Before the Federal Communications Commission
Washington, D.C. 20554

In the Matter of Revision of Part 15 of the Commission's Rules Regarding Ultra-Wideband Transmission Systems	Docket No. 98-153

Introduction

XtremeSpectrum, Inc. (previously before the commission as OC, Inc.) is a telecommunications company currently engaged in the development of ultrawideband (UWB) communications devices. We applaud the commission's initiative and initial efforts at developing regulations for ultrawideband technology. We submit these comments in response to the commission's Notice of Inquiry (NOI) released September 1, 1998 regarding ultrawideband transmission systems. We have chosen to respond to certain specific questions as outlined within the NOI.

Applications and General Characteristics of UWB Devices

As a member of the UWB working group (UWBWG), we are aware of the creation of both a list of UWB applications as well as a list of functional types of UWB devices. We agree with those lists. In addition, we would suggest that other communication and sensor applications will be developed where the natural physical advantages of UWB are manifest. These benefits are outlined below.

Benefits of UWB Systems

Broadly speaking, UWB benefits fall in to two main classes: those deriving from large processing gain; and those deriving from the propagation and phenomenology characteristics of ultrawide relative bandwidth (as defined here and in the UWB WG general industry submission).

Processing Gain Benefits of UWB

UWB can be viewed as an extreme form of spread spectrum (SS). Consider that a spread spectrum system might have bandwidth (BW) of 20MHz, while an UWB system might have 2GHz. UWB systems have orders of magnitude more bandwidth than spread spectrum systems.

This leads to a corresponding increase in process gain (PG) and all its attendant benefits. Processing gain can be defined as the ratio of transmit bandwidth over data bandwidth,

$$PG = \frac{transmit\ BW}{data\ BW}.$$

For equal data bandwidth, of say 2MHz, a spread spectrum system of 20MHz has processing gain of 10, while an UWB system of 2GHz has processing gain of 1000.

High Connectivity

High processing gain implies large code space. A large code space allows for many low cross correlation (good) codes. The large number of good codes enables high connectivity both in terms of simultaneous users and pool of unique addresses. UWB systems can have orders of magnitude more simultaneous users in a cell, with the same data rate and multiuser interference level, than a conventional spread spectrum system.

Near-Far Problem

The large processing gain of UWB systems can also be used to mitigate the near-far problem. The near-far problem results when one transceiver is communicating with two others, one of which is closer than the other. The problem develops when the nearer of the two drowns out the farther. Said another way, the cross correlation between the codes is not low enough to compensate for the path loss difference. Because UWB codes can be longer than typical spread spectrum codes, they can be selected to have lower cross correlation and are therefore less sensitive to the near-far problem.

Secure Communication

UWB signals can also provide secure communications. This is an important benefit that can be exploited for covert operations and for preventing theft of service. Engineered correctly, UWB devices produce low probability of detection\intercept (LPD\LPI) signals. A view on this is that a signal's detectability comes from how 'spikey' it appears to the instrument used to interrogate it. That is, signals are hard to detect if they have low peak–to–average ratios in the domain of the interrogating instrument. For instance, UWB signals that are properly modulated appear smooth in the frequency domain and are therefore hard to detect on a spectrum analyzer.

Phenomenological Benefits of UWB

There are four principals of physics at work that make UWB essential to solve certain classes of communication and remote sensing problems. They are: scattering behavior; penetration depth; coupling of resolution and bandwidth; and interferometric patterns. These are described separately below and are tied together in an ultrawideband implementation.

Scattering Behavior

The first principal is that the ratio of object size to wavelength (λ) governs the scattering off an illuminated object. Object size is characterized as being in the Rayleigh region when the object size is less than $\lambda/4$. In this case, the wave has little interaction with the object, little scattering occurs, and what does, is not directional. The scattering amplitude is typically proportional to F^2 (where F is frequency). When the object is between $\lambda/2$ and 6λ, the object is characterized as being in the resonant region. Here the scattering amplitude oscillates as the frequency is swept, and can be large at the peaks. The scattered energy is generally directional, but in a few broad beams. For objects larger than 6λ the oscillatory behavior damps down and the object is said to be in the optical region. The scattered energy tends to be highly directional in a large number of beams. The amplitude on any single beam generally takes the form F^a where a = -1, -.5, 0, .5, and 1, depending on the object shape and the feature causing the scattering. UWB radars take advantage of their frequency spectrum and use it to estimate a to identify scattering mechanisms.

These three regions are important for radar and communications because as the frequency goes down, the scattering lobes become broader, and objects scatter less or stop scattering. For the radar, this phenomenology reduces clutter. For the communications system, this phenomenon reduces the density of multipath reflections, and also reduces the variance in the multipath due to the broader scattering lobes.

Penetration Depth

The second principal is that the penetration depth into a lossy material/media is proportional to *l*. Therefore, if one wishes to detect a bunker buried underground, lower frequencies are more suitable. Similarly, if one wishes to communicate through walls and floors, lower frequencies are more suitable than higher ones. For example, measurements show that attenuation through a concrete wall is roughly 10*F* dB/m (*F* = GHz)[1]. Thus to penetrate, we need the lowest possible frequencies, but to resolve multipath reflections or image objects, we need the best resolution. Therefore, the optimum device to communicate or image through a concrete wall, is one that operates at the lowest possible frequency, yet provides the best resolution at those low frequencies. This is exactly what UWB—ultrawide *relative* bandwidth—devices do.

Bandwidth and Resolution

The third principal is that time and frequency resolution are inversely coupled. Wide bandwidth is required to get fine time resolution. Inversely, long time scales are required to get high frequency resolution. Similarly, putting notches in the spectrum must put time sidelobes into the time-domain waveform. The only way to get wide bandwidth, and the resulting fine time resolution, at low frequencies is to have wide relative bandwidth, which is the definition of UWB.

UWB waveforms provide optimal resolution at the lowest possible frequency. They take advantage of all three of the principals previously mentioned to mitigate multipath by both resolving it, and reducing it. Once resolved, UWB communications exploits multipath by phase correcting and coherently adding to form the final received signal. This process is sometimes referred to as RAKE processing. It gives UWB systems spatial diversity that can add reliability, and can reduce the power required to support a desired range and data rate.

Interferometric Patterns

The fourth principle is that interferometric processes begin to be ambiguous—having multiple peaks and nulls—when the relative bandwidth is small enough to allow multiple cycles in the (compressed) pulse. Again, this phenomena gets back to the definition of UWB as being wide relative bandwidth. An interference pattern always results when two or more waveforms arrive that are time shifted less than a pulse width. Figure 1 illustrates this phenomena by comparing a

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[1] John Aurand, "Measurement Of Short Pulse Propagation Through Concrete Walls", *Ultra-Wideband Short Pulse Electromagnetics 3*, (ed. Baum et al), Plenum Press, New York, 1997 pp. 239-246

1 GHz bandwidth UWB signal with a 1 GHz bandwidth narrowband (i.e. centered at 10 GHz) signal. The lower plot shows an inverted and non-inverted pulse summed, but time-shifted so that they are clearly separated. The UWB waveform is superimposed on the X-band waveform (that has many cycles). The upper plots show the output of a detector as the two pulses are shifted from exact overlap, to not-overlapped. It is clear that there are multiple fades with the narrowband signal, and that the fluctuations occur on a short time scale. By contrast, the detected UWB signal fluctuates slowly and has no multiple peaks or deep nulls.

Why is this important? Rapid multiple fades, and radar scintillation typical of narrowband communications and radar systems are largely mitigated with UWB for this reason—there are no multiple lobes. Tracking multiple terms and applying RAKE processing is easier with UWB due to this reduced scintillation, and the reduced rates of fluctuations. Most SAR (synthetic aperture radar) images, for example have speckle. Speckle is an interference pattern caused by multiple time shifted waves that are added together. Sometimes they add in-phase giving a magnified peak, and sometimes they add out-of-phase and cancel. UWB SAR has no speckle[2] because the sum of single-cycle waveforms sliding in time with respect to one another never add to make multiple nulls or a 2X peak, unless they are exactly aligned.

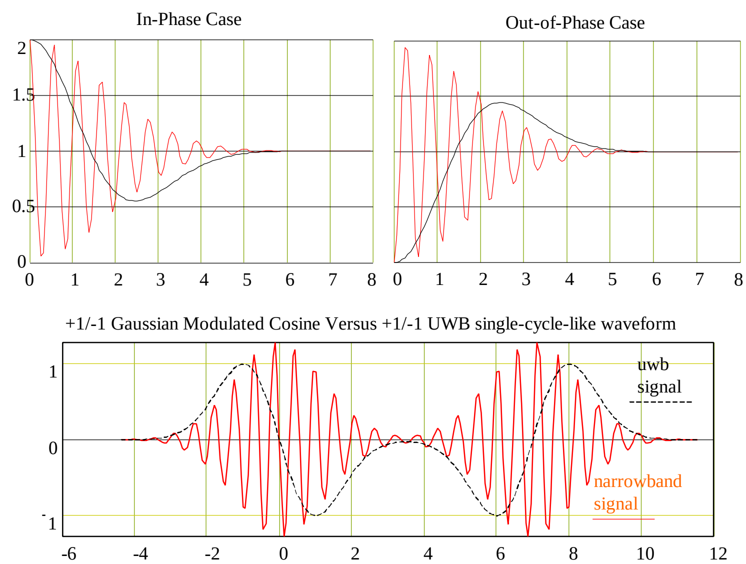

Figure 1. Upper plots show power received versus time-shift for a narrowband (i.e. 1 GHz bandwidth at 10 GHz) and a 1 GHz bandwidth UWB waveform. Lower plot shows the two waveforms.

Tying It All Together

UWB implementations provide performance advantages unavailable by any other approach because they take advantage of all four of the above principals of physics. A pictorial example illustrating the first three phenomena is shown in Figure 2. The tree shown being penetrated and scattering, could just as easily be a building wall or floor. The time domain plots are digitized

[2] John McCorkle, "Early Results from the Army Research Laboratory Ultra Wide Bandwidth Foliage Penetration SAR," SPIE Vol. 1942, ISBN 0-8194-1178-7/93 pp 88-95 April 1992

records taken directly from an antenna at the Army Research Lab[3,4]. It is clear from the time domain plot, that the scattering on each path contains all frequencies and provides very good time resolution. It is also clear from the frequency domain plot that deep fades occur. The deep fades, however, are not due to losses, but to multipath. Often measurements that pass as attenuation measurements, are actually unresolved multipath interactions. Also, note the change of wave shape in the time domain between path 1 and path 2. This waveform change is caused by the dielectric properties of the object as well as its shape, giving the F^a amplitude taper.

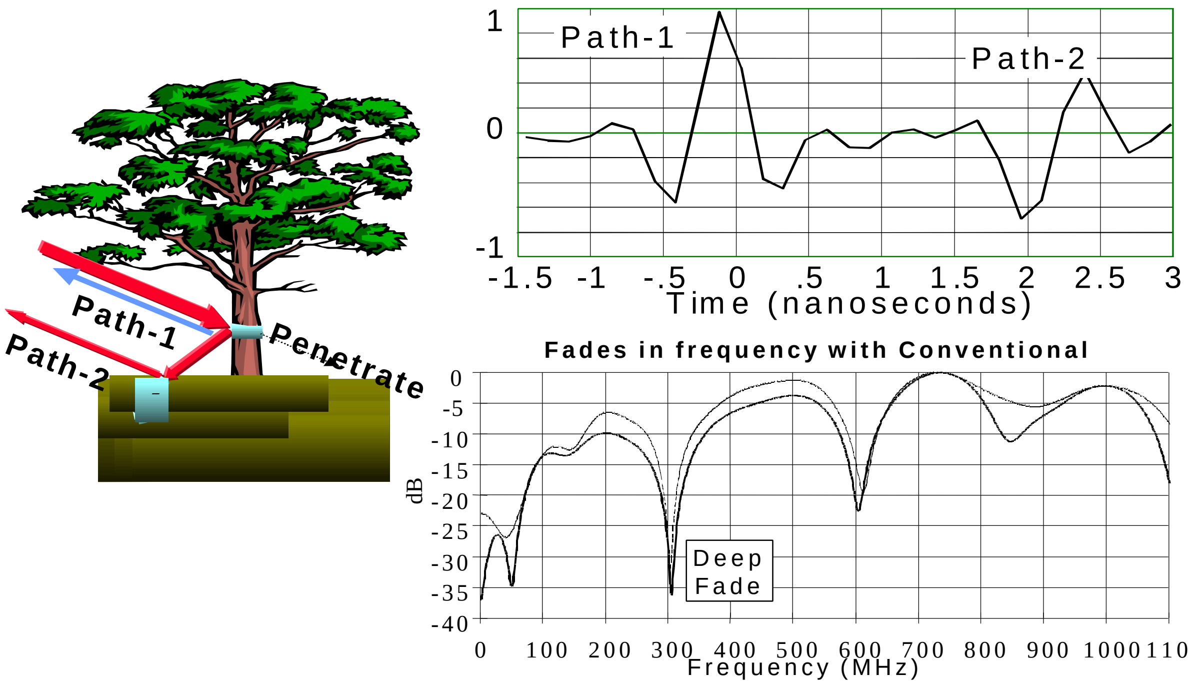

Figure 2. Illustration of scattering and penetration along with time domain and frequency domain plots.

Definition of UWB Technology

The commission has asked for comments on how it should define UWB technology. Someone may ask why not just define UWB as 1 or 2 GHz of bandwidth? Or ask what is the difference between 1 GHz at a center frequency of 2GHz, or 30 GHz, or 90 GHz? From a stealthy energy spreading perspective, or from a fine resolution perspective, bandwidth is bandwidth and center frequency is immaterial.

The motivation for preferring definitions based on bandwidth relative to center frequency follow from two primary desirable features. The first is immunity to scintillation and multipath. The only way to prevent scintillation (speckle or multipath fading, see also the discussion on interferometric patterns) is to have resolution that is approximately equal to the wavelength. The

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[3] John McCorkle, Lam Nguyen, *Focusing of Dispersive Targets Using Synthetic Aperture Radar*, Army Research Lab, Adelphi, MD ARL-TR-305, August 1994

[4] John McCorkle, "Focusing of Synthetic Aperture Ultra Wideband Data," IEEE Intl. Conf. On Systems Engineering: 1-3 Aug. 1991 ISBN 07803-0173-0

second is materials penetration with fine resolution which also requires resolution approximately equal to wavelength. This is equivalent to large fractional bandwidth, where fractional bandwidth B_f is

$$B_f = \frac{B}{f_c} = \frac{(f_h - f_l)}{(f_h + f_l)/2},$$

B is the bandwidth, f_c is the center frequency, and f_h and f_l are the high and low frequencies. These can be defined in a variety of ways. Common selections for f_h and f_l give the region in the frequency domain such that 90%, or 99% of the energy is contained between them, or they are the 20dB down points from the peak of the power spectral density envelop. This definition captures the idea that UWB systems match their bandwidth to their frequency content.

Licensed Regulation of Certain UWB Devices and Applications

XtremeSpectrum believes a program to grant licenses by site, or by application, may have merit in cases where power levels above the restricted band limits are needed. However, we prefer an unlicensed approach, or one where qualified operators self certify in a manner similar to the rules for tunnels and perimeter protection devices. Potential examples include steel mills and automobile manufacturing plants.

Sufficiency of Existing General Emissions Limits

The Class A and Class B restricted band limits have proven to be sufficient since their adoption in 1979. During that time digital systems (including personal computers) have proliferated widely. These systems unintentionally radiate in a manner very similar to the intentional radiation of UWB devices. The success of the general limits in protecting all users of the spectrum demonstrate their adequacy for UWB devices.

Should Different Limits be Applied to UWB Systems

At a minimum, UWB devices should be allowed to intentionally radiate at the Part 15 Class A and Class B limits. Under some conditions UWB devices should be allowed to radiate at higher levels. The basis for this is that the unintentional emissions of devices under Part 15 bring no benefits to society, while the intentional emissions of UWB devices can bring great and unique benefits, while causing no material increase to the ambient noise floor.

Cumulative Impact of UWB Emissions

Analysis, experiment, and practice all indicate that a proliferation of low power UWB devices will have a negligible effect on the noise floor. An XtremeSpectrum technical report that analyzes the effect of deploying a large set of UWB transmitters in a community is attached[5]. The key results are that the noise floor increases negligibly with a large proliferation of UWB devices, and that the noise floor decreases with increasing altitude (a key issue for aviators).

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[5] J. McCorkle, M. Rofheart. "Short Analysis on the Effects of a Large Number of UWB Systems", XtremeSpectrum, Inc., Technical Report TR-98-1, Fall 1998.

The analysis presented is conservative it that it made worst case assumptions for UWB. First it took the path loss model to be $1/R^2$ not $1/R^4$, and R^2 leads to a higher noise floor than R^4. Second, it assumed that vast areas were densely covered with transmitters, to an extent neither economically nor geographically feasible. Third, it assumed there were no losses through buildings or due to terrain, rough surfaces and intervening blockages or attenuation. All of these assumptions work together to lead the analysis to a higher upper (worst case) bound than should be expected.

Operational Restrictions on UWB to Protect Existing Users?

For UWB devices operating at the Part 15 Class A and Class B levels no operational restrictions are necessary. These limits have worked for unintentional radiators for some time, and will serve intentional radiators as well.

Necessity of UWB Modulation Techniques

UWB modulation techniques are necessary for communication and radar systems that must operate in opaque, lossy, inhomogeneous media and that simultaneously require high resolution. UWB is a unique asset that can simultaneously penetrate materials and resolve reflections. This enables foliage and ground penetration radar (FOPEN/GPEN) and wireless communications in buildings, urban and suburban environments, and foliage to be realized.

Short Analysis on the Effects of a Large Number of UWB Systems

John McCorkle
XtremeSpectrum Inc.
1077 30th Street NW, suite 311
Washington, DC 20007
johnm@comm-plus.net

Martin Rofheart
XtremeSpectrum Inc.
1077 30th Street NW, suite 311
Washington, DC 20007
martinr@cais.com

Abstract

This report analyzes the effect of deploying a large set of UWB transmitters in a community. They key results are that the noise floor does not increase without bound and that it decreases with increasing altitude. This result assumes free space propagation and does not depend on atmospheric attenuation. Intuitively, this follows from the transmit power falling with the square of the range from the antenna, while independent transmitters add in power not volts. Both analytic and simulated studies supporting this conclusion are included.

1 Victim Receiver Above Spherical Earth Analytic Formulation

We want to find the power received by a victim receiver as a function of its height above spherical earth. We will assume that all transmitters are non-coherent (i.e. negligible cross correlation between codes). This assumption is equivalent to saying that the transmitters are independent random variables with negligible cross correlation and zero mean. Thus, power adds, not voltage. If this were not the case, the solution would be a near-field antenna array pattern. This would be some moiré pattern with hot spots and nulls.

Due to the distance between the elevated receiver and the radiators, we will assume that a finite number of transmitters can be modeled as uniformly distributed power over the earth's surface. Figure 1 shows the geometry and the variable names. We will integrate the power from nadir to the horizon, much the way a calculation of surface area is done. We will assume a 4/3 earth radius model to account for refraction[1]. We will assume there is no atmospheric attenuation. Finally, we will assume isotropic radiation from the transmitters. Typically, one might assume that the antennas would be directed toward the horizon, and have reduced gain toward the sky. This gain reduction toward the sky would further reduce the power at higher altitudes.

The analysis proceeds as follows (power density normalized for convenience). Let

$P =$ xmit power density $= 1\ \mathrm{W/Hz/m^2}$ over surface of the earth

$h =$ height of victim receiver above earth

$d(q) = R\sin(q)$ = radius of the disk hitting the edge of the sphere

$c(q) = 2pd(q)$ = circumference of disk

$\mathrm{g}(q) = R(1-\cos(q))$

[1] L.M.Blake, Radar Range Performance Analysis, Chapter 5

$z(q) = h + g(q)$ = height of victim receiver above disk

$r^2(q) = z^2(q) + d^2(q) = h^2 + \left(2hR + 2R^2\right)\left(1 - \cos(q)\right)$ = square of path length

$P_r = \dfrac{P_t G_t}{4pr^2}$ = received power where r = range, P_t = xmit power, and G_t = xmit antenna gain

$b = \cos^{-1}\left(\dfrac{R}{R+h}\right)$ = the angle where the path is tangent to the surface of the sphere

$R\,dq$ = differential angle element

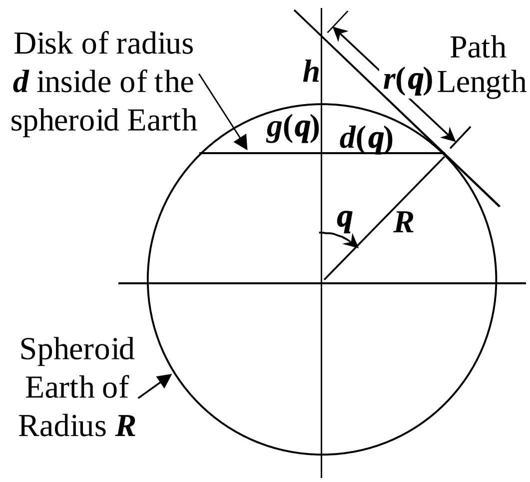

Figure 1. Geometry of victim receiver above spherical earth.

Then the power density received, in W/Hz/m^2 is

$$P_r = \int_0^b \frac{P\,c(q)}{4pr^2(q)} R\,dq = \frac{P\,R}{4(h+R)}\left(\ln\left(h(2R+h)\right) - \ln(h^2)\right).. \tag{1}$$

Figure 2 plots the received power versus the height for a victim receiver. The computation shows that as the altitude of the victim receiver goes up, the energy density at a victim receiver goes down. It would actually go down more if atmospheric attenuation were accounted for. Thus the worst case receiver position is at ground level. However, as the victim receiver altitude approaches zero, a discrete model is needed because the assumption that a finite number of transmitters can be modeled as a uniform density, breaks down.

2 Planar Analytic Formulation

We want to estimate a worst case upper bound on the effect on the noise floor due to a large set of ultrawideband (UWB) transmitters. We will model the earth as a square plane of area A with a grid of uniformly spaced UWB transmitters at spacing Δ. The surface area visible from a victim receiver at height h above a sphere is

$$A = 2pR^2 - \frac{2pR^3}{h+R}. \tag{2}$$

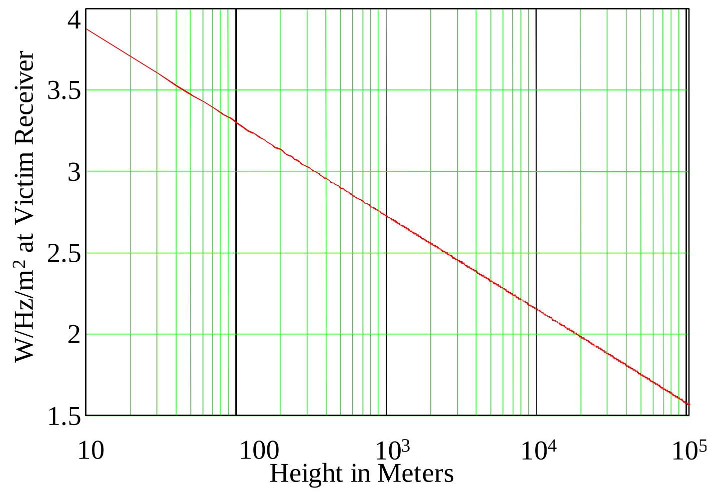

Figure 2. Plot of power at victim receiver versus its height for uniform 1W/Hz/m2 transmit power over the surface of the earth

For earth of radius $6.375\times10^{6}\,\text{m}$, using 4/3 earth radius to approximate refraction, and using a height of 2m, we find the surface area to be $A=1.07\times10^{8}\,\text{m}^2$. So the sides of a comparable square are $\sqrt{A}=10\,\text{km}$ long.

Figure 3 shows the square grid of transmitters and two cases for the victim receiver position. For case 1, the range from the victim to transmitter *(k,l)* is

$$\left\|r_{k,l}\right\|=\sqrt{\left(\Delta(k+.5)\right)^2+\left(\Delta(l+.5)\right)^2}=\Delta\sqrt{(k+.5)^2+(l+.5)^2} \tag{3}$$

and the number of transmitters along a side is $N=\sqrt{A}/\Delta$.

By symmetry, the power in each quadrant is identical, so we can compute the cumulative power received from a quadrant and multiply by four to find the total power density. Assuming for case 1, that N is even, the total power density at the victim receiver is

$$W_{upper}=\frac{P}{4p\Delta^2}\left(4\sum_{k=0}^{N/2-1}\sum_{l=0}^{N/2-1}\frac{1}{(k+.5)^2+(l+.5)^2}\right). \tag{4}$$

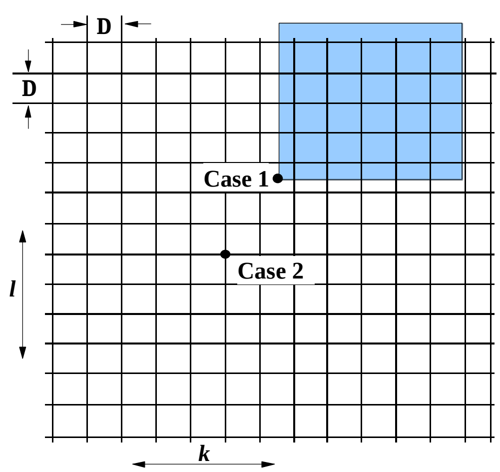

Figure 3. Uniform distribution of transmitters.

Again, by symmetry, the quadrant can be split into the lower triangle, upper triangle, and diagonal. So 4 can be rewritten as

$$W_{upper} = \frac{P_t}{4p\Delta^2}\left[8\left(\sum_{k=1}^{N/2-1}\sum_{l=0}^{k-1}\frac{1}{(k+.5)^2+(l+.5)^2}\right)+4\sum_{k=0}^{N/2-1}\frac{1}{2(k+.5)^2}\right] \tag{5}$$

where P_t is the transmitted power in W/Hz, and W is received power density in W/Hz/m^2

As an interesting note, if the plane were assumed infinite, the number of transmitters is also infinite, and the summation in (5) would be slowly divergent. However, as a practical matter, the problem is worst case bound by the finite surface of the earth and the finite density of UWB transmitters. Note also that the summations in (5) are best numerically conditioned if they are computed “backwards,” that is, from the edge of the square to the origin.

Case 2 (transmitter at the point removed) can be developed similarly, where we assume N is odd, and results in

$$W = \frac{P_t}{4p\Delta^2}\left(6\sum_{k=1}^{(N-1)/2}\frac{1}{k^2}+8\sum_{k=2}^{(N-1)/2}\sum_{l=1}^{k-1}\frac{1}{k^2+l^2}\right). \tag{6}$$

The plots in Figure 4 show the cumulative noise power from (5) and (6) as a function of transmitter separation (grid spacing). For the calculation, we set $P_t = 36p$ W/Hz so that each transmitter is producing 1W/Hz/m^2 at 3m from the isotropic antenna. This normalization is convenient because it allows one to easily scale the plots to any desired power density at the standard 3m specification.

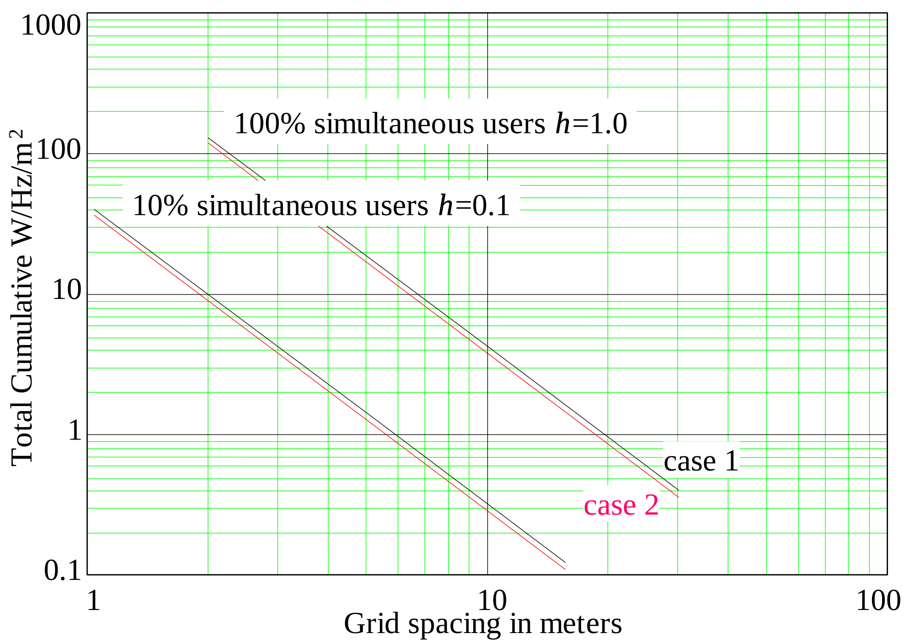

Figure 4 Total cumulative power a victim receiver located between grid points, when 36πW/Hz is being transmitted simultaneously at all grid points with isotropic antennas, on a 60 km X 60 km square.

The plots are given for activity levels of 100% and 10% (percent transmitters operating simultaneously). If uniform distribution of transmitters is assumed, other activity levels can be accounted for by an effective grid spacing Δ_e defined as,

$$\Delta_e = \Delta \sqrt{h} \quad (7)$$

where h is the activity level and translation is with respect to the h=1.0 curve.

As an example, if each transmitter were operating at the 75nW/MHz/m^2 restricted band level, with 10% operating simultaneously (h=0.1), then a spacing between transmitters of only 6m on grid maintains the restricted band level. This example is equivalent to placing 100 million transmitters into an area a little over 4 times the size of New York City. If transmitter separation is increased to 14m on grid, then the cumulative power due to UWB transmitters would drop to about 10% of the restricted band level (7.5nW/MHz/m^2).

A more realistic (and economically feasible) assumption on transmitter density might be 1000 per square mile (grid spacing ~50m). In this case, with 10% of transmitters operating simultaneously, the contribution to the noise floor would be 1% of the restricted band level (750pW/MHz/m^2). This transmitter density would still lead to about 50 million transmitters in and area equal to New York State alone.

Another way to look at the data is to take the ratio of the cumulative power outside of the closest transmitters, to the power received by the closest transmitters. For case 1, there are four close transmitters. For case 2, there are 8 close transmitters. Figure 5 shows the curves for the two cases.

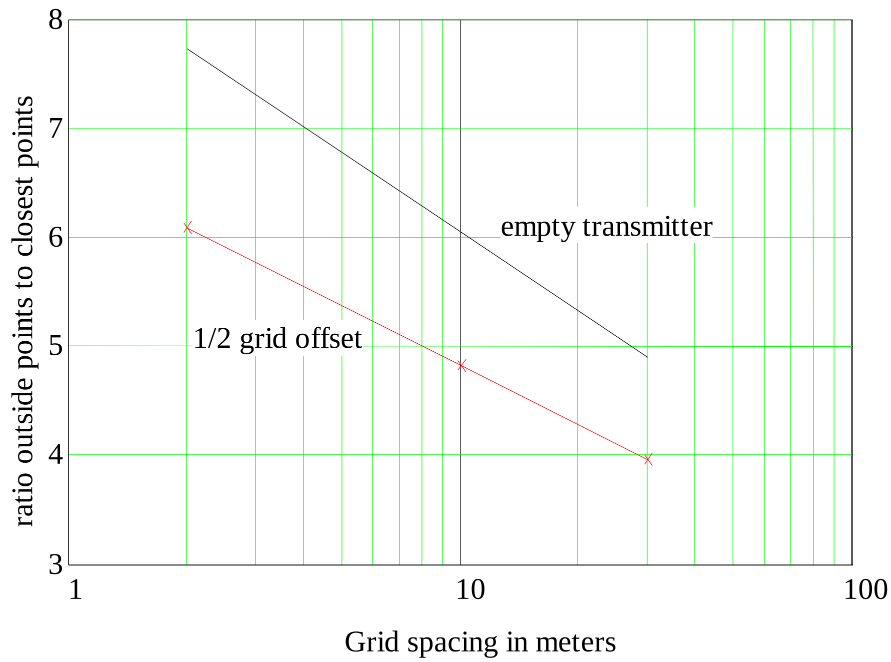

Figure 5 Ratio of total cumulative power to the power contributed by the closest four grid points.

3 Planar Simulation Results

A Matlab simulation was coded without the simplifying geometric assumptions used for the analytic case. Some specifics of the simulation are:

1. generated 1000 random codes of length 300 (not orthogonal, but 'low' cross correlation);
2. assumed a 20% duty cycle;
3. randomly generated distances for 1000 users in a square mile;
4. generated signals long enough in time that every user is on at least once during the collection time; and
5. randomly generated the phase for each user to insure that the transmitters are operating asynchronously.

As in the analytic case, the peak power at the receive point was dominated by the nearest user. The shape of the spectrum remained (nominally) the same as a single user (lying mostly between 200 MHz and 1300 MHz in this case). Also, the average power was considerably less than the peak power due to the random distribution of users and the 20% duty cycle.

4 Summary and Comments

It has been shown that as the altitude of a victim receiver goes up, the energy density at the victim receiver goes down. It would actually go down more if atmospheric attenuation were accounted for. Therefore, the worst-case receiver position is at ground level. On the ground, the power received by a victim receiver does not grow without limit since there are a finite number of transmitters over a finite area visible to a victim receiver. The power received is influenced most by the nearest transmitters due to the $1/R^2$ propagation.

The analysis presented is conservative it that it made worst case assumptions for UWB. First it took the path loss model to be $1/R^2$ not $1/R^4$, and R^2 leads to a higher noise floor than R^4. Second, it assumed that vast areas were densely covered with transmitters, to an extent neither economically nor geographically feasible. Third, it assumed there were no losses through buildings or due to terrain, rough surfaces and intervening blockages or attenuation. All of these assumptions work together to lead the analysis to a higher upper (worst case) bound than should be expected. Regardless of this, the shapes of the curves and their levels give insight into the problem, and do bound the expected levels.

Note that power can be reduced as the square of the range for the same data rate and BER performance. So, as transmitter-receiver density goes up, power go down. It would be interesting to tie together transmit power (and its effect on the noise floor) with performance (range, data rate, BER, etc.), and to optimize the aggregate throughput possible with a mesh topology like Figure 3, under a noise floor constraint.
