MULTISPECTRAL SOLUTIONS, INC.

Response to FCC Notice of Proposed Rule Making
ET Docket No. 98-153
"Revision of Part 15 of the Commission's Rules Regarding Ultra-Wideband Transmission Systems."

Submitted to
Federal Communications Commission, Washington, DC

By
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1. Introduction

Multispectral Solutions, Inc. (MSSI) is pleased to submit this document in response to the Federal Communications Commission (FCC) Notice of Proposed Rule Making (NPRM) ET Docket No. 98-153, pertaining to "Revision of Part 15 of the Commission's Rules Regarding Ultra-Wideband Transmission Systems."

MSSI is a Small Business located in Gaithersburg, MD and was incorporated in February 1989 with the charter to develop advanced electronic systems for both communications and radar applications. Since its inception, MSSI has been actively involved in the development of ultra wideband (UWB) hardware, primarily for U.S. Military and Government applications. MSSI's founder and president, Dr. Robert J. Fontana, has over sixteen years of experience in the design, development, test and evaluation of ultra wideband communications systems.

The purpose of our response is to demonstrate to the Commission that, on the basis of sound engineering fact and in the interest of protecting valuable electromagnetic spectrum which contains vast numbers of current and potential users:

(a) Unfiltered UWB systems (i.e., those utilizing direct impulse or step excitation of an antenna) should not be permitted under Part 15;

(b) Filtered UWB systems should initially be allowed above 3.1 GHz with UWB power limits based upon measured instantaneous peak power (1 Watt with +6 dBi antenna gain); and,

(c) UWB Ground Penetrating Radars (GPR) should be considered on a licensed basis.

Filtered UWB operation in other bands (e.g., below 3.1 GHz) should be treated under a subsequent NPRM which more fully addresses the impact of UWB on existing systems and services (e.g., the demonstrated potential for UWB interference to sensitive GPS and navigation frequencies).

The remainder of this paper is subdivided into three sections. The following two sections provide technical comments and backup material for the recommendations listed above. The final section discusses the strong similarities between spread spectrum regulatory history and policy and that of ultra wideband. This is intended to provide the Commission with an understanding of how the above recommendations have precedent within the FCC's rule making policies for novel, wideband transmission technologies.

2. Prohibit Unfiltered UWB Emissions under Part 15

2.1 Technical Discussion

The NPRM restricts consideration of UWB devices to those that "solely use pulsed emissions where the bandwidth is directly related to the narrow pulse width". For the purpose of generating an electromagnetic field, these narrow or "short" pulses are then applied to a radiating element or antenna, with or without prior filtering (e.g., bandpass, highpass, notch, etc.).

It has been claimed by some UWB proponents that filtering of the excitation pulse prior to radiation by the antenna is undesirable because of the deleterious effects such filtering might have on the transmitted pulse shape. However, as will be shown below, without such filtering, it is virtually impossible to prevent *significant* changes in both frequency and bandwidth with *accidental* changes or simple *external* modifications to the UWB antenna. Such accidental or intentional modifications can be as simple as antenna breakage, bending the antenna, placing a metal plate or object (e.g., pocket calculator, file cabinet, etc.) near the antenna or lengthening (or shortening) the antenna element(s).

In the past, the FCC has been concerned with the possibility that a user of a Part 15 device may attempt to replace or modify an antenna. FCC Part 15.203, for example, was established to ensure that no antenna, other than that furnished by the product manufacturer, would be used with a Part 15 device. This is typically accomplished through the use of a permanently attached antenna or through the design of an unique connector, thereby preventing the use of an unauthorized antenna or external power amplifier.[1] For non-UWB devices, however, modifications to an *existing*, manufacturer-supplied antenna do not typically result in the generation of out-of-band emissions. Unfortunately, as demonstrated below, UWB systems which utilize non-filtered, impulse excited antennas can be easily altered or tampered with to produce significantly narrower band emissions at other than the "design" frequency, and with power levels many dB higher than those contained in the original, unmodified emissions. The following figures illustrate this problem.

Figure 1(a) shows the measured output of a wideband, cylindrical dipole antenna which is tuned or "cut" for a center frequency of 2 GHz. The -10 dB bandwidth of this emitter is 1.12 GHz for a fractional bandwidth of 63%. The center frequency, as measured by the arithmetic average of the two -10 dB intercepts, is measured to be 1.78 GHz. In Figure 1(b), the same antenna was modified by attaching a small metal tube as an extension to one of the radiating elements of the dipole. Note that the center frequency shifted downwards by nearly 500 MHz, and the bandwidth similarly was reduced by nearly 500 MHz thereby producing dramatic changes to the unit's operational characteristics. The energy is now more highly concentrated in the spectral region containing both GPS L2 (1227.60 MHz) and L5 (1176.45 MHz) frequencies. Note that *significant* operational parameter changes occurred with the UWB emitter by simply lengthening one element of the broadband antenna – an operation that can be performed without replacement of the existing antenna. Note that an identical effect is observed if one accidentally breaks one end of a longer broadband dipole antenna.

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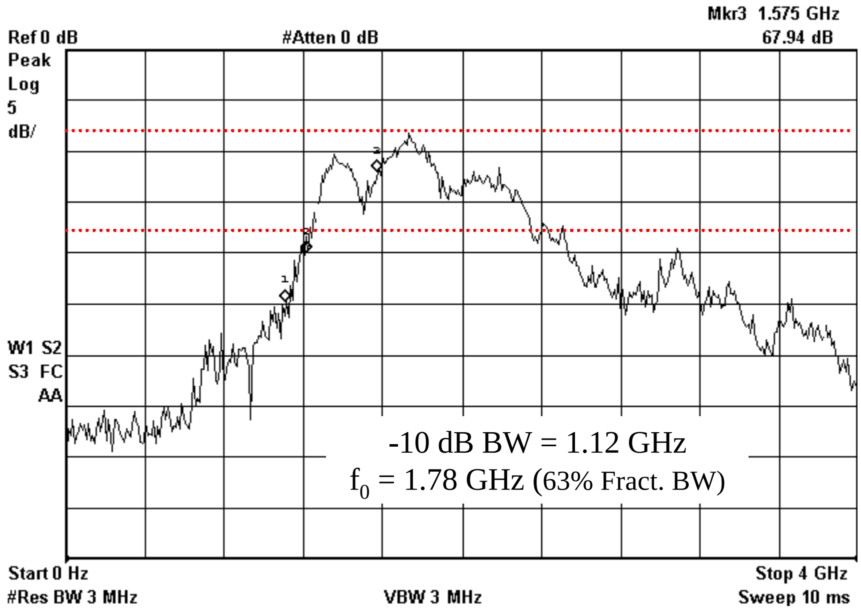
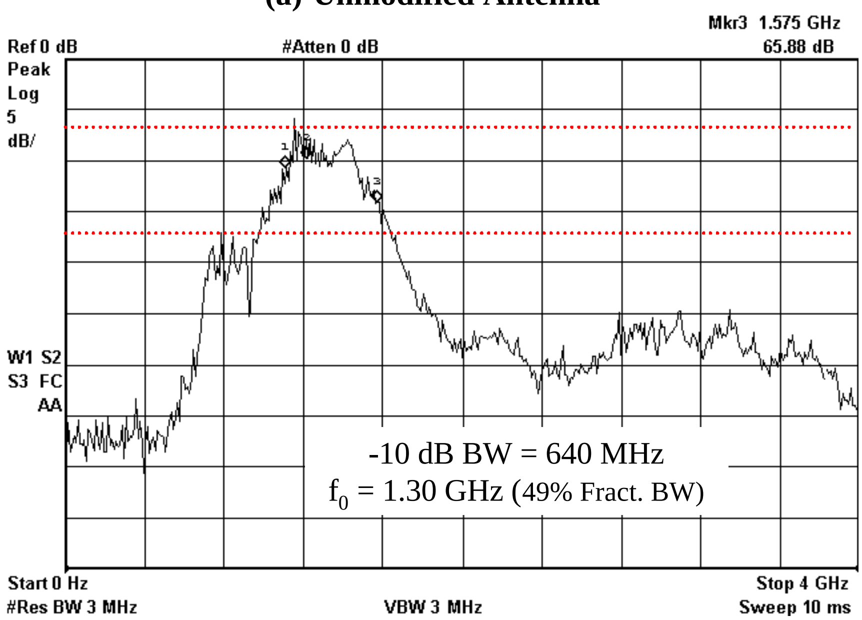
[1] Due to the popularity of MMCX, MCX, and reverse polarity SMA, BNC and TNC type antenna connectors, the FCC through a Public Notice DA 00-1087 dated May 22, 2000 (as clarified on June 22, 2000) will no longer allow their use after October 1, 2000. This action further demonstrates the FCC's desire to prevent unwanted modifications or changes to Part 15 radiating elements.



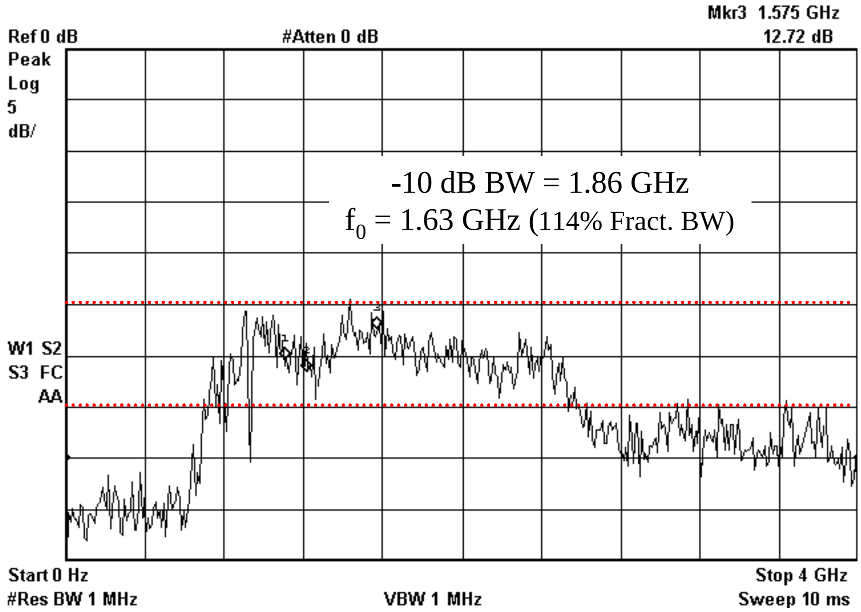
(a) Unmodified Antenna



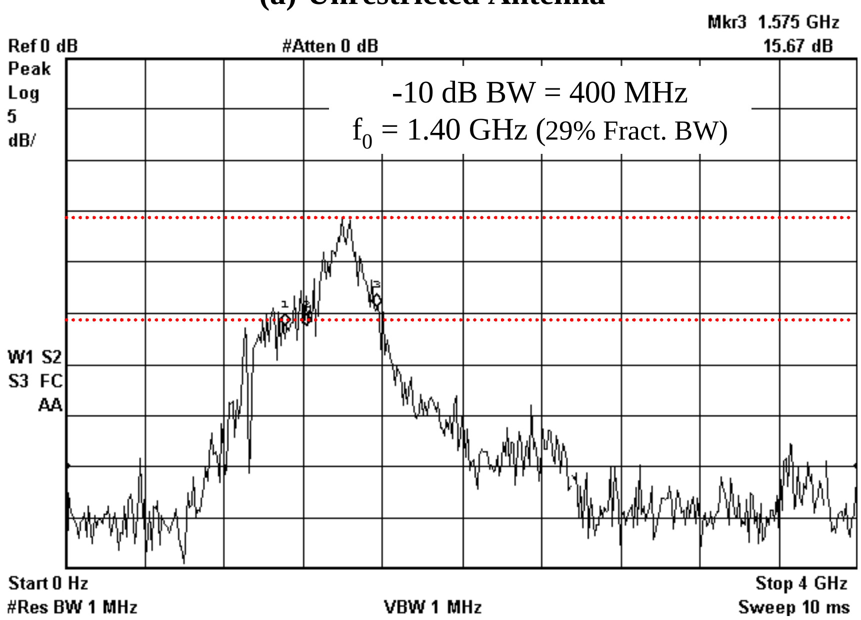
(b) Single Lengthened Element

Figure 1. Wideband Cylindrical Dipole

A second example is illustrated in Figure 2 below. Figure 2(a) shows the spectral content of a UWB emitter which uses a broadband "bow-tie" patch antenna. The patch antenna is a printed structure which is totally encapsulated in plastic, making it difficult for a user to physically lengthen or shorten the antenna as in the previous example. The -10 dB bandwidth of the source is 1.86 GHz, yielding a very broad operational fractional bandwidth of 114%. Figure 2(b) illustrates the effect of bringing a small piece of copper foil (approximately 2" x 2.5") into close proximity to the bow-tie radiator. Note that the results are even more dramatic than those shown in Figure 1. Here, the bandwidth dropped by nearly 1.5 *GHz* (to a resultant 29% fractional BW), while the center frequency shifted lower by 230 MHz. The particular copper "parasitic patch" chosen for this experiment happened to be resonant near 1.4 GHz; however, it is easy to see that by choosing different dimensions for the copper foil, one can essentially tune a spectral peak to sensitive frequency bands such as GPS, PCS/PCN and various TV channels. Also note that the spectral peak associated with these modified emissions increased by 10 dB.



(a) Unrestricted Antenna



(b) Antenna with 2"x2.5" Parasitic Copper Plate

Figure 2. Wideband "Bow-Tie" Antenna

Similar effects will occur if such an antenna is brought in close proximity to *any* metal object or object containing metalization – e.g., pocket calculator, watch, file cabinet, etc. Thus, while one may design a completely enclosed, printed circuit antenna; the parasitic effects of nearby metal objects can significantly alter radiated bandwidth, center frequency and emission levels.

In the above examples, the antennas were directly excited by a wideband impulse having the following properties:

UWB Source: MSSI TFP-1000 (S/N 001)[2]

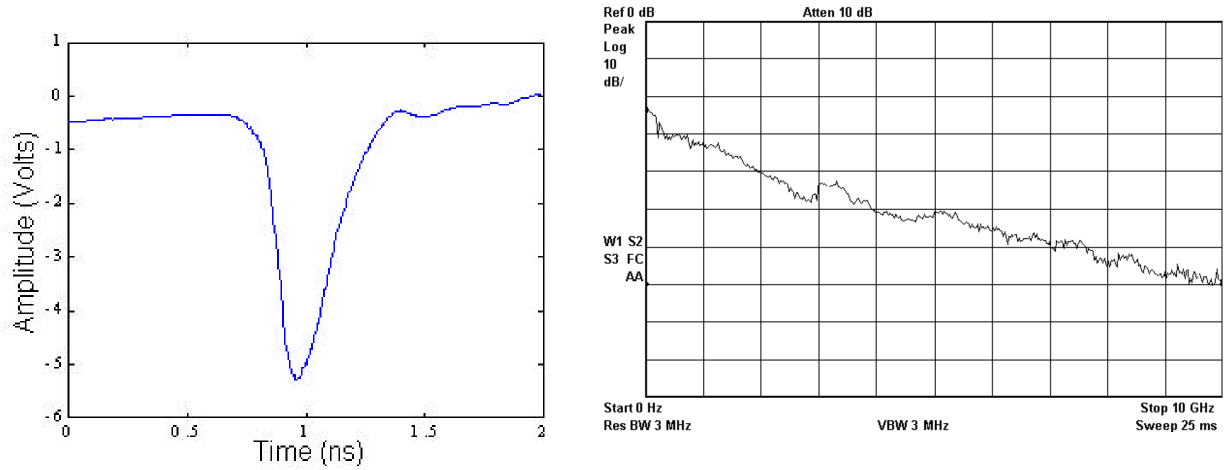
Rise Time: 269 ps

Fall Time: 127 ps

Width (RMS): 245 ps

Pk-to-Pk output: 5.39 V.

Figure 3 below illustrates both the time- and frequency-domain responses of this short pulse excitation.



(a) Time Domain Waveform **(b) Frequency Domain Response**

Figure 3. UWB Impulse Source (MSSI TFP-1000 S/N 001)

Note that the measured spectral content of this pulse extends from DC to beyond 10 GHz. These "doubly-exponential" pulses are readily generated with fast risetime digital circuits and minimal additional components making them very attractive for low cost UWB applications.

Another proposed wideband pulse excitation[3] is that of the theoretical "Gaussian monocycle" which has the mathematical relationship

$$p(t) = \frac{t}{t}\exp\left(-\left(\frac{t}{t}\right)^2\right)$$

and resultant Fourier transform

$$P(f) = -jp^{3/2}t^2 f \exp\left(-p^2 t^2 f^2\right).$$

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[2] This same source was provided to the National Telecommunications and Information Administration (NTIA) for its testing of potential UWB interference effects.

[3] Alan Petroff and Paul Withington, "Time Modulated Ultra-Wideband (TM-UWB) Overview," http://www.time-domain.com/Technology/findout_papers.html.

Obviously p(t) is physically unrealizable as it is anticipatory or non-causal, having an output response for negative time. However, causal approximations to p(t) can be generated with delay.

Plots of p(t) and P(f) for a value of τ = 100 ps are shown below in Figure 4.

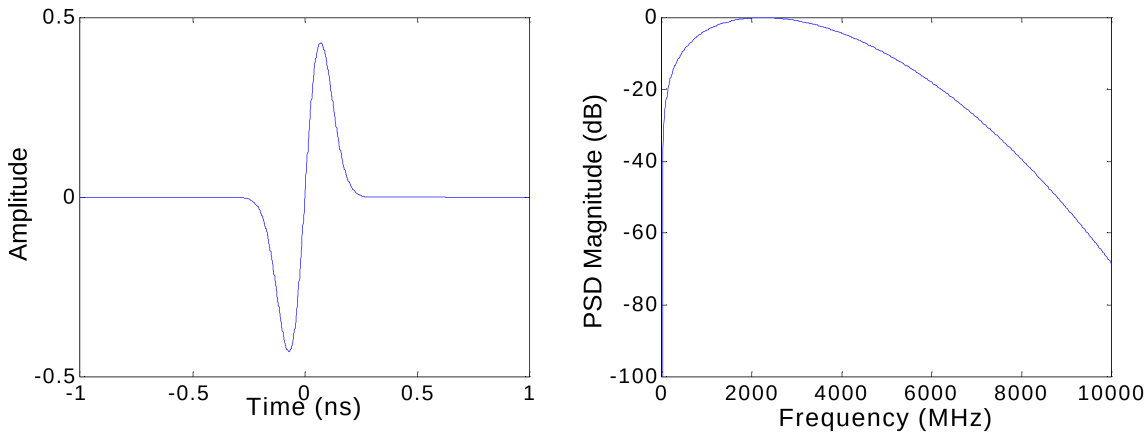

Figure 4. Theoretical Gaussian Monocycle and Power Spectral Density

For this hypothetical waveform, the center frequency is calculated to be 2.47 GHz with a -10 dB bandwidth of 4.02 GHz (-10 dB at 460 MHz and 4,480 MHz), or 162% fractional. Note, again, that the energy density of this excitation pulse covers a very extended frequency range.

Unfortunately, an antenna is a very poor electrical filter, with many natural resonances (both harmonic and non-harmonic) over a broad frequency range. Thus, the combination of a broadband, unfiltered excitation with an antenna can result in significant energy radiated at other than the antenna's so-called "design" frequency. Two additional examples are illustrated below.

In Figure 5, a commercially available, wideband omnidirectional antenna from Tecom Industries, Inc. (Tecom Model B19961-1), designed for the frequency range of 4.4-5.0 GHz, was directly excited by a broadband impulse source. As seen, in addition to the desired output in the 4.4-5.0 GHz region, strong unintended responses at frequencies far removed from the antenna's operational frequency range were observed in the far field of the antenna. In this example, strong outputs were also observed in the GPS bands at L1 (1575.42 MHz), L2 (1227.60 MHz) and L5 (1176.45 MHz). Peak levels out-of-band exceed those in-band by over 40 dB.

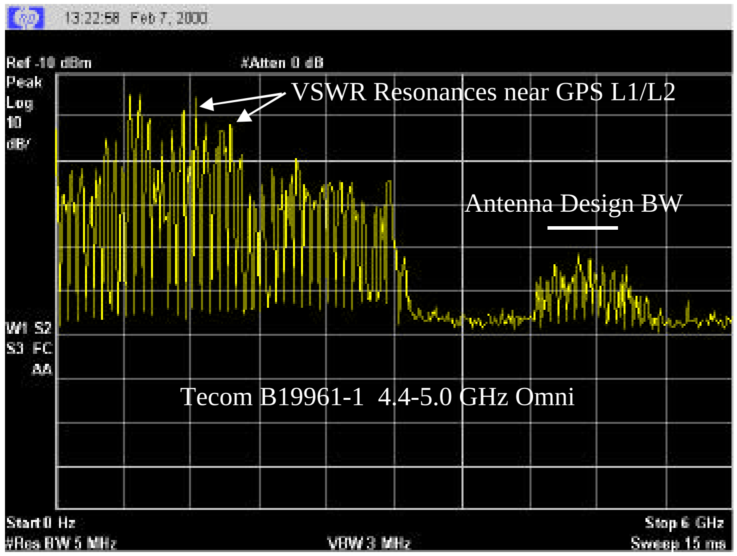

Figure 5. Impulse Excitation of Commercial 4.4-5.0 GHz Omni Antenna (Tecom B19961-1)

Similarly, Figure 6 illustrates the effects of impulse excitation of a broadband (1.5 GHz center frequency, 500 MHz bandwidth) sleeve dipole antenna designed by the Hazeltine Wheeler Laboratories. Again, energy is radiated at frequencies other than in the antenna's design frequency range.

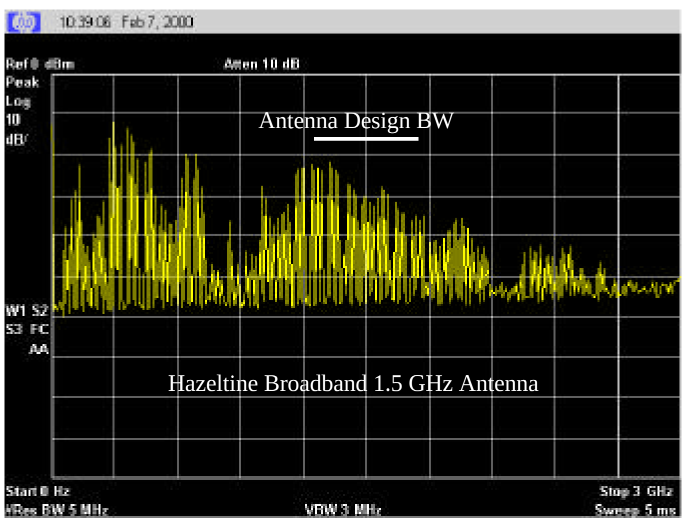

Figure 6. Impulse Excitation of Hazeltine Broadband 1.5 GHz Omni Antenna

2.2 Conclusions and Recommendations

For UWB systems which utilize unfiltered pulse excitation of an antenna, it is difficult if not physically impossible to preclude the possibility of radiating energy in unintended ways. Such unintended radiation can be caused by either intentional or accidental modifications to the antenna. Unfortunately, the resultant emissions can be far removed from the antenna design frequency.

Furthermore, it was demonstrated that the radiated spectrum of unfiltered systems can be easily modified through damage to the antenna, lengthening or shortening the antenna, or positioning the antenna near any metal object. Unfortunately, the result of such simple operations can be a significant reduction in instantaneous bandwidth with correspondingly increased power densities (Watts/Hz) in unintended regions of the spectrum.

Only pulse filtering *prior* to radiation by the antenna can eliminate these indeterminate, yet potentially interfering, spectral components. For all of the reasons mentioned above, Multispectral Solutions strongly recommends that the FCC prohibit the use of unfiltered UWB emissions under unlicensed Part 15 regulations.

3. Permit Filtered UWB Operation in the Frequency Bands above 3.1 GHz

3.1 Technical Discussion

In his 30 March 2000 " Briefing to Industry Leaders" on the Wireless Innovations in Communications Initiative (WICI), NTIA Administrator Gregory L. Rohde stated that "since demands for the spectrum are increasing rapidly by both the public and private sectors, there is an urgent need to ensure that this limited national resource is used in an effective and efficient manner." Mr. Rohde indicated that 1.4% of available spectrum is currently reserved for exclusive use by the Federal Government, 5.5% is reserved for exclusive use by the commercial sector, and 93.1% of available spectrum is available on a shared basis. In addition, 50% of Federal Government use is in bands below 3.1 GHz; while 40% of commercial use is below 3.1 GHz. Mr. Rohde went on to point out that the bands below 3.1 GHz are extremely congested; and this frequency range not only includes critical GPS and safety-of-life frequencies, but also frequencies for rapidly emerging third-generation (3G) wireless applications and others.

The vast majority of systems operating below 3.1 GHz are narrowband in nature, where by "narrowband" is meant systems having RF bandwidths of less than a few MHz. Some UWB proponents use this fact to argue that ultra wideband emissions, because their energy is "spread" over hundreds of MHz to multiple GHz, generate miniscule amounts of power within the RF bandwidths of these more conventional systems – a so-called "processing gain" advantage. The claim is that UWB systems can thus "reuse" existing spectrum. Unfortunately, such is not the case as will be shown in the following discussion.

In its First Interim Report to the Department of Transportation (DOT) entitled "Ultra-Wideband Technology Radio Frequency Interference Effects to GPS and Interference Scenario Development," dated 31 August 2000, the RTCA[4] summarized preliminary results from DOT-sponsored tests by Stanford University on UWB interference to GPS. The Stanford test plan was previously reviewed and coordinated through the government Interdepartment Radio Advisory Committee (IRAC). The Stanford data covered the effects of a *single* UWB emitter on one GPS receiver whose performance was typical of an aviation precision approach GPS receiver. A wide variety of UWB system pulse repetition frequencies (PRFs), burst duty cycles and modulations were considered.

A brief summary of these results follows:

(a) location of spectral lines relative to GPS C/A code lines was found to be important for all UWB PRFs, duty cycles, on-times and modulation;

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[4] RTCA, Inc. is a private, not-for-profit corporation that develops consensus-based recommendations regarding communications, navigation, surveillance, and air traffic management (CNS/ATM) system issues. RTCA functions as a federal advisory committee. Its recommendations are used by the Federal Aviation Administration (FAA) as the basis for policy, program, and regulatory decisions and by the private sector as the basis for development, investment, and other business decisions. Organized in 1935 as the Radio Technical Commission for Aeronautics, RTCA today includes over 200 government, industry, and academic organizations from the United States as well as other nations. Member organizations represent all facets of the aviation community, including the FAA, major airlines, airspace user associations, airline pilot and air traffic controller labor unions, airports plus aviation service and equipment suppliers.

(b) lower PRF (relative to receiver bandwidth) had less, but still observable, radio frequency interference (RFI) impact;

(c) lower duty cycle, longer burst on-time and random pulse position modulation (PPM) dithering seemed to lessen the RFI impact; and,

(d) UWB pulse trains with no modulation had a strong RFI impact.

The RFI aggregation effects of multiple UWB signals were not considered in these tests.

While preliminary, the Stanford results pointed out one important fact – that UWB emissions falling into sensitive GPS frequency bands can cause interference, even at emission levels currently being contemplated under a modified Part 15.

Several proposed UWB systems (cf. NOI responses) contemplate the use of high PRF (e.g., 10 or 20 Mpps and higher) emissions because of the need or desire to average multiple pulses to attain the desired operational signal-to-noise ratio. As pointed out by the Stanford tests, these high PRF waveforms have the highest potential for interference to GPS.[5] In particular, such high PRF emissions have significantly increased duty cycles (and, hence, average power output); and, without significant pulse dithering which is problematic at high PRFs, UWB energy is concentrated in a smaller number of discrete spectral lines, each containing a significant amount of the total transmitted power. Unfortunately, even with appreciable pulse dithering, discrete spectral lines will continue to be present (cf. Appendix A below).

Thus, there is substantive proof that UWB emissions, if allowed to fall within existing GPS frequency allocations, can cause significant interference to these sensitive satellite navigation systems. Furthermore, with the desire to use UWB for applications requiring high data throughput, such ultra wideband emissions will of necessity require high PRFs which will cause increased interference due to higher pulse duty cycles and the existence of discrete spectral lines.

However, the full impact of UWB emissions on GPS and on other systems is still unknown. The NTIA, for example, will only have preliminary results available for review by the end of December 2000, with a full analysis potentially taking several months. We agree with the FCC that the expedient introduction of new technologies into the marketplace should be a national priority, as long as such technologies do not jeopardize the thousands of existing users of our valuable electromagnetic spectrum. To introduce such technologies, without a complete understanding of the potential consequences for interference; may irreparably damage our nation's safety and security, potentially destroy the viability of the new technology itself, and create a precedent which will have a chilling effect on the development of future wireless technologies.

As MSSI has repeatedly pointed out in its responses to the FCC's Notice of Inquiry, and as has been further validated by successful UWB system developments from other industry participants, there is no reason for UWB systems to operate within restricted frequency allocations. The following discussion will further clarify this statement.

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[5] The NTIA is proceeding with additional testing of the impact of UWB on GPS, and according to their current test plan, should have results available for review by the end of December 2000.

As shown in Appendix B below, there is an extremely strong analogy between ultra wideband and spread spectrum emissions. UWB is another form of spread spectrum in which "spreading" is achieved because of the short pulse duration and not due to modulation with a PN code or hopping sequence. Unlike direct sequence or frequency hopped spread spectrum waveforms which are constant envelope in nature, UWB emissions are pulsed and are typically of very short duration. Thus, UWB emissions typically exhibit duty cycles which are significantly lower than unity and, as a consequence, have much higher peak-to-average ratios. Thus, for a given spread bandwidth and peak power, a UWB waveform will have a lower average power and, hence, lower potential for interference, than a spread spectrum system.

Within existing Part 15 rules, there is an unrestricted band which spans from 5.46 to 7.25 GHz. This band is particularly noteworthy since the FCC has already permitted the use of wideband, low energy density emissions in this region – e.g., Unlicensed National Information Infrastructure (U-NII) in the region 5.725 - 5.825 GHz with 1 Watt peak, 4 Watts ERP (+6 dBi antenna gain); spread spectrum waveforms under FCC Part 15.247 in the region 5.725 - 5.850 GHz again with 1 Watt peak and 4 Watts ERP; ISM FCC 18.301 in the region 5.725 - 5.875 GHz; and Intelligent Transportation Systems allocation in the region 5.850 - 5.925 GHz.

The precedent to move next generation, high speed wireless communications (e.g., U-NII and ITS) to this region of the spectrum has *not* prevented engineering designers from developing viable communications systems for wireless LANs (U-NII) and dedicated short range communications (DSRC) systems for intelligent transportation applications. Thus, the argument from portions of the UWB community that frequencies below 2 GHz are necessary for in-building communications have no basis in fact.

UWB ground penetrating radar (GPR) applications are a notable exception, typically operating below 2 GHz and with fairly large antennas to preserve the low frequency content necessary for ground penetration. However, for effective use, GPR devices typically utilize very high powers, measured in the hundreds of watts to several kilowatts. The FCC has recognized the limited market for such devices in granting a waiver for sales by U.S. Radar Inc. of only 25 units per year. The high power level requirements (up to several kilowatts), frequency of operation (over many restricted bands including GPS and TV), and limited market for UWB GPRs makes them inappropriate for Part 15 unlicensed use.

3.2 Conclusions and Recommendations

Stanford University, under funding from the U.S. Department of Transportation, has demonstrated that UWB emissions can and do cause interference to sensitive GPS receivers even at levels currently contemplated for Part 15. The levels of such interference, as a function of UWB system design parameters and range, are yet to be completely determined. The National Telecommunications and Information Administration (NTIA) has but recently begun testing on the impact of UWB on GPS, with a preliminary report due at the end of December 2000. Preliminary results from NTIA's non-GPS testing are expected to be made available by the end of October.

Unfortunately, while some UWB advocates have claimed that UWB operates in the "garbage band" and can superimpose its emissions on existing services without interference thereby "creating spectrum", such statements are without basis in fact and, in fact, have been shown to be false.

NTIA Secretary Gregory Rohde recently pointed out the extreme congestion of the electromagnetic spectrum below 3.1 GHz. Since, as pointed out above, the impact of UWB emissions on these systems is unknown at this time, FCC approval for the initial implementation of UWB systems above 3.1 GHz (for other than GPR applications) would represent an ideal starting point for the introduction of this technology into the commercial marketplace. Furthermore, from MSSI's extensive experience in UWB system development over the past 12 years; as well as from the experience of wideband system designers (e.g., U-NII, ITS, etc.); there is no compelling reason to operate below 3.1 GHz for the types of applications contemplated for UWB communications and radar. Rather, there is an established precedent within the FCC and other agencies to consider the introduction of high-speed, wideband systems in the frequency range above 3.1 GHz. Currently, 1.79 GHz of bandwidth exists within the *unrestricted* region (FCC Part 15.205) from 5.46 to 7.25 GHz. (Note: Restricted bands of operation are those in which only spurious emissions are permitted by Part 15 devices.)

As pointed out in MSSI's response to the Commission dated 1 March 2000, UWB systems are more properly classified as a "superclass" of spread spectrum waveforms; and, as such, are best characterized by a peak power constraint. Given such a peak power constraint, an increasing peak-to-average ratio now has the benefit of *lowering* the average power transmitted and received.

Thus, given the above facts, MSSI proposes the following changes to Part 15 to permit UWB communications systems. Note: GPR UWB applications will NOT be addressed further here, and should be considered separately by the FCC for the reasons given above.

1. **Definitions** (cf. Note 1)

    An **ultra wideband** (UWB) device is a device which utilizes short pulses for the means of generating a wide instantaneous bandwidth. Explicitly excluded are devices which achieve wide instantaneous bandwidths because of the use of high data rates (i.e., modulation dependent).

    A **full-bandwidth ultra wideband** (FB-UWB) device is any UWB device where the fractional bandwidth is greater than 0.25 or occupies 1.5 GHz or more of spectrum.

    A **partial-bandwidth ultra wideband** (PB-UWB) device is any UWB device where the bandwidth exceeds 200 MHz.

    Bandwidth is defined to be the difference of the upper and lower -10 dB emission points, i.e. ($f_H - f_L$), using the antenna that is designed to be used with the UWB device.

    Center frequency is defined to be the average of the upper and lower -10 dB points; i.e., $(f_H + f_L)/2$.

    Fractional bandwidth is defined to be the ratio of the bandwidth to the center frequency; i.e., $[2(f_H - f_L)/ (f_H + f_L)]$.

2. **Frequency Allocation** (cf. Note 2)

   UWB devices shall be allowed in the frequency range above 3.1 GHz; i.e., f_L as defined in 1. shall be greater than 3.1 GHz.

   All spurious emissions, defined as emissions falling below 3.1 GHz, shall be -40 dB relative to the peak emission level in-band.

3. **Power Levels** (cf. Note 3)

   Full-bandwidth ultra wideband (FB-UWB) emissions shall not exceed 1 Watt peak power and shall use an antenna with no higher than +6 dBi gain. Antenna gain shall be determined as the maximum achievable over the operational frequency range [f_L, f_H].

   Partial-bandwidth ultra wideband (PB-UWB) emissions shall be derated by the ratio of the bandwidth used to the maximum bandwidth defined for an FB-UWB emission utilizing the same center frequency. For example, a 300 MHz bandwidth PB-UWB emission at a center frequency of 5.8 GHz shall have a maximum peak power limitation of:

$$P = \frac{300\,\text{MHz}}{\min\left(1.5\,\text{GHz}, 0.25 \times 5.8\,\text{GHz}\right)} \times 1\,Watt = \frac{300\,\text{MHz}}{1450\,\text{MHz}} \times 1\,Watt = 207\ milliwatts$$

   As with FB-UWB emissions, PB-UWB emissions shall also allow the use of antennas having no greater than +6 dBi gain.

4. **Power Measurements** (cf. Notes 4 and 5)

   Peak power measurements shall be performed utilizing a wideband antenna and time-domain sampling oscilloscope (e.g., Tektronix 11801B or equivalent, with or without external wideband amplifier). Peak power at the emitter shall be derived from peak voltage measurements made in the far field of the UWB antenna.

Notes:

1. Note that *all* duty cycles are allowed, permitting the development of high-speed UWB systems. With a maximum ERP of +6 dBW, *any* duty cycle less than unity will result in a lower average power level. Thus, for UWB emissions as defined above, peak-to-average ratio is not a relevant parameter.

2. In the NPRM, the FCC stated that "We believe that UWB devices can generally operate in the region of the spectrum above approximately 2 GHz without causing harmful interference to other radio services." In addition, the FCC has expressed concern for the use of UWB within existing restricted bands. Thus, an alternative, and somewhat more restrictive, frequency allocation for UWB devices which avoids existing restricted bands can be stated as follows:

2'. Frequency Allocation

UWB devices shall be allowed in the frequency range 5.46 to 7.25 GHz; i.e., f_H and f_L as defined in 1. shall be contained in this range.

All spurious emissions, defined as emissions outside of the frequency interval 5.46 to 7.25 GHz, shall be -40 dB relative to the peak emission level in-band.

3. As pointed out in MSSI's response to the UWB NOI, and as demonstrated by UWB equipment provided by MSSI to the NTIA for test and evaluation, there are numerous applications for UWB which do not require 25% or greater fractional bandwidths. Indeed, to force a system to utilize a wide instantaneous bandwidth simply to satisfy an arbitrary definition is not necessarily the best engineering approach nor one which will result in viable commercial systems.

   However, it appears that the FCC's intent is to minimize the power spectral density (and hence the potential for interference to other systems) by spreading the energy as widely in frequency as possible.[6]

   Thus, it is MSSI's recommendation that an appropriate way to allow lesser bandwidth systems ,while maintaining the desire to keep the power spectral density low, is to penalize systems having less than the recommended 1.5 GHz or 25% fractional bandwidth. This approach is in line with the precedent established for U-NII in which systems operating with less than a 20 Mb/s modulation rate were also penalized in power proportionally to data rate. As a lower bound, a minimum bandwidth of 200 MHz was chosen; however, it has been demonstrated that viable UWB systems can be constructed with bandwidths as small as 20-30 MHz.[7]

4. Over the last few months, the NTIA has developed considerable experience with making power measurements in the time domain using wideband time-sampling oscilloscopes. Hopefully, details of these measurements will be made available in their published final reports. MSSI also utilizes the time domain for all of its power measurements and has found such measurements to be extremely reliable for computing expected range performances. While such time domain power measurements are not difficult to perform, it may be that fewer testing laboratories are currently configured for such measurement capabilities.

5. Alternatively, peak power can be deduced from a spectral measurement utilizing an appropriate pulse desensitization factor.

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[6] It should be pointed out, however, that for a pulse waveform, nearly 90% of the pulse energy is contained within the -3 dB bandwidth points. Thus, even a -10 dB bandwidth definition does not necessarily force a uniform spectral density to exist.

[7] The Sperry Marine *Intrusion Detection and Alert System (IDAS) utilized UWB short pulse techniques and had an operational pulsewidth of approximately 30 ns for an instantaneous bandwidth of roughly 33 MHz.*

4. FCC Precedents with Spread Spectrum Systems

4.1 Technical Discussion

In May 1985, the FCC completed a rule making allowing for the unlicensed use of spread spectrum in the Industrial Scientific and Medical (ISM) bands. This rule making occurred nearly four years after the issuance of a Notice of Inquiry (NOI) on September 15, 1981. There are several parallels to the pending rule making regarding UWB that are worth highlighting:

Spread spectrum technology has a very similar history to UWB in that the technology was originally developed for the military for low probability of intercept, covert communications. At the time of the proposed NOI in 1981, much of the military spread spectrum research had been declassified and new advances in technology were making component costs less and less expensive. The FCC realized that current rules forbidding spread spectrum may be inhibiting research and development into commercial applications. At the same time, the FCC stated that "the low power density and interference suppression capabilities of spread spectrum systems suggest a unique application, that of a band overlay. It may be possible in some circumstances to overlay spread spectrum systems on spectrum used by conventional services with little or no mutual interference. Obviously, this would increase spectrum efficiency of the affected band and could release additional spectrum for allocation to other services."[8]

> *These are nearly identical arguments to those being made by proponents of UWB technology today. Indeed, much of UWB technology has been declassified by the military; commercialization has been hampered due to existing Part 15 rules; component costs for UWB implementation are low; and spectrum overlay is possible for properly designed UWB systems.*

Opposition to a rules change for spread spectrum included such companies as Motorola, RCA, and GE. They cited the potential for interference to their licensed operations as a key concern.

> *The Airline Industry, GPS Council, Television Broadcasters, have all expressed significant concerns over the approval of UWB transmissions in their restricted bands of operation.*

The FCC originally contemplated the use of spread spectrum systems to operate on any range of frequencies above 70 MHz without any restrictions on their occupied bandwidth. In addition, up to 70 watts in output power was proposed.

> *Under the NPRM, the FCC has proposed the unlimited use of spectrum by UWB devices at lower power levels.*

The FCC finally settled on approving spread spectrum use in the Industrial Scientific and Medical bands (902-928 MHz, 2400-2483.5 MHz, and 5725-5875 MHz) at a peak power level of 1 watt. These bands were currently used for microwave ovens and heat diathermy equipment rather than for communications. This decision was deemed a “win-win” for the FCC in that

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[8] *The Cook Report* – www.users.on.net/tomk/library/wireless.htm

spread spectrum devices could effectively operate in spectrum not available to conventional narrowband radio technology.

> *Although the frequency bands and power levels were much lower than originally proposed, the FCC's action to permit unlicensed spread spectrum under Part 15 enabled a broad range of commercial products including cordless phones, wireless networks, tags, etc.*

It must be understood that ultra wideband is a form of spread spectrum in which the large, instantaneous bandwidths are generated by short pulses and not by modulation with a separate spreading sequence. As such, UWB has many of the same properties as its more conventional counterparts.

4.2 Conclusions and Recommendations

As shown in the previous section, there are many strong similarities between the introduction of direct sequence and frequency hopped spread spectrum under Part 15 and that currently contemplated for ultra wideband. In the end, a compromise was reached for spread spectrum that resulted in a huge win for the FCC, as well as a huge win for the "fledgling" commercial sector. Indeed, a multi-billion dollar industry was created and many companies and individuals benefited from the decision.

As was the case with conventional spread spectrum, there are today many outstanding issues that prevent the use of UWB on an unrestricted basis. The NTIA is currently involved in a very detailed test that will answer many of these issues. In the end, however, it is obvious that bandwidth and output power controls need to be applied to UWB systems so as to protect existing spectrum users without unduly restricting the commercialization of UWB technology.

On the other hand, it is also important to point out that two years have already elapsed since the FCC issued its NOI for UWB. Much of the delay has been related to the controversies regarding the potential for UWB interference to GPS. While this controversy continues opportunities are being lost.

Therefore, it is highly recommended that the FCC move quickly as mandated under Section 7 of the Communications Act to "encourage the provision of new technologies and services to the public" and issue a rule making that allows the responsible introduction of ultra wideband technology into frequency bands already set aside for digital communications at power levels approved for existing spread spectrum sources.

We urge the FCC to immediately approve UWB operation for frequencies above 3.1 GHz, or as a minimum in the 5.46 to 7.25 GHz (unrestricted) band, utilizing peak power levels commensurate with current allocations for spread spectrum technology (i.e., 1 Watt peak with +6 dBi maximum antenna gain). As pointed out in Section 3.2, these power levels would be reduced if the UWB emission bandwidth does not satisfy the minimum of 25% or 1.5 GHz. Since UWB emissions, by their very nature, have duty cycles less than unity (indeed, usually orders of magnitude less than 1), these power levels are significantly lower than those utilized with direct sequence and frequency hopped spread spectrum. In addition, the much wider spread bandwidths required for UWB will result in significantly lower power spectral densities, which in turn, will result in lower potential for interference.

Following this initial ruling which will enable commercialization of UWB devices, other frequency bands can and should be considered. In particular, GPS and other frequency band use will require careful study and analyses of the test data being developed by the NTIA/ITS.

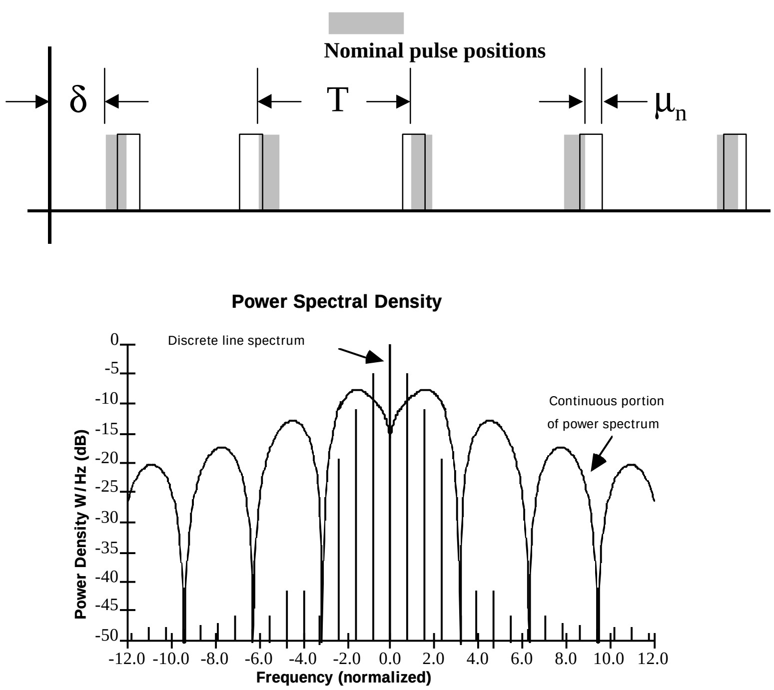
Appendix A
Power Spectral Density Calculations for Jittered Pulse Trains

It has been suggested that the use of pulse train dithering makes a UWB waveform appear to be "noiselike" to a narrowband receiver. However, a more careful mathematical analysis shows that this is not always the case. At elevated pulse repetition frequencies (PRFs), spectral lines produced by an ultra wideband transmitter will remain the leading cause of interference to narrowband systems, even with appreciable pulse dithering. The potential for such UWB emissions to interfere with sensitive, narrowband systems (e.g., GPS) is real and only aggravated by UWB systems which operate in-band and utilize elevated PRFs.

In this Appendix, it is shown that the power spectral density for a randomly dithered pulse train is given by the relationship

$$S_x(f) = \left(tA\,\mathrm{sinc}(ft)\right)^2\left[\frac{\mathrm{sinc}^2(2fb)}{4T^2}\sum_{n=-\infty}^{\infty}u_0\left(f-\frac{n}{T}\right)+\frac{2-\mathrm{sinc}^2(2fb)}{4T}\right]$$

where the pulse jitters $\{\mu_n\}$ (see Figures below) are uniformly distributed over the interval $[-\beta,\beta]$ and $u_0(f-f_0)$ is a spectral line ("impulse") at frequency f_0.



Dithered **Pulse Train and Power Spectral Density**

As seen from these results, there is NO amount of pulse dithering which will totally eliminate all spectral lines. For example, to simply reduce the first spectral line component by 20 dB requires pulse dithering over more that 90% of the pulse interarrival time – often an impractical solution because of significantly increased receiver complexity for synchronization. Thus, the only "sure" way to completely remove the potential for interference to sensitive narrowband systems is to operate UWB systems out-of-band.

Preliminaries

The power spectral density of a random process X(t) is given by the expression

$$S_x(f) = \int_{-\infty}^{\infty} R_x(t) e^{-2pft} dt$$

where $R_x(\tau)$ is the autocorrelation function for the process X(t) given by

$$R_x(\tau) \equiv E(X(t)X(t-\tau)).$$

Let $X_T(f)$ be the random variable which is the *truncated* Fourier transform of the random process X(t); i.e.,

$$X_T(f) \equiv \int_0^T x(t) e^{-j2pft} dt$$

where x(t) is a sample function from the random process X(t). Then it is straightforward to show that

$$S_x(f) = \lim_{T \to \infty} \frac{E\left|X_T(f)\right|^2}{T} \tag{1}$$

where the quantity $S_T(f) \equiv \dfrac{E\left|X_T(f)\right|^2}{T}$ is known as the *periodogram*.[9]

In general, as a *statistical* estimator, the periodogram S_T is a poor estimate of the true power spectral density; however, relationship (1) above is always satisfied. Thus, since we will be computing the *exact* statistical expectation of S_T in a variety of cases, the limit in (1) will provide the correct power spectral density expression. In other words, we are not using the periodogram as a statistical estimator, but rather taking its mathematical limit to obtain the true power spectral density. A parallel approach can be found in Schwartz et al.[10]

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[9] Davenport and Root, **An Introduction to the Theory of Random Signals and Noise**, McGraw-Hill, NY, 1958, pp. 107-108.

[10] Schwartz, Bennett and Stein, **Communication Systems and Techniques**, McGraw-Hill, New York, 1966.

Simple Pulse Train (no modulation)

Consider the example of a simple (unmodulated) periodic random pulse train (cf. Figure 1 below) which consists of a train of pulses, each of width τ and amplitude A, having a period T and with a random offset δ from the time origin. Here, the random variable δ can be considered to be uniformly distributed on the interval [-T/2,T/2].

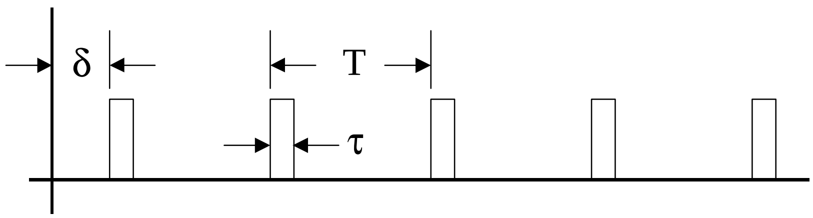


Figure 1. Simple Periodic Random Pulse Train

From Figure 1,

$$X_{KT}(f) \equiv \int_0^{KT} x(t)e^{-j2\pi ft}dt = \int_{\delta}^{\delta+\tau} Ae^{-j2\pi ft}dt + \int_{\delta+T}^{\delta+\tau+T} Ae^{-j2\pi ft}dt + \cdots + \int_{\delta+(K-1)T}^{\delta+\tau+(K-1)T} Ae^{-j2\pi ft}dt$$

where we have considered an integral multiple of periods K.

Performing the indicated integrations, one obtains after simplification that:

$$E\left|X_{KT}(f)\right|^2 = \left(A\tau\,\mathrm{sinc}(f\tau)\right)^2 \left(\frac{\sin(\pi fKT)}{\sin(\pi fT)}\right)^2$$

where

$$\mathrm{sinc}(x) \equiv \frac{\sin(\pi x)}{\pi x}.$$

Hence, the power spectral density of this process becomes:

$$S_x(f) = \left(A\tau\,\mathrm{sinc}(f\tau)\right)^2 \lim_{K\to\infty} \frac{1}{KT}\left(\frac{\sin(\pi fKT)}{\sin(\pi fT)}\right)^2.$$

It can be shown that

$$\lim_{K\to\infty} \frac{1}{KT}\left(\frac{\sin(\pi fKT)}{\sin(\pi fT)}\right)^2 = \frac{1}{T^2}\sum_{n=-\infty}^{\infty} u_0\left(f - \frac{n}{T}\right)$$

where $u_0(f)$ is the unit impulse function in frequency satisfying the defining relationships

$$u_0(f) = \begin{cases} 0, & f \neq 0 \\ \infty, & f = 0 \end{cases} \quad \text{and} \quad \int_{-\infty}^{\infty} g(f) u_0(f) df = g(0)$$

for any "well-behaved" function g. Note that the above relationships defines an "impulse train" in frequency.

Combining these results, one obtains the desired result that:

$$S_X(f) = \left(\frac{A t}{T} \text{sinc}(f t) \right)^2 \sum_{n=-\infty}^{\infty} u_0 \left(f - \frac{n}{T} \right) \text{ with no external modulation} \tag{2}$$

As can be seen from the above expression, the power spectral density for the simple (unmodulated) random pulse train consists of a collection of spectral lines (impulses in frequency) which are each separated by a distance 1/T in frequency where T was the pulse train period. The "width" of the power spectrum is determined by the pulse width τ; whereas the total power is related to the pulse duty cycle τ/T. Figure 2 below provides an example of a typical pulse spectrum.

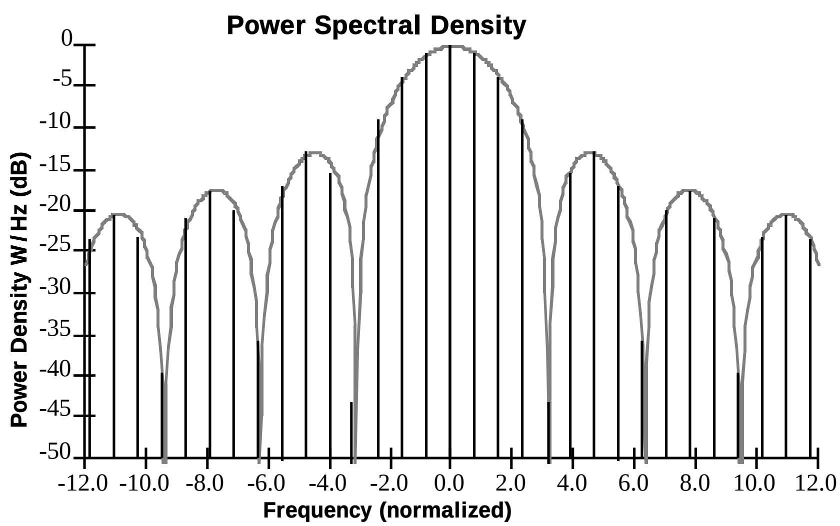


Figure 2. Pulse Spectrum of Random Pulse Train with no External Modulation
(envelope of spectral lines shown for reference)

The result in (2) could have been arrived at in a much simpler fashion; however, the same technique will be used in the next sections to derive the power spectral densities of much more complex random processes.

Simple Pulse Train (pseudorandom modulation)

As a simple extension to the above result, consider the case of pseudorandomly modulating the pulse train amplitude of the above random process by a random binary data stream having the values 0 or 1 with probability 1/2 each (non-negative modulation). In this case, one can show that:

$$X_{KT}(f) = tAe^{-j2pf(d+t/2)} \frac{\sin(pft)}{pft} \sum_{n=0}^{K-1} a_n e^{-j2pfnT}$$

where $\{a_n\}$ are statistically independent random variables having the distribution $P(a_n=0) = P(a_n=1) = 1/2$.

In this case, the expected value of $|X_{KT}(f)|^2$ becomes

$$E\left| \quad (f)\right|^2 \quad \left(A \ \ \mathrm{sinc}(\ t)\right) \sum_{n, \ =0}^{K-} E(a_n \ \ _m) e^{- \ 2pf(n- \ \ T} .$$

Now,

$$E(a_n a_m) = \begin{cases} \frac{}{2} & for\ n = m \\ \frac{1}{} & for\ n \neq m \end{cases} .$$

Hence, after rearranging terms,

$$E|X_{KT}(f)|^2 = \left(\quad t\,\mathrm{sinc}(ft)\right)^2 \left(\frac{K}{4} \quad \frac{}{4} \sum_{n,m=0}^{K \ \ 1} \quad {}^{j \ \ pf(n-m \ \ T} \right)$$

$$\left(\qquad (ft)\right) \left(\frac{K}{4} + \frac{1}{4}\left(\frac{p}{\sin \ \ fT} \right)^2 \right).$$

Dividing by KT and taking the limit yields:

$$S_x(f) = \left(\frac{At}{} \mathrm{sinc}(ft \quad \right) \left(\frac{T}{4} + \frac{1}{4} \sum_{n=-\infty}^{\infty} \ _0(f \quad \frac{n}{}) \right) \text{ for unipolar modulation.} \tag{3}$$

As can be seen from the above expression, the power spectral density with non-negative modulation consists of a continuous spectra in addition to the original set of spectral lines.

Theoretically, one can eliminate spectral lines by allowing the modulation to be bipolar; i.e., by letting the random variables $\{a_n\}$ take on negative as well as positive values. In this case, with $\{a_n\}$ statistically independent and $P(a_n=-1) = P(a_n=+1) = 1/2$, one can easily obtain that

$$S_x(f) = T\left(\frac{At}{T}\text{sinc}(ft)\right)^2 \text{ for bipolar modulation.} \tag{4}$$

In this case, all spectral lines have been effectively removed. The average power is given by

$$P_{ave} = \int^{\infty} \quad f)df = \left(\frac{t}{T}\right)^2$$

as expected. Unfortunately, any slight asymmetries in data probabilities or the addition of pulse train gating (e.g., packet switching or bursty communications) negates this result and spectral lines reappear.

Jittered Pulse Train

We next consider the power spectral density of a random process which jitters the positions of its individual pulses according to a random sequence $\{\mu_n\}$ as in Figure 3 below.

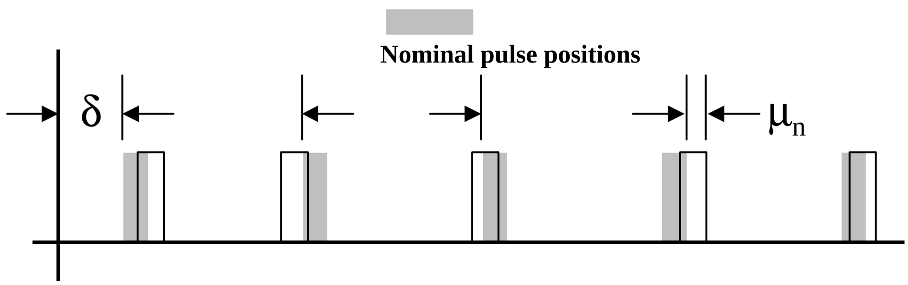


Figure 3. Jittered Periodic Random Pulse Train

Before computing the power spectral density for this random process, observe (from the above discussions) that the value for the random phase offset δ was seen to be irrelevant. Thus, without loss of generality, we can assume that δ = 0 with probability one. As above, we obtain

$$X_{KT}(f) \equiv \int_0^{KT} x(t)e^{-j2pft}dt = \int_{-t/2+m_0}^{t/2+m_0} Ae^{-j2pft}dt + \int_{-t/2+T+m_1}^{t/2+T+m_1} Ae^{-j2pft}dt + \cdots + \int_{-t/2+(K-1)T+m_{K-1}}^{t/2+(K-1)T+m_{K-1}} Ae^{-j2pft}dt$$

which, after performing the required integrations (and simplifying) becomes:

$$X_{KT}(f) = tA\frac{\sin(pft)}{pft}\sum_{n=0}^{K-1} e^{-j2pf(nT+m_n)}$$

Taking the expected value of the square of this relationship yields:

$$E|X_{KT}(f)|^2 = \left(tA\,\text{sinc}(ft)\right)^2 \Gamma(K, f)$$

where

$$\Gamma(\mathrm{K,f}) \equiv E\left|\sum_{n=0}^{K-1} e^{-j2\pi f(nT+\mu_n)}\right|^2 .$$

Expanding, one obtains

$$\Gamma(\mathrm{K,f}) = \sum_{n,m=0}^{K-1} e^{-j2\pi f(n-m)T} E\left(e^{-j2\pi f(\mu_n-\mu_m)}\right)$$

For $\{\mu_n\}$ statistically independent and uniformly distributed on the interval $[-\beta,\beta]$, the expectation above can be computed as follows:

For n=m, $E\left(e^{-j2\pi f(\mu_n-\mu_m)}\right) = 1$

For $n \neq m$,

$$E\left(e^{-j2\pi f(\mu_n-\mu_m)}\right) = \frac{1}{4\beta^2}\int_{-\beta}^{\beta} dx \int_{-\beta}^{\beta} dy\, e^{-j2\pi f(x-y)} = \mathrm{sinc}^2(2f\beta).$$

Combining these equations and simplifying, yields

$$\Gamma(\mathrm{K,f}) = \mathrm{sinc}^2(2f\beta)\left(\frac{\sin\pi fKT}{\sin\pi fT}\right)^2 + K\left(1-\mathrm{sinc}^2(2f\beta)\right)$$

or, taking the limit as K tends toward infinity,

$$\lim_{K\to\infty}\frac{1}{KT}\Gamma(K,f) = \frac{\mathrm{sinc}^2(2f\beta)}{T^2}\sum_{n=-\infty}^{\infty} u_0\left(f-\frac{n}{T}\right) + \frac{1-\mathrm{sinc}^2(2f\beta)}{T}$$

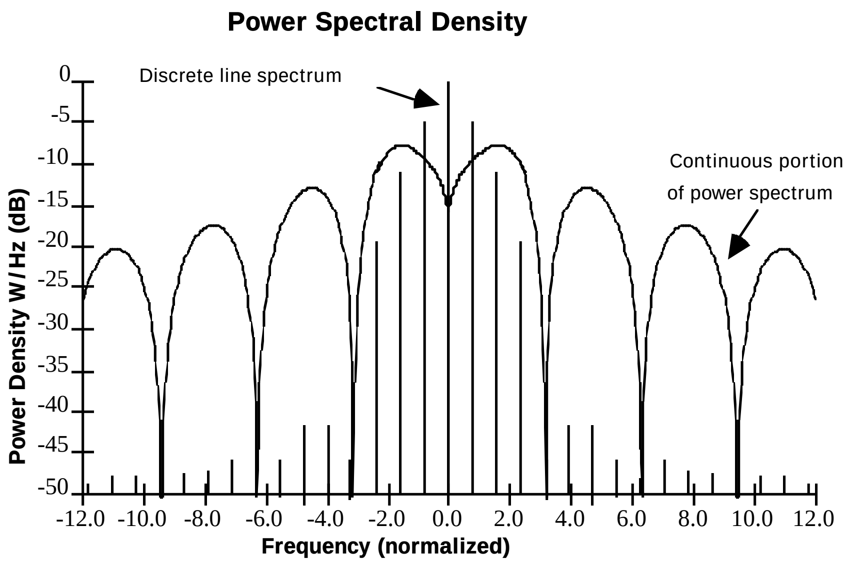
giving the final result for the power spectral density of

$$S_x(f) = \left(\tau A\,\mathrm{sinc}(f\tau)\right)^2\left[\frac{\mathrm{sinc}^2(2f\beta)}{T^2}\sum_{n=-\infty}^{\infty} u_0\left(f-\frac{n}{T}\right) + \frac{1-\mathrm{sinc}^2(2f\beta)}{T}\right]$$

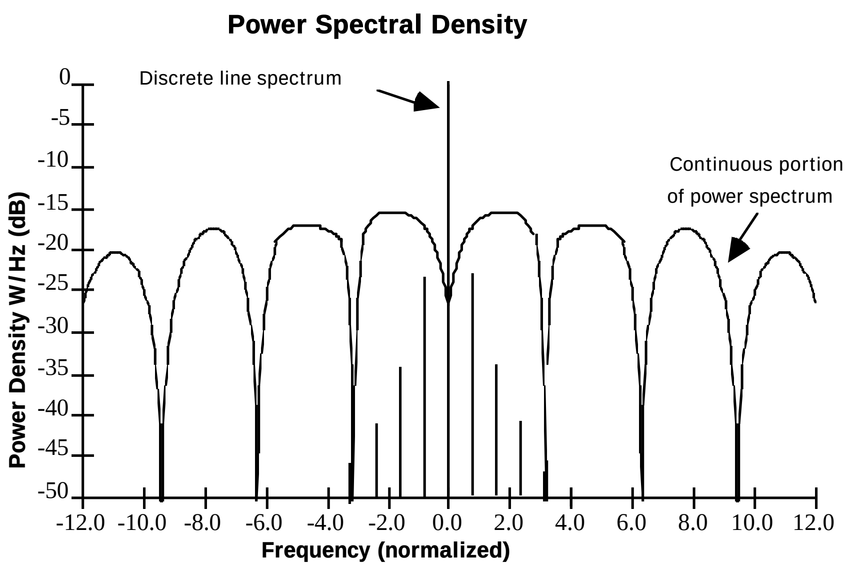
jittered pulse train, no modulation

(5)

As can be seen from relationship (5), the effect of random pulse jitter is to significantly attenuate the energy contained within the higher frequency spectral lines. In particular, the larger the value of β (relative to the pulse width τ), the quicker the decay of the term $\mathrm{sinc}^2(2f\beta)$, which multiplies the discrete spectral line component of the power spectrum, with increasing frequency. (See Figure 4 below.)



(small β)



(large β)

Figure 4. Power Spectral Density of Randomly Jittered Pulse Train

For a binary (nonnegative) modulation on top of this pulse jitter, the power spectrum can be shown to be

$$S_x(f) = \left(tA\,\mathrm{sinc}(ft)\right)^2 \left[\frac{\mathrm{sinc}^2(2fb)}{4T^2} \sum_{n=-\infty}^{\infty} u_0\left(f - \frac{n}{T}\right) + \frac{2 - \mathrm{sinc}^2(2fb)}{4T} \right]$$

jittered pulse train, unipolar modulation

(6)

(Note: This results in a further attenuation of the discrete spectral components by an additional 3 dB relative to the continuous part of the spectrum.

For bipolar modulation, the power spectral density can be shown to be identical to that of an unjittered random process with bipolar modulation, namely:

$$S_x(f) = T\left(\frac{A t}{T}\mathrm{sinc}(f t)\right)^2 \text{ jittered pulse train, bipolar modulation.} \tag{7}$$

Appendix B
A Comparison of Ultra Wideband and Spread Spectrum Waveforms

1. Introduction

It has been suggested[11] that an appropriate figure of merit for a low probability of intercept and detection (LPI/D) waveform is the quantity "Range x Bandwidth / Joule". That is, the further the range, the wider the bandwidth and the less amount of energy used to achieve these values, the more covert is the resultant communications system.

Since the received signal strength from a point source varies as R^{-2} for line-of-sight (LOS) communications and as R^{-4} for mobile communications (due to multipath cancellation), it is perhaps more mathematically appropriate to consider the "figure of merit" as the ratio

$$x \equiv \frac{R^2 B}{E_b} \tag{1}$$

where R is the communications range, B is the signal bandwidth and E_b is the signal energy per bit. (From the range equation, the received signal-to-noise ratio (SNR) is inversely proportional to ξ.) Note that $E_b = P\tau_b$ where τ_b is the bit duration and P is the signal power, assumed to be a constant over the bit duration.

2. Ultra Wideband Waveforms

2.1 UWB LPI/D Figure of Merit

For an ultra wideband (UWB) waveform, the bit duration and the instantaneous bandwidth are related by the Fourier transform relationship between time and frequency. That is, the wide bandwidth in an ultra wideband waveform is produced by pulse duration/shaping and not by spreading with a chipping or hopping sequence as performed by direct sequence and frequency hopping spread spectrum. Thus, the waveform's time-bandwidth product is given by[12]

$$B\tau_b \approx 1. \tag{2}$$

From the communications range equation, the received signal-to-noise ratio (SNR_R) is given by the expression

$$SNR_R = \frac{P_T G_T G_R \lambda^2}{(4\pi)^2 R^2 kTB} \tag{3}$$

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[11] Telephone conversation with Dr. Mark McHenry, DARPA/TTO, 13 March 1998.

[12] For a rectangular pulse, the time-bandwidth product for a 3 dB bandwidth is approximately $B_{3dB}\tau_b \approx 0.886$. The (90% energy) time-bandwidth product is $B_{90\%}\tau_b \approx 1.22$, and the (99% energy) time-bandwidth product is $B_{99\%}\tau_b \approx 2.96$.

where P_T is the transmitted power; G_T and G_R are the transmit and receive antenna gains, respectively; λ is the transmission wavelength; k is Boltzmann's constant; and T is the effective system noise temperature.[13]

Combining relationships (2) and (3) into equation (1), one obtains that[14]

$$x = \frac{m}{(SNR_R)t_b} \tag{4}$$

with

$$m = \frac{l^2 G_T G_R}{16p^2 kT}. \tag{5}$$

Note that the quantity μ does not depend upon bandwidth or pulsewidth, but rather is a function of system operational parameters such as antenna gains, center frequency and system noise temperature (e.g., LNA performance). Of course, for any communications system, the received signal-to-noise ratio (equivalently, energy per bit ratio E_b/N_0) determines the resultant bit error rate (BER) for a given modulation strategy.[15]

A cursory examination of equation (4) would suggest that, for a given received signal-to-noise ratio, the LPI/D Figure of Merit can be made arbitrarily large by simply reducing the pulsewidth τ_b. Unfortunately, as τ_b decreases, the peak transmit power also needs to increase in order to keep the energy per received bit a constant.

> ***Thus, a practical limit on the achievable LPI/D Figure of Merit for a UWB communications system is determined by the minimum achievable pulsewidth given a peak power constraint at the transmitter.***

Fortunately, for most practical applications, these constraints are very mild as is seen by the following example.

---

[13] Note that for any spread bandwidth system, λ is an extended value with a more accurate representation for SNR being an integral over the frequency range of interest; where $P_T = P_T(\lambda)$, $G_T = G_T(\lambda)$, $G_R = G_R(\lambda)$, etc. However, a reasonable estimate of SNR can be found by using the nominal operating wavelength.

[14] In mobile communications, or general multipath propagation, the received signal-to-noise ratio can be shown to be $SNR_R = \frac{l^2}{(4pR)^2}\left[2\sin\left(\frac{2p}{l}\frac{h_T h_R}{R}\right)\right]^2 \frac{G_T G_R P_T}{kTB} \approx \frac{(h_T h_R)^2}{R^4}\frac{G_T G_R P_T}{kTB}$ where h_T (h_R) are the transmit (receive) antenna heights, respectively. Thus, a more appropriate LPI/D measure may be $\xi = R^4 B/E$.

[15] Van Trees, H.L., **Detection, Estimation and Modulation Theory**, Vol. 1, Chapter 4, Wiley, NY, 1968.

2.2 UWB Examples

2.2.1 Example 1: T1 (1.544 Mb/s) Data Transmission

Consider an ultra wideband communications system requiring a range of 10 miles utilizing one omnidirectional (0 dBi) antenna (e.g., UAV or MAV mounted) and a low gain (+8 dBi) antenna such as an omnidirectional wideband transmission line or patch design. In addition, let the system operate with an L-band center frequency of 1.5 GHz, a 2 dB noise figure and a required (uncoded) Eb/No of +15.6 dB.[16] The required peak power vs. pulsewidth for this hypothetical system is shown in Figure 1 below.

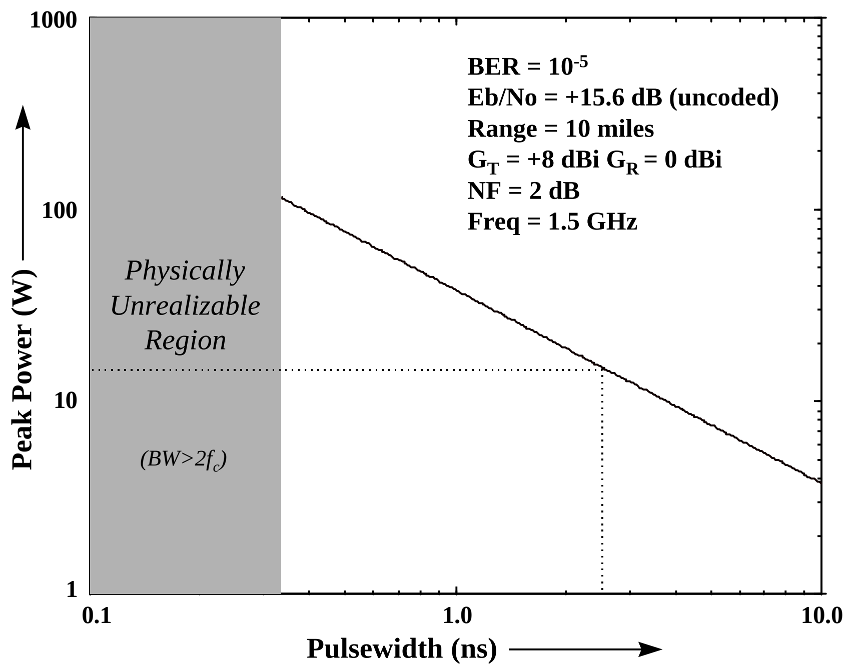

Figure 1. Power vs. Pulsewidth for Example UWB Communications System.

As expected, the requisite peak power increases for a decrease in UWB pulsewidth; however, note that with a 2.5 ns pulse (approximately 400 MHz instantaneous bandwidth), a peak power of approximately 14.5W is required to communicate a distance of 10 miles. [Note that forward error correction (FEC) coding gain can further reduce this peak power requirement, but only by a small amount.] With currently available components, power levels in excess of several hundred watts peak are now achievable.

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[16] For ON-OFF keying (OOK), the bit error probability is given by the relationship $P(e) = Q\left(\sqrt{\frac{E_b}{2N_0}}\right)$ where Q(x) is the complementary error function defined as $Q(x) = \frac{1}{\sqrt{2p}}\int_x^{\infty} \exp(-u^2/2)du$. Eb/No = +15.6dB corresponds to a 10^{-5} BER.

The average power of such a UWB emitter can be very low. For example, at a T1 data rate of 1.544 Mb/s, the average output power is approximately 56 mW with a 14.5W peak waveform. This corresponds to a peak power density of 36 nW/Hz, and an average density of only 140 pW/Hz. By way of comparison, a 300 MHz garage door opener has a peak power output of approximately 1 mW and a bandwidth (determined by a dielectric resonator) of roughly 500 kHz. This corresponds to an average (as well as peak) power density of 2 nW/Hz – or 11.5 dB *higher* than for the UWB system which has a communications range of over 10 miles.

2.2.2 Example 2: 32 kb/s Digital (CVSD) Voice Transmission

In a UWB system, the energy per bit does not depend upon the data rate. That is, doubling the rate does not require a corresponding doubling in power to keep the product $P_T\tau_b$ a constant, since τ_b stays fixed. Thus, the peak power is selected to achieve the desired BER; while the average power depends upon the data rate. Lower data rates yield lower average powers because of the reduced duty factor.

Consider reducing the data rate from 1.544 Mb/s to 32 kb/s as used in continuously variable slope detection (CVSD) digital voice. For CVSD voice, a significantly higher BER can be tolerated, e.g. 10^{-3}. At a 10^{-3} BER, the required Eb/No for OOK is now 12.8 dB. Thus, a peak power of only 7.6W is now needed for a 10 mile range. *Note that the peak power was reduced because of an increase in the acceptable BER and* not *because of a decrease in data rate.*

For the 400 MHz bandwidth example above, the average power output at a 32 kb/s data rate would be roughly 600 μW, corresponding to an average power density of only 1.5 pW/Hz.

2.3 Coherent Addition in UWB Processing

The above discussion has been limited to "single pulse" detection of a UWB waveform. However, it is of interest to consider the coherent addition of pulses in an effort to further reduce the LPI/D signature.

From the derivation in Section 2.1, $x = \frac{m}{(SNR_R)t_b}$ where τ_b was defined as the pulsewidth and SNR_R was the single pulse signal-to-noise ratio.

Suppose that a single bit of information is now further subdivided into a sequence (possibly pseudo-randomly generated) of N UWB pulses each of duration τ_b. As before, τ_b sets the ultimate system bandwidth, but the required signal-to-noise ratio can decrease by the factor N since the noise adds noncoherently. Thus, for coherent-UWB

$$x = \frac{Nm}{(SNR_R)t_b} \,. \tag{6}$$

Thus, the effect of utilizing a coherent addition scheme is equivalent to increasing the bandwidth of the UWB waveform by the factor N.

The primary difficulties in achieving coherent-UWB are the following:

a. maintaining coherence over a large number of very short duration pulses can place severe requirements on oscillator stability, particularly at low data rates; and,

b. at high data rates, the improvement factor N becomes limited by physical realizability (For example, at a T1 data rate, N=100 requires a pulse rate of 154 megapulses per second.).

However, the advantages can be substantial. In contrasting UWB with DSSS below, it will become evident that coherent-UWB can significantly outperform any realizable DSSS communications system, even for very low values of N.

As an example, consider the 32 kb/s CVSD voice waveform discussed above. With an N of only 10, the required (uncoded) Eb/No can be reduced to +2.8 dB, requiring a peak power of only 760 mW. Note, however, that the *average* power, and hence the *average* power density, remain the same since the duty cycle is also increased by the same factor N – i.e., 600 μW and 1.5 pW/Hz, respectively.

> NOTE: Various researchers have considered the use of multiple UWB pulses to represent a single bit of information. Unfortunately, in each of these cases, the single pulse detection performance of the receiver was very poor. Pulse addition, therefore, was *necessary* in order to achieve a sufficiently high probability of detection at the receiver. This defeats the purpose of coherent combining for LPI/D and simply results in more energy per unit time being transmitted.
>
> For coherent combining to be of any value for LPI/D, it is therefore essential that a detector be used which has sufficient sensitivity to detect a single UWB pulse with the minimum Eb/No required for reliable communications. In this fashion, each bit of information can be further subdivided into UWB “chips”, each of which by themselves would be deeply buried in the background thermal noise. Coherent combining results in an N-fold SNR enhancement which then enables the combined waveform to trigger a detection event.
>
> MSSI utilizes a sensitive tunnel diode detector which has been shown to permit detection near the thermal noise floor. This detector permits single pulse detection and would form the basis for a coherent combining receiver processor.

3. Spread Spectrum Waveforms

3.1 Direct Sequence Spread Spectrum Figure of Merit

For a direct sequence spread spectrum (DSSS) waveform, a single bit of information is further subdivided into a number of spreading “chips”. The ratio of the bit duration τ_b to the chip duration τ_c is denoted as the spreading or processing gain G_P. Thus, the waveform’s time-bandwidth product is given by

$$B\tau_c \approx 1. \tag{7}$$

For a DSSS waveform with processing gain G_P, the received signal-to-noise ratio (SNR_R) is given by

$$SNR_R = G_P \, \frac{P_T G_T G_R \lambda^2}{(4\pi)^2 R^2 kTB} \, . \tag{8}$$

Thus, combining relationships (7) and (8) into equation (1) noting that $E_b = P_T\tau_b$, one obtains that

$$\xi = \frac{G_P \mu}{(SNR_R)\tau_b} = \frac{\mu}{(SNR_R)\tau_c} \tag{9}$$

where μ is defined in (5).

From relationship (9), for a given received signal-to-noise ratio, the LPI/D Figure of Merit for a DSSS system can be made arbitrarily large by reducing the "chip" width τ_c. For a given bit duration or signaling rate, this corresponds to increasing the system processing gain as expected. Unfortunately, as the processing gain increases, the complexity of the DSSS system also increases.

> ***Thus, a practical limit on the achievable LPI/D Figure of Merit for a direct sequence spread spectrum system is determined by the maximum achievable processing gain given a realizable level of receiver complexity.***

Note that, for a spread spectrum waveform with a given processing gain, the peak power constraint at the transmitter is determined by the bit duration. Note that for any constant envelope waveform (e.g., PSK, GMSK, FSK, etc.), the peak and average power levels are identical.

3.2 DSSS Examples

3.2.1 Example 1: T1 (1.544 Mb/s) Data Transmission

Consider the same example as was considered for the UWB communications system. That is, a 10 mile range is required at 1.5 GHz using an omnidirectional (0 dBi) antenna at one end of the link, and a low gain (+8 dBi) antenna at the other. Assuming a T1 (1.544 Mb/s) binary phase-shift keyed (BPSK) waveform, a 10^{-5} BER corresponds to an Eb/No of +9.6 dB (6 dB better than for an OOK waveform commonly used by UWB systems).

The requisite peak power required for the DSSS can be computed from (8) to be approximately 14.6 mW. The following table provides a summary of the average power densities for the DSSS for different processing gains. Note that the system complexity increases significantly in attempting to achieve the higher processing gains.

Table 1. DSSS Power Densities vs. G_P (1.544 Mb/s System)

Processing Gain G_P (dB)	Bandwidth	Ave. Power Density	Receiver Complexity	Logic Family
10	15 MHz	950 pW/Hz	Low	CMOS
20	150 MHz	95 pW/Hz	Moderate-High	CMOS/ECL
30	1500 MHz	9.5 pW/Hz	Extremely High	GaAs?
33 (theoretical max)	3000 MHz	4.7 pW/Hz	???	???

Note that, on an *average power density basis*, a BPSK DSSS system with a spreading gain of 18.3 dB (100+ MHz BW) is comparable to the 400 MHz bandwidth OOK noncoherent-UWB system. Both systems were designed to achieve the required BER performance.

3.2.2 Example 2: 32 kb/s Digital (CVSD) Voice Transmission

Unlike a UWB system (cf. Section 2.2.2), the energy per bit for a given transmitter peak power *does* depend upon the data rate in a constant envelope system such as DSSS. At a 32 kb/s rate and 10^{-3} BER, the DSSS peak power can be further reduced to 158 µW. Table 2 illustrates the resultant power densities as a function of processing gain for this system design:

Table 2. DSSS Power Densities vs. G_P (32 kb/s System)

Processing Gain GP (dB)	Bandwidth	Ave. Power Density	Receiver Complexity	Logic Family
10	0.32 MHz	500 pW/Hz	Low	CMOS
20	3.2 MHz	50 pW/Hz	Low	CMOS
30	32 MHz	5 pW/Hz	High	CMOS
40	320 MHz	0.5 pW/Hz	Very High	ECL

As seen from the above table, the primary difficulty in achieving high bandwidth (and hence high LPI/D) is the high processing gain required. The higher the processing gain, the more complex the receiver architecture.

4. LPI/D Figure of Merit Comparisons

From the above examples, it is clear that a DSSS system can use substantially less peak power than a noncoherent (single pulse) UWB system to achieve the same communications system performance. From relationships (4) and (8), the relative LPI/D performance is given by

$$\frac{x_{UWB}}{x_{DSSS}} = \frac{(SNR_R^{DSSS})\, t_c^{DSSS}}{(SNR_R^{UWB})\, t_b^{UWB}} \; . \qquad (10)$$

For comparable modulation formats[17], the minimum required SNRs are the same and one obtains that

$$\frac{x_{UWB}}{x_{DSSS}} = \frac{t_c^{DSSS}}{t_b^{UWB}}, \tag{11}$$

the ratio of chipping time (for DSSS) to pulsewidth (UWB).

For coherent-UWB and DSSS,

$$\frac{x_{UWB}}{x_{DSSS}} = N \frac{(SNR_R^{DSSS})t_c^{DSSS}}{(SNR_R^{UWB})t_b^{UWB}} \tag{12}$$

with N the number of coherently summed UWB pulses.

In the above examples:

T1 (1.544 Mb/s) Data Transmission

The 400 MHz bandwidth OOK UWB waveform has the same LPI/D Figure of Merit as a 100 megachip/second (Mcps) BPSK DSSS waveform. (This takes into account the 6dB loss for OOK vs. BPSK signaling.) The required direct sequence processing gain is thus 18.1 dB. Note that a DSSS processing gain of 24.1 dB would be required to have the same LPI/D performance as an antipodal UWB modulation (+/- pulses).

To compete with an N=10 coherent-UWB signaling scheme, the DSSS system would require a chip rate of 1 Gigachip per second – a very complex design.

32 kb/s Digital (CVSD) Voice Transmission

As in the previous example, a 100 Mcps BPSK DSSS waveform has the same LPI/D performance as a 400 MHz bandwidth UWB signal. In this case, however, the direct sequence processing gain required is 35.0 dB. Note that a DSSS processing gain of 41.0 dB would be required to have the same LPI/D performance as an antipodal UWB modulation (+/- pulses).

Again, to complete with an N=10 coherent-UWB signaling scheme, the DSSS system would require a chip rate of 1 Gigachip per second.

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[17] An orthogonal OOK UWB waveform has a theoretical 6 dB performance disadvantage over an antipodal BPSK DSSS signaling scheme. However, antipodal modulation has also been used for UWB. This has the added advantage of removing spectral lines as was shown in Ross, G., R. Price and R. J. Fontana, "The Suppression of Spectral Lines for Improved Covertness in Ultra Wideband (UWB) Transmissions," **Proc. MILCOM 95**, San Diego, CA, November 1995.

5. Conclusions

An analysis of the LPI/D Figure of Merit, defined as

$$x \equiv \frac{R^2 B}{E_b},$$

demonstrated the equivalence of *noncoherent*-UWB and direct sequence spread spectrum communications for a given bandwidth and Eb/No to achieve a desired bit error rate. (OOK or amplitude shift UWB had a 6 dB disadvantage in Eb/No relative to BPSK DSSS.[18])

The practical limit on the achievable LPI/D Figure of Merit for a UWB communications system was determined by the minimum achievable pulsewidth given a peak power constraint at the transmitter; while the practical limit for DSSS was determined by the maximum achievable processing gain given a realizable level of receiver complexity.

However, it was also shown that *coherent*-UWB has a distinct LPI/D advantage over wideband DSSS systems even for small values of N and appears extremely promising for further development.[19]

Other UWB advantages include:

1. Cost – The primary advantage of UWB over DSSS is significantly lower cost at high levels of LPI/D. For example, a 500 or 1000 MHz instantaneous UWB bandwidth is readily achieved by proper design of transmit/receive filters, amplifier and antenna. The digital electronics is common for all bandwidths and depends solely upon the modulation rate. For DSSS, on the other hand, a 500 or 1000 Mcps system would be expensive to implement, with design costs increasing exponentially with decreasing data rates (due to higher spreading gains).

2. Data rate – At low data rates, it is very difficult to achieve sufficient spreading (processing gain) with a DSSS system to achieve the LPI/D performance of either a noncoherent- or coherent-UWB system. Similarly, at very high data rates (tens of Mb/s and higher), it is difficult to achieve any processing gain with DSSS. Both limitations are due to system realizability and cost constraints. In contrast, UWB

[18] A recent paper – Fontana, R.J., "A Novel Ultra Wideband (UWB) Communications System," **Proc. MILCOM 97**, Monterey, CA, November 2-5, 1997 – considered the detection-theoretic properties of a high-speed UWB detector which utilizes the charge-sensitive properties of a tunnel diode. The tunnel is a negative resistance device which is extremely responsive to low energy, subnanosecond pulses. In this paper, the author points out the advantages of this type of detector vs. a noncoherent energy detector and demonstrates a signal-to-noise ratio enhancement. This SNR improvement was not considered in the current paper.

[19] The LPI/D advantages of coherent-UWB were also pointed out to the author by Dr. John Betz, The MITRE Corporation. Dr. Betz is a member of the U.S. Government's Low Probability of Intercept Communications Committee (LPICC).

system bandwidth does not depend upon the underlying modulation data rate.[20] Thus, there has been considerable interest in UWB for very high data rate applications such as real-time video transmission and multi-terminal networking.

3. Multipath immunity – Modern high-speed UWB detectors are able to trigger close to the leading edge of the received pulse. As a consequence, multipath returns which occur later than the pulse duration do not affect the received signal strength. For example, with a 2.5 ns UWB pulse, any return due to path differentials larger than 2.5 feet ($c \approx 1$ ft/ns) is effectively gated out. Thus, UWB has been found to be extremely effective in in-building, vehicle-to-vehicle and vehicle-to-roadside communications.

   DSSS can also have good multipath immunity provided the spread bandwidth exceeds the reciprocal multipath delay. In this case, immunity is provided by the orthogonality of the PN code with its time-shifted replica. Unfortunately, most commercial applications of DSSS have been restricted to the three ISM bands (902-928, 2400-2483.5 and 5725-5850 MHz) where the available bandwidths are limited.

4. Dual Use – A UWB communications waveform is essentially indistinguishable from a low power UWB radar pulse. As a consequence, much of the same electronics can be used for both communications and high resolution radar.[21] In addition, since UWB detectors are capable of response times faster than 100 ps, the pulses can also be used for high precision geolocation.

   DSSS has also been used in precision ranging applications; however, precision is a function of spreading bandwidth which becomes very expensive for resolutions finer than a few feet.

[20] This independence of UWB spectrum occupancy on data rate is significant for another reason as well. DSSS has a familiar sin(x)/x structure which is readily exploited for identification (e.g., chip rate, carrier frequency, etc.); whereas UWB has a relatively “noise-like” structure which is more difficult to exploit.

[21] For example, in a Phase II SBIR program for the Navy’s Program Executive Office for Unmanned Aerial Vehicles and Cruise Missiles, MSSI developed a common UWB radar/communications module for radar altimeter, collision/obstacle avoidance and data link functions.