Cumulative Issues and Ultra-Wideband

I. Introduction

One major issue surrounding the use of ultrawide band (UWB) systems is the concern that a proliferation of UWB transmitters might raise the RF noise floor and harm the performance of other RF systems. In other words, the concern is that the cumulative impact of large numbers of UWB products might be to raise the potential for harmful interference to an unacceptable level.

The intent of this paper is to facilitate the FCC's Technology Advisory Council's (TAC) review of the cumulative impact issue by presenting the four analyses related to the cumulative impact of UWB. The papers, which follow this cover note, were submitted during the FCC's recent Notice of Inquiry (NOI) on Ultra-Wideband.

II. Background Information on Cumulative Impact

Clearly, signals from different UWB emitters will add. However, since none of the applications described in the Comments submitted to the FCC during the NOI process mentioned synchronized transmissions (which might lead to coherent emissions), then UWB emissions would be non-coherent and, therefore, these signals would add as noise power. The critical question is then just how would these additional signals impact the noise floor.

Numerous factors determine the cumulative impact of large numbers of UWB emitters. The key factors are:

- **Emitted Power.** The emitted power of each unit is a key factor. While UWB systems might incorporate power control algorithms, conservative models would assume all transmitters operating at their maximum legal power.

- **Propagation.** Propagation factors limit the amount of electromagnetic radiation at any given distance away from a transmitter. Free space propagation assumes that radiated power falls off as the square of the distance. Natural and made-made sources of attenuation (foliage attenuation, Fresnel attenuation, losses due to walls, structures, and people, and blockages from buildings and hills) are all frequently present and make likely that propagation paths are worse than free space. Thus, using free space propagation models would be a conservative choice; more accurate models would incorporate additional sources of attenuation.

- **User Density.** The density and distribution of UWB transmitters also plays a part in the cumulative impact. It is inaccurate to model emission levels from an aggregate number of UWB sources by simply summing the radiated power from each device. The separation among devices needs to be considered (along with appropriate propagation factors). Simple models would assume a uniform distribution of UWB emitters. More complex models would look at the possibility of non-uniform distributions.

- **User Duty Cycle.** The percentage of time that any UWB device operates is a factor that also limits the impact of UWB emissions. Few products are in operation continuously. Therefore, cumulative impact is lessened because not all UWB emitters will be operating simultaneously.

III. UWB Studies from the Notice of Inquiry (NOI)

The studies analyzing the cumulative impact of UWB from the NOI were conducted by experts on behalf of four UWB technology firms.

1. "Cumulative Electromagnetic Radiation from Multiple TDSI Transmitters," Time Domain Corporation, Dr. Jerry Raines.

- Dr. Raines' report describes calculations concerning the total electromagnet radiation from multiple Time Domain transmitters. Taking into account the shielding effectiveness of floors and ceilings in office buildings, it showed that thousands, if not tens of thousands, emitters can operate simultaneously indoors and outdoors before their cumulative radiation reaches the sensitivity level of avionics receivers in aircraft flying low over an urban environment. Outdoors, the devices are widely dispersed and space attenuation limits the cumulative radiation at any single receiver. Indoors, the attenuation of floors and ceilings compensate for the concentration of devices within a single building.

2. "An Analysis of Noise Aggregation from Multiple Distributed RF Emitters," Interval Research Corporation, W. C. Lynch, Ph.D., K. Rahardja, Ph.D., S. Gehring.

- The analysis from members of the technical staff of Interval Research starts with the assumption that emitters are uniformly distributed and shows that "noise buildup from an aggregation of emitters within a 45 degree cone below an airborne victim receiver is very limited…." Furthermore they state: "[I]f the analysis … is faulty we would conclude that we would observe unbounded aggregate power levels from the many contemporary RF sources that are spatially divide. Such sources include cellular phone systems, FM radios and even AM radio stations. *No such aggregation is observed*."

3. "Short Analysis on the Effects of a Large Number of UWB Systems," XtremeSpectrum, Inc., John McCorkle and Martin Rofheart, Ph.D.

- This report evaluates two scenarios. One where the victim receiver is above a spherical earth on which there is a uniform distribution of emitters. The other assumes the victim receiver is 2 meters above the ground and surrounded by a planar surface filled with a uniform distribution of emitters. In both cases, the authors assume free space attenuation and isotropic antennas. In the first case, analysis suggests that power falls off with increased altitude above the surface, but more slowly than pure free space attenuation. In the second case, the authors conclude that "the power received is influenced most by the nearest transmitters due to the $1/R^2$ propagation."

4. "The Effect of Proliferation of Wideband Devices," A.D. Little Corporation

- The A.D. Little Corporation maintains that the proliferation of UWB devices can be studied in light of the emissions of individual devices, their distribution in space and the propagation conditions surround them. The report calculates the effect of individual device emissions at the level of existing general limits, and defines a minimum distance beyond which another system is unlikely to suffer interference because the received power becomes less than the thermal noise power of the receiver. Proliferation scenarios were defined, and a model was constructed which allows interfering field strengths and signal levels to be estimated for different levels of extreme proliferation. To the extent that the models fairly approximated reality, it was found that the effect of UWB devices was undetectable except in very close proximity. This result suggested that UWB devices operating in high concentrations which coincide with a lossy propagation environment may indeed be benign toward other users.

5. "Cumulative Impact of Large Numbers of TM-UWB Users," Time Domain Corporation, Paul Withington

- The analytic technique in this report is different from the others. Assuming free space attenuation, the author created a simulation that randomly distributed increasingly larger numbers of emitters over an area and then calculated the field strength at a large number of points within that area. From these calculations, the RMS value was calculated. The results suggest that even with 100 users randomly distributed over an area of 50 meters by 50 meters, the average field strength was only slightly more than 1 dB above the field strength from a single emitter (measured at 3 meters). A worst case analysis was also conducted. This worst case analysis in which 100 users were randomly distributed found that the mean value of the worst cases from each of 1,000 simulations was less than 6 dB greater than the field strength of a single emitter.

IV. Conclusion

Four independent studies taking various approaches with different models have resulted in the same conclusion — there will be no significant rise in the RF noise floor. The noise floor is set by the closest UWB transmitters.

Just as the light from street lamps is blocked and absorbed by trees, buildings and natural land formations, a driver or pedestrian at night will see only what is illuminated from the nearest street lamp. Likewise, there are perhaps an infinite number of stars in the sky, but we see only individual points of light. In the case of UWB emitters, those in the closest proximity are what set the level of the noise floor. A single UWB transmitter within ten feet of someone in Atlanta determines the noise floor, not the existence of any number of devices in New York City.

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Please Note: The contact information for XtremeSpectrum has changed to the following,
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CUMULATIVE ELECTROMAGNETIC RADIATION FROM MULTIPLE UWB TRANSMITTERS

December 4, 1998
Report Prepared for:
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INTRODUCTION

This report describes calculations concerning the total electromagnetic radiation from multiple TDSI transmitters. Of particular interest is the power incident upon various avionics receivers in an aircraft flying low over an urban environment. Taking into account the shielding effectiveness (SE) of the floors and ceilings in office buildings, it will be shown that thousands, if not tens of thousands, of emitters can operate before reaching the sensitivity levels of these avionics.

The calculations were performed using an analytic model that was reported in December 1991. The derivation of that model, excerpted from that report, is included in the Appendix here. Briefly, the original model represented various environments as cylinders. Depending upon the dimensions of the cylinder, that shape could model a tall building, a sprawling building, or an entire populated area. Propagation within and around the cylinder was modeled using the extensive measurements of Okumura, at a frequency very near the TDSI frequency of interest here.

For the present report, the model was extended to include stacks of cylinders, or wafers. Each wafer in the stack is separated by an attenuating slab. This accounts for the SE of floors and roofs as reported by Owen and Pudney. For example, Exhibit 1 shows the model for a 25-story office building, one of the environments of interest here.

DESCRIPTION OF THE COMPUTATIONS

Three different avionics receivers and two different emitter environments were considered. The receivers were chosen from a longer list shown in Exhibit 2. We chose what appear to be the worst case receivers, in terms of sensitivity and/or bandwidth. They are: 1) voice communication; 2) DME (Distance Measuring Equipment); and 3) GPS (Global Positioning System). It is seen that we consider both aircraft voice communications and aircraft navigation. For those receivers which operate on many channels, we selected the lowest frequency because, according to our model, that is the worst case. So, our computations should provide a good indication concerning whether aircraft safety is affected.

The two different environments are: 1) outdoors throughout an urban environment with radius 8,000 meters and height 50 meters; and 2) indoors throughout the 25-story office building shown in Exhibit 1.

In all cases, the aircraft was 300 meters above the environment. Within a congested (i.e., urban) area, Federal Aviation Rules require a minimum clearance of 1,000 feet between aircraft and structures below. We brought the aircraft about 100 feet lower than that, mostly for the sake of round numbers; however, in practical flying a 100-foot altitude error may well occur.

Also in all cases, two different emitter powers were considered, 50 microwatts and 200 microwatts. These correspond to non-industrial and industrial applications, respectively. The power is radiated uniformly over a 2 GHz bandwidth.

Voice Communications

Exhibits 3 and 4 show the computational results for the voice communications receiver. It is seen that thousands of 200-microwatt emitters can operate simultaneously before the net power reaches the sensitivity of the receiver. In the case of 50-microwatt emitters, tens of thousands of emitters can operate. Thus, there is little chance that aircraft voice communication will be interrupted.

DME Receiver

Exhibits 5 and 6 show the computational results for the DME receiver. Due to the low sensitivity of the receiver, it is seen that over one-million emitters may still operate simultaneously indoors or outdoors.

GPS Receiver

GPS receivers are very broadband and extremely sensitive compared to the previous two receivers. The permanently installed receive antennas, however, are mounted on top of the aircraft fuselage. Even the portable units available for general aviation feature antennas that are mounted with suction cups to the windshield. Therefore, in any case, the antenna is shielded by the fuselage from ground based emissions. The shielding is substantial.

Exhibit 7 shows the computed radiation pattern of a GPS antenna with radiation center 0.15 meters (about 6 inches) over a 4-meter diameter fuselage. This is intended to model a typical small commuter plane. It is seen that the SE at the underside of the fuselage is greater than 30 dB. Even if the plane is banked 30 degrees, which would be a steep turn for a scheduled airline, the SE is still greater than 30 dB.

Using a SE of 30 dB, Exhibits 8 and 9 show the computational results for a GPS receiver. It is seen that tens of thousands of emitters can operate simultaneously both indoors and outdoors before their cumulative radiation reaches the sensitivity of the GPS receiver.

CONCLUSIONS

Exhibit 10 summarizes the results of the computations. It is seen that either indoors or outdoors, thousands, if not tens of thousands, of emitters may operate simultaneously without affecting either aircraft communications or navigation. The reasons agree with intuition. Outdoors, the devices are widely dispersed and space attenuation limits the cumulative radiation at any single receiver. Indoors, the attenuation of floors and ceilings compensate for the concentration of devices within a single building.

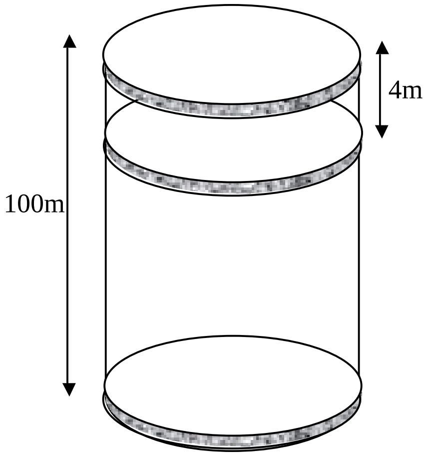

Exhibit 1. Geometry of a 25-story building. Each floor introduces attenuation.

Characteristic Receiver	Frequency MHz	Bandwidth MHz	Sensitivity MHz
Voice	**118**	**0.025**	**-103**
DME	**962**	**0.300**	**-85**
VCR	**108**	**0.020**	**-81**
NDB, ADF	**0.190**	**0.012**	**-41**
ILS Localizer	**108**	**0.010**	**-41**
ILS Glide Slope	**329**	**0.034**	**-56**
GPS using C/A Code	**1600**	**2**	**-133**

Exhibit 2. Summary of avionics receivers and their properties. The three worst cases (voice, DME, and GPS) were chosen for detailed analysis.

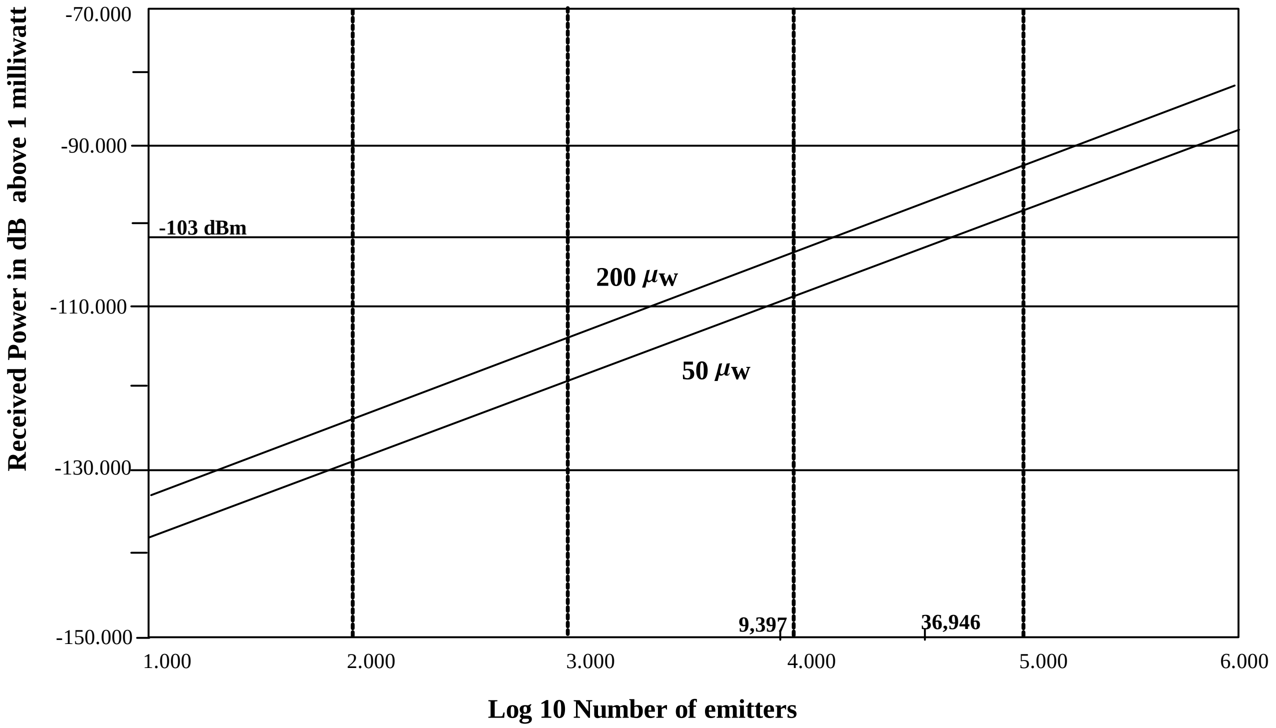

Exhibit 3. Computational results for voice receiver 300 meters above an open urban environment.

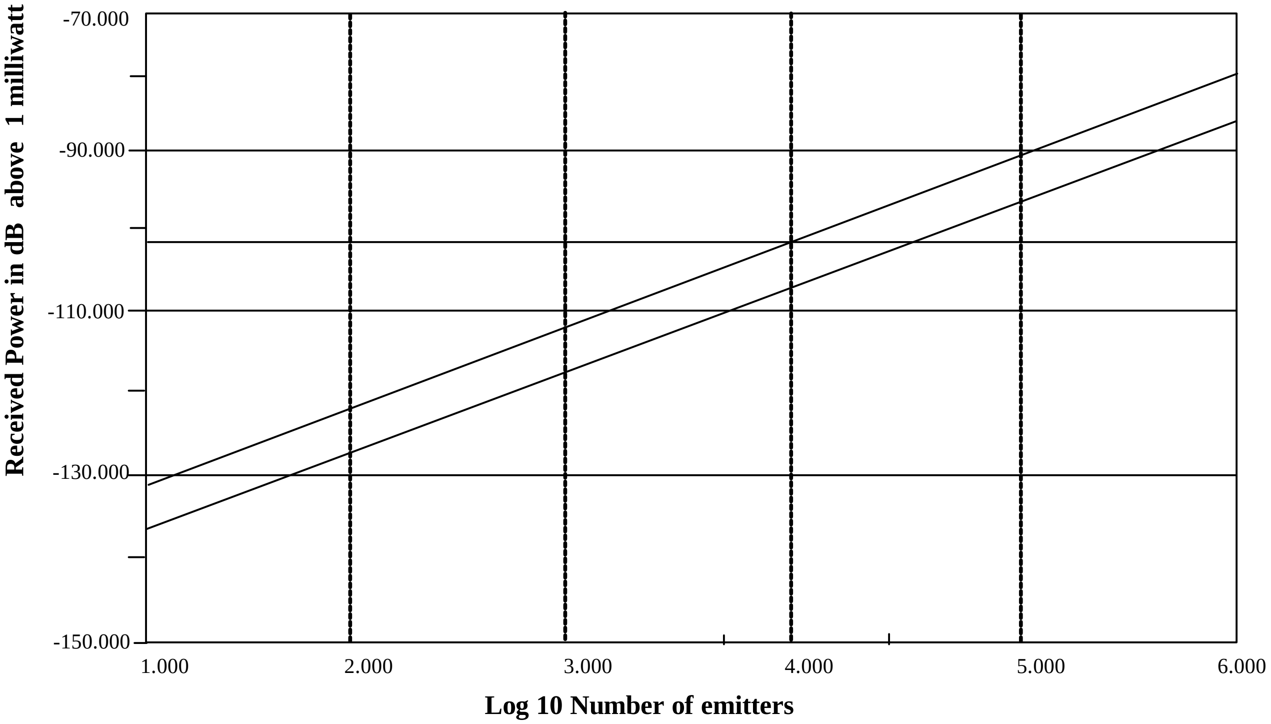

Exhibit 4. Computational results for voice receiver 300 meters above a 25-story building.

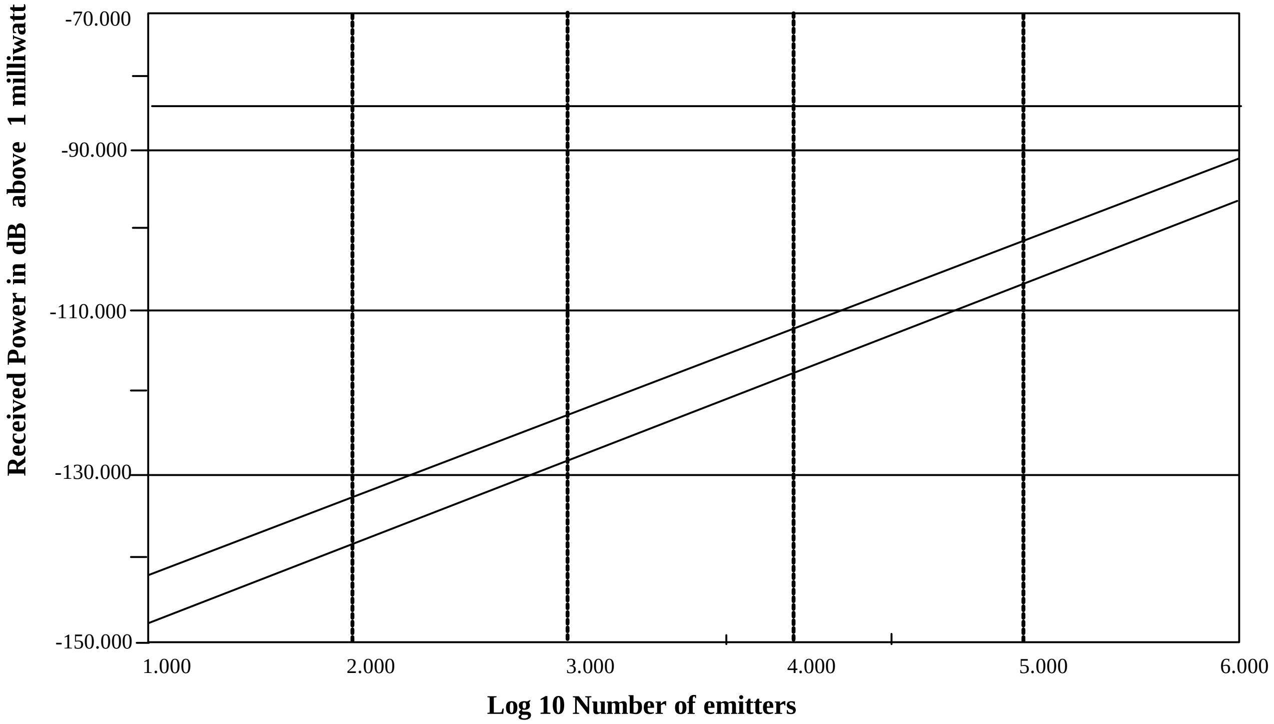

Exhibit 5. Computational results for a DME receiver 300 meters above an open urban environment.

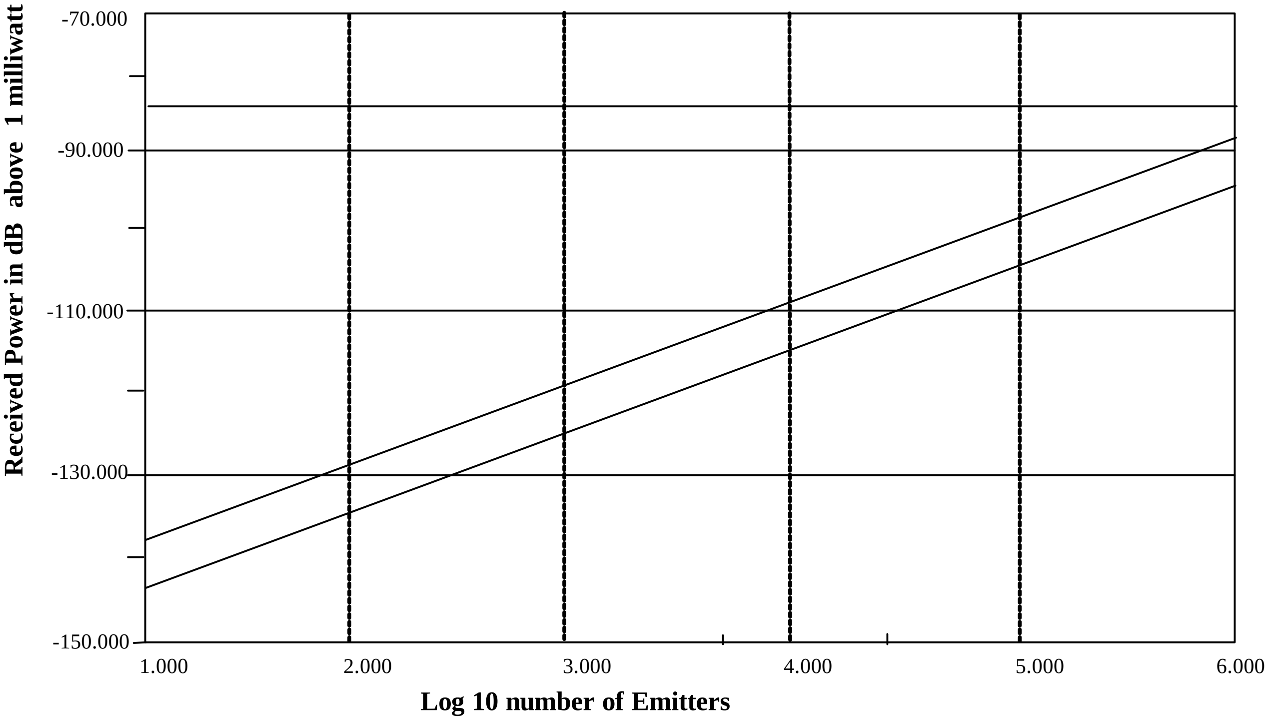

Exhibit 6. Computational results for a DME receiver 300 meters above a 25-story building.

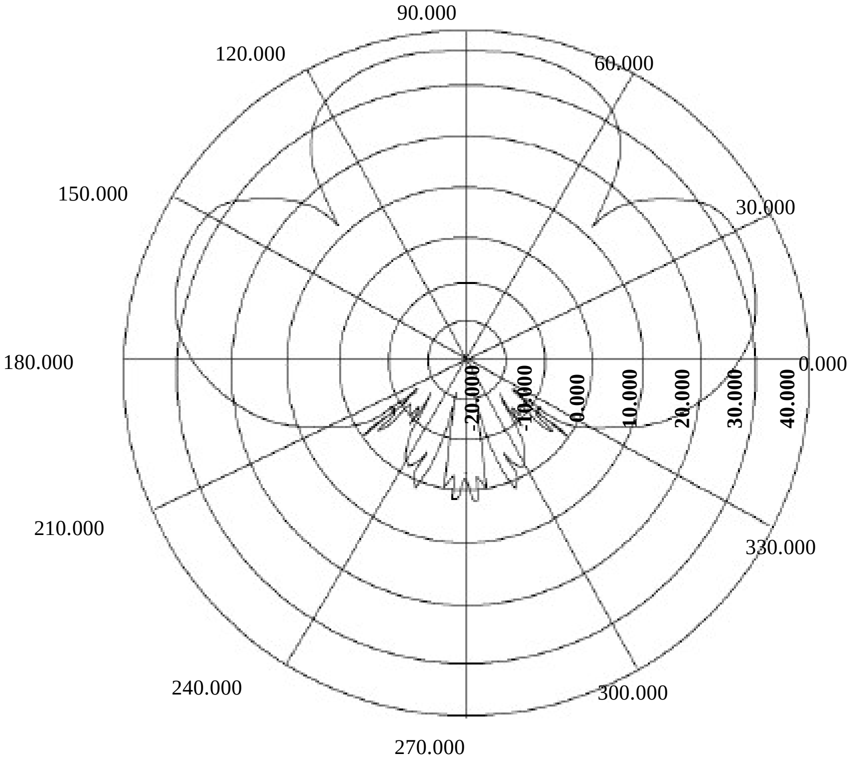

Exhibit 7. Computed radiation pattern for a GPS antenna with center of radiation 0.15 meters (about 6 inches) above a 4-meter diameter fuselage.

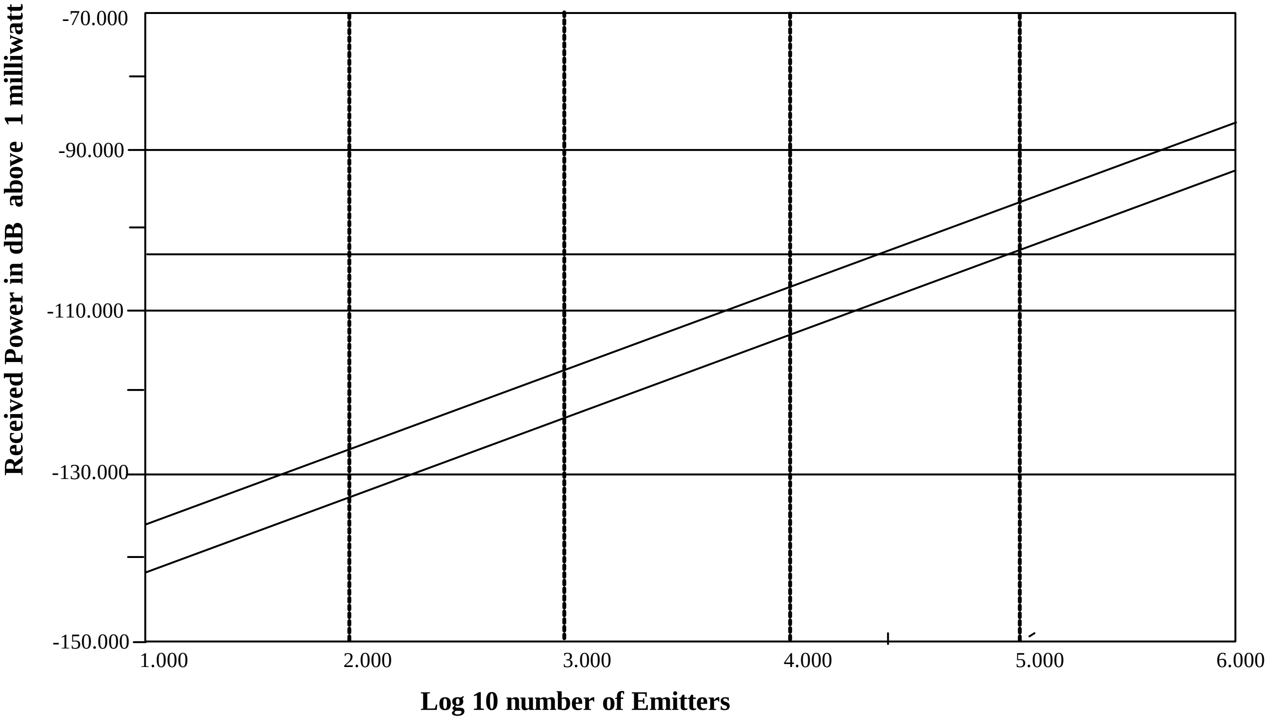

Exhibit 8. Computational results for a GPS receiver 300 meters above an open urban environment.

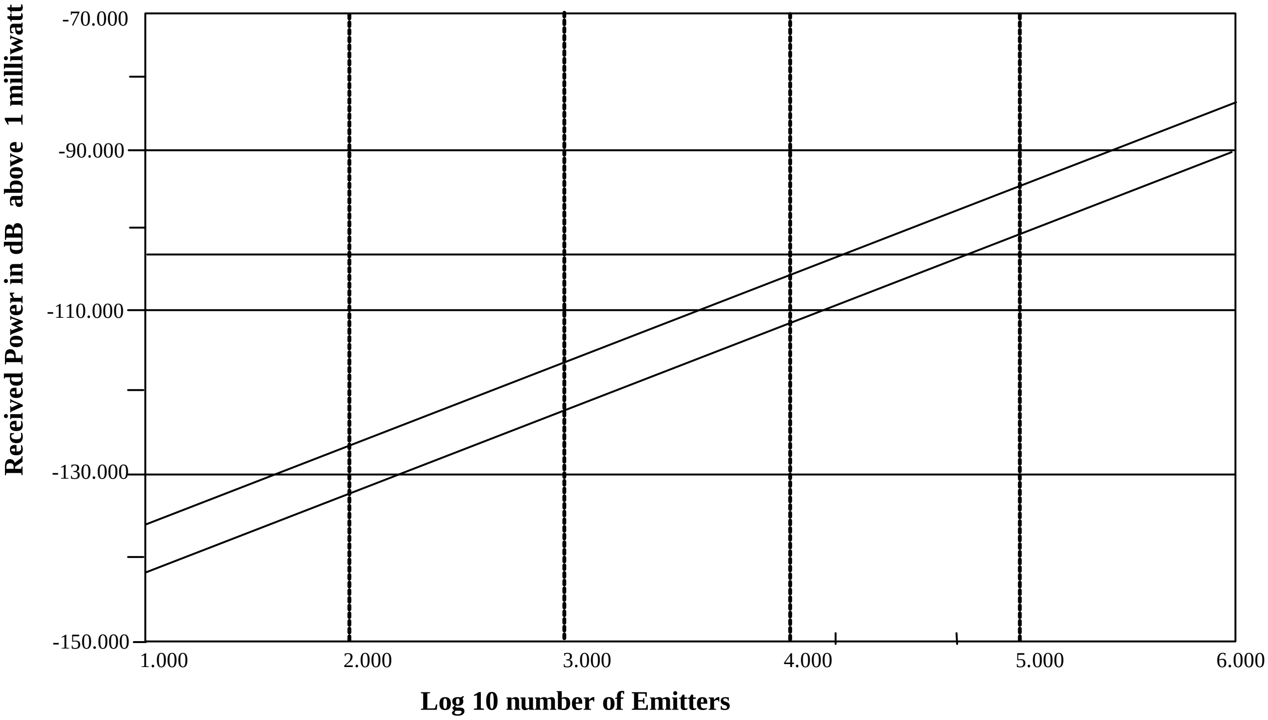

Exhibit 9. Computational results for a GPS receiver 300 meters above a 25-story office building.

Receiver Emitter Environment	Voice	DME	GPS using C/A Code
Open Urban Area	**9,397** **36,946**	$>10^6$ $>10^6$	**23,899** **100,000**
25 Story Building	**5,367** **23,899**	$>10^6$ $>10^6$	**12,434** **50,432**

Exhibit 10. Number of emitters which may operate simultaneously before total received power equals receiver sensitivity. The top and bottom values correspond to emitter powers of 200 and 50 microwatts, respectively.

Jeremy K. Raines received a Ph.D. in Electromagnetics from MIT, Cambridge, Massachusetts, in 1974; an M.S. in Applied Physics from Harvard University, Cambridge, Massachusetts, in 1970, and a B.S. in Electrical Science and Engineering from MIT in 1969. He is a Senior Member of the Institute of Electrical and Electronic Engineers and a member of other professional organizations, including the American Physical Society, the Applied Computational Electromagnetics Society, the Bioelectromagnetics Society, and Tau Beta Pi. He was president of the Association of Federal Communications Consulting Engineers for the 1983-1984 term and president of the MIT Chapter of Eta Kappa Nu for the 1968-1969 term. Dr. Raines has been a consultant since 1972, specializing in the design and analysis of antennas, antenna arrays, radio propagation paths, and radar targets. He has also modeled and designed telecommunications systems for the U.S. Navy, U.S. Air Force, and NATO, in the United States and Europe. He taught courses at MIT from 1969 to 1973 concerning electromagnetism, solid-state circuits, and bioelectronics. He taught an antenna course at George Washington University, Washington, D.C., from 1975 to 1988. In 1991, he was a guest lecturer concerning bioelectromagnetics at the Rockefeller University in New York City. Dr. Raines is a registered Professional Engineer in the state of Maryland.

An Analysis of Noise Aggregation from Multiple Distributed RF Emitters

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December 6, 1998

Abstract

The purpose of this technical note is to explore the aggregate noise generated by a large number of distributed radio emitters. There have been concerns that the widespread and ubiquitous use of ultra-wide-band (UWB) devices might increase the ambient noise levels beyond today's conditions. There are particular concerns regarding aircraft safety due to substantial line-of-sight propagation through the air.

Both the theoretical analysis [1] and past experiences with actual, spatially reused, radio systems are related to this theoretical model and *strongly indicate that substantial noise build-up does not and will not occur.*

From our derivations, it becomes clear that problems cannot come from an aggregation of emitters within a 45 degree cone below the victim receiver. On the other hand, the effects of an aggregation of emitters near the horizon are controlled by either of the curvature of the Earth or damping at ground level near the emitters.

The developed model applies equally to all radio emitters, addressing spatial reuse of AM and FM radio, spread spectrum, and UWB sources alike. The density of the emitters is not an issue, only the spatial reuse. The longstanding observation of non-aggregation of noise of such emitters as AM and FM radio and cellular systems speaks to the effectiveness of damping and the finite Earth in mitigating the effects of an aggregation of emitters on the horizon.

1. Aggregation Model

We consider the aggregate power at the apex of a solid cone resulting from the aggregate power emitted by the disk forming the base of the cone (Fig. 1). We will eventually apply this model with the base of the cone on the surface of the Earth and the apex at some height above the surface. We take the radius of the disk to be r and the height of the apex above the ground plane to be h. The areal power density in the base disk is P. Using the inverse square law we can integrate in cylindrical coordinates over the base disk and arrive at P_{apex}, the apex receiver power density per unit area of apex receiver antenna (x is the radius from the base of the cone):

$$
\begin{aligned}
P_{apex} &= \int_0^x P \frac{2\pi x_*}{h^2 + x_*^2} dx_* = \pi P \int_0^x \frac{d\left(h^2 + x_*^2\right)}{h^2 + x_*^2} = \\
&= \pi P \ln\left(h^2 + x_*^2\right)\Big|_{x_* = 0}^{x_* = x} = \pi P \ln\left(\frac{h^2 + x^2}{h^2}\right) = \pi P \ln\left(\sin^{-2}(\theta)\right)
\end{aligned}
\qquad (1)
$$

If $\theta = \pi/4$ then the power density at the apex is

$$P_{apex,\theta=\pi/4} = \pi P \ln\left(\sin^{-2}(\pi/4)\right) = \pi P \ln(2) = 2.178P \qquad (2)$$

This is not a very big increase.

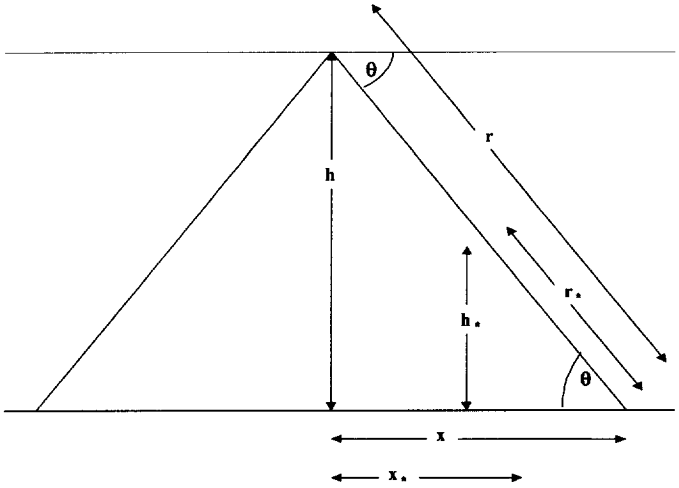

Fig 1 – Setup Geometry

Beyond $\theta = \pi/4$ we are ultimately limited by the radius of the Earth R_E=6,375,000 m, whose effect is not negligable. For $h << R_E$ (true for any altitude in the atmosphere) we have $hR_E = {x_H}^2$ where x_H is the distance from directly below the apex to the horizon.

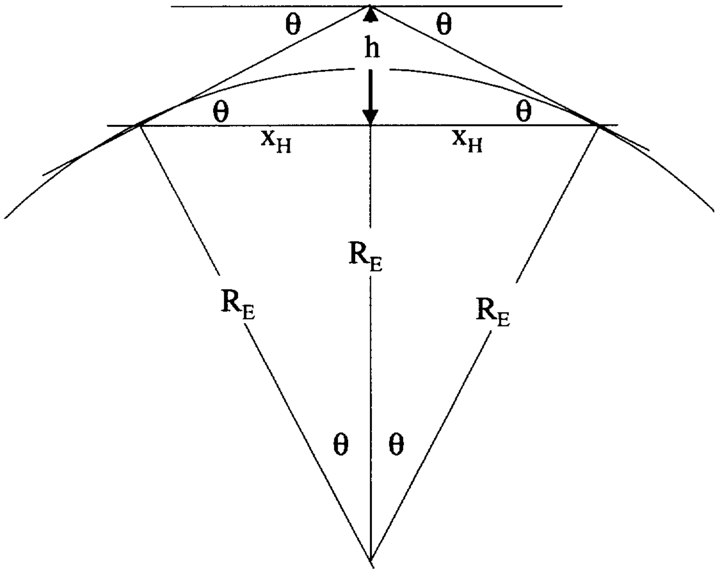

Fig 2 – Earth Curvature

Then we have

$$P_{apex\ to\ horizon} = \int_0^{\sqrt{hR_E}} P\frac{2\pi x_*}{h^2+{x_*}^2}dx_* = \pi P\ln\left(1+\frac{R_E}{h}\right)$$
$$= \pi P\ln\left(\sin^{-2}\left(\theta_H(h)\right)\right) \approx 2\pi P\ln\left(1/\theta_H(h)\right) \qquad (3)$$

As an example, if the apex height h is 100 m we will have

$$P_{apex,\ h=100m} = \pi P\ln\left(1+\frac{6{,}375{,}000}{100}\right) = 34.75P \qquad (4)$$

2. Electromagnetic Damping

There are only two possible dispositions for emitted photons. They may either be lost to space or they may be absorbed here on Earth. Such absorption in this context is referred to as *damping*. Interaction with matter which is neither perfectly conducting nor perfectly insulating (i.e., most materials) will result in a non-zero proportion of the photons being absorbed. Damp materials found close to the surface of the Earth are particularly effective in absorption. Moreover, the complex natural and man-made geometry near the surface of the Earth causes many reflections and other changes of course to the photons, resulting in increased interaction with absorbing materials.

We therefore need to modify the above derivation to take damping into account.

Damping is characterized by an absorption coefficient b_* which describes the proportion of photons absorbed in traversing a unit length of a given material. We will not assume that the absorption coefficient is a constant, but rather that it varies widely for different materials. In our context we will assume that it varies with the distance from the apex and with the height h_* above the surface of the Earth. (Do not confuse h_*, the height of a photon in propagation, with h, the height of the apex.) We expect the height to be the parameter causing the largest variations.

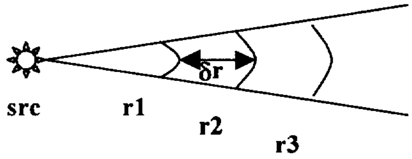

Fig 3 – Signal Propagation

The signal power degrades as it travels farther away from the source (Fig. 3). If the signal strength at the distance *r1* is *P(r1),* then, with the inverse quadratic law, the signal strength at the distance *r2* can be described by the following equation.

$$P(r_2) = \frac{r_1^{\;2}}{(r_1 + \delta r)^2}(1 - b_*(h_*(r_2), r_2)\delta r)P(r_1) \tag{5}$$

This process is repeated and thus at a distance of r_n, the signal strength is the following:

$$\begin{aligned} P(r_n) &= \prod_{i=1}^{r_n/r_0} \frac{r_i^{\;2}}{(r_i + \delta r)^2}(1 - b_*(h_*(r_i), r_i)\delta r)P(r_1) \\ \ln(P(r_n)/P(r_0)) &= \ln\left(\frac{r_0^{\;2}}{(R + \delta r)^2}\right) + \sum_{i=1}^{r_n/r_0} \ln(1 - b_*(h_*(r_i), r_i)\delta r) \\ &\approx \ln\left(\frac{r_0^{\;2}}{r_n^{\;2}}\right) - \sum_{i=1}^{r_n/r_0} b_*(h_*(r_i), r_i)\delta r \approx \ln\left(\frac{r_0^{\;2}}{r_n^{\;2}}\right) - \int_{r_0}^{r_n} b_*(h_*(r_*), r_*)dr_* \end{aligned} \tag{6}$$

In the limit as $\delta r \rightarrow 0$ we have

$$P(r_n)/P(r_0) = \frac{r_0^{\;2}}{r_n^{\;2}} e^{-\int_{r_0}^{r_n} b_*(h_*(r_*), r_*)dr_*} \tag{7}$$

Equation (1) is then generalized to

$$P_{apex} = \int_0^r P \frac{2\pi x e^{-\int_0^{\sqrt{h^2+x^2}} b_*(h_*(r_*), r_*)dr_*}}{h^2 + x^2} dx \tag{8}$$

In the case where b_* is a function of h_* alone the value of b_* will be noticeably greater than zero for small h_* (near the Earth's surface) and negligibly small for larger h_* where the propagation path is "line-of-sight" through the air. The integral of b_* along a ray is still definitely greater than zero. Notice that in the geometry of Fig. 1 that $h_* = \sin(\theta)r_*$

$$\begin{gathered} b_*(h_*(r_*), r_*) = b_*(h_*(r_*)) \Rightarrow \\ \int_{r_*=0}^{r_*=\sqrt{h^2+x^2}} b_*(h_*(r_*), r_*)dr_* = \csc(\theta)\int_{h_*=0}^{h_*=h} b_*(h_*)dh_* = r\frac{1}{h}\int_0^h b_*(h_*)dh_* = br \end{gathered} \tag{9}$$

where we define

$$b = \frac{1}{h}\int_0^h b_*(h_*)dh_* \tag{10}$$

Therefore, in this case, the damping integral is still O(r). The aggregated signal power at the apex, considering damping, is

$$P_{apex,damped} = \int_0^{\sqrt{hR_E}} P\frac{2\pi x_* e^{-br}}{h^2+x_*^2}dx_* = \int_0^{\sqrt{hR_E}} P\frac{2\pi x_* e^{-b\sqrt{h^2+x_*^2}}}{h^2+x_*^2}dx_* =$$

$$= \int_0^{\sqrt{hR_E}} P\frac{\pi e^{-b\sqrt{h^2+x_*^2}}}{h^2+x_*^2}d\left(h^2+x_*^2\right) = \int_h^{h\sqrt{1+\frac{R_E}{h}}} P\frac{\pi e^{-bu}}{u^2}du^2 = \int_{bh}^{bh\sqrt{1+\frac{R_E}{h}}} P\frac{2\pi e^{-v}}{v}dv = \qquad (11)$$

$$= 2\pi\left(\exp\mathrm{int}(bh) - \exp\mathrm{int}\left(bh\sqrt{1+\frac{R_E}{h}}\right)\right)P$$

It's not so clear what happens when the damping coefficient b is very small. If $bh\sqrt{1+\frac{R_E}{h}} << 1$ we obtain

$$P_{apex,damped,b\ small} = \int_{bh}^{bh\sqrt{1+\frac{R_E}{h}}} P\frac{2\pi e^{-v}}{v}dv \approx \int_{bh}^{bh\sqrt{1+\frac{R_E}{h}}} P\frac{2\pi}{v}dv =$$

$$= 2\pi\left(\ln\left(bh\sqrt{1+\frac{R_E}{h}}\right) - \ln(bh)\right)P = 2\pi\ln\left(\sqrt{1+\frac{R_E}{h}}\right)P = \pi P\ln\left(1+\frac{R_E}{h}\right) \qquad (12)$$

so that the aggregation is bounded even if b is zero (as in eq. 3) so long as h is not.

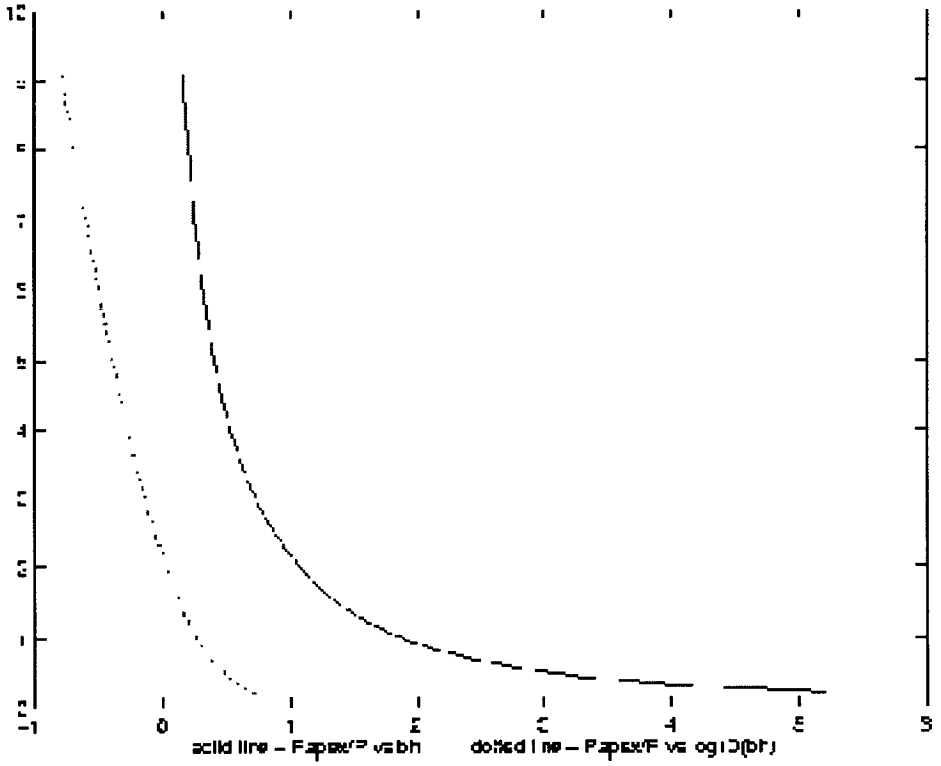

Figure 4 – Relative apex power vs. scale height

Thus this integral is finite for all positive values of h. Rather than speculate on the values of b, we'll shortly address the question qualitatively. A similar computation shows that the apex aggregate power is finite even if the damping integral increases as slowly as $O(\ln(r))$.

Thus it is clear that very small amounts of damping prevent the aggregate power from growing large.

Figure 4 graphs the aggregation factor as a function of the *scale height bh* and also of the $\log_{10}$ of the scale height.

3. Application to Spacially Reused Radio

An examination of the preceding arguments reveals that the model depends neither on the bandwidth nor on the modulation of the signal. The arguments depend only on the spatial reuse of the frequencies to the extent that a continuous emitting source plane is a good approximation. However, as any aggregate is linear in the power density, that aggregate will be finite if both the height and damping are positive (non-zero) and remains so as long as the power density has an upper bound (surely so if there are a finite number of transmitters).

Conversely, if the analysis given above is faulty we would conclude that we would observe unbounded aggregate power levels from the many contemporary RF sources that are spatially divided. Such sources include cellular phone systems, FM radios and even AM radio stations. *No such aggregation is observed.*

4. Conclusions

A theoretical analysis for the noise aggregation of spatially reused radio systems has been developed. Both this analysis and past experience with actual spatially reused radio systems related to this model *strongly indicate that substantial noise build-up does not and will not occur.*

From our analysis, it is clear that noise buildup from an aggregation of emitters within a 45 degree cone below an airborne victim receiver is very limited (approximately a factor of two).

Aggregation of noise from emitters near the horizon is controlled by either of the curvature of the Earth or damping at ground level near the emitters. . Such radiation departs its source essentially parallel to the plane (clearly not perpendicular to it). Damping of these plane parallel rays is significant as described in the next section.

The developed model applies equally to all radio emitters, addressing spatial reuse of AM and FM radio, spread spectrum, and UWB sources alike. The density of the emitters is not an issue, only the spatial reuse. The longstanding observation of non-aggregation of noise of such emitters as AM and FM radio and cellular systems speaks to the effectiveness of damping in controlling horizontal aggregation.

References

[1] T. Shepard, "*Decentralized Channel Management in Scalable Multihop Spread-Spectrum Packet Radio Networks*", Ph.D. Thesis, MIT/LCS/TR-670, July 1995.

[2] M. Rofheart, J. McCorkle, "*Short Analysis on the Effects of a Large Number of UWB Systems*", OC Technologies Inc. Technical Report, 1998.

Appendix A – Numerical Approximation and Simulation

Alternative to an analytic solution of the problem stated, one might be tempted to numerically approximate the problem. However, as we will show in the following, it is extremely difficult to numerically calculate large RF aggregations accurately without inadvertently introducing the equivalent of some damping. To illustrate this, consider the numerical summation of $\sum_{i=0}^{\infty} \frac{1}{i}$

The obvious way of calculating the (divergent) summation is to set a running sum to zero and then add terms in the order of indexing until convergence is obtained. Numerical convergence generally will be obtained and we can approximate the converged value. Suppose that the calculation is performed with single precision IEEE arithmetic, with 24 bits of mantissa. Eventually the running sum will become 2^24 times the running sum and further additions will not increase it.

Let this happen after N terms. Then the running sum will be about ln(N) so we need ln(N) ~ 2^24/N. Solving for N we obtain 1,198,700. So "convergence" is obtained after a million terms and the running sum is ln(N) = 14, approximately! In effect the terms that are 2^24 times smaller are "damped" to zero.

Such series are well known to be difficult to sum. Since the terms are positive, any convergence will be absolute so that the sum can be calculated in any order. If, say, 3.25x10^6 = 1.2*e terms are summed from smallest to largest the running sum will increase from 14 to 15 and we can get the sum to 16 by summing 1.2*e^2 terms. Double precision with 56 bits of precision will converge with 2*10^15 terms yielding a summation value of just 35.

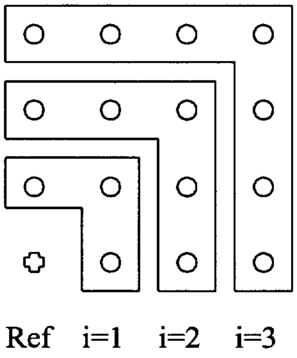

Fig 5 – Field of Emitters

Even worse, it is clear that any absolute or any relative convergence criteria will eventually be met, even with very high precision arithmetic. In essence, we must know that the series diverges in order to program the calculation correctly!

A double summation of the form $\sum_{j>0,k>0} \frac{1}{j^2+k^2}$, is closely related to the integral in section 1 and diverges in the same way. A divergent lower bound can also be calculated in layers as Fig. 5 illustrates.

$$\sum_{j>0,k>0} \frac{1}{j^2+k^2} > \frac{3}{1^2} + \frac{5}{2^2} + \frac{7}{3^2} + \bullet$$

yields the corresponding lower bound series.

$$\sum_{j>0,k>0} \frac{1}{j^2+k^2} > \sum_{i=1}^{\infty} \frac{2i+1}{i^2} > 2\sum_{i=1}^{\infty} \frac{1}{i} > 2\int_1^{\infty} \frac{dx}{x} = \ln(x)\Big|_1^{\infty} = \ln(\infty) \tag{14}$$

a slowly diverging one that goes to infinity.

Appendix B – Estimating the Damping

Empirical studies have often fit their data with a propagation law that is not inverse square ($\frac{1}{r^2}$), but rather a higher power ($\frac{1}{r^{2+\varepsilon}}$).Any positive, non-zero value of ε leads to finite aggregate power [1] for all values of *bh*, including zero. These studies [1] generally have found $2.4 \le 2 + \varepsilon \le 4$.

There is a particular form for the damping $b(h(r),r)$ that reconciles this empirical form with the earlier analysis. From equation (8) we have

$$P_{apex} = \int_0^r P \frac{2\pi x e^{-\int_0^{h^2+x^2} b(h(r),r)dr}}{h^2+x^2} dx = \int_0^{\infty} P \frac{2\pi x}{\sqrt{h^2+x^2}^{\,2+\varepsilon}} dx \tag{15}$$

and this will be satisfied if

$$e^{-\int_0^{h^2+x^2} b(h(r),r)dr} = \sqrt{h^2+x^2}^{\,-\varepsilon} \tag{16}$$

Taking the log and the differentiating each side

$$\begin{gathered} -\int_0^{h^2+x^2} b(h(r),r)dr = \ln\left(\sqrt{h^2+x^2}^{\,-\varepsilon}\right) = -\frac{\varepsilon}{2}\ln\left(h^2+x^2\right) \\ \frac{d\left(\int_0^{h^2+x^2} b(h(r),r)dr\right)}{d\left(h^2+x^2\right)} = \frac{\varepsilon}{2}\frac{d\left(\ln\left(h^2+x^2\right)\right)}{d\left(h^2+x^2\right)} \end{gathered} \tag{17}$$

we end up with

$$b(h(x),x)=\frac{\varepsilon/2}{h^2+x^2} \tag{18}$$

This damping function decreases rapidly with distance but is still sufficient to limit aggregation. Physically, it is consistent with a "foamy" propagation medium where the matrix is lossy and where there is a suitable "long-tailed" distribution of void sizes. Such a propagation environment seems consistent with the interiors of buildings. It also seems consistent with the tangent plane out-of-doors where the role of the lossy matrix is played by vegetation and tree canopies, structures, and terrain relief.

Appendix C – Matlab Code for Figure 4

```
for i = 24:-1:1,
   x(i) = exp(0.15*(12-i));
   y(i) = WhiteSky(x(i));
end;
hold off;
plot(x, y, 'b');
hold on;
plot(log(x)/log(10), y, ':r');
xlabel('solid line - Papex/P vs bh        dotted line - Papex/P vs log10(bh)');
print -dbmp256 'C:\WINDOWS\Desktop\WhiteSky.bmp';

function v = WhiteSky(H);

global bh;
if  H > 1/10^8,
   bh=H;
   A=1;
   v = quad8('Integrand', A, 14); % the range of integration must be split
   while A > H/1000,              %   in order to avoid excessive recursion depth
      A=A/8;                      %   errors in quad8
      v = v+quad8('Integrand', A, 8*A);
   end;
   v = v+quad8('Integrand', 0, A);
   v = 2*pi*v;
   % disp(v);
else
   v = 2*pi*(log(1/H)+log(10^-4)+expint(10^-4));
   %    2*pi*(log(10^-4)+expint(10^-4))= -3.6269;
end

function u = Integrand(t)

global bh;
u = t.*exp(-t)./(bh*bh+t.*t);
```

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

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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

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

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

$R\,dq$ = differential angle element

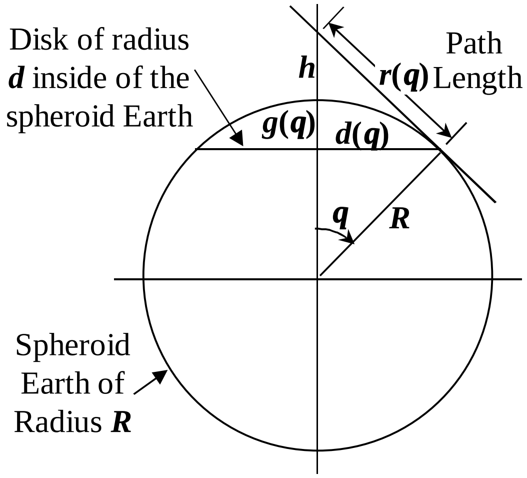

Figure 1. Geometry of victim receiver above spherical earth.

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

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

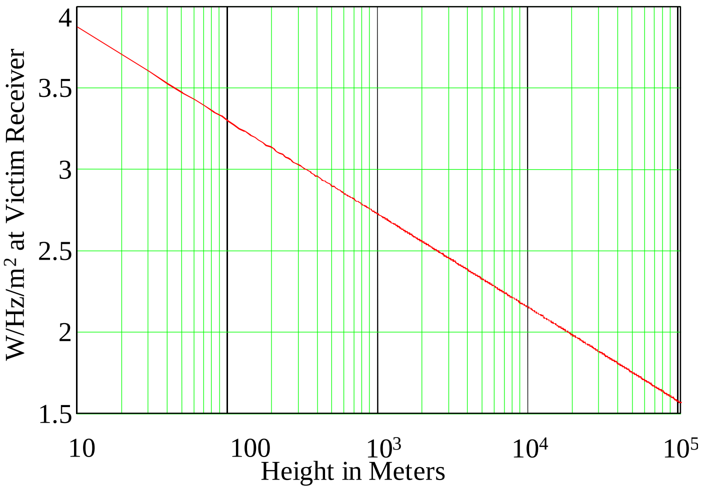

Figure 2. Plot of power at victim receiver versus its height for uniform 1W/Hz/m2 transmit power over the surface of the earth

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

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

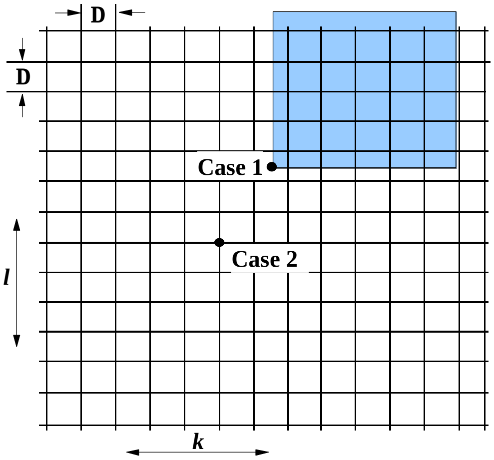

Figure 3. Uniform distribution of transmitters.

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.

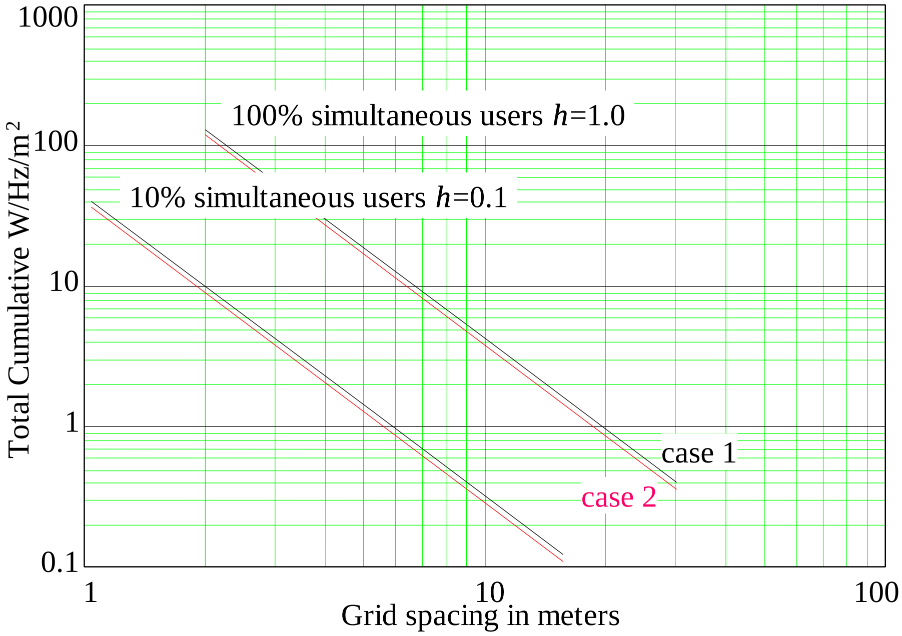

Figure 4 Total cumulative power a victim receiver located between grid points, when 36πW/Hz is being transmitted simultaneously at all grid points with isotropic antennas, on a 60 km X 60 km square.

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,

$$\Delta_e = \Delta \sqrt{h} \tag{7}$$

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.

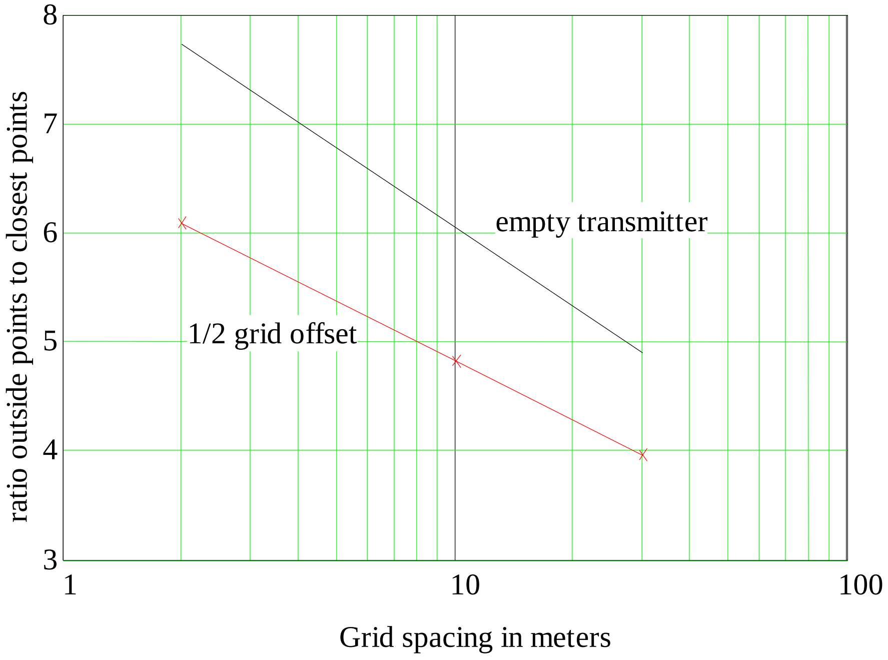

Figure 5 Ratio of total cumulative power to the power contributed by the closest four grid points.

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.

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2 THE EFFECT OF PROLIFERATION OF WIDEBAND DEVICES

Proliferation of wideband (or ultrawideband) devices can be studied in the light of the emissions of individual devices, their distribution in space, and the propagation conditions surrounding them.

2.1 Individual devices

For individual devices we can calculate the effect of emissions at the level of existing general limits. We can define a minimum distance beyond which another system is unlikely to suffer interference, because the received power becomes less than the thermal noise power of the receiver. This distance is small, suggesting that individual devices will be benign, as experience suggests.

The emission levels equivalent to the provisions of 15.209 are:

Frequency (MHz)	**EIRP (in 1MHz BW)**
216-960MHz	12nW
Above 960MHz	75nW

Table 3: Emission Levels

The test bandwidth is stated as a minimum of 1MHz. A wideband transmitter which meets this limit will have spectral power density (nW/MHz) values equal to those shown in Table 3.

We can calculate the distance at which the level of power received falls below thermal noise in a receiver with an isotropic antenna (0dBi) and a noise figure of 6dB, and with the receiver at the peak of the emitter's beam. We measure receiver noise and interference over the same bandwidth. A conservative estimate of the maximum distance at which another device will see interference is shown in Table 4.

Since the majority of receiving equipments employ a degree of processing gain, these figures are probably conservative. They suggest that applications where the devices are separated normally by 10 metres or more, wideband applications above 5GHz will be reliably benign at these levels.

Frequency	Distance
500MHz	40 metres
960MHz	20 metres
1000MHz	50 metres
2.45GHz	20 metres
6.5GHz	10 metres

Table 4: Range for interference to fall below victim's thermal noise

2.2 What does proliferation mean? A distribution scenario

Examples of applications which would constitute a high degree of proliferation are provided by domestic intruder alarms and car collision warning aids. If successful commercially, these could be owned by a large proportion of the population and become integrated into its increasingly radio-aided lifestyle. This scenario is worth considering without prejudice. The value of the market for devices incorporating such sensors could be worth many billions of dollars.

In a possible scenario a national population of 100 million people live in 50 million dwellings and offices, with 50 million cars, distributed between large and small cities and towns over an area of 200,000 square miles. In this population there may be 1 billion sensors of this kind. The highest concentration of devices might be in a city of 10 million, with 10% of these devices within an area of 1100 square miles.

The sensors emit a maximum spectral power density of 75nW/MHz. Their operating cycles and beam patterns will vary with the application, but we will consider a worst case scenario in which they are all working simultaneously.

To build up a picture of the threat posed by these devices we need to consider many different scenarios.

The urban environment is built up, with devices operating in buildings or in the street.

The rural environment is relatively sparse, but without the obstructions of the urban setting.

Roads represent a particular case where many devices may operate, and in a non-random orientation.

Special cases such as large shopping malls, sports stadia etc. should also be considered.

Such scenarios could be used to discuss objectively what their effect would be on mobile phones, GPS and other classes of service. In our study to date we have considered what we believe to be the worst case; that of a large city, with respect to remote platforms such as aircraft, and local radio users in the street.

2.3 Propagation conditions

We have constructed a simple model which allows interfering field strengths and signal levels to be estimated for different levels of proliferation up to extreme examples in an urban environment. The model does not attempt to calculate phase delays or fading effects important to communications systems, but addresses the gross power attenuations to be expected in propagation through a built environment.

Experience with cellular communications and with solids-penetrating radar sensors has given us substantial knowledge of the effects of such materials, and of multiple scattering. We have used this experience to build a simple but effective model to investigate the issue of proliferation.

We want to calculate the field strengths which might be experienced by victim receivers in a number of locations, such as:

1. Inside a building;
2. On top of a tall building at 100m;
3. In a busy street;
4. In a park;
5. In an aircraft at 500 - 10,000m.

Many of the difficulties which might arise from such proliferation are seen as involving either airborne systems or cellular communications, and in this preliminary discussion we have given priority to items 3 and 5.

3 FIELD STRENGTH ESTIMATES IN THE URBAN ENVIRONMENT

Our preliminary results are based on devices operating over a wide (~2GHz) band centred at 6.5GHz, with EIRP of 75nW/MHz.

3.1 An aircraft flying over a city

With respect to systems on board an aircraft, the major threat may come from flying over such a city, at any altitude.

We will consider a city of 10 million inhabitants, with 100 million short range devices, all operating simultaneously, within an area of 2800 square kilometres (with a radius of 30km).

We assume that the devices emit an average of 75nW/MHz EIRP in the horizontal plane but have sidelobes decreasing to zero in the vertical direction with a reasonable beam profile approximating a $\cos^2$ function.

20 million devices on vehicles (parking, collision warning, blind-spot aids, etc.) operate in the open, and are distributed with a maximum density of 1 per $10m^2$ in the street. The streets occupy

20% of the area of the city. We apply a density varying from a peak of 20,000 devices per square kilometre near the city centre to a value reduced by 1/4 at the periphery.

Looking down on the street at a height h and an angle η from the vertical, signals traverse a number of buildings. The model uses a building separation equal on average to the building height, near the city centre, and estimates the number of buildings traversed, limited by diffraction effects and the reducing average height of buildings near the periphery.

Building materials absorb radio frequency energy at a rate depending on the frequency, the materials and the geometry. At a few GHz, building materials absorb at rates of tens to the lower hundreds of dB per metre penetrated. For devices in the street we approximate this effect by considering the shadowing effect plus absorption. If buildings are on average as high as the street width, the shadowing can be approximated by a multiplier of $(1-\tan\eta)$ up to 45°. For $\eta>45°$, we introduce a fixed loss of 10dB per building traversed by the propagating signal. In fact this loss is made up of several components, but taking an average over many devices and locations, a single conservative loss parameter will provide a useful first indication of the effects.

In the model an additional 80 million devices are in buildings (intruder alarms, lighting controls, safety perimeters, stud finders, etc.) and will be approximated by introducing a fixed dielectric loss due to the building for $\eta<45°$, then increasing as the number of buildings traversed.

We consider two cases: one where the receiver is vertically polarised; that is, omnidirectional in azimuth with a null vertically down as $\sin\eta$; in the other the receiver is horizontally polarised, with a maximum lobe vertically downwards, decreasing to zero on the horizon as $\cos\eta$. (Some studies have performed a scalar aggregation of Poynting vector magnitudes over a hemisphere, which can not be justified; the receiver characteristics must be considered.)

The model suggests that for both cases, most power is received from a circular area on the ground whose radius is about twice the altitude of the aircraft. The first-order effects of shadowing and dielectric loss can be demonstrated.

For the aircraft, the ratio of power received from these devices to thermal noise is shown in Figure 1 as a function of altitude, for the vertically polarised case. It varies slowly from –8dB to –6dB between 500m and 5km altitude, falling again above that height.

3.2 Radio users at street level

For the user of other devices in the street, we also include the effect of the channeling of device concentrations along the street. The model suggests that at these high densities noise may be degraded by up to 6dB compared with thermal. This is as a result of the immediate proximity of up to 25 devices within 15 metres of the victim, not due to devices hidden behind vehicles or buildings.

This result suggests strongly that any problems of interference which may arise in this case will be at the level of the individual device, when the victim is placed in the direct field of view of the emitting device, not as a result of massive proliferation over an area.

Undesirable though any degradation is, this effect is minor when compared with the known effects of poor propagation for phones due to buildings, tunnels etc.

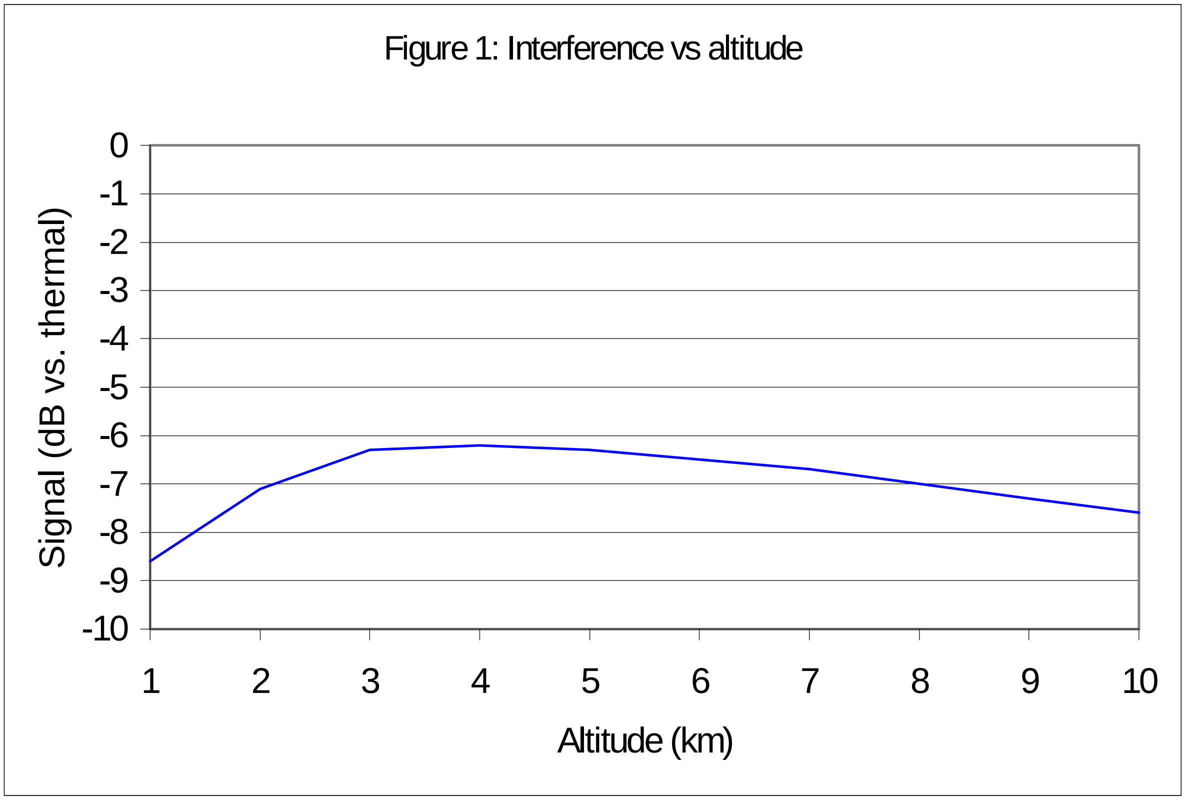
4 PRELIMINARY ASSESSMENT OF THE THREAT

We have used this model to describe an extreme case of proliferation.

To the extent that the model provides a fair approximation to reality, we find that any effect of these devices will be undetectable except in very close proximity.

This result would suggest that such devices, operating in high concentrations which coincide with a lossy propagation environment, may indeed be benign toward other users. This is contrary to the natural presumption that 100 million unlicensed emitters would represent a significant threat, and the conclusion needs to be validated.

This result has been obtained for devices operating in the 5-7GHz region. These devices would benefit from a relaxation of the restricted bands below 5.4GHz and above 7.2GHz. Other frequency ranges also require attention.



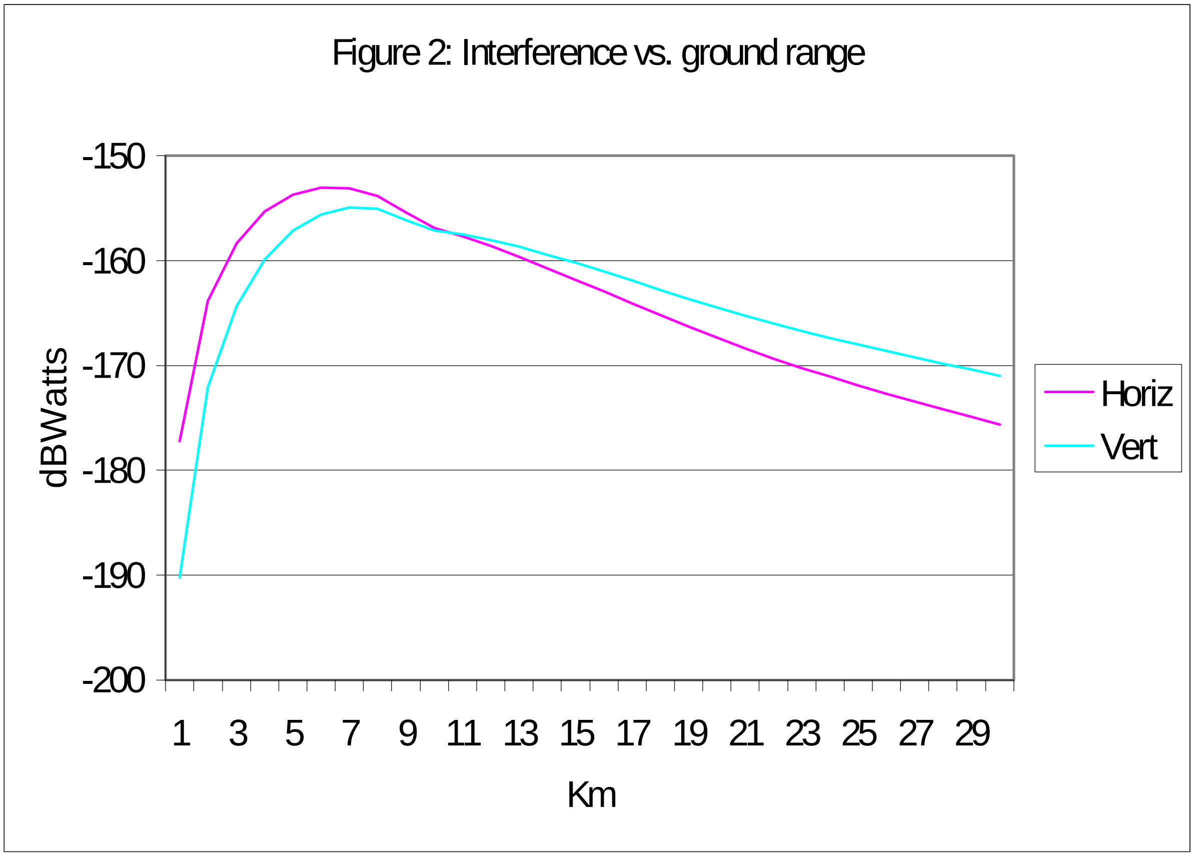


Figure 2: Interference vs. ground range

Appendix C

Cumulative Impact of Large Numbers of TM-UWB Users

Introduction

An often expressed concern is that large numbers of time modulated ultra-wideband transmitters each emitting a signal that complied with the Part 15 mandated field strength limits might create a situation where the cumulative field strength of the emitters would significantly exceed the field strength limits established by Part 15. This paper examines this issue and by means of a Monte Carlo simulation estimates the impact of increasing densities of time modulated emitters.

Overview

Under special circumstances, the impact on the RF noise floor of numerous co-located Part 15 certified digital devices might be noticeable, e.g., when large numbers of high speed computers are in close proximity (major brokerage houses can have hundreds of personal computers, workstations, and ancillary equipment all in a single room). Fortunately, propagation losses are significant and even a modest distance between emitters can mitigate the cumulative impact of large numbers of users.

Unlike computers, which are often in close proximity when in use, it would be highly unusual for law enforcement officers to be using time modulated radios in extremely close proximity.

This analysis estimates the cumulative field strength of increasingly larger numbers of randomly distributed transmitters. The analytical approach was:

1. Randomly distribute N users over a 100 x 100 meter area (for N = 5 to 100 in steps of 5).

2. Calculate the cumulative field strength of the N users at 81 points within that area, assuming that there is always one transmitter 1 meter from the sample point (which ensures that field strength will be equal to or greater than the field strength of a single transmitter – a worst case assumption). The field strength was calculated assuming a $1/R^2$ propagation path loss and no transmitter could be closer than 1 meter from the measurement point.

3. Repeat step (2) 1000 times for different random distributions of N users.

4. Calculate the mean value of the RMS field strength at the 81 sample points for all 1000 Monte Carlo simulations, i.e., average over 81,000 samples. Also, for each of the 1000 random distributions, select the largest RMS value from the 81 sampling points, then determine the average value of these 1,000 samples.

Figure 1 shows graphically the area over which simulated emitters were distributed and the area within which the simulated field strength was calculated.

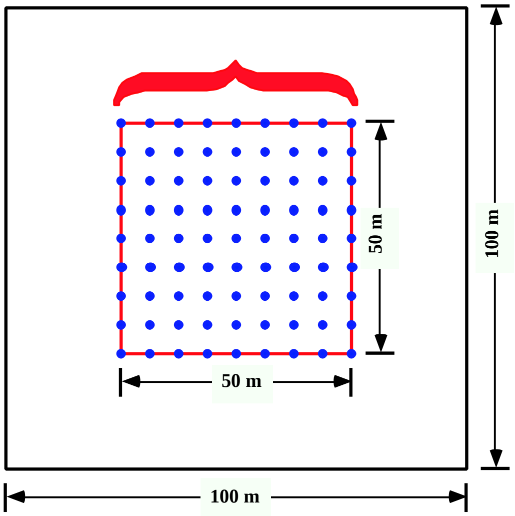


Figure 1. Graphical depiction of simulated operational area.

As shown in Figure 1, the sample points are distributed over the central area (50 m x 50 m) of the simulated operating area. This was done because with a uniform distribution of emitters over the 100 m x 100 m area, the greatest impact of large numbers of simultaneous emitters would probably be within this central area.

Results

Figure 2 shows the resulting values from the simulation. The results show the significant impact of propagation losses on the cumulative field strength of multiple users. Even with 100 users distributed over the 100 by 100 meter area, the RMS value of the field strength at the 81 measurement points is up only 1.2 dB over the field strength contributed by a single user and the RMS of maximum values is up less than 6 dB.

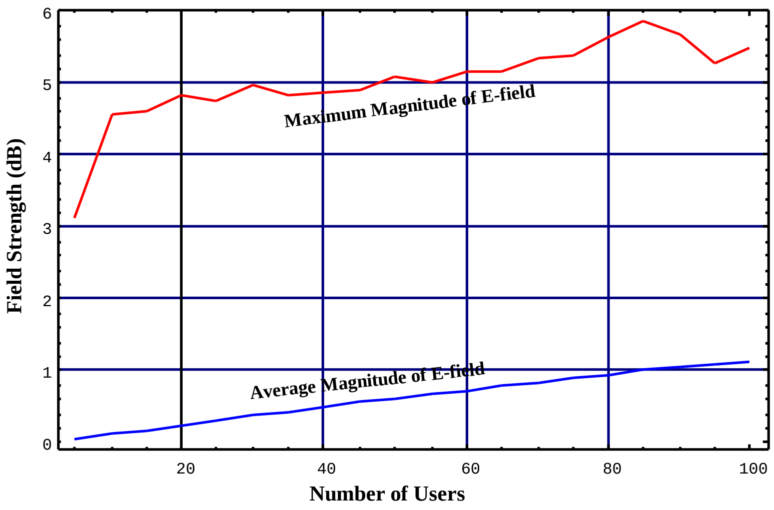


Figure 2. Simulation results: RMS and Maximum RMS field strength values.

Assuming that for every transmitter there is at least one receiver, then 100 emitters within a 100 m x 100 m area implies there are at least 200 people in an area about the size of a baseball field and on average there would be at least two emergency services personnel within each 10 m x 10 m area. Such a high concentration of emergency services personnel would probably be physically difficult to make covert, rendering the need for a covert RF communication capability a moot point.

Conclusions

Even in the worst case, the cumulative field strength of multiple simultaneous time modulated users would be a small increase over the contribution of a single user.