance metrics on the multi-band monopulse-UWB approaches assume ability to co-locate with 802.11a, GPS, PCS, and U-NII band cordless phones.

Conclusions

This paper separately addressed the application of the term "spectral flexibility" to three independent concepts. The first deals with international regulations and how extensible the proposed implementation was at meeting differing or changing regulations. The second deals with RFI and the performance of the proposed implementation in RFI and the third deals with co-location. In all cases, the monopulse-UWB approaches offered advantages in performance over the pulsed-sub-band approaches.

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