Technical Appendices
to the Reply Comments of Time Domain Corporation

ET Docket 98-153

Prepared by the Technical staff members of
Time Domain Corporation

Appendix A.
Analysis of the Impact of UWB Emissions on a 1.9 GHz CDMA PCS System

Summary

Time Domain has been working with Sprint PCS to develop an understanding of the nature of the interaction between Time Modulated-UWB and a 1.9 GHz CDMA PCS ("CDMA") system and to account for the interactions under a wide variety of situations.

Crucial findings of this work on which both Sprint and TDC agree were that:

1. For a Time Modulated UWB emitter with a PRF greater than the bandwidth of the CDMA channel, the UWB signal can be accurately modeled as Additive White Gaussian Noise;
2. The model predicts blocking when the CDMA signal is at –95 dBm and the handset is within 1.5 meters of a continuously transmitting UWB device;
3. When operating in an anechoic chamber, the test results conform to the model's predictions; and
4. That UWB emissions are unlikely to have an impact on the reverse link when the base station has an outdoor elevated antenna, *i.e.*, that the CDMA base station receiver will not be affected by UWB emissions.

TDC differs from Sprint on the following points:

1. The claim that CDMA signal levels below –95 dBm are sufficiently reliable to constitute a useful coverage area;
2. The assumption in the model that all UWB transmitters emit UWB signals continuously when most of the applications that have been identified for UWB are likely to be highly intermittent (e.g., packet radio wireless LANs);
3. The belief that UWB causes loss of cell capacity; and
4. The claim that an aggregation of TM-UWB units will significantly increase the probability of harmful interference.

The Telcordia model submitted jointly by TDC and Sprint PCS in this proceeding is an excellent theoretical analysis of the interaction between a 1.9 GHz CDMA PCS system and TM-UWB emissions. However, results from real-world testing differed dramatically from the model's predictions. Radiated tests were conducted in an anechoic chamber and also in real-world out-of-doors environments. These results were then compared to the mathematical models describing how the PCS system would react to UWB emissions. The anechoic chamber tests conformed to the Telcordia model; however, the out-of-doors radiated test results differed significantly.

The reasons for this difference appears to be that many real-world noise sources are always present to a varying extent and combine to limit the impact of TM-UWB on CDMA communications. The effect was very apparent when TDC compared the anechoic chamber test result to those taken in the field. The chamber eliminated all but thermal noise, but in the field a surprisingly large number of frame errors occurred, even when the CDMA signal was -85 dBm (*i.e.*, 20 dB above the minimum useful signal level) with no TM-UWB signal present. One need only observe the fluctuation of the signal strength indicator of a PCS phone to get a sense of this issue.

Among the factors that TDC believes must be incorporated into the model to make it more representative of the real world, are the influences of the CDMA propagation channel (*e.g.*, Rayleigh fading and other sources of noise), and also the likely characteristics of UWB transmissions. The following sections discuss this issue in detail.

CDMA and TM-UWB Interaction

Analysis

TDC and Sprint PCS decided to pursue an analytical model to be augmented by both laboratory and field tests. The model presents a wide variety of equations linking the CDMA system response to increases in white noise, develops statistical relationships, integrates responses over the structure of an entire CDMA cell, and presents them as families of curves. The mathematics derived in this model does allow flexibility as the situations change.

The single most important limitation of the analytical model is the real-world factors of consideration of multipath and fading. Including these factors would bring the model closer to portraying the interaction with CDMA technology in a more realistic context.

The actual field performance imposes many other system impairments that mask the TM-UWB signal until the situation becomes extreme, *i.e.*, the CDMA signal becomes too weak and the TM-UWB device comes in too close proximity to the handset. Examples of these impairment scenarios include Rayleigh fading, multipath signal distortion, man-made ambient noise, as well as other Part 15 noise sources, and self-induced CDMA noise.

Although the Telcordia model considered the impact of TM-UWB duty cycle less than 100%, only the case where the TM-UWB transmitter was constantly transmitting was presented. The vast majority of TM-UWB applications require a very low duty cycle. At transmission rates of 10 to 100 Megabits per second, for example, complete messages are sent in a matter of a few hundred microseconds, after which the transmitter is quiet for relatively long time periods. During this “off” time there is no possibility of interference.

The Two Potential Interference Mechanisms

The Telcordia model concentrated on interference to the forward link because it was the main concern. In this link there are two potential mechanisms through which TM-UWB might cause interference to the forward link (handset receive) of CDMA systems:

Blocking: The handset receive signal (the "forward link") may be blocked if the signal is sufficiently weak while the TM-UWB transmitter is close by (*i.e.*, the UWB signal raises the noise floor to such an extent that an otherwise useful CDMA signal is drowned out).

Forward Channel Power Control: The CDMA handset has the ability to monitor the frame error rate of the received signal. When the quality of the received signal deteriorates (*i.e.*, has a drop in the bit energy to noise ratio) for whatever reason, the handset asks the base station to increase the power in the forward link. The extent to which the power control mechanism can raise the traffic channel power is limited. For a single phone call, the power control can rise only to a maximum level that is 7.3% of the total forward link power. Only when the handset requires more additional power to maintain the required bit energy to noise ratio and no additional power allocation remains, is the call dropped. There is a concern, however, that since power allocation from the base is limited and all phone calls on a base station must share the limited available power, that unnecessarily increasing the power allocation to any call due to TM-UWB interference might reduce cell capacity.

TDC explains below that each of these concerns is unwarranted.

Tests and Results

Sprint PCS and Time Domain conducted two sets of tests to measure the interaction between TM-UWB and the CDMA handset. These tests confirmed that the Telcordia model accurately predicted the results obtained in an ideal environment, but did not match the results from real world testing. These tests were:

Tests in the anechoic chamber. In this case, the chamber shielded all but thermal noise. The anechoic chamber tests were structured to determine the minimum signal characteristics and antenna losses of a CDMA handset and the effects of a TM-UWB device radiating nearby. The CDMA base station signals were simulated with a signal generator. Free space losses of the TM-UWB signal were confirmed, along with the impact of a handset user holding the handset in a variety of positions.

During the anechoic chamber tests with no TM-UWB present, the diagnostic monitor showed a frame error rate that remained equal to zero until the CDMA signal (from the signal generator) was reduced to a few tenths of a dB above the handset's noise floor. A sharp knee in the error curve occurred between the onset of the first errors and loss of signal. These results conformed to the Telcordia model.

Live tests on a dedicated base station in the field. The live field tests were conducted over two days. On both days the CDMA test handset was the only device radiating on the test frequency. On the first day the test handset provided the only traffic to the base station, while on the second day a traffic load of 50% was simulated in software at the base station. Tests were performed at three sites on both days, at locations where the received signal strength was approximately –86, -94, and –103 dBm. In each case the CDMA handset was set up, a call established, the TM-UWB source turned on at a distance of 3 meters from the handset, then moved closer until the call was eventually blocked.

Because the real world environment contains elevated ambient noise levels and multipath fading even under the best conditions, it is unreasonable to compare the impact of UWB under only a thermal noise impaired environment. In one set of field tests, with a fairly strong CDMA signal (*i.e.*, -85 dBm), the frame error rate was low but unstable, reaching intermittent peaks of 8% with no TM-UWB present, nearly a 20 dB difference from anechoic chamber results!

During another set of the outdoor tests, with the CDMA signal at –94 dBm, the forward traffic channel transmit power spanned the range from 16 to 21 dBm with the TM-UWB turned off. The base station was dedicated to this test, so there was no possibility of CDMA co-channel interference. The test site had buildings at about 50 yards, moving traffic at 30 yards away, and line of sight to the base station.[1] According to the analytical model, as the TM-UWB to CDMA handset separation decreased, the increased noise at the handset should have caused a steady increase in the channel power. But, as Figure 1 below shows, it did not. The fading environment caused a 5 dB variation in the forward power and caused frame errors before the TM-UWB was ever turned on.

Time Domain contends that the test results depicted in Figure 1 represent a worst-case impact of TM-UWB. Average received signal strength was –94 dBm prior to the UWB noise generator being turned on; the base station transmit power was varying by approximately 5 dB (apparently to deal with fading); and the UWB emitter was aligned with the handset to ensure maximum coupling of the UWB RF energy.

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[1] (This is a classic geometry for multipath fading of signals where there is a direct signal path. *See* W.C. Jakes, Microwave Mobile Communications, IEEE Press, 1974, Ch. I. Signal statistics would be strongly Rayleigh if the direct path contained less than about half the power, Ricean if the direct component was more than half the power. The 5 dB span in transmitter power correction suggests that the received signal had a significant Rayleigh component.)

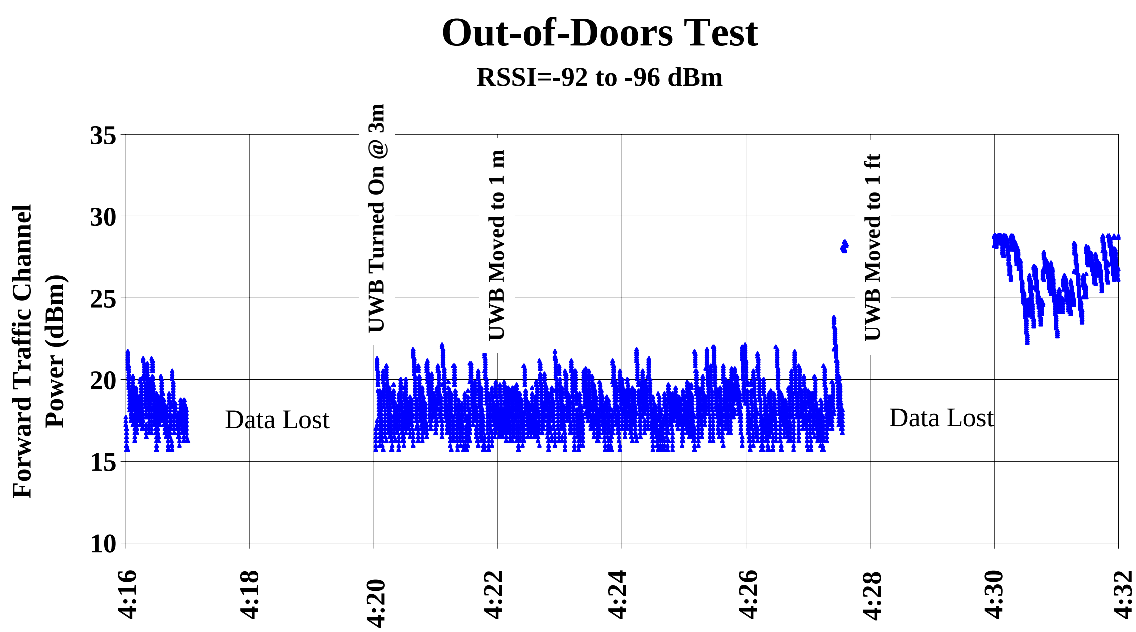

Figure 1. The impact of a TM-UWB emission on a CDMA forward link[2]. Average received signal strength was –94 dBm (implying a path loss of approximately 112 dB). Power control fluctuations are occurring prior to the UWB emitter being turned on (Forward Traffic Channel power varied between 16 dBm and 21 dBm). A significant increase in the power allocated to this call did not occur until the UWB emitter was within one foot of the CDMA handset.

Following is the sequence of events for this test:

1. The recording starts at 4:16 PM with the TM-UWB transmitter turned off. The received CDMA signal strength was averaging –94 dBm at the handset. Using the relationship $\alpha = \frac{1}{M_J}(\frac{N}{P_{rx}} + F_{no})$,[3] the model predicts a rise in the forward

[2] Data from joint TDC/Sprint PCS testing as plotted by TDC.

[3] Sprint PCS TDC Joint NPRM Comments Filing at 3, eqn 3.

power allocation of 2.6 dB, given a received signal strength of –94 dBm and outdoor non-orthogonality factor[4] of 0.1.

2. The TM-UWB device was turned on at 4:20 PM at a distance of 3 meters from the CDMA handset. Based on the model the relationship $\Delta\alpha = \frac{I_{uwb1}}{d^2 M_J P_{rx}}$ predicts that the presence TM-UWB signal should cause the system to raise the forward power allocation by 2.3 dBm, but any rise is totally masked by other noise and no TM-UWB impact is apparent. As a matter of fact, no average power increase at all can be seen in the test data until 6 minutes after the TM-UWB device was initially turned on.

3. At 4:22 PM, two minutes after the TM-UWB emitter was turned on, the TM-UWB device was moved to within 1 meter of the CDMA handset, where test results show that the frame error rate reached 2%. At this point the model predicts that the forward power should rise by 8.7 dB. Yet Figure 1 shows no increase in the forward channel power

4. Finally, the TM-UWB device was moved to 1 foot from the CDMA handset at 4:28 PM, at which time the interference caused the call to be dropped.[5] It is not until the call is actually blocked that an increase (the several data points at 4:27:30, just prior to a recording loss) in the channel power is noticed. The rise in

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[4] Several CDMA channels are broadcast on a single carrier, each with a unique spreading code. These codes are orthogonal under ideal conditions, however, real-world influences reduce the orthogonality and this fact is incorporated in the Telcordia model as the non-orthogonality factor.

[5] The data recorder operator inexplicably stopped the recordings at 4:17 – 4:20 and 4:27:30 – 4:30.

the traffic channel power, from 16 dBm to 28 dBm (12 dB rise), is exactly as would be predicted by the model set for an outdoor non-orthogonality factor of 0.1. It is critical to note that only in the extreme case of call blocking at 1 foot does the test data match the model's prediction of a 12 dB rise in the traffic channel power. The predicted rise should be gradual, but the measurement shows an abrupt change. This is a worst-case example because the TM-UWB was left constantly on. As TDC has stated in the main body of this pleading (and in detail below[6] the vast majority of TM-UWB devices will only transmit occasional bursts.

This example emphasizes the impact of a practical environment scenario, in which TM-UWB transmission is an exceedingly small factor. In a real-world environment, many factors combine to increase the traffic channel power before TM-UWB interference becomes a factor. These other noise factors are explained further below.

Multipath Noise Impairment

In nearly all environments in which CDMA handsets are used, multipath induced fading is a major problem. In environments where the CDMA handset is likely to encounter TM-UWB signals (e.g., within buildings) the CDMA propagation channel will likely be dominated by Rayleigh fading. As discussed in Appendix B, when a received signal is on average at its minimum threshold level, then 63% of the time, the received signal will be below that minimum threshold. Thus, while a CDMA receiver might be

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[6] *See* "Inclusion of TM-UWB Duty Cycle" Section, *infra*.

sensitive down to –105 dBm, it is unrealistic to expect the link to be sufficiently reliable to meet the 2% frame error rate criteria.

Moreover, if the average signal strength is:

- 5 dB above that threshold, the received signal will be below the minimum threshold 27% of the time;

- 10 dB above, the received signal will be below the minimum threshold 9% of the time; and

- 15 dB above, the received signal will be below the minimum 3% of the time.

It is only when the average received signal strength is 20 dB above the threshold that the probability that the received signal will be below the threshold is less than 1% of the time.

While the CDMA signal format provides some robustness against multipath fading, the delay spread within buildings is very short (tens of nanoseconds) relative to the CDMA chip length (approximately 1.25 microseconds), which suggests that robust operation must include a fading margin. Sprint's assumption that the system can operate down to –105 dBm does not include such a margin.

Other Noise Impairments

The effective sensitivity of the CDMA handset, as measured in the anechoic chamber, results in an received signal strength of –105 dBm (noise figure equal to 8 dB). This figure degrades seriously in practical use due to the following four significant sources of RF noise:

1) There is ambient noise present to a varying extent. ITS/NTIA has reported ambient signals of no less than 12 dB at 1.9 GHz in recent surveys at three major metropolitan areas.[7] An ambient of this level would raise the effective noise figure of the receiver by 1.6 dB.

2) Outer Cell Interference (OCI) is phenomena whereby a CDMA handset receives interference from nearby base station transmitters; this typically occurs where there is fringe coverage and/or in preparation for soft handoff. It is important to note that base stations that are not carrying the phone call act as interferers, and lower the effective sensitivity of the handset. This effect has a real impact, particularly in the fringe reception outdoor scenario. This is an outdoor scenario where the non-orthogonality factor equals 0.1. The model[8] predicts that the handset sensitivity can be derived from $P_{RX\,\min} = \frac{N}{M_J \alpha_{\max} - F_{no}}$ and found to be equal to –106.5 dBm[9]. However, in the presence of OCI the receiver's effective sensitivity is now –101.5 dBm, a reduction in sensitivity of 5 dB.

3) Loss of code orthogonality, again a form of CDMA self-interference, is characteristic of the CDMA system that varies the real-world sensitivity of the

[7] NTIA ITS documents; #99-367 NTIA Technical Report "Broadband spectrum survey at San Francisco, California May-June 1995", #97-334 NTIA Technical Report "Broadband spectrum survey at San Diego, California", #95-321 NTIA Technical Report "Broadband spectrum survey at Denver, Colorado."

[8] Sprint PCS TDC Joint Filing at 26, Figure A-6

[9] Sprint PCS TDC Joint Filing at 4, eqn 9.

CDMA handset to vary according to the relationship $P_{RX\ \min} = \dfrac{N}{M_J \alpha_{\max} - F_{no}}$.[10]

As the non-orthogonality factor varies from 0 to 1, the value of P_{RXmin} will vary from –106.8 dBm to –102.1 dBm.

4) Co-channel interference is caused by the base station’s forward channel power when numerous cell phones are talking at the same time. The base station will transmit all traffic channels on the same frequency at the same time. All undesired channels merely add to the noise floor, in similar fashion to TM-UWB interference.

Adding these noise sources suggests that the while the handset receiver thermal noise floor might be sensitive to –105 dBm, the effective noise floor is closer to –100 dBm in the presence of many real-world noise impairments.

Bounding of the Issue

Time Domain believes that Figure 2 describes the bounds on potential interference of TM-UWB to CDMA. As derived from theory[11], the curved line represents the minimum distance that can be tolerated between a TM-UWB transmitting device and a CDMA handset over a region of received signal strengths from the CDMA base station, before a call is dropped. The three areas represent regions where the different impacts are predicted by the Telcordia analysis combined with Time Domain’s analysis.

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[10] Telcordia at 4, derived from eqn 9.

[11] Derived from Sprint PCS TDC Joint Filing at 3, equation 3.

The data in Figure 1 suggests that the system needs at least 5 dB for fading (and this data was taken in an open environment and not indoors where a direct path is unlikely). The analysis above of other noise suggests that an additional 5 dB of margin is necessary to deal with other noise sources. Thus, these two factors strongly support TDC's belief that a more rational noise floor assumption is –95 dBm.

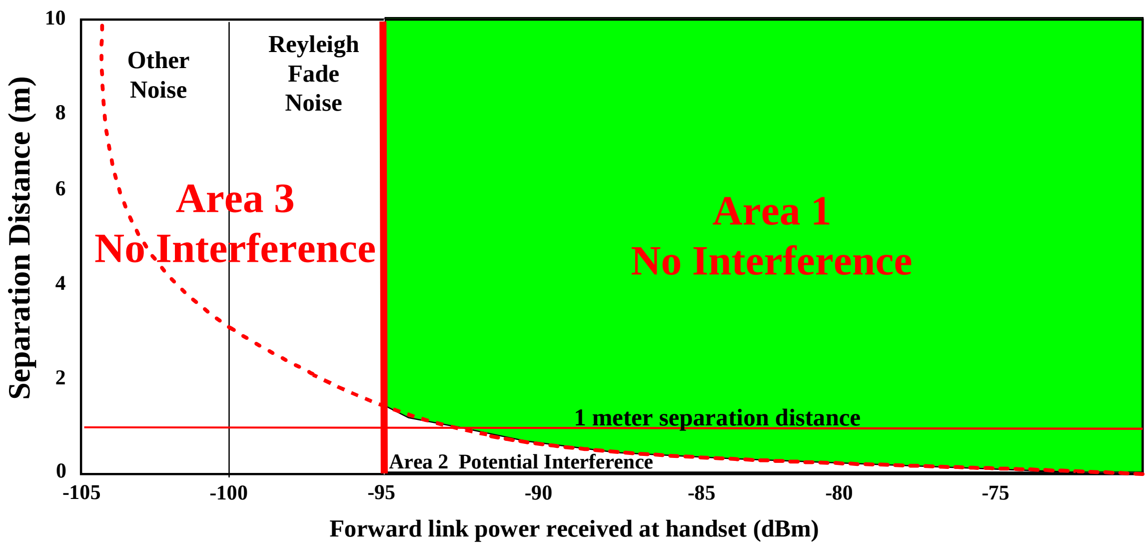

Figure 2. When real-world factors are considered, the area in which a UWB emitter might cause interference is very small. Multipath and other noise sources imply a practical noise floor of –95 dBm and the Part 15 power limits imply that above the dotted line curve[12] blocking should not occur. Therefore only Area 2 is where blocking seems at all possible and most of Area 2 is where the distance between a CDMA handset and a TM-UWB emitter is less than 1 meter.[13]

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[12] Sprint PCS TDC Joint Filing at 4, equation 9 was used to calculate the dotted curve.

[13] To put the 1 meter distance in perspective, recall that the Class B digital device limits (*i.e.*, the Part 15 general limits) were developed on the assumption that a user would have a large measure of control over the user's immediate environment to a distance of 10 meters.

Area 1: TM-UWB interference is not a problem in this region. In this region there is sufficient received power that the handset can retain acceptable communications if a TM-UWB emitter were turned on. There should be no impact in this area, other than the change in power allocation close to the line and even those power changes should be small relative to the fluctuations due to the changes in the propagation channel.

Area 2: Interference in this region is possible when the distance between a handset and a TM-UWB device is at most 1.5 meters and generally less than 1 meter. Social and physical factors will discourage people from operating devices in such extremely close proximity, so the probability of interference situations occurring in this region are small.

Area 3: This region is below a combination of the effective noise floor of the CDMA handset and the 5 dB fading margin. This margin was chosen to be equal to the fluctuations shown in Figure 1; this fade margin is arguably insufficient because traditional Rayleigh fade margins suggest 10 to 20 dB margins are necessary. There is no reason for concern regarding interference from TM-UWB in this region.

Inclusion of TM-UWB Duty Cycle

Sprint has voiced concern about the potential for large numbers of emitters to raise the noise floor in the band to a degree that might cause the CDMA system to lose capacity. Capacity would decrease if additional base station transmit power had to be allocated to any handset to overcome an increase in the noise floor due to UWB emissions. As was shown during the UWB NOI,[14] only the closest UWB emitters had

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[14] *See* NOI comments of TDC, XtremeSpectrum, and Fantasma.

the potential to increase the effective noise floor. As was shown in Figure 1, there was no measured response when a UWB emitter was turned on within 3 meters of a handset receiving a signal with a strength of –94 dBm, and that same data did not show any impact until the UWB emitter was within 1 foot. This impact would have been reduced further if the UWB transmitter were transmitting short bursts as it would if it were a wireless local area network device, for example.

The Telcordia model briefly mentions[15] that it is the density of the active TM-UWB transmitters that is of interest in determining the effect of the TM-UWB emissions, but does not develop the concept further. It is an important consideration and an additional factor that must also be considered: the duty cycle of the devices, *i.e.*, how frequently and for how long they transmit.

Most of the applications identified for UWB technologies do not require continuous transmissions; instead they will be intermittent and, in all likelihood, even when transmitting, the transmissions will be brief.

Many of the UWB manufacturers are targeting the wireless local area network marketplace. Consider the case of a standard Ethernet LAN. TDC measured the traffic of a PC. As shown in Figure 4 the traffic is highly intermittent. During the 69 minute period, 170 kilobytes was transmitted in each direction. Roughly half of the dots represent transmissions from the hub, while the remainder represents transmissions from the remotely located PC. Some 921 transmissions were logged during a period of 4177 seconds. The average transmission length was 364 bytes; the shortest transmission was 60 bytes, and the longest was 1514 bytes.

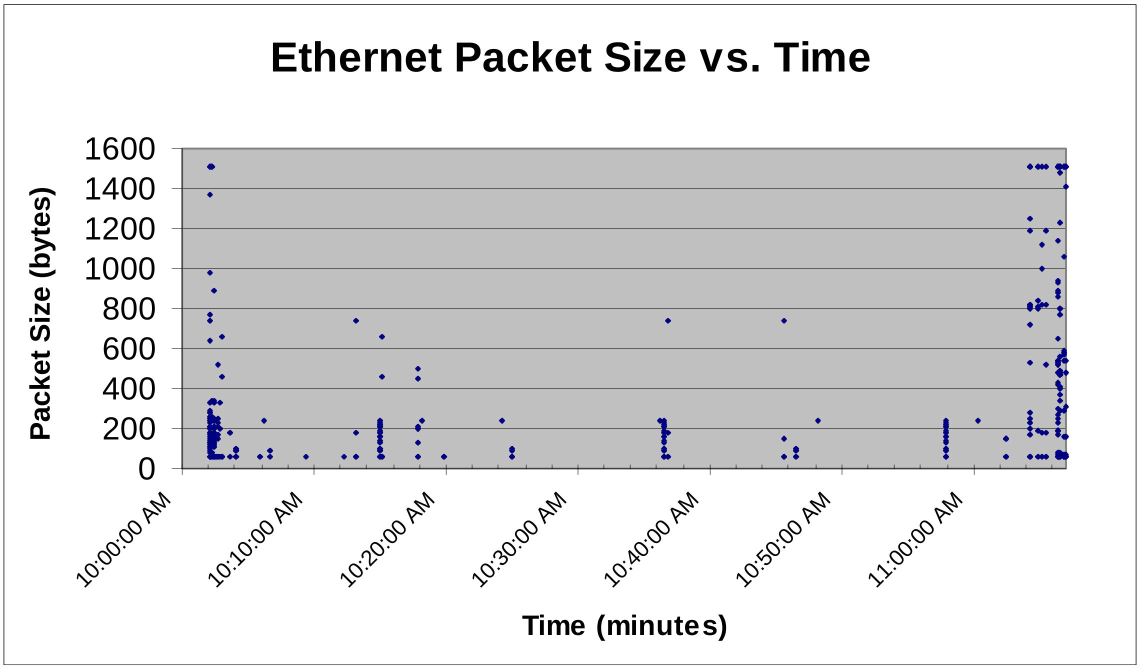

Figure 4. Ethernet traffic to and from a PC. Each dot represents a transmission between a PC and a switched hub near the network server during a little over an hour period. During this period a 170kB of data in each direction was uploaded to the PC.

Consider a conceptual UWB wireless LAN running at 10 megabits per second. The average message length would be 364 times 8 bits/byte times 10^{-7} = 442 microseconds and the longest transmission would have been 1.37 milliseconds. Incorporating a 3X factor to account for synchronization time and overhead, implies that the average message length would have been approximately 1.5 ms and the longest about 4 ms. For the traffic shown in Figure 4, the total transmission time during the 69 minutes of observation would be less than 700 ms, an average on-time of less than 0.02%!

The above test highlights the case where the TM-UWB device transmits in very bursty, intermittent segments with exceedingly short messages. There are occasions

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[15] Sprint PCS TDC Joint Filing at 5.

apparent in Figure 4 where many of the TM-UWB messages are close together, and could potentially corrupt a number of sequential CDMA frames (20 milliseconds in length) during a span of several seconds. When large messages must be transmitted, the bursts occur rapidly in succession, and as many as ten packets could hit a single frame. But for the vast majority of the time only isolated frames are subject to interference corruption. And the disruption to PCS would only be present if the handset and UWB device were within 1.5 meters of one another and the handset had the lowest practical signal level.

To put the impact of the UWB packet transmission in perspective, it must be remembered that the PCS system also has to deal with the impact of multipath. Signal fading occurs at intervals of a wavelength, *i.e.*, approximately six inches for 1.9 GHz CDMA PCS. If the handset is moving with respect to the fading at a speed of 1 mile per hour (1.5 feet per second), then the handset will move through a complete fading cycle in about 330 ms and may be in a fade for about half that time, 165 ms (which equals about eight CDMA data frames). This suggests that for CDMA to work within an in-building environment, it must be able to tolerate noise bursts of a few milliseconds, which may be present due to UWB transmissions. Given other sources of RF noise (e.g., personal computers), it seems unlikely the UWB emissions will be deleterious.

Conclusions

The Telcordia model is very useful, has good potential, but is not sufficiently complete to accurately characterize the relationships between CDMA systems and TM-UWB systems in the real-world. It does not include the impact of the many real world vagaries, which includes fading, that simultaneously combine to render the noise impact of TM-UWB minor. It considers only TM-UWB at 100% duty cycle. It also portrays

TM-UWB as the only interfering signal, thus giving the impression that TM-UWB is the only noise that interferes with the CDMA system. TDC has shown that other noise effects can have a greater impact.

TM-UWB signals are very similar to additive white Gaussian noise effects on the CDMA system. In order for the TM-UWB signal to have an impact of the CDMA handset, the handset must be within 1.5 meters and generally closer than 1 meter of a continuously transmitting TM-UWB emitter. When the UWB emitter is transmitting in intermittent bursts, as is typical, then it seems unlikely that the CDMA phone would have an observable impact on the service.

Appendix B
UWB Spectrum

Summary

Claims have been made that UWB systems with high pulse repetition frequencies and time dithering are not noise-like because they have spectral lines.[16] All radios have power spectral densities that are composed of components at discrete frequencies (*i.e.*, lines in the spectrum). Even radios controlled by pseudo-random finite-state machines, *e.g.*, direct sequence or time-hopped modulation, have this characteristic. By properly choosing the pseudo-noise coding sequence, the designer can make the spectral lines of a time modulation radio arbitrarily dense and the power spectral density smooth. This in general minimizes the impact of UWB signals on other systems.

Pulse Shape

Models of UWB spectra must use accurate descriptions of the radiated waveform if such models are to be useful; thus, models that assume waveforms with DC content, *e.g.*, a *sinc* function with a DC component, are likely to be misleading. For example, a model using a *sinc* function[17] would incorrectly imply spectral lines with significant power at very low frequencies.

The narrowband approximations that most engineers use in thinking about radio propagation do not hold for ultra-wideband propagation. For example, the process of propagation from the transmitting antenna aperture to a point in the far field of the

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[16] *See* Comments of MSSI at 19.

[17] *See* Comments of MSSI at p. 19.

antenna involves at least one differentiation, in addition to further spectral shaping by the antennas. Hence the channel system function contains a factor $j2\pi f$, meaning that constant ($f = 0$) electric fields do not propagate, and that the higher the frequency of a component, the better that component will propagate, neglecting filtering properties of the antenna. This effect, along with the filtering characteristics of the antennas and medium, define the system function from the transmitter's antenna port to the receiver's antenna port. R. C. Robertson and M. A. Morgan (in their paper: "Ultra-Wideband Impulse Receiving Antenna Design and Evaluation" in *Ultra-Wideband Electromagnetics 2*, L. Carin and L. B. Felsen, eds., Plenum Press, 1995) provide an analytical model of these effects and verify them experimentally.

Efficient power transfer from UWB transmitter to UWB receiver therefore requires that the pulses driving the transmitting antenna have an energy density that is as near zero as possible at $f = 0$ and is maximum within the passband of the antenna system. Typically these signals that drive the transmitting antenna might be modeled by the first derivative of a Gaussian pulse, a waveform with no DC content. Thus a free-space model of the far-field electrical field intensity would be shaped like a derivative of a Gaussian pulse and would have the form:

$$m(t) = e^{-2\pi\left(\frac{t}{tau}\right)^2}$$

Where *tau* is a time decay constant that defines the duration of the pulse.

In real terrestrial channels, an additional filtering factor, caused by multipath and other effects of the propagation environment, is present in the channel transfer function.

Modulation Formats without Data

As shown below, with perfect clocks and without random non-periodic modulation of some sort, all radios have power spectral densities that are composed of components at discrete frequencies (lines in the spectrum). Even radios (*e.g.*, with direct sequence or time-hopped modulation) controlled by pseudorandom finite-state machines have this characteristic.

Any signal that consists of a waveform $m(t)$ repeated periodically to form

$$r(t) = \sum_n m(t - nT)$$

has a power density $S_r(f)$, based on Fourier series analysis, that is

$$S_r(f) = \frac{1}{T^2}|M(f)|^2 \sum_k \delta_D(f - k/T)$$

where $M(f)$ is the Fourier transform of $m(t)$.

$$M(f) = \int_{-\infty}^{\infty} m(t) e^{-j2\pi ft} dt$$

The Dirac delta function samples $\frac{1}{T^2}|M(k/T)|^2 \delta_D(f - k/T)|$ in $S_r(f)$ represent discrete power components of the signal at frequency k/T and power $\frac{1}{T^2}|M(k/T)|^2$.

Assuming that the power in the signal is held constant, *i.e.*,

$$\text{Constant} = \frac{1}{T}\int_0^T |r(t)|^2 dt = \sum_k \frac{1}{T^2}|M(k/T)|^2,$$

the average of the individual line powers $\frac{1}{T^2}|M(k/T)|^2$ must go down as the period *T* of the modulation increases and the line spacing T^{-1} in frequency decreases. Ideally in pseudo-randomly controlled modulations, all of the lines individually would decrease as the period of the modulation is increased.

Suppose that the waveform *m(t)* used to construct the periodic waveform $r(t)$ is composed of a string of pulses which can be inverted or shifted in time, *i.e.*,

$$M(t) = \sum_{n=1}^{N_p} a_n p(t - \tau_n)$$

where $p(t)$ is the elementary pulse shape in the modulation (as indicated above, its precise shape depends on where it is being measured in the system), a_n represents the amplitude of the n^{th} pulse and τ_n represents the time shift of the n^{th} pulse. Then the function $M(f)$ that determines the envelope of the spectral lines of the periodic signal is

$$M(f) = P(f) \sum_{n=1}^{N_p} a_n e^{-j2\pi f \tau_n},$$

where $P(f)$ is the Fourier transform of the elementary pulse shape $p(t)$. Then the spectral density of *r(t)* is

$$S_r(f) = \underbrace{\frac{1}{T^2} \left| P(f) \right|^2 \overbrace{\left| \sum_{n=1}^{N_p} a_n e^{-j2\pi f \tau_n} \right|^2}^{\text{spreading function}}}_{\text{spectral envelope}} \sum_k \delta_D(f - k/T),$$

where the envelope of the spectral lines is shaped by two functions: the pulse transform $P(f)$, and the spreading function which depends only on a pseudo-randomly controlled amplitude and/or time-hopping modulation.

When the a_n are all the same sign (e.g., $a_n = 1$ for all *n*) then the spreading function is very large for $f \approx 0$ because time hopping is less of an impact on this portion of the power spectral density. However, this is not significant in practice because the base waveform does not have appreciable power at low frequencies, *i.e.*, $P(f) \approx 0$ for $f \approx 0$. And the spectral content of the unmodulated time-hopped signal in this region is quite low.

Another artifact in the power spectral density of a time-hopped signal (e.g., $a_n = 1$ for all *n*) occurs when the time delays are all integer multiples of a given delay T_c which is a building block in the transmitter. Then again the spreading function will be large near integer multiples of T_c^{-1}. These lines can be effectively eliminated by making T_c^{-1} a frequency that is significantly above the frequency range of the elementary pulse's spectrum $|P(f)|^2$. (For example, $T_c \approx 3ps$ in radios Time Domain is building today, which implies these spectral features would appear at frequencies above 300 GHz.)

Conclusion

With proper signal design, *e.g.*, high pulse repetition frequencies and pseudo-noise coding, the spectral features of a UWB signal are composed of many spectral lines with no dominant lines. This minimizes the impact of UWB signals on any given narrowband receiver.

Waveforms with periodic structures will all have discrete spectral lines. A UWB waveform, by using pseudo-noise time modulation can make the spectral lines arbitrarily dense and the power spectral density arbitrarily smooth.

Appendix C
UWB Measurement Techniques and Issues

(This appendix was filed electronically as a separate file.)

Appendix D
Antennas as Spectral Filters in UWB Systems

Summary

It has been stated that UWB antennas were susceptible to significant changes in both frequency and bandwidth with accidental changes.[18] The argument presented was that this “susceptibility” means that UWB systems with very large bandwidths could not be trusted to remain in compliance with the FCC’s rules. As discussed below, well-designed and properly implemented UWB systems will have stable characteristics, just as narrowband systems would. Thus, unless there is purposeful tampering with[19], damage to, or a failure in a UWB transmitter, the output characteristics will not somehow change to be out of compliance with its initial certification, just as is true with narrowband transmitters.

Overview

The performance of any wireless system is affected by its antenna. The spectral response of the transmit antenna must be convolved with the response of the rest of the radio frequency (RF) transmission system in order to yield the overall radiated spectrum. Antenna spectral filtering is an inherent part of all wireless systems: narrowband, wideband, or ultra-wideband (UWB). If an antenna is intentionally modified by a skilled

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[18] *See* Comments of MSSI at 3-9.

[19] Representatives of the U.S. GPS Industry Council have even suggested (*see* US GPS Industry Council Ex Parte presentation of Sept. 29, 2000) that UWB devices might be deliberately converted into GPS jammers. TDC finds it ludicrous to think that someone would try to modify devices with microwatts of RF output power given the simplicity of creating multiwatt narrowband noisemakers within the GPS band.

RF technician to increase out of band gain, the spurious emissions of any wireless system can be made to be undesirably high. The stability, reliability and predictability of antenna response in typical usage have been demonstrated by a number of UWB developers and manufacturers. TDC urges the FCC to avoid unduly limiting the technical means by which the challenges of UWB may be met.

UWB Antennas

In earlier comments,[20] TDC has provided comparisons of measurement vs. predictions for UWB systems using diamond dipoles.[21] Measured values of component spectral responses (including the antenna response) are used to predict the overall response of a system. The performance of TDC's diamond dipole vividly demonstrates that with good RF practice, the spectral response of an antenna can be as predictable as the spectral response of an in-line circuit filter or any other RF device or system. This is not an achievement unique to TDC. Farr Research, Inc. sells impulse UWB antennas with stable properties over decades of bandwidth.[22] A wide variety of other UWB device manufacturers have provided comments on their own specific UWB systems. Only one appears to have encountered difficulty obtaining stable and reliable performance from UWB antennas.[23] TDC recognizes that creating reliable and predictable antennas is a design requirement for any system attempting to achieve performance provided by a matched filter. Creating reliable UWB antennas may pose a significant technical hurdle.

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[20] *See* Comments of TDC at 38

[21] Larry Fullerton, "*Time Domain Radio Transmission System*," U.S. Patent 5,363,108, Nov. 8, 1994.

[22] *See* Farr Research Inc. website, available at http://www.farr-research.com/.

[23] Comments of MSSI at 3-9.

Nevertheless, this hurdle has been overcome by TDC and many other UWB device manufacturers. TDC believes that baseless concerns over antennas should not be allowed to impede the rulemaking process.

Stability of Response

Although the spectral response of an antenna is no less predictable than that of any other RF device or system, it has been argued that an antenna is more vulnerable to external influences that may alter its spectral behavior.[24] MSSI has presented several examples where an antenna was deliberately sabotaged by a skilled RF technician. These included changing the length of an antenna, as well as adding a tuned resonant patch in close proximity. These external influences may be grouped into two broad categories: damage and coupling. Further, changes to an antenna may be either intentional or unintentional.

First, consider unintentional damage. It is very difficult to imagine an accident scenario with sufficient violence to fundamentally alter an antenna's geometry that nevertheless somehow leaves the typically much more sensitive RF connections leading to the antenna unscathed. In the rare instances when antenna damage occurs, the damage most likely at the delicate solder joints where an RF connection is made. This renders the system inoperable until the antenna is repaired or replaced. The resulting open circuit radiates far less energy than would the antenna. Accordingly the idea that random unintentional damage is likely to significantly improve antenna performance over some portion of its operating bandwidth strains credulity.

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[24] Comments of MSSI at 3.

Second, consider unintentional coupling. So long as the integrity of the near field region about the antenna feed is maintained (within about 0.16 wavelength; 1" for a 2 GHz system) radiative coupling will tend to be the dominant mechanism. Since an efficient antenna is typically about 0.25 wavelength in dimension (about 1.5" for a 2 GHz system) this type of spacing is easy to achieve. Even as close as a half wavelength away (about 3 inches for a 2 GHz system), typical reactive field levels are about 10 dB below the radiated field strengths. Reactive coupling is thus extremely unlikely to occur. The predominant coupling mechanism is likely to be radiative, and the worst case outcome if the antenna happens to be placed precisely ¼ wavelength away from a large flat conducting plane is effectively about a 3 dB reinforcement above the original undistorted UWB signal due to reduction in the bandwidth.

Where a RF technician deliberately sabotages an antenna with a tuned resonant patch so as to alter its spectral response, the antenna’s performance as a broadband radiator is significantly impaired (from 114% to 29% BW in one example.[25]) Thus, continued use of an unintentionally impaired device is unlikely to continue for long because of performance degradation.

The idea that unintentional coupling might actually improve antenna performance over some portion of its operating bandwidth is similarly difficult to believe. Even assuming for the moment that antenna coupling or damage is a reasonable scenario, these concerns apply equally to conventional wireless systems. Spurious out-of-band emissions from conventional wireless systems are comparable in power to the radiated UWB emissions the Commission is currently contemplating. Thus, if antenna damage or coupling were likely to significantly alter out-of-band performance, conventional wireless would be similarly afflicted. The lack of significant out-of-band interference from the damaged or coupled antennas of conventional wireless devices argues strongly that similar concerns about UWB devices are unfounded. The same argument could be made regarding any emitter currently limited by Part 15 levels.

Finally, there has been concern that intentional antenna modifications of the kind demonstrated by MSSI constitute a "recipe on how to convert a UWB device to a GPS jammer."[26] It is difficult to believe that one skilled in RF techniques would chose a low power broadband device as a starting point for constructing a narrowband jammer. These fears seem exaggerated.

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[25] *See* Comments of MSSI at 5.

[26] Comments of U.S. GPS Industry Council, ex parte filing, Oct. 2, 2000 at 13.

Conclusion

TDC believes that the FCC should not unduly limit the technical means by which UWB device manufacturers can comply with radiated emissions standards. These means include using the spectral response of an antenna alone, or (if necessary for a particular manufacturer's system) a filter in conjunction with the antenna. TDC believes the FCC should not mandate any particular technical means of shaping a transmitted pulse so as to achieve an overall desired system spectral response. The inability of any particular UWB device manufacturer to successfully implement a particular technical means should not be taken as justification to prevent its use by other manufacturers.

The predictability, stability and reliability of UWB antennas have been put into practice by TDC and others. TDC does not believe that concerns about significant random changes in UWB antenna performances are sufficiently credible to be a matter of concern for the Commission. Neither is intentional sabotage of an antenna any more a meaningful danger for UWB than it is for conventional narrowband systems.

Appendix E
Assessment of UWB Impact on Generic Receivers

Summary

Although Motorola recognizes that UWB technologies are promising for applications such as location sensing and short range communications, its theoretical analysis of interference to a generic receiver is flawed in that the effects of Rayleigh fading and log-normal shadowing are not considered. These effects completely overshadow the effects of UWB devices. When the analysis of UWB to a mobile receiver and UWB to a tower-mounted base receiver is correctly performed, the separation distances are an order of magnitude less than presented in the Motorola comments of September 12, 2000.

Generic Receiver Methodology

Motorola's presentation of an analysis based on the generic receiver method erroneously concludes that UWB devices with Part 15 emission levels will cause unacceptable degradation of the receiver noise floor at distances of 13 meters. The interference from a time modulated UWB transmitter into a narrowband receiver can be accurately modeled as Gaussian noise, as claimed by Motorola; and, it may be valid to consider interference from a generic UWB transmitter in terms of its ability to increase the noise floor of the narrow band receiver,[27] but only if multipath fading and other impairments are correctly included. Even assuming a 100% duty cycle for UWB pulse transmissions, it can be shown with Motorola's equations (adjusted to make consistent use of antenna gain reference levels) that in scenarios consistent with prudent system design, the noise floor rise in a narrow band receiver remains below 1 dB in those rare cases where the receiver is operating at the system design limits, and the UWB transmitter is operating within approximately 1 meter of the receiver. Stated as an *effect*, in a properly designed system operating at the limit of system performance, this 1 dB noise rise will increase the receiver outage probability from 2% to a value of 2.6% within 1 meter of the UWB transmitter during those portions of the duty cycle that the UWB transmitter is operating.

Motorola's Equations 1-3 [28] (corrected to make consistent use of antenna gain reference levels) can be used to understand the minimal impact of a UWB transmitter operating at 100% duty cycle with power at current Part 15 Rule levels. While Time Domain Corporation does not endorse the use of a 1 dB noise rise as the relevant criterion to measure interference potential, it is useful here to point out a discrepancy with the idealized case studied by Motorola and presented in their comments. Table 1 here reproduces the Table 1 case of Motorola,[29] except here we consider system margin requirements for operation at a 2% outage rate in a fading scenario as is consistent with coverage requirements into a building. Rayleigh fading and a 5.5 dB standard deviation

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[27] Nonetheless, Motorola's analysis fails to point out that the level of interference is directly determined by the signal to noise ratio; that uses a 1 dB increase in the noise floor, is very suspect

[28] *See* Comments of Motorola at 12, 13.

[29] *See* Comments of Motorola at 17.

component of building loss variation is used in this analysis (without the addition of median building loss). Margin is always required in practical system designs.[30]

Table 1. Link Budget Analysis for UWB-to-Narrow band Mobile, for 1 dB Noise Floor Rise

	Parameter	TDC Adjusted Value	Motorola Original Value
1	Thermal noise, *kT*	-174 dBm/Hz	-174 dBm/Hz
2	Narrow Band Receiver Bandwidth (*BW*)	25 kHz	25 kHz
3	Narrow band Receiver Noise Figure (*NF*)	10 dB	10 dB
4	Narrow band Receiver Noise Floor = *kT* + 10 log(*BW*) + *NF*	-120.02 dBm	-120.02 dBm
5	System margin required for 2% outage rate with 5.5 dB shadowing standard deviation and with Rayleigh fading	20 dB	--
6	Allowed Interference level (5.85 dB below the noise floor)* ** Motorola used 6 dB*	-105.87 dBm	-126.02 dBm
7	UWB transmitter in a 1 MHz bandwidth	-41.25 dBm	-41.25 dBm
8	UWB transmission scaled to a 25 kHz bandwidth	-57.27 dBm	-57.27 dBm
9	UWB transmitter antenna gain	0 dBi	0 dBi
10	Narrow band receiver antenna gain	-8 dBi	-8 dBi
11	Path loss required for < 1 dB noise floor rise	40.6 dB	60.75 dB
12	Narrow band-to-UWB separation assuming free space path loss at 2 GHz for < 1 dB noise floor rise	1.3 meters	13 meters

[30] Hess, Garry C., LAND-MOBILE RADIO SYSTEM ENGINEERING at 13, Boston, Artech House,1993.

As seen in Table 1, a 1 dB noise floor rise will change the 2% outage to 2.6%, but only if the narrow band receiver is within 130 cm of the UWB transmitter and only while the UWB transmitter is operating while the receiver is operating. The outage probability decreases as the actual UWB transmitter duty cycle decreases. The system margin requirements were calculated using the Motorola system design method presented to the United States Telecommunications Training Institute (USTTI).[31] The combined Rayleigh and log-normal probabilities were used in the fading calculations.[32] The log-normal standard deviation component of 5.5 dB accounts for the variation in building losses,[33] but not the median building loss itself, hence is a valid application of system margin value. The idealized Motorola calculation proposes a noise limited sensitivity power level with no margin, which would result in 63% outage rate considering just Rayleigh fading.

Figure A depicts a 10 wavelength square area showing an example of signal outage in a Rayleigh faded scenario having 0 dB margin. In other words, this is the case where the average power delivered to the narrow band receiver of Table 1 is –120 dBm. The light areas correspond to signals above the sensitivity threshold, while the dark areas correspond to 63% of the area where Rayleigh fading (alone) results in signal outages. Additional noise from a UWB transmitter at any distance is irrelevant under this condition. Practical systems experience this kind of fading everywhere in the coverage

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[31] Outlined in W. J. Kuznicki, "The World of Paging," presented to the USTTI by Motorola, Inc., Washington, D. C., 12 October 1993

[32] *See* Equation (8.7) Kazimierz Siwiak, RADIOWAVE PROPAGATION AND ANTENNAS FOR PERSONAL COMMUNICATIONS at 228**,** 2d Ed., Artech House, Norwood, MA, 1998.

[33] Siwiak, Figure 7.17, at 209.

zone, and particularly at the coverage limits. Adding 20 dB of signal margin (Row 5 in Tables 1 and 2) reduced the outage region to just 2% outage probability.

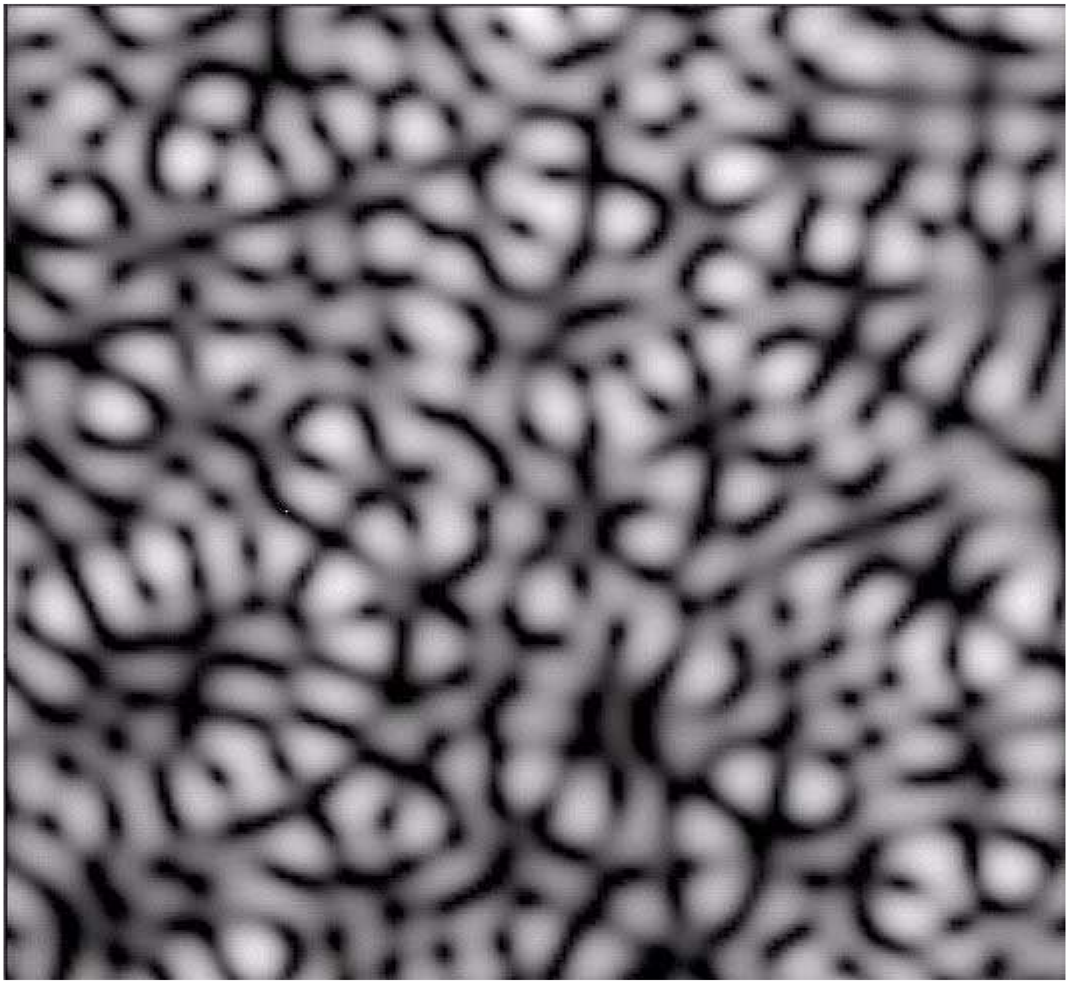

Figure A – Signal outages (dark) in a Rayleigh faded 10 wave length square area with average power at the narrow band receiver threshold level.

Typical hand-held cellular receiver devices have antenna gains of –8 dBi, or worse when hand-held or in close proximity to the body, so Figure 2 in Motorola's comments [34] is irrelevant, and in any case overstates the "separation distances" by a factor of 10 because system margins were omitted. Their subsequently analyzed

[34] *See* Comments of Motorola at 18

statistical models likewise are based on simplistic assumptions regarding fading margin, rendering them irrelevant.

UWB-to-Base Station Case

It is also possible to analyze the interference from UWB transmitters into narrow band base stations using the methodology applied to the UWB-to-mobile case, again, as long as realistic assumptions regarding signal quality are applied. In the UWB-to-base station case, UWB transmitters deposit energy into the base station receiver of a wireless communications system.

Base station receivers, particularly those receiving signals from extended ranges experience signals that arrive from the mobile station through a multipath scenario which results in a fluctuating signal that has signal levels described very closely by Rayleigh statistics with the addition of a log normal component for shadowing variation. Hence robust system designs require margins for the path from the mobile to the base that are similar to the reverse path. Table 2 here shows the analysis that accounts for required system design margin, in contrast to the unrealistic thermal noise limited case presented by Motorola.

Table 2. Link Budget Analysis for UWB-to-Narrow band Base, for 1 dB Noise Floor Rise

	Parameter	TDC Adjusted Value	Motorola Original Value
1	Thermal noise, *kT*	-174 dBm/Hz	-174 dBm/Hz
2	Narrow Band Receiver Bandwidth (*BW*)	25 kHz	25 kHz
3	Narrow band Receiver Noise Figure (*NF*)	10 dB	10 dB

	Parameter	TDC Adjusted Value	Motorola Original Value
4	Narrow band Receiver Noise Floor = *kT* + 10 log(*BW*) + *NF*	-120.02 dBm	-120.02 dBm
5	System margin required for 2% outage rate with 5.5 dB standard deviation and with Rayleigh fading	20 dB	0 dB
6	Allowed Interference level (5.85 dB below the noise floor)* ** Motorola used 6 dB*	-105.87 dBm	-126.02 dBm
7	UWB transmitter in a 1 MHz bandwidth	-41.25 dBm	-41.25 dBm
8	UWB transmission scaled to a 25 kHz bandwidth	-57.27 dBm	-57.27 dBm
9	UWB transmitter antenna gain	0 dBi	0 dBi
10	Narrow band receiver antenna gain	12 dBi	12 dBi
11	Path loss required for < 1 dB noise floor rise	60.6 dB	80.75 dB
12	Narrow band-to-UWB separation assuming free space path loss at 2 GHz for < 1 dB noise floor rise	13 meters (no clutter loss)	73 meters (includes 5 dB "clutter loss")
13	Separation assuming UWB device is out of the main antenna beam (20 dB *less* base antenna gain).	1.3 meters	--

In point of fact, at distances close to the base antenna tower, the actual antenna gain at the ground is many 10s of dB below the peak antenna gain assumed in Table 2. This analysis shows that a narrow band base station receiver would in fact never be at risk from a UWB transmitter.

The Commission suggests that UWB devices be permitted to operate below 2 GHz at emission levels 12dB below the Part 15 Rules. Motorola proposes to extend this limit to all frequencies,[35] yet, Motorola has argued previously before the Commission in other proceedings that spurious emissions at the current Part 15 level are satisfactory, as shown below:

> "Motorola suggests that the Commission provide for a lower limit of -13 dBm (50 microwatts) below which attenuation is not required, in accordance with the limits established for other similar services and provided for internationally" …
>
> "*See e.g.*, 47 C.F.R. §§ 24.238, 27.53, 90.669, 90.691; *c.f.* ITU-R Appendix S3 and attenuation enables lower output power transmitters to comply with the current emission mask without extensive filtering. Any attenuation below -13 dBm fails to provide further interference protection to adjacent systems because this value is recognized as the permissible spurious emission level. Requiring additional filtering for low power systems does not enable added use of the spectrum, nor does it supply additional interference protection to neighboring services."[36]

Time Domain concludes, therefore, that Motorola has no problem with emissions at current levels of Part 15 Rules above 2GHz.

Conclusion

The effect of UWB transmitters operating at 100% duty cycle and transmitting power at 500 microvolt/meter measured at 3 meters, is negligible at distances greater than

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[35] *See* Comments of Motorola at 37.

[36] Comments of Motorola in WT Docket No. 00-19, In the Matter of Amendment of Part 101 of the Commission's Rules to Streamline Processing of Microwave Applications in

approximately 1 meter from narrow band receivers operating in properly designed radio systems. The distance of 1 meter is commensurate with the cell phone to cell phone interference distance quoted by Motorola. The probability of the event of an UWB transmitter transmitting, while a narrow band receiver is operating at the limit of system margin, and while within about 1 meter of the UWB transmitter is small; hence the probability of interference is small.

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the Wireless Telecommunications Services received by the Commission (Aug. 4, 2000), at 5-6.