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August 25, 2000

School of Engineering

Department of Electrical Engineering-Systems

Communication Sciences Institute

Magalie Roman Salas
Office of the Secretary
Federal Communications Commission
445 12th Street, S.W., TW-A325
Washington, D.C. 20554

DOCKET FILE COPY ORIGINAL

Re: ET Docket 98-153

Dear Ms. Salas,

I have a few brief comments regarding the interference of ultra-wideband radio signals with GPS navigation signals. We performed a rooftop test in Los Angeles (in compliance with our experimental license, File # 0049-EX-PL-1999, Call Sign WB2XAM) in which we measured the carrier-to-noise ratio in a NovAtel GPS receiver (PROPAK-II-3151 R) employing a NovAtel GPS antenna (Model 531 Rev 2). The results of this test will be published as part of a paper "Ultrawideband Deployment Challenges" that will be presented at the IEEE-sponsored conference PIMRC 2000 in London, UK this September. I have attached a copy of the paper, which also deals with the link budget issues that affect the kinds of applications suitable for UWB radio communications technology.

In our experiment involving a single UWB interferer, we found that the effects interference was discernable only at distances less than 10 meters. Theoretical work tracked these results to some extent, but showed higher losses than were actually measured below 5 meters. With our limited data, I would estimate a 4 to 5 dB loss in carrier to noise ratio at 1 meter separation between the UWB radiator and the GPS antenna. Of course so much depends on the geometry of the measurement system, the electromagnetic environment, the radiated power, the quality of the GPS receiver, etc., that there is nothing definitive about such test results. However, the data and documentation of the experiment may be useful to you.

Sincerely,

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UWB Radio Deployment Challenges[1]

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ABSTRACT

The challenges related to the deployment of ultrawideband (UWB) radios are posed in terms of interference issues that UWB radio systems will encounter. The problem of coexistence with a Global Positioning System (GPS) receiver is used as an experimental example. Calculation of an upper bound to UWB transmitter power illustrates the effect of one possible type of regulation for a given UWB antenna system. The inteference environment for a UWB receiver is used to lower bound the UWB transmitter power necessary for a given data rate. Sample measurements are provided.

INTRODUCTION

Ultrawideband radios often are defined to have the property that their 3 dB bandwidth is at least 25% of the center frequency of the radiation. This characteristic means that such radios normally must coexist with many other narrowband signals that occupy their extremely large transmission bandwidth, with none of these systems suffering intolerable interference problems.

The rationale for deploying UWB radio systems lies in the benefits of exceptionally wide bandwidths at the lowest possible frequencies for those bandwidths: (1) very fine time resolution for accurate ranging, imaging, and multipath fading mitigation, and (2) the material penetration capability of relatively low frequencies.

Tolerance of interference to/from coexisting systems comes at a price. The primary objective of this paper is to lay out this problem and give measured examples of the signal environments which may be encountered.

LINK MODELS

A visual model for the interference problem is shown in Fig. 1, which indicates the radiating entities, the receivers of interest, and notation for signals at antenna terminals and useful signals after r.f. processing. The collection of other radiators represents all emitters that radiate power within the bandwidths of the two receivers, including possibly other UWB transmitters, other narrowband systems, etc. Our basic model for the signals present at the outputs of an ultrawideband receiver's antenna and the other

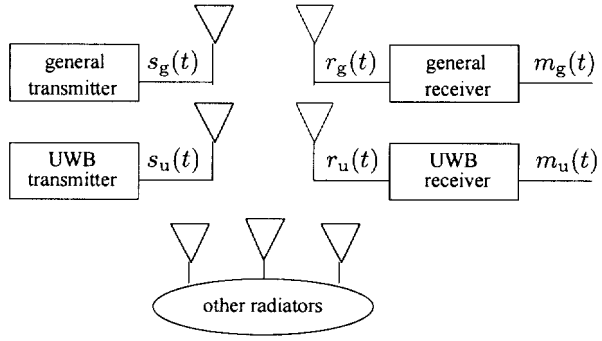

Figure 1: A conceptual block diagram of the interfering signal environment.

general receiver's antenna are denoted by $r_u(t)$ and $r_g(t)$ respectively, where

$$r_u(t) = h_{uu}(t)\star s_u(t)+h_{ug}(t)\star s_g(t)+n_u(t)+i_u(t), \quad (1)$$

$$r_g(t) = h_{gu}(t)\star s_u(t)+h_{gg}(t)\star s_g(t)+n_g(t)+i_g(t), \quad (2)$$

$n_a(t)$ denotes an equivalent receiver noise that represents noise generated within receiver "a", $i_a(t)$ represents the signal induced at the input to receiver "a" by external interference, and the operator $\star$ denotes convolution. For the purposes of these computations, we have represented the transformations from transmitter "a"s antenna input to a receiver "b"s antenna output by a linear time-invatiant transformation with impulse response $h_{ba}(t)$. We further assume that the component signals on the right side of either equation above (e.g., $s_u(t)$, $s_g(t)$, $n_u(t)$, and $i_u(t)$ in the first equation) are wide-sense stationary, mean zero, and uncorrelated with each other.

Although mobility adds another level of complexity to performance calculations and is not considered here, there are no fundamental limitations that would preclude the use of UWB radios in most mobile systems.

Then the power spectral densities of the received signals are given by

$$S_{r_u}(f) = |H_{uu}(f)|^2 S_{s_u}(f) + |H_{ug}(f)|^2 S_{s_g}(f) + N_u + S_{i_u}(f) \quad (3)$$

$$S_{r_g}(f) = |H_{gu}(f)|^2 S_{s_u}(f) + |H_{gg}(f)|^2 S_{s_g}(f) + N_g + S_{i_g}(f), \quad (4)$$

where subscripted $S(f)$ functions represent the corresponding power spectral densities (in watts/Hz), and subscripted $H(f)$ functions represent the system functions (unitless) of the indicated linear time-invariant channels. These system functions are Fourier transforms of the channel impulse responses with the same subscript indicators.

$$H(f) = \mathbb{F}\{h(t)\} = \int_{-\infty}^{\infty} h(t)e^{-j2\pi ft}dt. \quad (5)$$

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[2] Dr. Scholtz is Professor of Electrical Engineering. Messrs Hilmes, Homier, Lee, Taha, Weaver, and Wilson are graduate students associated with the Ultra-wideband Radio Laboratory.

As indicated in (3) and (4), the power densities of the equivalent receiver noises are assumed constant and denoted by level N_a in receiver "a".

The receivers of Fig. 1 include those portions of their processing that will improve signal-to-noise ratio, including (a) the rejection of out-of-band signals by filtering, and (b) the achieving of processing gain by spread-spectrum techniques. Let's assume that receiver "a"s desired signal has center frequency f_a, its noise bandwidth is B_a, and its data rate is D_a. We estimate the effective interference power I_a in receiver "a" from other radiators by

$$I_a \approx \int_{f_a - B_a/2}^{f_a + B_a/2} S_{i_a}(f) df \tag{6}$$

We assume that the power spectral density of the UWB signal at the input to a narrowband general receiver can be approximated by a constant

$$U_g = |H_{gu}(f_g)|^2 S_{s_u}(f_g) \tag{7}$$

over the operating range of the receiver. We also assume that the desired signal is processed by the receiver without significant distortion and that its total power at the receiver input is denoted by

$$P_a = \int_0^\infty |H_{aa}(f)|^2 S_{s_a}(f) df \,. \tag{8}$$

Some rough measures of signal quality at the receiver outputs can be calculated from these pieces of information. Specifically the carrier-power-to-noise-power-density ratio at the general receiver can be estimated to be

$$\left(\frac{C}{N_{tot}}\right)_g \approx \frac{P_g}{N_g + U_g + \frac{I_g}{B_g}} \,, \tag{9}$$

and the equivalent bit-energy-to-noise-power-density ratio is related to this quantity by

$$\left(\frac{E_b}{N_{tot}}\right)_g = \frac{1}{D_g}\left(\frac{C}{N_{tot}}\right)_g \,. \tag{10}$$

Here we have used N_{tot} to represent the effective noise density from all sources including receiver noise and external interference. The effect of interference spectrum spreading in the receiver is embedded in the approximate representation of the interference noise density as flat at the level of the ratio of the interference power to the receiver's noise bandwidth. Similar equations can be written for the corresponding ratios in the UWB receiver.

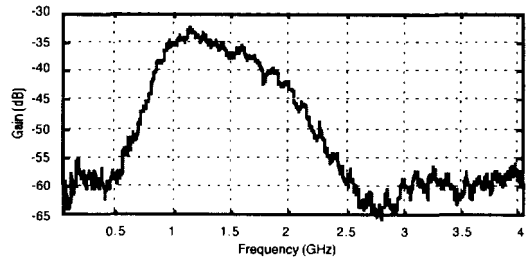

Figure 2: An average of 32 traces of $|H_{uu}(f)|^2$ from the input terminals of a typical small UWB antenna to the output terminals of an identical antenna 1 meter away. Both antennas were vertically polarized and had identical dipole-like antenna patterns. Each antenna was in the maximum-gain direction of the other. The average was taken over measurements in 32 different locations in an indoor environment.

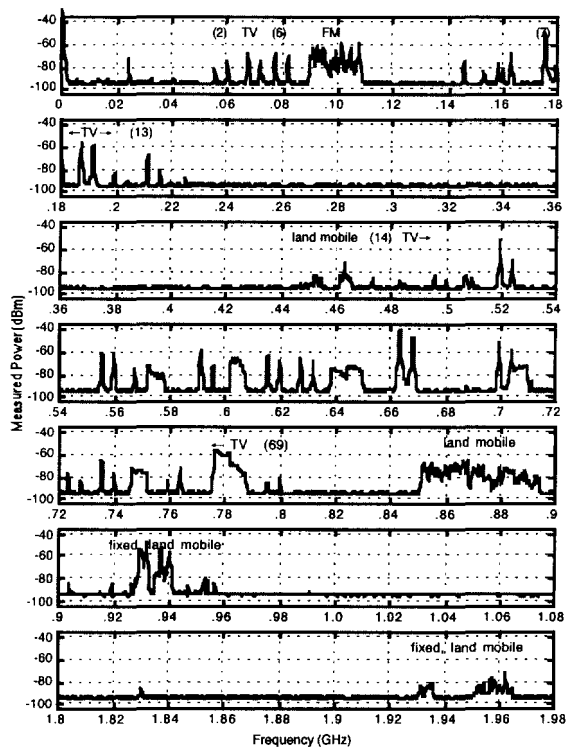

Figure 3: A measurement of interfering signals through one of the UWB antennas of Fig. 2, made in a windowed office on the fifth floor of an office building in Los Angeles. The resolution bandwidth of the spectrum analyzer was set at 300 kHz, and hence the -94.5 dbm measured noise floor corresponds to an equivalent noise power density of -149.3 dBm/Hz. No large interfering signals were measured in the range 1.08 - 1.8 GHz.

INTERFERENCE FROM OTHER RADIATORS

The general and UWB receivers operate under significantly different interference environments, not only because they are not co-located, but also because the general receiver is assumed to be operating in a dedicated frequency band, while the UWB receiver must contend with a potentially large number of narrowband radiators within its bandwidth. The external interference to the UWB receiver is strongly antenna dependent.

Example: Fig. 2 illustrates the measured system function of one possible UWB antenna system (from transmit to receive). Figure 3 shows a crude spectrum analyzer measurement of the interference-only output of one

such UWB antenna in an urban indoor environment. (See [1] for a detailed outdoor radio survey in the Los Angeles area.) It is clear that, at least for this antenna design and environment, a significant amount of lower-frequency interference power (TV, FM, and land mobile radiators) comes through the antenna's frequency sidelobes below the main passband of the UWB antenna system. Hence without any band-limiting filters in the front end of the UWB receiver, the interference power received by an antenna of Fig. 2 in the interference environment of Fig. 3 can be conservatively estimated to be

$$I_{\mathrm{u}} = -33.5\,\mathrm{dBm} \qquad \text{(no bandlimiting)}. \tag{11}$$

This level of interference can be reduced by bandpass filtering in the front end of the UWB receiver.

Reducing the available antenna system bandwidth of Fig. 2 by filtering to the frequency range (780 MHz, 2.05 GHz) eliminates much of the interference power, while utilizing almost 97% of the antenna system's noise bandwidth.

$$I_{\mathrm{u},97\%} = -40.9\,\mathrm{dBm} \quad \text{(97\% bandwidth usage)}. \tag{12}$$

If filtering bandwidth is reduced further to (960MHz, 1.93GHz) to eliminate the strong interferers near its band edges, the interference power in this example is bounded by the noise floor of the spectrum analyzer,

$$I_{\mathrm{u},86\%} < -60\,\mathrm{dBm} \quad \text{(86\% bandwidth usage)}. \tag{13}$$

The progression from (11) to (13) symbolizes the trading of small amounts of the UWB signal's bandwidth (and possibly power) for relatively large reductions in the interference levels in the UWB receiver. Tunable notch filters may be necessary to eliminate the worst narrowband interferers and further reduce I_{u}.

Certainly the interference power I_{u} is a critical and highly variable parameter in determining the UWB transmitter power that is required for proper operation of the UWB receiver. Let $(E_{\mathrm{b}}/N_{\mathrm{tot}})_{\mathrm{u,min}}$ denote the minimum operating bit signal-to-noise ratio that gives satisfactory performance in the UWB receiver. Then, using equations analogous to (9) and (10) for the UWB receiver and assuming that the interference U_{g} from the general system has been included in the measurement of I_{u}, one can show that satisfactory operation is achieved when the received energy per bit $P_{\mathrm{u}}/D_{\mathrm{u}}$ satisfies

$$P_{\mathrm{u}}/D_{\mathrm{u}} > \left[N_{\mathrm{u}} + \frac{I_{\mathrm{u}}}{B_{\mathrm{u}}}\right](E_{\mathrm{b}}/N_{\mathrm{tot}})_{\mathrm{u,min}}. \tag{14}$$

It is worth noting that if I_{u} is dominated by a few strong narrowband interferers, then I_{u} may be highly sensitive to the location of its measurement, the interference suffering from multipath enhancement/fading.

The bound (14) on received signal power P_{u} can be converted to a bound on the transmitted signal power $\overline{P}_{\mathrm{u}}$ for any given channel. Assuming that the transmitted power density is nearly constant over the passband $(f_{\min}, f_{\max})$ of the UWB antenna system, this bound is simply

$$\begin{aligned} P_{\mathrm{u}} &= \int_{f_{\min}}^{f_{\max}} |H_{\mathrm{uu}}(f)|^2 S_{s_{\mathrm{u}}}(f)df \\ &\approx B_{\mathrm{u}} S_{s_{\mathrm{u}}}(f_{\mathrm{u}}) G_{\mathrm{uu}}(R) \approx \overline{P}_{\mathrm{u}} G_{\mathrm{uu}}(R), \end{aligned} \tag{15}$$

where the avarage power gain of the UWB channel is given by

$$G_{\mathrm{uu}}(R) \stackrel{\mathrm{def}}{=} B_{\mathrm{u}}^{-1} \int_{f_{\min}}^{f_{\max}} |H_{\mathrm{uu}}(f)|^2 df. \tag{16}$$

Here we have indicated explicitly the dependence of the channel gain on the range R between the UWB transmitter and receiver, this relationship being embedded in $H_{\mathrm{uu}}(f)$.

UWB INTERFERENCE TO OTHER SYSTEMS

The Federal Communications Commission (FCC) regulates the maximum interference to which a radio system can be subject by an out-of-band interferer. Currently the FCC has no regulation in place which will allow the deployment of commercial UWB products, but proposed regulations are expected to be announced in the near future [2].

Regulations are posed as a function of the electric field strength at a prescribed distance from the transmitting antenna. For two polarization-aligned identical antennas a distance R apart, matched for maximum power transfer to their associated circuits, there is evidence that one can model the transfer function $H_{\mathrm{uu}}(f)$ from one pair of antenna terminals to the other by [3]

$$H_{\mathrm{uu}}(f) = \frac{(j2\pi f)\eta_0}{2\pi c R Z_0} e^{-j2\pi f r/c} [H_{\mathrm{R}}(f)]^2 \tag{17}$$

where $H_{\mathrm{R}}(f)$ is the receiving transfer function[3] (in units of meters) from the electric field reference point near the receiving antenna to the antenna terminals, Z_0 corresponds to the identical source and load impedances, and $\eta_0 = 377\Omega$ is the intrinsic impedance of free space. The $j2\pi f$ in (17) represents a differentiation that is present in the radiation process. We will make use of the power relationships that this equation embodies.

The transfer function $H_{\mathrm{Eu}}(f)$ from the terminals of the transmitting antenna to the electric field at the reference point of the receiving antenna is

$$H_{\mathrm{Eu}}(f) = \frac{H_{\mathrm{uu}}(f)}{H_{\mathrm{R}}(f)}. \tag{18}$$

The transfer function $H_{\mathrm{uu}}(f)$ can be measured by a network analyzer, and hence $H_{\mathrm{R}}(f)$ can be calculated from (17) and $H_{\mathrm{Eu}}(f)$ from (18). The transfer function $H_{\mathrm{Eu}}(f)$

[3] The power gain of the UWB antenna in the direction in which $H_{\mathrm{R}}(f)$ is measured and at frequency f and wavelength λ is given by $|H_{\mathrm{R}}(f)|^2 \times \frac{4\pi}{\lambda^2} \times \frac{\eta_0}{Z_0}$.

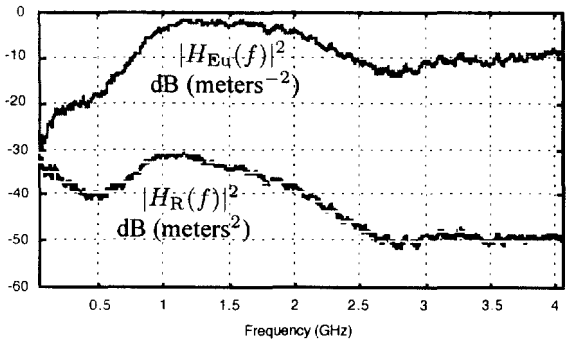

Figure 4: A decomposition of the function $|H_{uu}(f)|^2$ of the antenna system of Fig. 2 into its component functions.

(in units of meters^{-1}) is a key component of electric field calculations for regulatory purposes.

One possible form of regulation for UWB radio signals is to specify that the rms electric field strength measured in any bandwidth B_{reg} at a distance R_{reg} be at most E_{reg} volts/meter. This translates into the bound

$$Z_0 \int_{f_0 - B_{reg}/2}^{f_0 + B_{reg}/2} \left[|H_{Eu}(f)|^2 \right]_{R=R_{reg}} S_{s_u}(f) df < E_{reg}^2 \tag{19}$$

for all f_0. Assuming that the integrand above is a smooth function and that the peaks of $H_{Eu}(f)$ and $S_{s_u}(f)$ approximately coincide for efficiency, (19) can be restated as

$$\max_{f_0} S_{s_u}(f_0) < S^*, \tag{20}$$

where

$$S^* \stackrel{\text{def}}{=} \frac{E_{reg}^2}{Z_0 B_{reg} \max_{f_0} \left[|H_{Eu}(f_0)|^2 \right]_{R=R_{reg}}}. \tag{21}$$

The quantity S^* can be interpreted as the effective regulatory bound on the transmitted UWB signal's power spectral density at the frequency which is most efficiently transmitted by the given UWB transmitting antenna.

If the power spectral density bound S^* is observed by the UWB transmitter across the bandwidth B_u of its antenna system, then the transmitted UWB power $\overline{P}_u$ is reasonably bounded by

$$\overline{P}_u < S^* B_u. \tag{22}$$

An Example: Let's suppose that by regulation a UWB transmitter must create an electric field strength E_u that is at most 500 microvolts/meter at 3 meters from the transmitting antenna, in any 1 MHz band.[4] Compliance with this requirement would have to be checked in an anechoic chamber with a calibrated receiving antenna.

[4] Part 15.109 of Section 47 of the *Code of Federal Regulations* indicates that for signals above 960MHz, the unintentional radiated emission limit for all but Class A devices is 500 microvolts/meter at 3 meters. The example's regulation modifies this in three ways: (1) the emission is intentional, (2) here the level of emission is allowed in every 1 MHz band in which the UWB transmitter radiates, and (3) the example's field strength is not limited to frequencies above 960MHz.

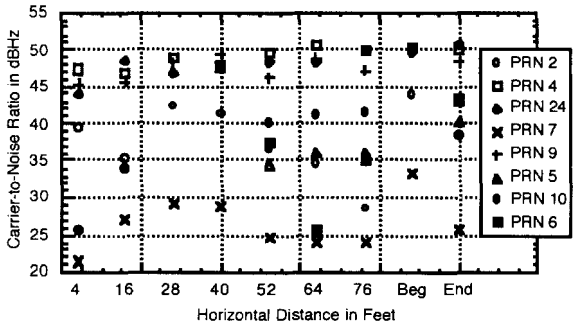

Figure 5: Carrier-to-noise ratios in a GPS receiver for different GPS satellite signals (identified by their PRN codes), as a function of the distance between the fixed GPS receiver and a UWB emitter. The time ordering of the measurements was Beg, 40′, 28′, 16′, 4′, 52′, 64′, 76′, End. The Beg and End measurements were made with the UWB emitter off.

Suppose that a UWB system employing the antenna system of Figs. 2 and 4 must comply with the above requirement. Then the power density bound at 1.15 GHz for the signal being supplied to the transmitting antenna is

$$\begin{aligned} S^* &= \frac{(5 \times 10^{-4})^2}{50 \times 10^6 \times 3^{-2} \times 10^{-.2}} \text{ Watts/Hz} \\ &\approx -131 \text{ dBW/Hz}. \end{aligned} \tag{23}$$

Assuming that this antenna system's bandwidth is roughly 900 MHz, the transmitted power supplied to this antenna would be approximately -12 dBm.

A GPS INTERFERENCE TEST

While FCC regulations are and will be the basis for controls on UWB emitters, it is informative to study the problems that come up in a test of UWB interference to a GPS receiver. Notwithstanding the great variety of GPS antennas and receivers, as well as UWB waveforms, we performed a test in which the UWB antenna of Figs. 2 and 4 was pulsed by a subnanosecond pulse of approximately Gaussian shape (standard deviation parameter = .24 ns) at a rate of a million pulses per second, creating an interference line spectrum with 1 MHz spacing to the GPS receiver. The GPS receiver itself was designed to have a front-end bandwidth of 16 MHz, thereby collecting several of these lines. The results of this interference on the CA code carrier-to-noise ratio $(C/N_{tot})_g$ at the L1 carrier frequency 1.57542 GHz for all satellites in view is shown in Fig. 5.

Certainly it is possible to predict theoretically the observed interference effects based on linear front-end processing in the GPS receiver and knowledge of its noise floor. The experiment described above can approximate the effect of a flat received UWB interference density U_g (see (7)) in the GPS band because there are several spectral lines from the test UWB signal within the RF bandwidth of the GPS receiver. Spread-spectrum processing of the GPS receiver will spread this interference power smoothly over the receiver's correlator output bandwidth, spectrally approximating white noise. The transmitted UWB power is -41 dBW, corresponding to a transmitted power density of ap-

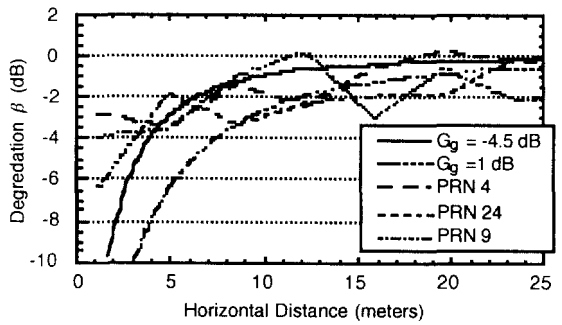

Figure 6: Degredation plots as a function of horizontal distance between the UWB transmitting antenna and the GPS receiving antenna, for the three GPS satellite signals that were stable for the duration of the test.

proximately -76 dBW/MHz in the GPS band, and 5 dB lower than the value of S^* in the example of (23).

Estimating the effect of the GPS receiving antenna on the vertically polarized incident UWB electric field requires taking into account the interaction of this field with the upward looking circularly polarized GPS antenna. (The output terminals of the GPS antenna were not accessible for a network analyzer measurement of the UWB-to-GPS antenna system.) With the UWB antenna at a horizontal distances between 4 and 76 feet from the GPS antenna and roughly 2 feet higher, there are significant axial ratio and linear to circular polarization losses (estimated from specifications) that must be included along with the GPS antenna gain pattern in the calculation of U_g.

When the GPS receiver operates in a linear fashion on the incoming interfering signal, the degredation β in carrier-to-noise ratio $(C/N_{\text{tot}})_g$ that is caused by the presence of a UWB signal is computed in terms of changes in the effective noise power density in the GPS receiver, i.e.,

$$\beta = \left(\frac{N_g}{N_g + U_g}\right), \tag{24}$$

where U_g is given in (7). Using an effective GPS receiver noise temperature of 300°K, the theoretical and experimentally measured values of $(C/N_{\text{tot}})_g$ degredation β are shown in Fig. 6. It is assumed that the effects of multiple-access interference from other GPS signals are included in the GPS receiver's noise power density N_g.

There is good agreement in Fig. 6 between measurement and theory for distances beyond 5 meters, but our predictions of degredation at shorter ranges are worse than the measured degredations. While there are many approximations that could partially account for these discrepancies, one conjecture that might explain this difference is that the GPS receiver's processing was driven out of its linear region at short range by the impulsive nature of the UWB pulse interference, reducing the interfering pulse power by clipping the UWB pulses.

In all of these measurements, the GPS receiver always produced a position measurement, i.e., it always could access enough satellite signals to complete a position location estimate. We believe that the selective availability effects

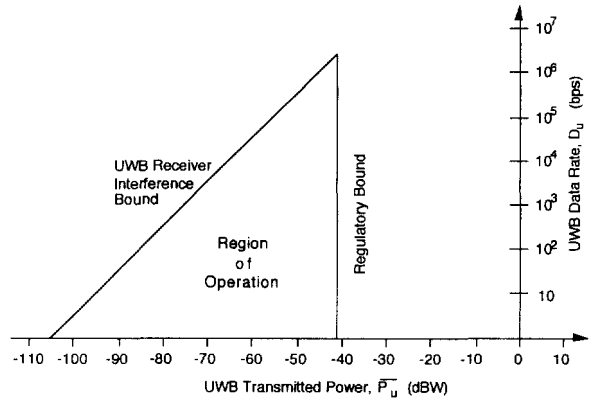

Figure 7: The region of the $(\overline{P}_u, D_u)$ plane representing the operating range of UWB systems. The numerical values used in plotting the bounds on the region of operation come from the examples used in this paper, with numerical values provided by (13) and (23), scaled to an operating range of 30 meters, with $(E_b/N_{\text{tot}})_{u,\min}$=10 dB.

imposed on the satellite signals for ordinary GPS navigation would completely mask the error effects caused by the UWB interference in these tests. The UWB interference effects may have somewhat more effect on differential GPS systems, but the carrier-to-noise ratio effects are the same in both cases. For experiments with a variety of GPS receivers, but not instrumented for $(C/N_{\text{tot}})_g$ measurements, see [4].

UWB SIGNAL POWER BOUNDS

The upper bound on UWB transmitted power $\overline{P}_u$ based on interference to other systems, and the lower bound based on the effects of interference to the UWB receiver are summarized here.

$$S^* B_u > \overline{P}_u > \frac{D_u}{G_{uu}(R)} \left[N_u + \frac{I_u}{B_u}\right] (E_b/N_{\text{tot}})_{u,\min} \tag{25}$$

It is worth noting that there is always a critical value of data rate D_u below which the upper bound exceeds the lower bound and communication is feasible in principle.

The deployment challenges for UWB systems are epitomized by the region of operation in in Fig. 7, both in defining that region, and in controlling its boundary to increase the maximum bit rate at which communication will be possible. Clearly, dB changes in the range of allowable transmitter power $\overline{P}_u$ for a given data rate $D_u$translate directly into dB changes in the potentially achievable data rate D_u. There are significant dB uncertainties in these bounds, even for the examples in this paper, because of approximations in the mathematical models used, and uncertainties in the real environment into which a system will be deployed.

The upper bound on the transmitter power can be raised by expanding bandwidth, improving antennas, etc., and is subject to conjecture until the FCC settles regulatory issues.

The lower bound is dominated by interference that may occur in the UWB receiver, and in particular by the quan-

tity I_u/B_u. Since I_u is measured in the operating bandwidth B_u, The system designer should explore the choice of passband to maximize this ratio, within the constraints imposed by propagation effects and hardware constraints.

The boundaries of the operating region have been illustrated here in a relatively simple way. Assumptions have been made in developing these bounds that may be optimistic or pessimistic for a given system and environment. When the bounds on $\overline{P}_u$ are tight and account for the inefficiencies and the realities of an implementation, then the difference between the upper and lower bounds in (24) for a given data rate D_u represents a measure of the achievable link margin for the UWB system. Hence the higher the data rate D_u, the lower the margin available to accomodate unforseen interference and propagation problems. Using the example of Fig. 7 which indicates a critical data rate of roughly 3 Mbps, a margin of 20 dB in the power budget would could be achieved only for data rates below 30 Kbps.

ISSUES IN COMPLETING THE UWB LINK

Communication over paths with a clear line-of-sight can be done in a variety of ways. The potential advantage of UWB radio comes from the ability of low-frequency radio waves to penetrate materials [5]. It is this capability that makes UWB systems competitive with other higher-frequency systems of comparable bandwidth. From another viewpoint, it is the very large bandwidth of a UWB system, which makes it ideal for ranging and provides multipath resolution, that makes it competitive with narrower bandwidth systems within its frequency range.

In many environments, the UWB signal undergoes a significant amount of distortion in the process of propagating from transmitter to receiver. A sub-nanosecond pulse may reverberate in an indoor environment for a few hundred nanoseconds, making complete reception or equalization of the UWB signal difficult. The UWB receiver must track (or compensate for) these distortions to take full advantage of all of the received power for communication purposes. Estimates [6] of the number of resolvable signal components that must be tracked to capture a given percentage of the total incident UWB signal power in an indoor environment can vary significantly over relatively small changes in antenna location because of individual path shadowing, etc. The temporal diversity inherent in such a selective-Rake UWB receiver may be equivalent to a level of directional/ spatial diversity because different components of the received signal arrive at the receiver along spatially distinct paths [7]. These all are considerations in the design of a robust and efficient UWB receiver processing algorithm.

Deployment of UWB radio systems in large numbers with multiple access to the environment can be accomplished by code-division multiple-access techniques. However, accurate prediction of the numbers and possible spatial distribution of UWB radios that may occur in the future is very difficult to estimate or bound. Hence, the aggregate interference that the successful deployment of UWB technology may cause to other systems is not a reliably predictable quantity at the present time. Indeed this concern may lead to regulations that are ultimately too restrictive (or too liberal) in their control of UWB emissions.

ACKNOWLEDGMENT

The authors wish to thank Profs. Keith Chugg, Won Namgoong, and Aluizio Prata for their useful comments and suggestions.

REFERENCES

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[2] See the Ultrawideband Working Group's web page at http://www.uwb.org.
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