An Investigation into the Potential Impact of Ultra-Wideband Transmission Systems

February 2000

RA0699/TDOC/99/002

This report was commissioned by the Radiocommunications Agency.

Multiple Access Communications Ltd
Epsilon House, Enterprise Road
Chilworth Research Centre
SOUTHAMPTON
SO16 7NS, UK
Tel: +44 (0)23 8076 7808
Fax: +44 (0)23 8076 0602

Executive Summary

Ultra-wideband transmission systems

The Federal Communications Commission (FCC) has initiated an inquiry into the possibility of regulating ultra-wideband (UWB) systems on an unlicensed basis. UWB systems have very large bandwidths and cover the bands of numerous licensed services. The power spectral densities (PSDs) of such systems are very low, but their proliferation could cause serious interference problems to existing licensed services. Multiple Access Communications Limited (MAC Ltd) was commissioned by the Radiocommunications Agency (RA) to carry out a brief study into UWB systems. In particular the RA is interested in the feasibility of UWB systems, the conditions that lead to multiple UWB systems degrading the performance of conventional users of the spectrum, the commercial threat to cellular services, and the issues involved in regulating UWB systems.

The first types of applications are likely to be low powered and short range. The systems will be used by the medical, automotive, radar, and consumer communications industries. There has already been significant development in UWB systems by the US federal government and military. Time Domain Corporation have pioneered time modulated UWB (TM-UWB) technology and have built both radar and communication systems. A typical UWB communication system has a centre frequency of 2GHz, a bandwidth of 1.6GHz, a transmission rate of 32kbps and a range of 1km. This proves that UWB systems are technically feasible. The main limiting factor of a UWB system is the antenna, which acts as a filter and limits the transmission bandwidth.

MAC Ltd has developed an analytical interference model to investigate the impact of the interference from multiple UWB sources to a victim receiver. The maximum UWB transmitter power levels that would cause negligible cumulative interference on victim receivers, ie, 1dB performance degradation, are determined for various propagation environments. For example, the maximum UWB transmitter power for a variety of transmission bandwidths is plotted in Figure 1 against the number of UWB transmitters per square km. The victim cellular receiver has an operating frequency of 900MHz and is part of an urban CDMA cellular system.

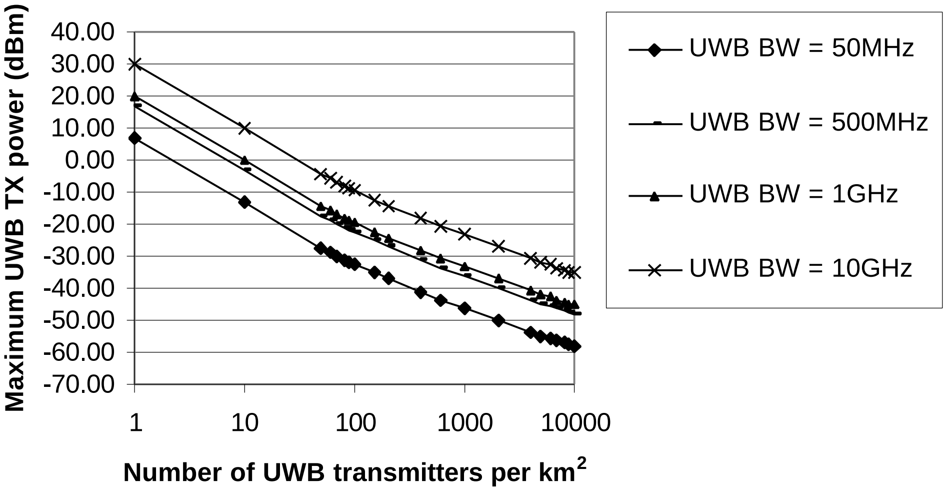

Figure 1 Graph of the maximum UWB transmitted power for a variety of transmission bandwidths and a 1dB performance degradation. The victim receiver has an operating frequency of 900MHz and is part of an urban CDMA cellular system.

Assuming that the UWB transmitter power is regulated by the FCC’s current unlicensed radiator limit, which is –19.2dBm for a 1GHz transmission bandwidth, then referring to Figure 1, the maximum density of UWB sources is 100 per square km. This is a reasonable density of UWB devices in an urban area. Similar results are obtained for rural areas, where the maximum number of UWB sources per square km is approximately 50. In an urban area, the performance of an interference-limited cellular system such as GSM only degrades for UWB densities of 2500 per square km.

We also show that a GPS receiver is unlikely to be affected by the interference from UWB devices in urban and rural areas, provided that the density of UWB devices is restricted to 300 and 100 per square km, respectively. Up to five UWB devices can be located in a residential home without interfering with a television (TV) receiver. This is a conservative estimate as the low gain of the TV antenna on the roof in the direction of the UWB devices is not considered. A cellular phone is likely to operate without noticeable UWB interference effects in a large single storey building, such as a supermarket, provided the density of UWB devices is less than 150 over a 100m x 100m floor area. Published theoretical results show that the interference from terrestrial UWB devices to navigational devices in low flying aircraft is not likely to cause a problem.

Interference problems are likely to occur for a victim receiver that is close to and in line-of-sight (LOS) of a UWB device. This could prove to be serious in a scenario where there is a high likelihood of LOS propagation from a victim receiver to UWB devices. There are many likely scenarios of UWB distributions provided for example by UWB wireless local loop, dense urban UWB microcellular networks, and collision avoidance UWB radar sensors in cars. A mobile receiver located in an urban street is very likely to suffer interference from the nearest UWB device that is in LOS of the mobile receiver. To minimise the interference caused by the above scenarios, it would be appropriate to set the PSD regulation limits to at least 10dB below the current FCC unlicensed radiator limits. Assuming these limits are enforced, this means that only low bit rate, short range UWB communication systems will be possible, thus eliminating the commercial threat on current cellular or future third generation systems.

The most versatile method of measuring the emissions from UWB devices is to measure the power spectral density in a similar manner to that prescribed by current FCC procedures.

Prepared by Multiple Access Communications Ltd, August 1999.

Table of Contents

List of Abbreviations 8

List of Symbols 10

1 Introduction 12

2 Definition of UWB and future systems 13

2.1 Definition 13

2.2 First types of UWB systems 13

2.2.1 What does current technology allow? 15

2.2.1.1 Radar 15

2.2.1.2 Communications 16

2.3 Evolution of UWB systems 18

3 Evaluation of maximum PSD levels 19

3.1 Current Part 15 emission level regulations 19

3.2 Derivation of the interference from multiple UWB sources 20

3.3 Derivation of the maximum possible UWB PSD 24

3.3.1 Maximum UWB PSD for a FDMA/TDMA cellular system 26

3.3.2 Maximum UWB PSD for a CDMA cellular system 27

3.4 Maximum UWB PSD results 29

3.4.1 Interference on noise-limited systems or CDMA systems 29

3.4.1.1 Interference on rural GSM cellular systems 31

3.4.1.2 Interference on an urban IS-95 CDMA system 33

3.4.2 Interference on FDMA/TDMA systems in urban areas 35

3.4.3 Interference on Global Positioning System (GPS) receivers 39

3.4.4 Interference on television receivers 41

3.4.5 Interference on mobile receivers inside buildings 43

3.5 Review of other UWB cumulative interference models. 44

- 3.5.1 Interval Research Corporation 44
- 3.5.2 Time Domain Corporation 45
  - 3.5.2.1 Cumulative impact of multiple UWB transmitters 45
  - 3.5.2.2 Interference on various avionics receivers 49
- 3.5.3 Arthur D Little Inc. 49

3.6 Different UWB source distributions 50

3.7 Summary of results 54
- 3.7.1 Rural area, FDMA/TDMA noise limited or a CDMA system 54
- 3.7.2 Urban area, CDMA system 54
- 3.7.3 Urban area, FDMA/TDMA system (interference limited) 55
- 3.7.4 GPS receivers 55
- 3.7.5 Television receivers 55
- 3.7.6 FDMA/TDMA noise-limited receivers in buildings 55
- 3.7.7 Navigation devices in aircraft 56
- 3.7.8 General comments 56

4 Likely UWB system parameters and services 56

4.1 Parameters and services suggested by Time Domain Corporation 56

4.2 Our comments 59

5 Regulation issues 60

5.1 Method of measuring the emissions from UWB devices 60

6 Conclusions 62

References 64

List of Abbreviations

2D	two-dimensional
BER	bit error rate
BS	base station
CDMA	code division multiple access
FCC	Federal Communications Commission
FDMA	frequency division multiple access
GPR	ground penetrating radar
GPS	Global Positioning System
GSSI	Geophysical Survey Systems Project
GSM	Global System for Mobile communications
IF	intermediate frequency
IS-95	Interim Standard 95
LOS	line-of-sight
LPI/D	low-probability-of-intercept-and-detection
MAC Ltd	Multiple Access Communications Ltd
MIR	Micropower Impulse Radar project
MS	Mobile station
MSSI	Multispectral Solutions Inc
NLOS	non-line-of-sight
NOI	notice of inquiry
PN	pseudo-random noise
PSD	power spectral density
RA	Radiocommunications Agency
RF	radio frequency
SAR	synthetic-aperture radar

SIR	signal-to-interference-ratio
SINR	signal-to-interference-plus-noise-ratio
TDMA	time division multiple access
TM-UWB	time modulated ultra-wideband
UHF	ultra-high frequency
UWB	ultra-wideband
WLAN	wireless local area network
WLL	wireless local loop

List of Symbols

r	density of UWB sources
l	wavelength
B_{RX}	victim receiver bandwidth
d_0	free space reference distance
E_b	energy per bit
G_p	ultra-wideband transmitter power spectral density
I_{CDMA}	uplink CDMA interference power
I_0	cellular interference power at a victim receiver
I_T	cellular interference plus noise power at a victim receiver
I_{UWB}	cumulative UWB interference power at a victim receiver
J_0	combined PSD of interference and noise at a CDMA BS receiver
M	ratio in dB of UWB interference power to victim receiver noise power or interference power, or for a CDMA system it is the ratio of S_{UWB} to S_{NO_UWB} in dB.
n	path loss coefficient
N	number of mobiles communicating with a CDMA BS
$N_o(W)$	thermal receiver noise power in watts
$N_o(dBm)$	thermal receiver noise power in dBm
N_{UWB}	number of UWB sources in Time Domain Corporation's interference model
P_{C0}	power received at close in reference distance, d_0 from a cellular base station
P_0	power received at free space distance, d_0
P_r	receiver power from a victim receiver from a UWB source
P_t	BS transmitter power
r	distance from victim receiver to UWB sources
R	cell radius

R_b	transmission bit rate
R_L	distance from victim receiver to the nearest UWB sources
R_0	average distance between UWB sources
S	target received power at a CDMA BS receiver
S_{UWB}	target received power at a CDMA BS when UWB interference is considered
S_{NO_UWB}	target received power at a CDMA BS when UWB interference is not considered

1 Introduction

The spectrum regulator in the USA, the Federal Communications Commission (FCC), is currently conducting an inquiry into the use of unlicensed ultra-wideband (UWB) radio transmission systems. The proposed UWB systems generally have bandwidths in excess of 1GHz and they operate across the bands of numerous licensed services. However, as a result of the huge transmission bandwidth, the power spectral density (PSD) of the UWB signal is generally lower than the current regulated spurious emission levels. Nevertheless, many UWB systems operating within a small area could cause serious interference to existing licensed services. As a consequence, regulatory bodies need to understand the problems UWB systems may pose, and consider whether the UWB systems can be regulated, and if they can, what regulations might be required. To this end, the spectrum regulator in the UK, the Radiocommunications Agency (RA) has engaged Multiple Access Communications Limited (MAC Ltd) to perform a short study into some of the key issues associated with UWB systems from a regulator's perspective.

The objectives of this study are as follows:

1) To examine the feasibility of UWB communication systems being deployed in the near future.

2) To consider the types of services that could be carried by UWB systems.

3) To examine the viability of UWB communication systems as a competitor to cellular services.

4) To examine the effects of UWB interference on cellular radio services.

5) To address the problem of regulating UWB communication services.

The main information on UWB systems can be found in documents relating to the FCC inquiry. The FCC invited comments on their notice of inquiry (NOI) that detailed the proposed revisions to Part 15 of the FCC's rules regarding ultra-wideband transmission systems, and many organisations filed comments in response. The FCC then invited interested parties to reply based on all the filed comments received. The comments and replies are publicly available, and contain a wealth of information on UWB systems.

In this report we present the results of the study. In Section 2 we discuss the definition of UWB systems followed by the identification of the first types of ultra-wideband systems, and a discussion on how they might evolve. The cumulative interference from UWB systems on existing radio receivers is evaluated using an analytical interference model developed by MAC Ltd in Section 3. The maximum UWB PSD levels are determined based on the results of the interference model and conclusions are drawn based on the comments and reply comments on the FCC NOI. In Section 4, based on the maximum PSD levels likely to be enforced by regulatory bodies, the UWB system parameters and types of services are postulated. The commercial threat of UWB communication services on existing cellular or future third generation services is also considered. The regulation of UWB devices and the possible forms it might take are considered in Section 5 and, finally, we present our conclusions in Section 6.

Due to the short timescales of this study much of our effort has been focused on examining the effects of UWB interference on cellular radio services. We consider this aspect of UWB systems to be of key importance in determining the best way of regulating UWB systems.

2 Definition of UWB and future systems

2.1 Definition

The commonly agreed definition of a UWB transmission is a signal whose fractional bandwidth, η, is larger than 0.25, where the fractional bandwidth is defined as

$$\eta = \frac{2(f_H - f_L)}{f_H + f_L} \tag{1}$$

and f_H and f_L are defined as the highest and lowest frequencies in the transmission, respectively. The frequency limits, f_H and f_L, mark the frequencies at which the PSD is 20dB below the maximum measured PSD of the signal. Conventional radio communications and radar systems have small fractional bandwidths of much less than 0.25.

2.2 First types of UWB systems

Before considering the possible first types of UWB systems, let us first consider the advantages of UWB technology over traditional technologies. The key advantages of the UWB technology are as follows:

- The low power spectral density potentially causes low interference levels to existing services.
- The effects of multipath fading are less severe, which means UWB systems require less transmitted power for communications.
- It can offer high processing gains.

In the reply comments and comments made by various organisations on the FCC Part 15 NOI, some potential applications of the UWB technology were suggested and these are listed below:

- High capacity short range secure wireless links, eg, wireless local area networks (WLANs) for offices, homes, rooms, and people.
- RF identification tagging and tracking devices.
- Sensors for automobiles, eg, air bag deployment control, reversing assistance, collision avoidance systems, remote keyless entry, and intelligent highway applications.
- Ground penetrating radars to locate various objects or features, eg, victims lost in rubble, mineral deposits, soil contamination, non-metallic pipes, archaeological sites, flaws in bridges, highways, and airport runways, explosives including plastic land mines and suspected crime scenes, such as secret burials and drug caches.
- Devices to locate cables in walls and floors at construction sites.
- Radar industrial liquid level gauges.
- Local position determination devices.
- Navigational systems to assist the blind and those with mobility disabilities.
- Monitors to measure heart rate, breathing, and inner body fluctuations.
- Radars for police and fire departments for seeing through walls.
- Covert communications systems for law enforcement.

- Virtual electronic fences for security applications.

Notice that the applications mentioned so far are low-powered and short range. The applications listed above can be more generally grouped into the following categories:

1. Medical applications [1].
2. Consumer communications applications [2].
3. Automotive applications [3,4].
4. Consumer and industrial construction applications [5].
5. Ground penetrating radar (GPR) systems [6].
6. Industrial liquid level gauges [7,8,9,10].
7. High performance data communication systems [11,12].

2.2.1 What does current technology allow?

There are two main applications where development into UWB systems is being and has been carried out. The first application is radar and the second application is communications.

2.2.1.1 Radar

The US federal government and military have been using UWB radar for several decades. Geophysical Survey Systems Inc. [6] (GSSI) has been in the business of developing and selling GPR systems for 28 years. The Micropower Impulse Radar (MIR) project was undertaken at the Lawrence Livermore National Laboratory [13], a US government research and development facility. MIR exploits ultra-wideband technology, and has been licensed to 26 commercial companies for applications such as radar for seeing through walls, and liquid level measurement. TEM Innovations [14] for example has been developing wideband pulsed-RF sensors, such as a 5.8GHz wideband radar rangefinder for 1mm accuracy over a 10 metre range, and a 5.8GHz wideband differential pulse Doppler motion sensor

Radar level measurement systems from several manufacturers exist on the market. Endress and Hauser [10] produces and is developing pulsed UWB systems. The centre frequencies of the systems lie between 5.8GHz and 76GHz, and the bandwidths vary between 0.7 and 10GHz. The operation distance is between 20m and 100m.

Time Domain Corporation [11] has developed a ‘through-wall’ motion detection system with a centre frequency of 2GHz and a bandwidth of 1.6GHz. The output power is –13dBm and the range resolution is less than 4 inches. The device can detect motion from a distance of about 10 metres. Multispectral Solutions Inc. (MSSI) [12] has developed an intrusion sensor radar with a bandwidth of 400MHz (27% fractional bandwidth), and a centre frequency of 1.5GHz. The average power density is 0.625 pW/Hz, and the range extends to 2000 feet.

2.2.1.2 Communications

MSSI has been actively involved in developing UWB hardware since 1989. The following is a list of military and government UWB systems that have been developed by MSSI:

- A UWB handheld transceiver for low-probability-of-intercept-and-detection (LPI/D) communications. The transceiver allows full duplex voice and data communications. The line-of-sight (LOS) range is 1km to 2km. The data rate is 9.6kbps and 128 kbps for digital voice and data, respectively. The average power spectral density is 1.6pW/Hz, and the frequency ranges are somewhere between 1 and 2GHz, with a fractional bandwidth of 27%.

- Prototype non-line-of-sight (NLOS) UWB voice/data radios to operate in high interference environments. The frequency ranges are between 30 and 50MHz, with a bandwidth of 20MHz (50% fractional). The data rate is 9.6kbps and 128kbps for digital voice and data, respectively. The average power spectral density is 5.1nW/Hz and the range is 1 to 5 miles over land.

- Prototype UWB packet radios for LPI/D communications. The centre frequency is approximately 1.5GHz, and the bandwidth is 400 MHz (27% fractional). The data rate is 9.6kbps and 128 kbps for digital voice and data, respectively. The average power spectral density is 8.0pW/Hz and the range is 3 to 4 miles with small omnidirectional antennas.

- A short range UWB tagging system, for short range communications from vehicle to vehicle or from vehicle to the roadside. The centre frequency is 1.5GHz, the bandwidth is 400 MHz (27% fractional), and the data rate is 115.2kbps. The average power density is 0.18pW/Hz, and the range from a moving vehicle to a tether on the roadside is 2000 feet.

Time Domain Corporation [11] has also developed numerous UWB radios, including the following:

- A simplex radio with a centre frequency of 650MHz and a bandwidth of 600MHz. The output power is –3dBm and the range is in excess of 7km using 2dBi antennas.

- A simplex radio with a centre frequency of 1.3GHz and a bandwidth of 800MHz. The output power is –15dBm. The radio was tested at a transmission rate of 125kbps, from a –9.6dBi antenna, through 6 to 8cm of simulated biological tissue to a receive antenna 2 to 3 metres away.

- Full duplex radios with a centre frequency of 1.3GHz and a bandwidth of 800MHz. The output power is 0dBm. At 156.25kbps the range is 5km, using 8dBi antennas.

- Full duplex radios with a centre frequency of approximately 2GHz and a bandwidth of 1.6GHz. The output power is 2.6dBm and the range is 1km for a transmission rate of 32kbps using 2dBi antennas.

The technology developed by Time Domain Corporation is called time modulated UWB (TM-UWB). TM-UWB has been demonstrated as a feasible technology for UWB communication systems and for a full description the reader is referred to Appendix B of Time Domain Corporation’s comments on the FCC’s NOI [11]. Basically the transmitters produce short ‘Gaussian’ pulses. Typical pulse widths are between 0.2 and 1.5ns, and the pulse-to-pulse intervals are normally in the range of 25 to 1000ns. The modulation employed is pulse position modulation. The pulse-to-pulse interval is varied according to two components; an information signal, and a channel code that is a pseudo-random noise (PN) sequence. The TM-UWB receiver has a front end correlator that uses the channel code to convert the received pulse train to a baseband signal directly.

In the frequency domain the transmitted TM-UWB signal has a relatively flat PSD. The spikes that would be caused by a regular train of pulses are smoothed out through the use of pulse position modulation using a PN code.

Time Domain Corporation has invested in developing advanced silicon-germanium integrated circuits to implement some of the transceiver functions, with the remaining functions implemented in standard CMOS.

The key attributes of TM-UWB systems are as follows:

- Very large processing gains (45dB at 32kbps centred at 2GHz).
- TM-UWB can have a large number of channels. Time Domain Corporation has estimated that 10,000 users could operate 10kbps links with a bit error rate (BER) of 1×10^{-3} from a single cell.
- TM-UWB signals appear like white noise.
- TM-UWB offers high radar range resolution with low operating frequencies.
- TM-UWB radios are capable of extremely high timing precision (1000 times greater than Global Positioning Systems (GPS)).
- TM-UWB systems achieve high performance at an affordable cost.

According to Time Domain Corporation’s comments [11], practical considerations force conventional RF designs to millimetre wavelengths above 10GHz for a 1GHz bandwidth. Apart from the antenna design being simpler for a broadband antenna at higher centre frequencies, which incidentally should also equally apply for TM-UWB and conventional RF designs, the frequency synthesisers, amplifiers, filters, and other components are simpler to design for lower fractional bandwidths.

2.3 Evolution of UWB systems

As integrated circuit technology improves, the chip rates of direct sequence spread spectrum technology will increase. However, the practical considerations that force conventional wide bandwidth designs to higher frequency ranges and lower fractional bandwidths are unlikely to be overcome in the short term. TM-UWB technology does not have the same problems as conventional RF designs, but it is limited by the antenna that acts as a band-pass filter.

Antennas seem to be the main obstacle in the way of UWB systems achieving bandwidths close to 10GHz. The important design parameter of antennas is the ratio of the upper frequency to lower frequency of the transmitted signal. If the ratio is small then the antenna is generally practical to build. As a rule of thumb, antennas with a bandwidth such that the ratio of maximum to minimum frequency is more than two are not practical to build. Therefore, an UWB signal spanning the frequency range 1MHz to 10GHz, has a maximum to minimum frequency ratio of 10,000, and, practically, it is very difficult to build an antenna to provide this bandwidth.

The first low frequency range UWB systems are likely to have a bandwidth of approximately 1GHz. The problems associated with building high fractional bandwidth antennas are likely to restrict the bandwidth of low frequency range UWB systems. Also, the propagation characteristics of UWB signal bandwidths approaching 10GHz are going to vary considerably with frequency and cause further problems. Therefore, UWB systems may evolve from 1GHz bandwidth systems to 3 or 4 GHz, but the bandwidths are not likely to change by an order of magnitude.

3 Evaluation of maximum PSD levels

We will now evaluate the maximum PSD levels of UWB devices that would cause negligible cumulative interference on existing cellular or proposed third generation (3G) systems, TV receivers and GPS receivers. We also review published interference models. Based on the results of the interference analysis we will assess whether the existing spurious emission level regulations are sufficient, and we will also examine the cumulative effect of many UWB devices. First of all let us review the current FCC Part 15 emission level limits.

3.1 Current Part 15 emission level regulations

The current Part 15 unlicensed *intentional* radiator emission limit is 12nW/MHz for frequencies of less than 960MHz, and 75nW/MHz for frequencies of more than 960MHz. Therefore, for a 1GHz UWB bandwidth, the maximum transmitted power is –19.2dBm, and -11.2dBm, for frequencies of less than and more than 960MHz, respectively, assuming a flat

PSD. For a 10GHz bandwidth UWB signal, the maximum transmitted power is –9.2dBm and –1.2dBm, for frequencies of less than and more than 960MHz, respectively.

The FCC Part 15 *unintentional* radiator emission limits are split into two classes, Class A and Class B. A Class A device is marketed for use in a commercial, industrial or business environment. On the other hand, a Class B device is marketed for use in a residential environment, for example calculators, PCs, etc. The Class B limits are identical to the intentional radiator limits above. The Class A limits are 147nW/MHz and 300nW/MHz for frequencies of less than and more than 960MHz, respectively.

3.2 Derivation of the interference from multiple UWB sources

In this section we will investigate the impact of the interference from multiple UWB transmitters to a victim cellular receiver using the arrangement shown in Figure 2. In Figure 2 the victim receiver is shown as a dot and the UWB transmitters are shown as crosses. The interference needs to be estimated to determine the maximum UWB PSD that would inflict negligible interference on a cellular receiver.

We will assume that the UWB transmitters are distributed with an average density, ρ, throughout a two-dimensional (2D) plane. The PSDs, G_p, of the UWB transmitters are assumed to be equal. Consider a victim cellular receiver, labelled RX in Figure 2, located in the 2D plane, having a receiver bandwidth, B_{RX}.

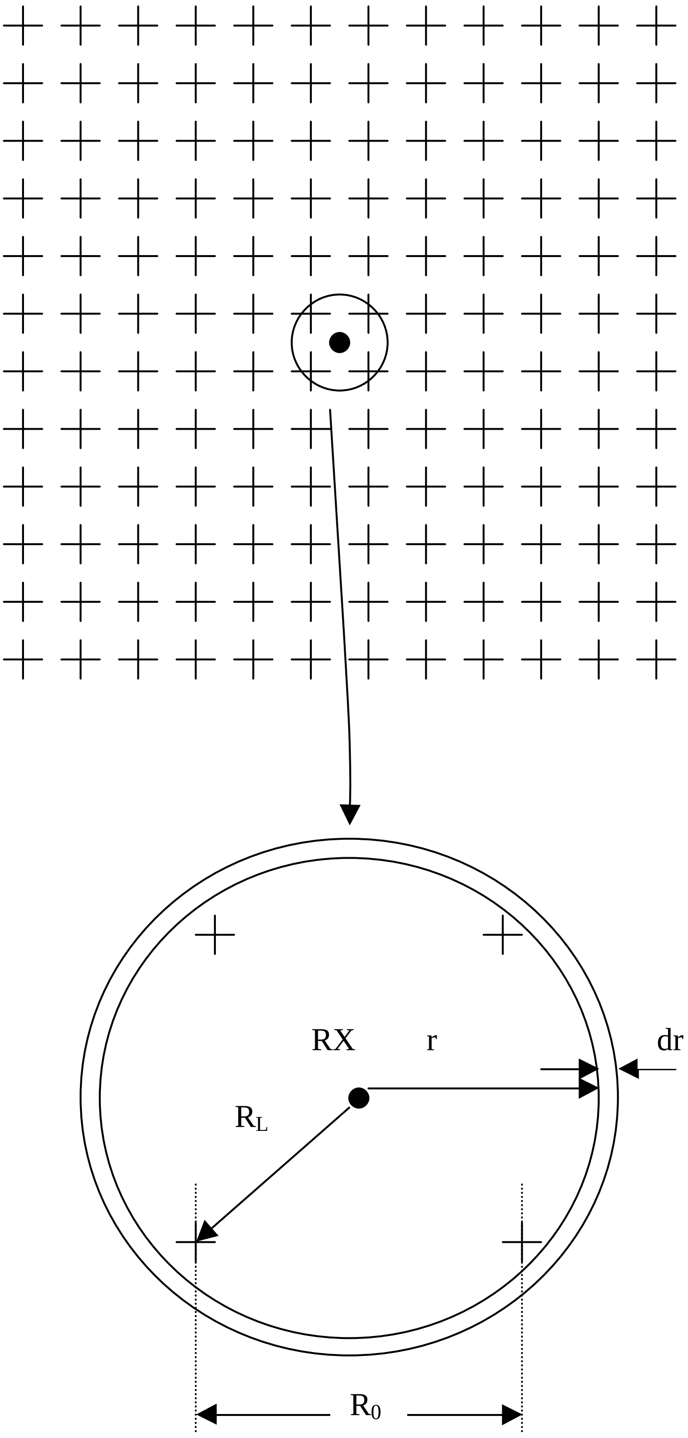

Figure 2 The top half of the diagram shows multiple UWB transmitters, denoted by crosses, distributed about a 2D plane, and a cellular receiver at the position marked by a black dot. The bottom diagram is an enlarged version of the centre of the top diagram, and shows some of the dimensions required for the derivation of the interference power from the UWB transmitters to the receiver.

The total interference power at the receiver from the UWB transmitters, I_{UWB}, can be calculated by evaluating the following integral

$$I_{UWB} = \int_{R_L}^{\infty} P_r \, r \, 2prdr \tag{2}$$

where P_r is the received power from a UWB transmitter located at a distance r from the receiver. The distance of the receiver to the nearest UWB transmitters is R_L, which can be expressed in terms of the average distance between UWB transmitters, R_0, by

$$R_L = {}^{R_0}\!\!/_{\sqrt{2}} \, . \tag{3}$$

The received power can be approximated by

$$P_r = P_0 \left(\frac{r}{d_0} \right)^{-n} \tag{4}$$

where P_0 is the power received at a free space reference distance, d_0, in the far-field region of a UWB transmitting antenna, and n is the path loss coefficient. It is appropriate to assume a d_0 of 100m for urban macrocells. P_0 can be expressed as

$$P_0 = \frac{G_p B_{RX} \, l^2}{(4p)^2 {d_0}^2} \, . \tag{5}$$

Therefore, the total interference power at the receiver can be expressed as

$$\begin{aligned} I_{UWB} &= \int_{R_L}^{\infty} \frac{G_p B_{RX} \, l^2 r^{-n} {d_0}^{n-2} \, r \, 2prdr}{(4p)^2} \\ &= \frac{G_p B_{RX} \, l^2 \, 2prd_0^{\,n-2}}{(4p)^2} \int_{\frac{R_0}{\sqrt{2}}}^{\infty} r^{1-n} dr. \end{aligned} \tag{6}$$

Now provided $n > 2$, the interference power is

$$I_{UWB} = \frac{G_p B_{RX}\, l^2\, r d_0^{\,n-2}}{8p}\left[\frac{r^{2-n}}{2-n}\right]_{\frac{R_0}{\sqrt{2}}}^{\infty} \tag{7}$$

and given that for $n > 2$, $\frac{r^{2-n}}{2-n} \to 0$ as $r \to \infty$, then the interference power at the receiver is

$$\begin{aligned} I_{UWB} &= \frac{G_p B_{RX}\, l^2\, r d_0^{\,n-2}\left(\frac{R_0}{\sqrt{2}}\right)^{2-n}}{8p\,(n-2)} \\ &= \frac{G_p B_{RX}\, l^2\, r d_0^{\,n-2}\,\sqrt{2}^{\,n} R_0^{\,2-n}}{16p\,(n-2)}. \end{aligned} \tag{8}$$

The average distance between UWB transmitters is related to the density of UWB transmitters by

$$R_0 = \frac{1}{\sqrt{r}}. \tag{9}$$

Hence, the interference power, I_{UWB}, can be expressed as a function of the density of UWB transmitters

$$I_{UWB} = \frac{G_p B_{RX}\, l^2\, \sqrt{2}^{\,n}\, \sqrt{r}^{\,n}\, d_0^{\,n-2}}{16p\,(n-2)}. \tag{10}$$

For UWB transmitters distributed with density, r, such that $R_0/\sqrt{2}$ is less than or equal to d_0, then free space propagation can be assumed from UWB transmitters within a distance of d_0 from the cellular receiver. The condition above, $\left(\frac{R_0}{\sqrt{2}}\right) \le d_0$, can be rewritten as $r \ge 1/2d_0^{\,2}$. When this condition is true, Equation 2 becomes,

$$
\begin{aligned}
I_{UWB} &= \int_{\frac{R_0}{\sqrt{2}}}^{d_0} \frac{G_p B_{RX}\, l^2\, r\, 2prdr}{(4p)^2 r^2} + \int_{d_0}^{\infty} \frac{G_p B_{RX}\, l^2 d_0{}^{n-2} r^{-n}\, r\, 2prdr}{(4p)^2} \\
&= \frac{G_p B_{RX}\, l^2\, r}{8p}\left[\ln\left(\frac{\sqrt{2}d_0}{R_0}\right) + d_0{}^{n-2}\int_{d_0}^{\infty} r^{1-n} dr\right] \\
&\approx \frac{G_p B_{RX}\, l^2\, r}{8p}\left[\ln\left(\sqrt{2}\sqrt{r}\, d_0\right) + \frac{1}{n-2}\right].
\end{aligned}
\tag{11}
$$

A general expression for the UWB interference can be formulated by combining Equation 10 and Equation 11,

$$
I_{UWB} = G_p B_{RX} F(l, r, d_0, n) \tag{12}
$$

where $F(l, r, d_0, n)$ is described by

$$
F(l, r, d_0, n) = \begin{cases} \dfrac{l^2\, r}{8p}\left[\ln\left(\sqrt{2}\sqrt{r}\, d_0\right) + \dfrac{1}{n-2}\right] & for\ r \geq \dfrac{1}{2d_0{}^2} \\[2ex] \dfrac{l^2 \sqrt{2}^{\,n} \sqrt{r}^{\,n} d_0{}^{n-2}}{16p\,(n-2)} & for\ r < \dfrac{1}{2d_0{}^2} \end{cases}. \tag{13}
$$

3.3 Derivation of the maximum possible UWB PSD

Now let us derive an expression for the UWB PSD that would increase the noise power at the victim receiver by a margin, M dB, assuming that the total interference power from the UWB transmitters adds non-coherently to the noise power. This derivation enables us to calculate the maximum UWB PSD that produces a certain level of interference to the receiver, ie, a certain value of *M*. Excluding the UWB interference, the noise power (in Watts), $N_0(W)$, at a receiver that has a noise factor, N_{factor}, and a bandwidth, B_{RX}, at a temperature, *T*, is

$$
N_0(W) = kTB_{RX} N_{factor}. \tag{14}
$$

We note that the noise figure of a receiver is the noise factor expressed in decibels. The noise power in watts can be converted into dBm using the following expression

$$
N_0(dBm) = 10\log\left(\frac{N_0(W)}{10^{-3}}\right). \tag{15}
$$

The total UWB interference and noise power at the receiver that is equal to the noise power plus a margin, *M*, in deciBels is defined by the following expression

$$10\log\left(\frac{N_0(W)+I_{UWB}}{10^{-3}}\right)=M+N_0(dBm)\,. \tag{16}$$

The expression for the total UWB interference power in Equation 12 can be substituted into the above equation, and the subsequent equation rearranged to obtain an equation for the UWB PSD to increase the receiver noise power, by a margin *M* (dB),

$$\begin{aligned} G_p &= \frac{\left[\left[10^{\left(\frac{M+N_0(dBm)}{10}-3\right)}\right]-N_0(W)\right]}{B_{RX}F(l,r,d_0,n)} \\ &= \frac{\left[10^{\left(\frac{M}{10}\right)}-1\right].N_0(W)}{B_{RX}F(l,r,d_0,n)} \\ &= \frac{\left[10^{\left(\frac{M}{10}\right)}-1\right].kT}{F(l,r,d_0,n)}. \end{aligned} \tag{17}$$

In the interference analysis so far we have assumed that the cellular receiver is operating in a noise-limited environment, and have considered the impact of the interference of UWB transmitters on the receiver noise power. Noise-limited cellular systems are generally found in low user density areas, such as rural areas. The above equation could be used to estimate the maximum UWB PSD that would shrink the link budget of cells of such a cellular system by *M* dB.

Cellular networks that are deployed in high user density areas, such as urban areas, are generally interference-limited, and require an alternative equation to Equation 17, to determine the maximum UWB PSD. In this case a cellular receiver is subject to co-channel interference from the cellular system itself, in addition to the interference from UWB transmitters. The UWB interference has to be greater than the cellular interference to have a detrimental effect on the cellular system performance. A similar equation to the one above can easily be derived for the UWB PSD, G_p, that increases the receiver's co-channel interference plus noise power by *M* dB,

$$G_p = \frac{\left[10^{\frac{M}{10}} - 1\right] I_T(W)}{B_{RX} F(l, r, d_0, n)}, \tag{18}$$

where I_T is the cellular interference at the receiver, I_0, plus the receiver noise power, N_0,

$$I_T(W) = I_0(W) + N_0(W)\,. \tag{19}$$

3.3.1 Maximum UWB PSD for a FDMA/TDMA cellular system

Consider a FDMA/TDMA cellular system that has four cells per cluster, and three sectors per cell, as shown in Figure 3. The worst case interference for a cellular receiver occurs when the receiver is at the boundary of a cell. The co-channel interference from the three cells that are in the first tier of co-channel cells is approximately

$$I_0 = P_{c0} {d_0}^{n} \left(\left(\sqrt{13}R\right)^{-n} + \left(\sqrt{19}R\right)^{-n} + \left(\sqrt{31}R\right)^{-n} \right) \tag{20}$$

where P_{C0} is the power received at a close in reference distance, d_0, from a cellular base station (BS), and R is the cell radius.

Let us assume free space propagation up to the distance d_0. Therefore, the power received at d_0 from the BS is

$$P_{C0} = \frac{P_t l^2}{(4p)^2 {d_0}^2} \tag{21}$$

where P_t is the BS transmitter power. We can now rewrite the expression for the co-channel interference (Equation 20) as

$$I_0 = \frac{P_t l^2 {d_0}^{n-2}}{(4p)^2} \left(\left(\sqrt{13}R\right)^{-n} + \left(\sqrt{19}R\right)^{-n} + \left(\sqrt{31}R\right)^{-n} \right). \tag{22}$$

Equations 18, 19, and 22 can be used to determine the maximum UWB PSD to increase the receiver interference and noise power by M dB. This is equivalent to degrading the signal-to-interference ratio (SIR) at the receiver location by M dB.

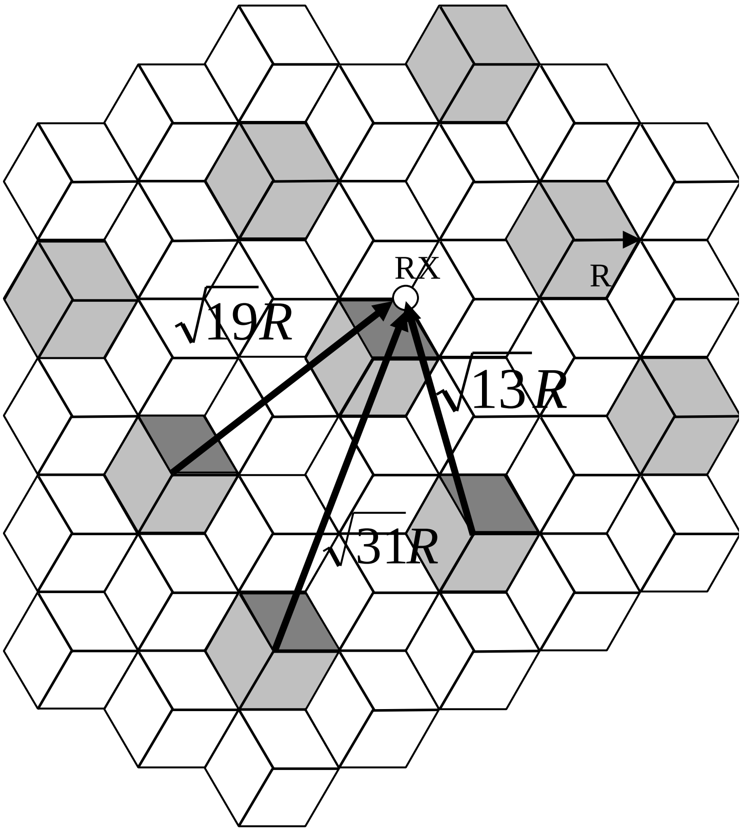

Figure 3 Illustration of the first tier of interfering cells of a sectorised cellular system, with three sectors per cell and four cells per cluster. The marked distances were estimated to facilitate the interference analysis.

3.3.2 Maximum UWB PSD for a CDMA cellular system

The TDMA/FDMA interference analysis performed in the last section examined the downlink from the interfering BSs to a cellular receiver. Now let us consider the interference in a CDMA system, and examine the uplink to a CDMA base station. In CDMA, the uplink is generally the limiting link in terms of capacity [15]. Consider *N* mobiles communicating to a single isolated BS. Assuming perfect power control, the signal from each mobile is received at the BS at its target power, *S*. Therefore, the interference from *N*-1 interfering MSs is

$$I_{CDMA} = (N-1)S + N_0(W)\,. \tag{23}$$

Now the interference due to the UWB transmitters can be introduced to modify I_{CDMA} to

$$I_{CDMA} = (N-1)S + N_0(W) + I_{UWB}\,. \tag{24}$$

The signal to interference ratio, *SIR*, for a particular user's signal arriving at the BS is

$$SIR = \frac{S}{(N-1)S + N_0(W) + I_{UWB}}. \tag{25}$$

The total interference power can be expressed as

$$J_0 B_{RX} = (N-1)S + N_0(W) + I_{UWB} \tag{26}$$

where J_0 is the combined PSD of the interference and receiver noise.

The power, *S*, received from each MS is the product of the energy per bit, E_b, and the transmission bit rate, R_b,

$$S = R_b E_b. \tag{27}$$

Therefore, we can calculate ${E_b}/{J_0}$,

$$\frac{E_b}{J_0} = \frac{G}{(N-1) + \frac{N_0(W) + I_{UWB}}{S}} \tag{28}$$

where *G* is the processing gain, which is ${B_{RX}}/{R_b}$. Equation 28 is based upon the analysis of a single isolated cell. Due to the limited time scales associated with this study, factors such as imperfect power control, voice activity, and intercell interference have not been considered in this analysis.

Equation 28 can be rearranged to calculate the target received power, *S*, which we now denote as S_{UWB},

$$S_{UWB} = \frac{N_0(W) + I_{UWB}}{\frac{G}{{E_b}/{J_0}} - (N-1)}. \tag{29}$$

A similar expression can be written for the target received power, S_{NO_UWB} when the CDMA BS receives no interference from UWB transmitters,

$$S_{NO\_UWB} = \frac{N_0(W)}{\frac{G}{E_b/J_0} - (N-1)}. \tag{30}$$

The received powers, S_{UWB}, and S_{NO_UWB}, required to maintain a target E_b/J_0 can be calculated, and the UWB interference that makes S_{UWB} greater than S_{NO_UWB} by M dB can be evaluated. In this way the UWB PSD that increases the received power by a particular amount, M dB, can be identified. The increase in received power is

$$M = 10\log\frac{S_{UWB}}{S_{NO\_UWB}} = 10\log\left(\frac{N_0(W)+I_{UWB}}{N_0(W)}\right) = 10\log\left(1+\frac{I_{UWB}}{N_0(W)}\right). \tag{31}$$

Equations 12 and 31 can be combined to derive the UWB PSD, G_p, that increases the MS transmit power in a CDMA system by M dB

$$G_p = \frac{\left[10^{\left(\frac{M}{10}\right)} - 1\right].kT}{F(l, r, d_0, n)} \tag{32}$$

This equation is identical to Equation 17, which was derived for a noise limited system.

3.4 Maximum UWB PSD results

Having derived expressions for the maximum UWB PSD that degrades the performance of a cellular receiver by *M* dB, let us determine typical maximum UWB PSD values.

3.4.1 Interference on noise-limited systems or CDMA systems

Before we present the main results, let us first show the variation of maximum UWB transmitted power as a function of UWB density, assuming a 1GHz transmission bandwidth. The graphs in this section show the maximum UWB transmitter (TX) power that increases the noise floor of a noise limited cellular system by 1dB, ie, *M* has been set to 1dB. A receiver noise figure of 6dB is assumed.

The propagation model used is free space up to a distance, d_0, and beyond that distance a fourth order power law is used. In the following example we will assume a distance, d_0 of 100m. As can be seen from Figure 4, as the density of UWB transmitters is increased the maximum UWB transmitted power decreases, as one would expect.

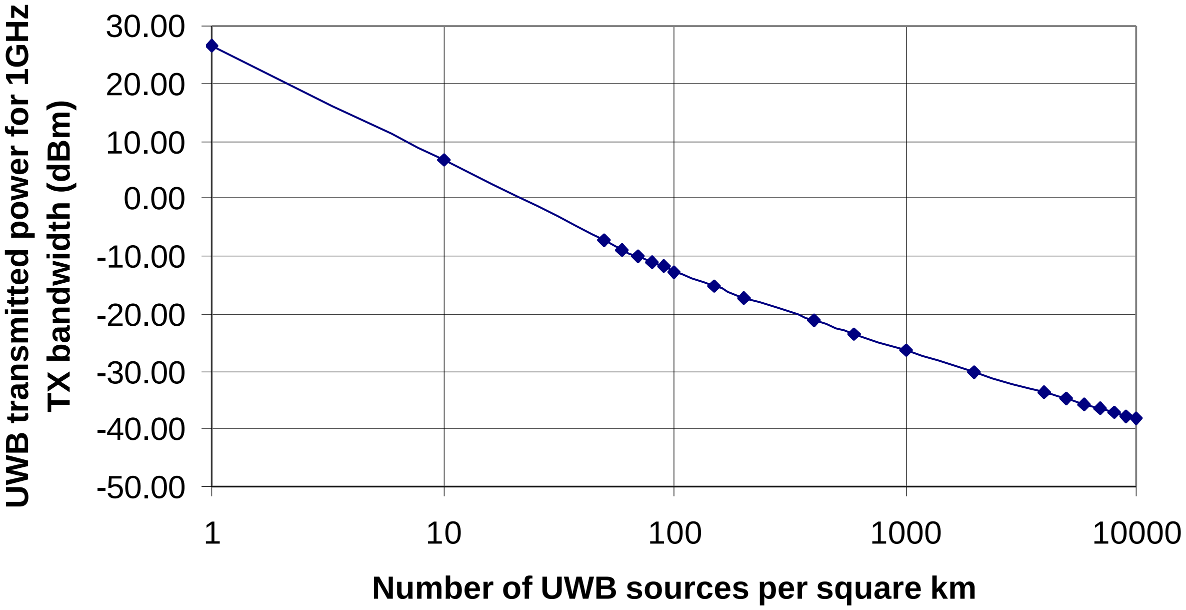

Figure 4 Graph of the maximum UWB transmitted power for a 1GHz transmission bandwidth plotted against the density of UWB sources for a 1dB degradation.

The slope of the graph changes, just beyond a density of 50 UWB sources per square km. This is the point at which some UWB transmitters begin to be within free space transmission range of the cellular receiver. The density of UWB sources when this occurs is $1/2d_0^2$, which is 5×10^{-5} per square metre, ie, 50 per square km. To understand why the slope of the graph in Figure 4 decreases beyond a density of 50 UWB sources per square km, consider the graph in Figure 5, which shows the UWB transmitted power plotted as a function of the average distance between UWB transmitters, R_0. The change in slope occurs when R_0 reaches a value of $1/\sqrt{r}$, which is 141m. For UWB transmitters spaced less than 141m apart, the power received by the cellular receiver is due to free space transmission, whereas beyond 141m the power received from all the UWB transmitters is determined by the fourth order power law. Referring to the graph in Figure 5, increasing the average UWB separation from 10m, the maximum UWB transmission power increases at more than 20dB/decade, until a separation distance of 141m. Beyond 141m the maximum UWB transmission power increases much more steeply at approximately 40dB/decade. In this region the UWB transmission power can be increased at a faster rate compared to the region below 141m because the received power at the cellular receiver decreases at a faster rate, ie, fourth order power law. On the other hand for UWB separations below 141m some of the UWB sources are within free space transmission range, and therefore as the UWB separation is increased, the received power at the cellular receiver decreases at a slower rate.

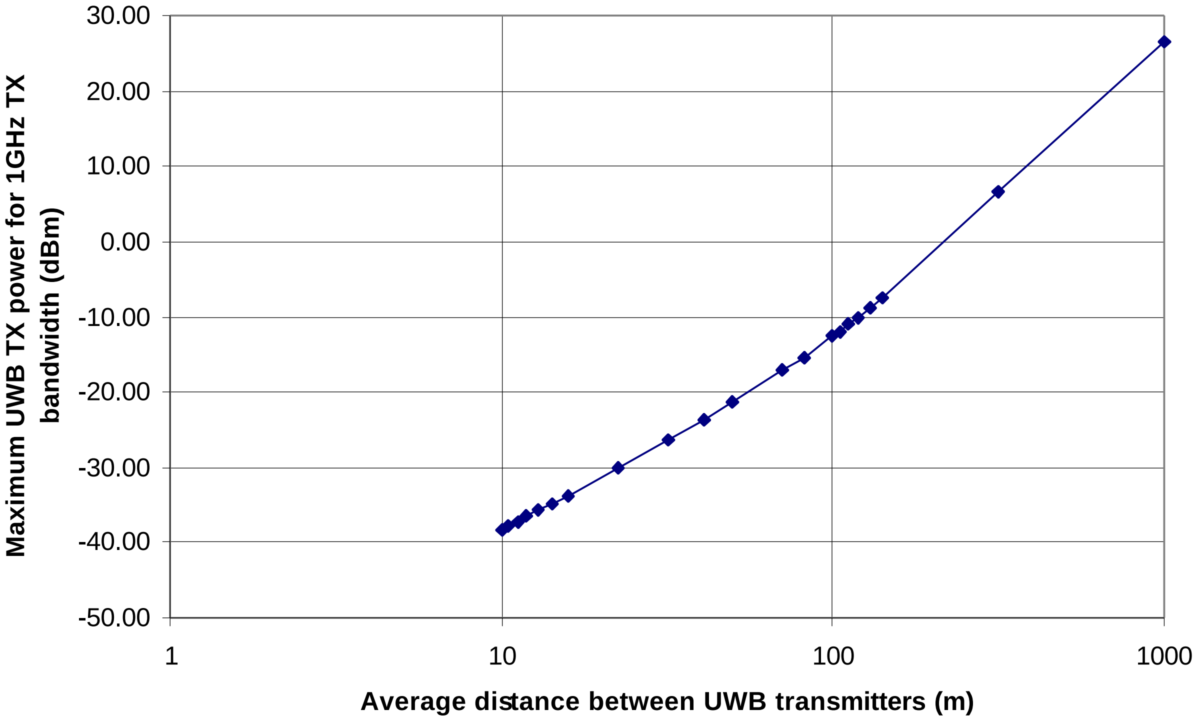

Figure 5 Graph of the UWB transmitted power for a 1GHz transmission bandwidth plotted against the average distance between UWB sources (1dB degradation).

3.4.1.1 Interference on rural GSM cellular systems

Let us investigate the interference of UWB transmitters on a rural area cellular network, and in particular the interference on a cellular BS. To appropriately model the radio propagation in rural areas from the UWB transmitters to the cellular receiver, free space propagation is assumed up to 1km from the UWB transmitters, and then an inverse fourth power law with distance, ie, d_0 is 1000m, and n is 4 in our propagation model. The worst case scenario would be for the UWB transmissions to come from mobile handsets, assuming that the number of active mobiles is greater than the number of base stations. This assumes that the UWB system is itself a cellular-like system. The graph in Figure 6 shows the maximum UWB PSD that increases the noise floor of the cellular system by 1dB. Two plots are shown for cellular receivers that operate at frequencies of 900MHz and 1800MHz. The cellular system is assumed to be GSM, ie, GSM900 and GSM1800. The receiver bandwidth of a GSM system is 200kHz, however, the PSD results are independent of receiver bandwidth, as shown by Equation 17. Raising the receiver bandwidth does increase the UWB interference but the thermal noise power of the receiver increases by the same amount. The receiver temperature is assumed to be 290K, and the receiver noise figure is 6dB.

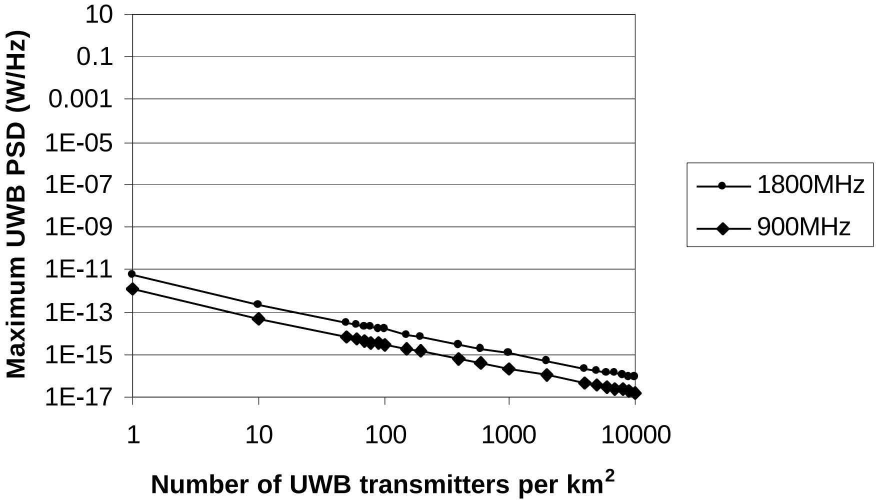

Figure 6 Graph of the maximum UWB PSD plotted against the density of UWB transmitters. Two plots are shown, one assuming that the victim cellular receiver operates at 900MHz and the other for a cellular receiver operating at 1800MHz.

The graph in Figure 7 shows the maximum UWB transmitted powers for a variety of UWB transmission bandwidths.

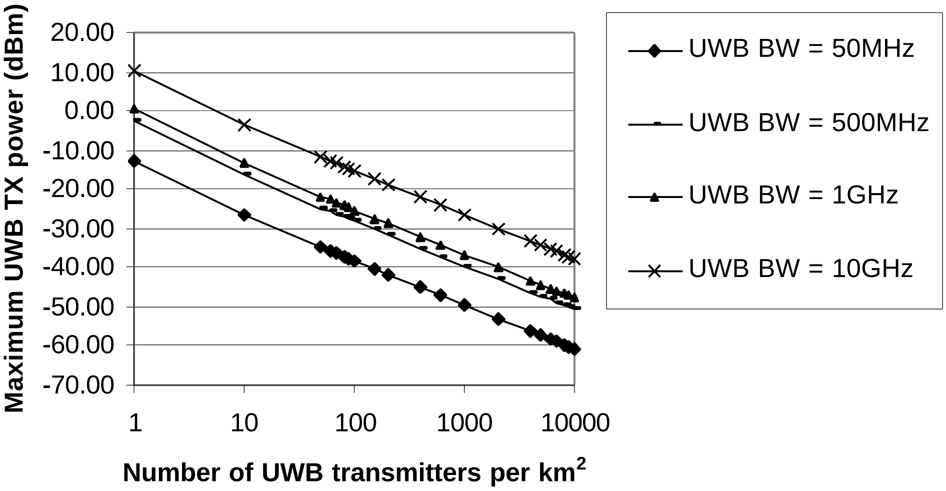

Figure 7 Graphs of the maximum UWB transmitted power for a variety of transmission bandwidths. The victim cellular receiver has an operating frequency of 900MHz.

Assuming that the UWB system is a cellular-like system, we would not expect many UWB users in rural areas, perhaps only one per square km, which from the graph above, for UWB transmitters of 1GHz bandwidth, allows a maximum UWB transmitter power of about 0dBm.

3.4.1.2 Interference on an urban IS-95 CDMA system

From earlier discussions we are aware that the UWB interference on a CDMA system has an identical effect as the interference on a noise-limited TDMA/FDMA cellular system. Therefore, the results above also apply for a CDMA system in a rural area. Now let us consider the maximum allowed PSDs of UWBs in an urban area. To appropriately model the radio propagation in urban areas from the UWB transmitters to a CDMA BS, free space propagation is assumed up to 100m from the UWB transmitters, and then an inverse fourth power law with distance is used, ie, d_0 is 100m, and n is 4 in our propagation model. This is done because large urban cells have harsher propagation characteristics than large rural cells. The worst case scenario would be for the UWB transmissions to come from mobile handsets, assuming that the number of active mobiles is greater than the number of base stations. This assumes once again that the UWB system is a cellular system. The graph in Figure 8 shows the maximum UWB PSD that increases the noise floor of the cellular system by 1dB. Two plots are shown for cellular receivers that operate at frequencies of 900MHz and 1800MHz. The cellular system is assumed to be IS-95.

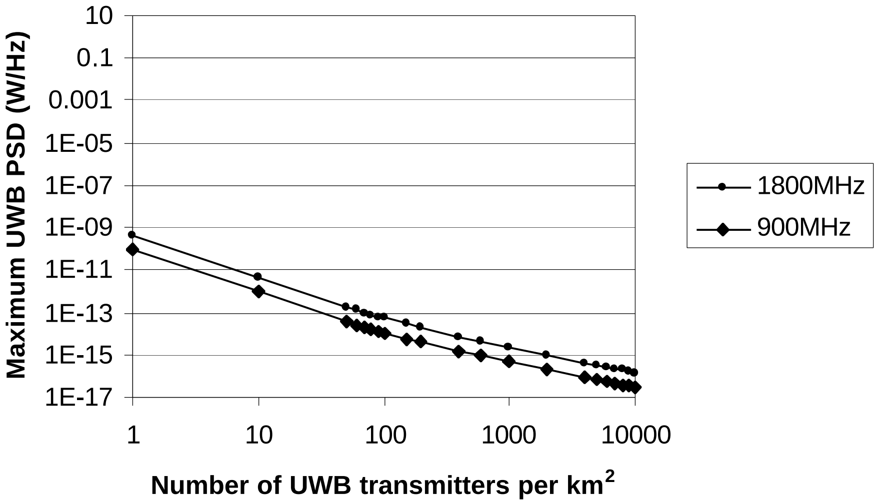

Figure 8 Graph of the maximum UWB PSD plotted against the density of UWB transmitters. The maximum UWB PSDs were calculated based on the interference that would be caused on an urban CDMA system for a 1dB degradation. Two plots are shown, one assuming that the victim cellular receiver operates at 900MHz and the other for a cellular receiver operating at 1800MHz .

The graph in Figure 9 shows the maximum UWB transmitted powers for a variety of UWB transmission bandwidths.

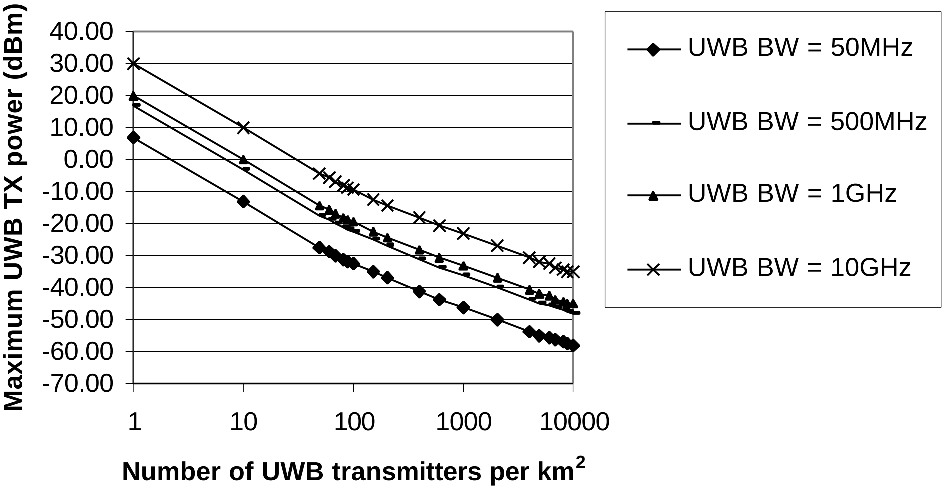

Figure 9 Graph of the maximum UWB transmitted power for a variety of transmission bandwidths. The victim cellular receiver has an operating frequency of 900MHz and is part of an urban CDMA cellular system.

Assuming that the UWB system is a cellular-like system, we would expect perhaps a maximum of 100 active users per square km, which from the graphs in Figure 9, for UWB transmitters of 1GHz bandwidth, allows a maximum UWB transmitter power of about -20dBm. The maximum UWB TX power that only increases the noise floor by 1dB for an IS-95 CDMA system would be the same as for a third generation (3G) CDMA system, because the receiver bandwidth does not affect the maximum allowed UWB transmission power.

3.4.2 Interference on FDMA/TDMA systems in urban areas

We will now consider the effect of UWB interference on a FDMA/TDMA cellular system such as GSM, and present the results for the UWB PSD that inflicts a 1dB degradation on a GSM mobile in urban areas. The propagation related factors are chosen as before for a CDMA system in an urban area, ie, n is 4 and d_0 is 100m. The GSM system in this analysis has four cells per cluster, and three sectors per cell.

To evaluate the interference on a cellular receiver, Equation 22 can be used. However, a suitable cell radius, R, needs to be chosen that is typical for a GSM urban cellular network. The signal-to-interference-plus-noise (SINR) ratio for the GSM system, ignoring for the moment the interference from the UWB transmitters, can be plotted as a function of the cell radius, as shown in Figure 10 for an operating frequency of 900MHz. Notice that the signal-to-interference-plus-noise ratio rather than the signal-to-interference-ratio is plotted since the latter ratio is independent of cell radius. To understand the relationship between SINR and cell radius consider the graph in Figure 11.

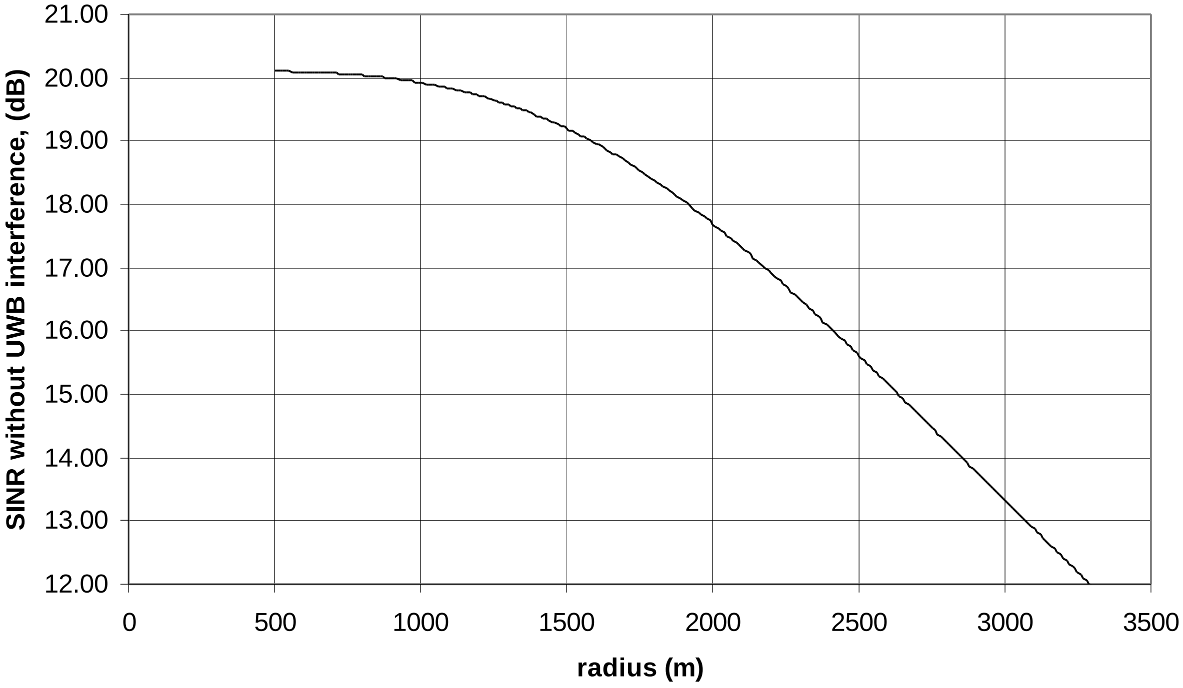

Figure 10 Signal to co-channel interference plus noise ratio at a mobile receiver at the perimeter of the serving cell plotted against the cell radius.

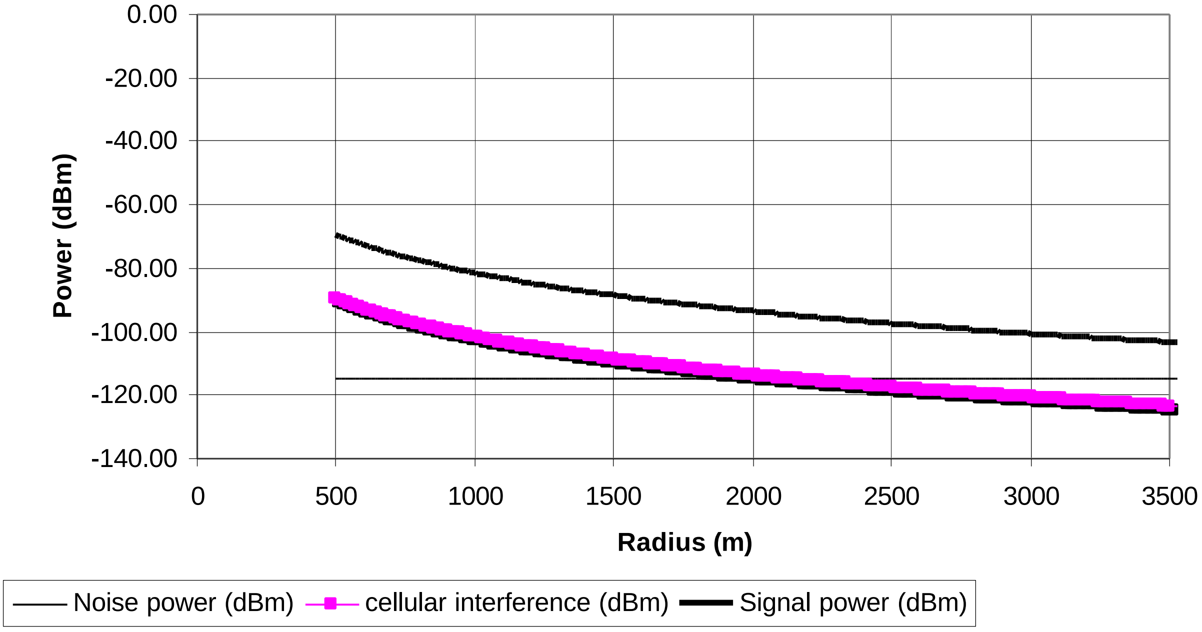

Figure 11 Graph of the signal, co-channel interference, and noise power received by a mobile at the edge of a cell plotted as a function of cell radius.

In Figure 11, the signal power, co-channel interference power and receiver noise powers received by a mobile at the edge of a cell are plotted as a function of cell radius. We will consider two cell radii, 750m and 1500m. For a cell radius of 750m the SINR is similar to lower cell radii, and hence the system is clearly interference limited. However, for a cell radius of 1500m the receiver noise power is significant, but the interference power is still above the noise power, so the system is just about still interference limited.

The maximum UWB transmitter PSD to increase the cellular interference by 1dB is shown in Figure 12 and Figure 13 for cell radii of 750m and 1500m, respectively. The maximum UWB PSD is higher for cell radii of 750m compared to cell radii of 1500m. This is because for smaller cell radii the system is clearly interference limited and the UWB interference has to overcome the cellular co-channel interference.

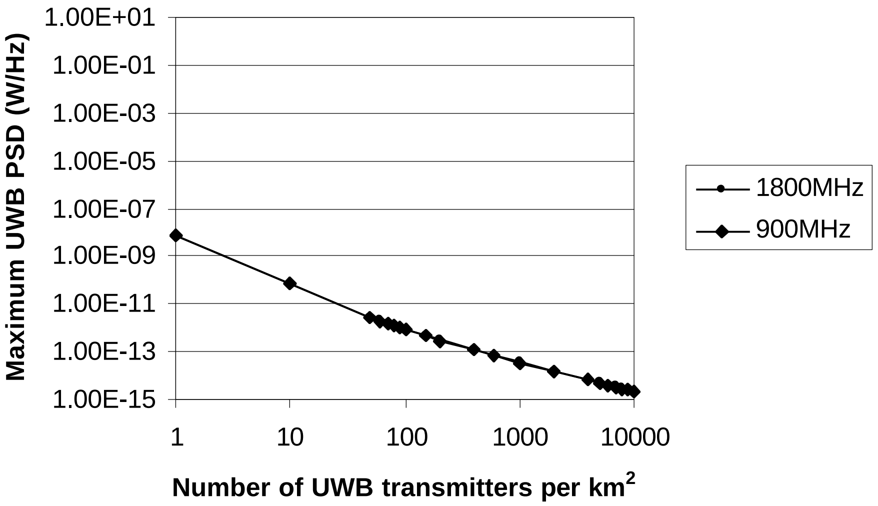

Figure 12 Graph of the maximum UWB PSD against the density of UWB transmitters for 1dB degradation. The cell radius of the GSM system is 750m.

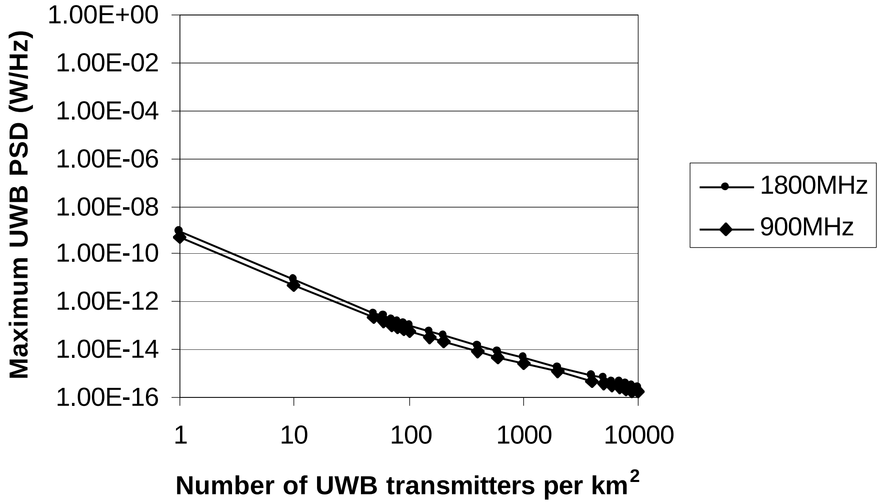

Figure 13 Graph of the maximum UWB PSD against the density of UWB transmitters. The cell radius of the GSM system is 1500m.

The maximum UWB transmitter powers for various transmission bandwidths are plotted as a function of UWB density in Figure 14, assuming the GSM cell radius is 750m, and GSM900 is the cellular system deployed, (ie, the frequency is 900MHz).

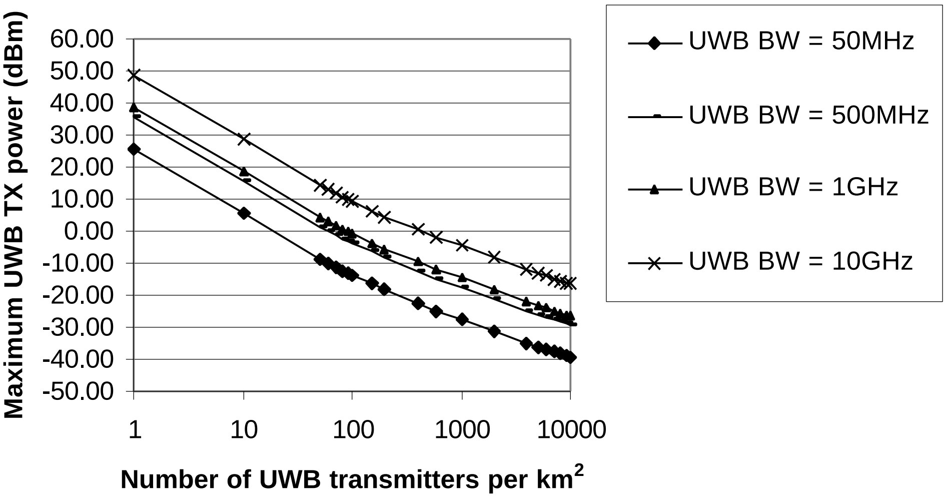

Figure 14 Graph of the maximum UWB transmitted power for a variety of transmission bandwidths. The victim cellular receiver has an operating frequency of 900MHz and is part of an urban TDMA cellular system.

Assuming that the UWB system is a cellular-like system, we would expect perhaps a maximum of 100 active users per square km in an urban area, which from Figure 14, for UWB transmitters of 1GHz bandwidth, allows a maximum UWB transmitter power of about 0dBm. This value for the maximum UWB transmitter power is 20dB more than the equivalent value found when considering the interference on a CDMA system in an urban area.

3.4.3 Interference on Global Positioning System (GPS) receivers

The FAA [16], TEM Innovations [14], U.S. GPS Industry Council [17,18], American Airlines [18], the General Aviation Manufacturers Association [18], Stanford University [18], and United Airlines [18] have expressed concerns that UWB operations will produce harmful interference in the GPS bands. The FCC has tested the impact on a GPS receiver from a Time Domain Corporation Part 15-qualifiable radar, where the emissions from the radar prevented the GPS receiver tracking a satellite when the GPS receiver was one foot away from the radar, and the GPS receiver was prevented from acquisition when the radar was 10 feet away. Time Domain Corporation [19] performed a similar test in an open field using a handheld GPS receiver, and has also carried out some theoretical analysis on the compatibility between a GPS system and UWB emissions. The required isolation between a GPS receiver and a UWB device was calculated to determine the range at which GPS no longer works. The required isolation was calculated assuming that the UWB device was limited to Part 15 Class B unintentional radiator emission levels. The range was determined by assuming free space propagation between a UWB device and a Navstar GPS receiver. The theoretical ranges were found to be 19.8m for acquisition, and 7.1m for tracking and demodulation. These values are greater than the results of the FCC tests, and also greater than measurement tests performed by Time Domain Corporation, which found that reliable positioning information was lost for a separation of four to six feet. The handheld GPS receiver was kept relatively level at a normal operating height. The discrepancy between measured and theoretical results was accounted for by considering gains in the GPS systems not accounted for in the theoretical analysis. This meant the theoretical analysis gives a conservative estimate of the range.

Let us calculate the maximum UWB density that would degrade the performance of the GPS receiver used in Time Domain Corporation's theoretical analysis [19]. The required isolation was determined by Time Domain Corporation to be 62.4dB and 53.4dB, for acquisition and tracking, respectively. The derivation of the isolation figures have accounted for the ratio of UWB to GPS bandwidth. The GPS operating frequency is 1575MHz, which is equivalent to a wavelength of 0.19 m in our calculations. The predicted isolation can be derived from Equation 12, and is $1/F(l,r,d_0,n)$, where $F(l,r,d_0,n)$ was defined in Equation 13.

Figure 15 shows the predicted path loss plotted against the UWB density in an urban area, ie, d_0 is 100m. The maximum UWB densities to cause the GPS acquisition and tracking to fail are approximately 300 and 1500 sources per square km, respectively. This is more than the 100 sources per square km previously considered as an appropriate density of UWB devices in an urban area. A similar graph is plotted in Figure 16 of predicted path loss for a rural area, ie, d_0 is 1000m. The maximum UWB densities to cause the GPS acquisition and tracking to fail are approximately 100 and 750 sources per square km, respectively. This is more than the one source per square km previously considered as an appropriate density of UWB devices in a rural area.

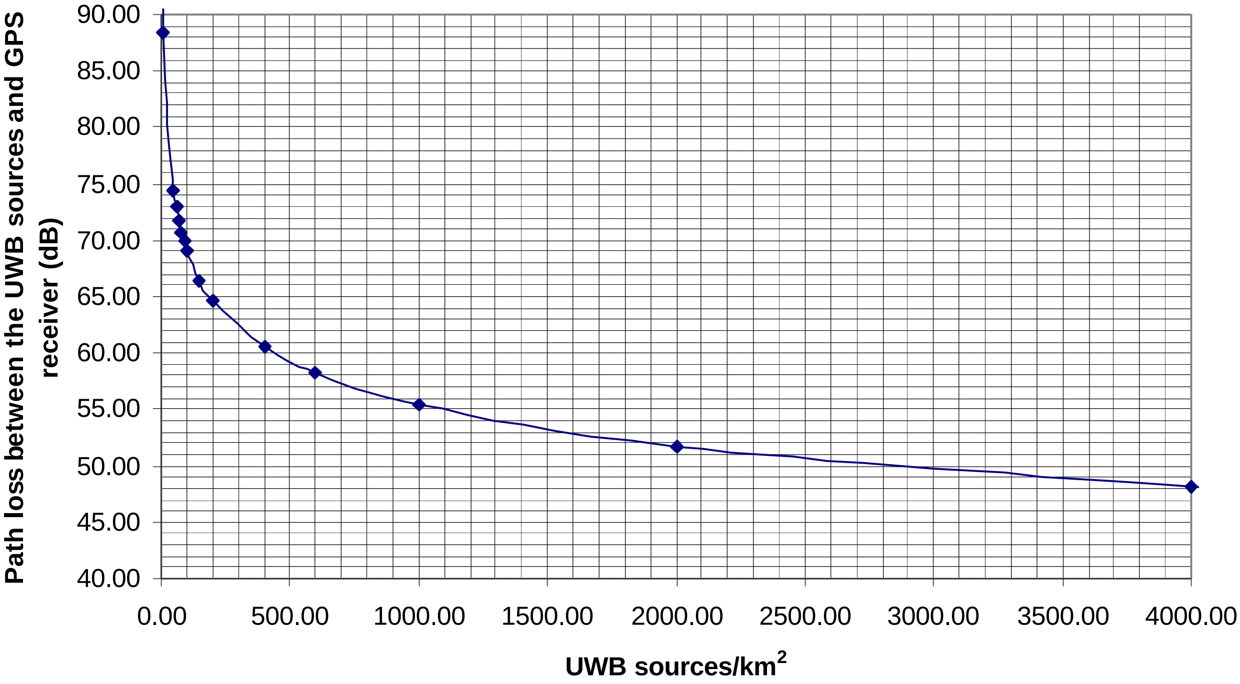

Figure 15 Isolation between UWB sources located in an urban area and a GPS receiver plotted against the density of UWB sources.

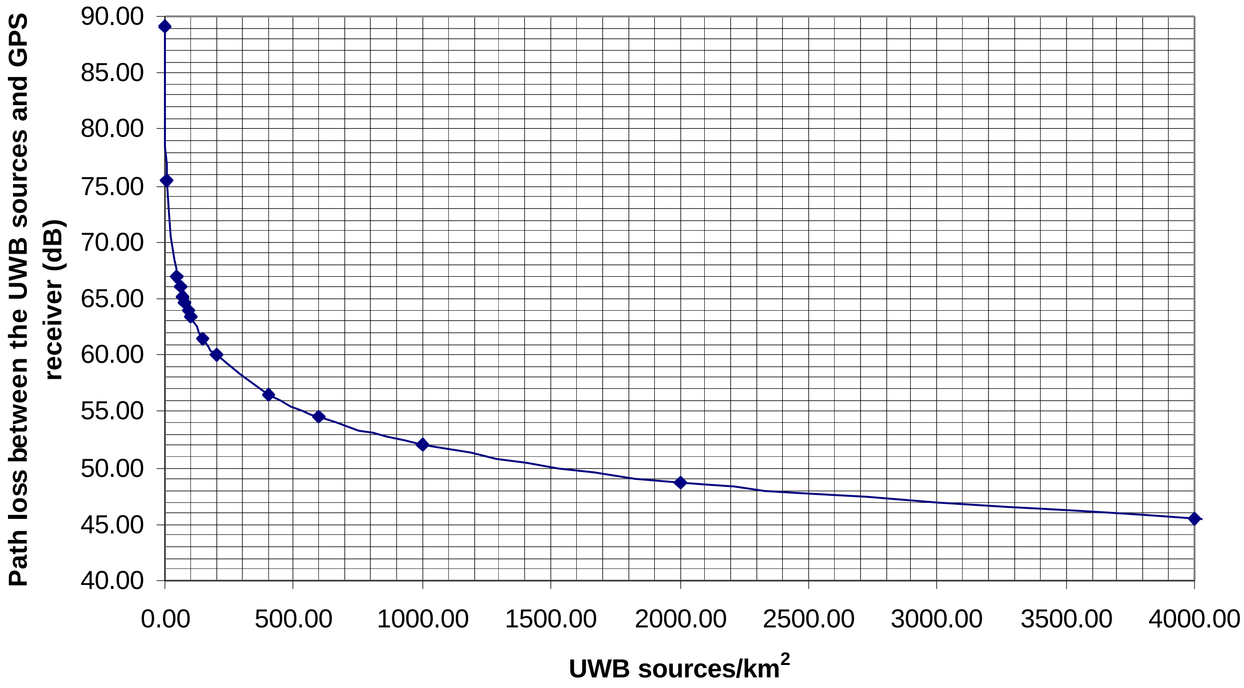

Figure 16 Isolation between UWB sources located in a rural area and a GPS receiver plotted against the density of UWB sources.

The GPS system was designed so that the received power at the terminals of a GPS receiver is –130dBm. Time Domain Corporation assumed this value for the received power at a GPS receiver in their derivation of the required isolation between a UWB source and the receiver. The isolation for acquisition and tracking was determined so that the signal-to-noise ratio was equal to the minimum required signal-to-noise ratio for acquisition and tracking, respectively. This method of quantifying the performance degradation of a GPS receiver is fair, rather than by determining the isolation that degrades the noise floor by 1dB.

Therefore, we can conclude that the interference caused by a proliferation of UWB devices on GPS receivers is of less concern than the interference caused to cellular systems. Of course if you put a UWB device in the near vicinity of a GPS receiver then it is going to cause a problem, but this is going to be the case for practically any electronic device. There are methods of isolating a GPS receiver from other electronic devices, for example, Multispectral Solutions Inc [12] have UWB devices operating in the GPS band without interference with an integral GPS receiver built in.

3.4.4 Interference on television receivers

Let us now consider the interference at a TV receiver due to multiple UWB sources. In the UK the TV band is around 500MHz. Consider a TV receiver in a residential area. Let us use the propagation model that was previously used to model the propagation in rural areas, ie d_0 equal to 1000m. We also assume a noise figure of 6dB. The maximum UWB transmitted power to degrade the noise floor by 1dB is plotted against UWB source density in the figure below.

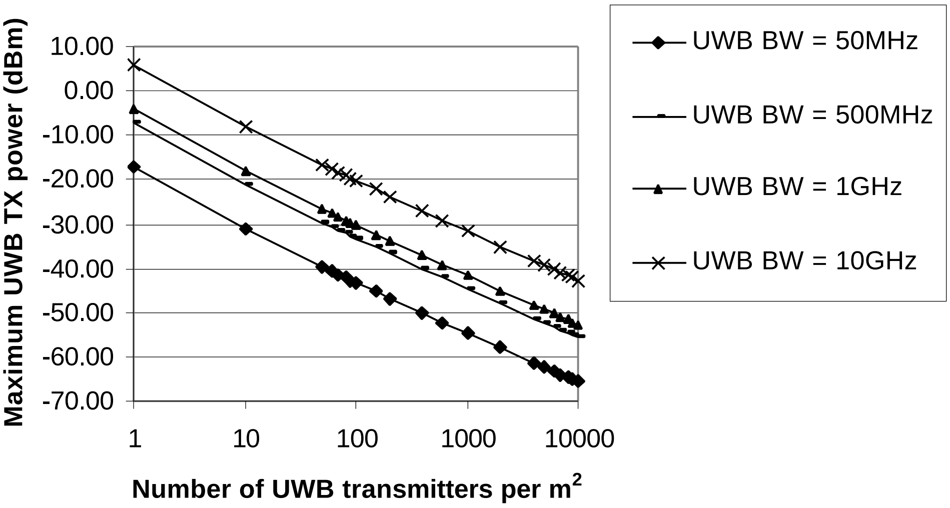

Figure 17 Graph of the maximum UWB transmitted power for a variety of transmission bandwidths for a 1dB degradation. The victim receiver is a TV receiver located in a residential area.

Earlier we considered a density of one active UWB source per square km to be appropriate for rural areas. For a 1GHz bandwidth the maximum UWB transmitted power is more than the minimum level for Part 15 unintentional radiator Class B emissions (-19.2dBm, see Section 3.1). Therefore, we can conclude that the interference on TV receivers in residential areas should not be a problem if the UWB devices have their transmitted powers limited to Part 15 Class B limits and the density of UWB sources is limited to one per km^2. Perhaps a more interesting scenario is an outdoor roof-mounted TV aerial and multiple UWB sources inside a residential home. The indoor UWB devices could form an in-building wireless local area network (WLAN), for example. To model the in-building propagation, let us choose d_0 to be 1m and a path loss exponent, *n*, of 4.5. In addition a 10dB roof penetration loss is added to the calculated path loss. The curves of the maximum UWB transmitted power for a variety of transmission bandwidths are plotted against UWB density in Figure 18.

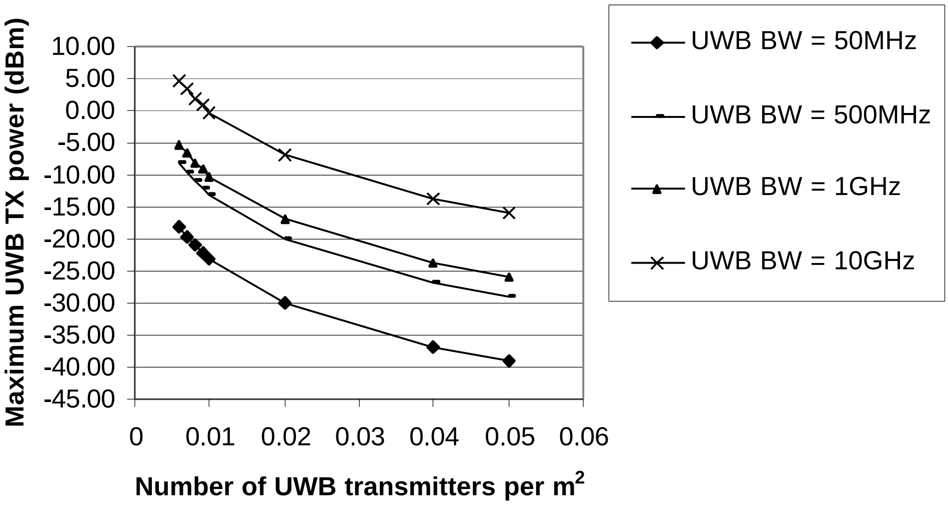

Figure 18 Graph of the maximum UWB transmitted power for a variety of transmission bandwidths. The victim receiver is a TV receiver located on top of a house in a residential area. The UWB sources are located within the house and neighbouring houses.

For 1GHz UWB devices, only 0.025 UWB devices per square metre would be able to operate at Part 15 Class B limits of –19.2dBm. For a single-storey house having a floor space of 200 square metres, the number of UWB devices in the house is five. The UWB interference is the cumulative interference from multiple UWB devices distributed over a large area, which means that neighbouring houses also contain UWB devices. We have not modelled the antenna pattern of the TV antenna, which is usually directional, and thus is likely to have very little gain in the direction of the UWB devices. Therefore, we would expect many more UWB devices to operate in a residential home without causing interference to a TV receiver.

We have not considered the UWB interference on digital TV receivers, which are reportedly more sensitive to wideband interference than analogue receivers. This is a topic for future work.

3.4.5 Interference on mobile receivers inside buildings

We established earlier that a noise-limited FDMA/TDMA system or a CDMA system is more susceptible to UWB interference than an interference-limited FDMA/TDMA system. Let us consider the interference on a 900MHz FDMA/TDMA noise-limited mobile receiver located inside a building. Assuming the same propagation model employed for looking at the interference perceived by a TV receiver from UWB devices located inside the building. The 10dB roof penetration loss is not modelled as the mobile receiver is located inside the building rather than on the roof. The maximum UWB transmitted power for a 1dB degradation is plotted against UWB source density in Figure 19 for a variety of transmission bandwidths.

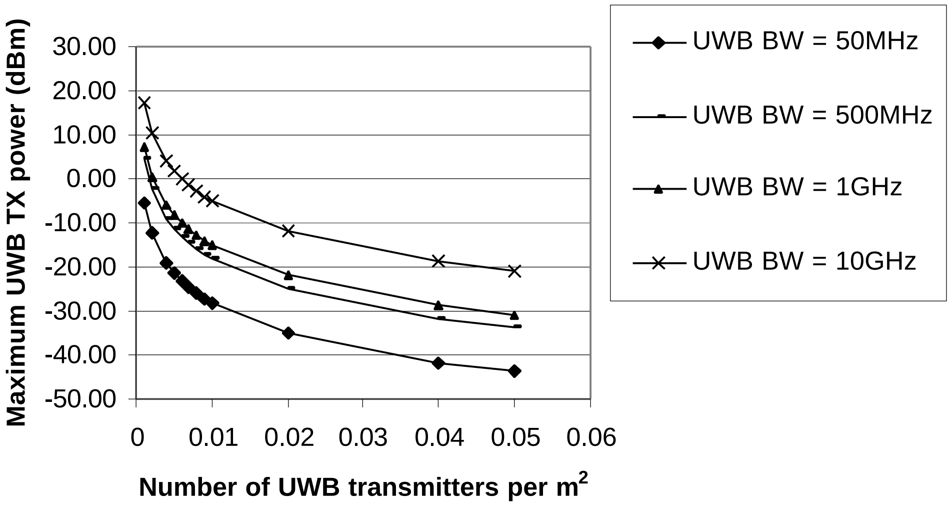

Figure 19 Graph of the maximum UWB transmitted power for a variety of transmission bandwidths. The victim receiver is a noise limited 900MHz FDMA/TDMA mobile receiver located inside a building containing UWB devices.

For a 1GHz UWB bandwidth, the density of UWB devices is about 0.015 per square metre, if the Class B emission limits are applied. This corresponds to about 150 UWB devices, in a shopping mall, for example, that has a floor space of about 100 x 100 metres.

3.5 Review of other UWB cumulative interference models.

A number of interference models exist that are designed to predict the cumulative interference effects of UWB sources. In this section we present a brief review of these interference models.

3.5.1 Interval Research Corporation

The Interval Research Corporation model [2] addresses concerns of aircraft safety due to line-of-sight to UWB devices on the ground. The model calculates the aggregate power at the apex of a cone resulting from the power emitted by the base of the cone on the surface of the earth. It is shown that the interference from UWB transmitters at the base of a 45 degree cone is negligible. Instead, any possible interference must come from an aggregation of UWB transmitters at the horizon. It is demonstrated that this interference is also negligible due to effect of the curvature of the earth, and the emitted photons being damped by the earth's surface.

3.5.2 Time Domain Corporation

3.5.2.1 Cumulative impact of multiple UWB transmitters

Time Domain Corporation [11] investigated the difference in received signal strength from a UWB transmitter 1m away from a receiver and the cumulative impact of multiple UWB transmitters, where one of them was always 1m away. In particular, the difference in received signal strength was estimated for various UWB densities. The analysis was carried out by means of a Monte Carlo simulation, described below:

1. N_{UWB} UWB sources were distributed over a 100 metre x 100 metre area.
2. The cumulative field strength was calculated for N_{UWB} users at 81 receiver points (50 metre x 50 metre area) in the centre of the 100 metre x 100 metre area, assuming that there is always a UWB source 1m away from a receiver point. A $1/R^2$ path loss propagation model was assumed.
3. Step 2 was repeated 1000 times for different random distributions of N_{UWB} users.
4. The mean value of the RMS field strength was calculated, ie, an average of 81,000 samples, and also for each of the 1000 random distributions, the largest RMS value from 81 receiver positions, was averaged over 1000 random distributions.

The results showed that even with 100 UWB sources over a 100 metre x 100 metre area, the RMS field strength value was increased by only 1.2dB over the field strength from one UWB source, and less than 6dB for the RMS of the maximum values. It was concluded that the cumulative field strength of multiple UWB sources is not significantly greater than the contribution from one UWB source.

The reason why the cumulative interference from multiple UWB sources was not significantly greater than the contribution from one UWB source is that one UWB source was always 1 metre away. We have tried doing a similar test using our interference model, with the interference from one nearby UWB source and multiple UWB sources calculated by two different methods, denoted as Method 1 and Method 2. The aim of Method 1 is to show the difference between the interference from the nearest UWB source to the cumulative interference from all UWB sources using our analytical model. The aim of Method 2 is to reproduce results similar to Time Domain Corporation's results, by adjusting our interference model to behave in a similar manner to their model, ie, by always having a close interferer.

The first method (Method 1) of calculating the interference from the nearest UWB source is to evaluate the interference using integration as shown in Section 3.2, but restricting the limits of integration from the near-in distance, R_L, specified in Equation 3, to a distance further away, such that the area swept out by the integral contains one UWB source. The total cumulative interference from multiple UWB sources is calculated using our conventional analytical interference model, ie, integrating from R_L to infinity.

The second method (Method 2) of calculating the near in interference from a UWB source is to use the interference integral, but now we restrict the limits of integration from a near-in distance of 1m, to a distance further away, such that the area swept out by the integral contains one UWB source. The total cumulative interference of multiple UWB sources is calculated using our conventional analytical interference model, but integrating from 1m to infinity, rather than from R_L to infinity.

In both methods, the ratio of the cumulative UWB interference to the interference from the nearest UWB source, expressed in decibels is plotted in Figure 20 against UWB source density. The propagation coefficients adopted are n equal to 4 and d_0 equal to 100m, and the cellular receiver has an operating frequency of 900MHz.

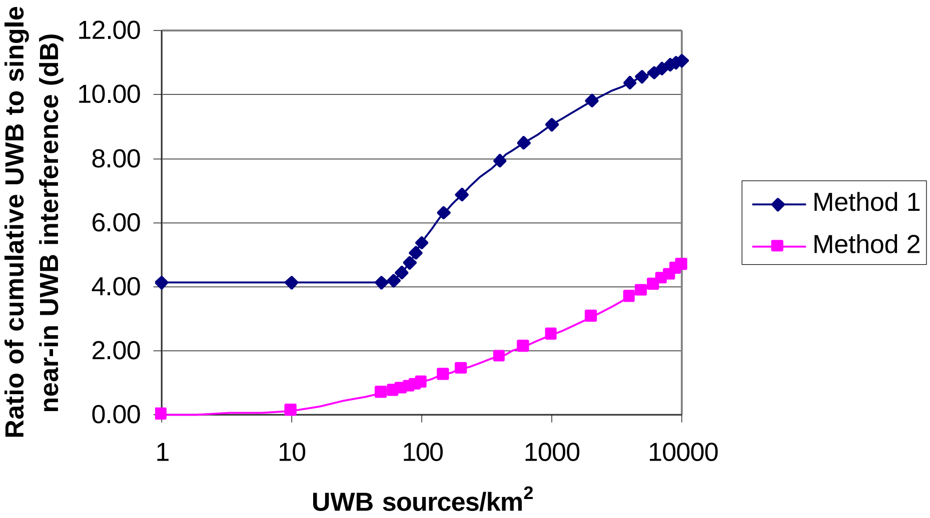

Figure 20 Graph of the multiple UWB interference to close-in single UWB interference (dB), calculated by Method 1 and Method 2 (refer to main text).

Note that for Method 2, the ratio of cumulative interference to the interference from a single UWB source increases from 0dB to 5dB as the density of UWB sources increases from 1 to 10000 sources per km^2. These results are similar to those presented by Time Domain Corporation, and the results are as expected, as the difference between the interference from a UWB source 1m away and the total interference from all UWB sources is not going to be considerable. However, for Method 1, the ratio of total interference to the interference from a single UWB source is much greater. In this case, the interference has a constant ratio of approximately 4dB for UWB densities up to 50 per square km. This is the point when UWB sources start to appear within free space transmission range of the receiver. Beyond that point the interference ratio increases more dramatically as more UWB sources are within free space transmission range.

We believe that Method 1 gives more realistic results, compared to those obtained by Method 2, or Time Domain Corporation's method. Using our UWB interference analytical model (Method 1), where R_L is equal to the distance to the nearest UWB source, which is related to the density of UWB sources, means that the distance to the nearest interferers is related to the density of UWB sources. On the other hand, Time Domain Corporation's model does not relate the nearest UWB interferer's distance to the density of UWB sources. In this case it is not surprising then that increasing the UWB source density has little impact on the cumulative interference when there is always a UWB source 1m away from the victim receiver.

At this point it is worth verifying that the choice of the lower limit of integration in our analytical interference model (Method 1) is reasonable. To do this a simulation was set up of UWB sources distributed about a 100km x 100km square grid. The victim receiver was put in the centre of the grid of UWB sources, and the total interference from the UWB sources was calculated. The density of UWB sources was varied and the total interference re-evaluated. In Figure 21 the relative interference power is plotted against UWB density. One parameter that does influence the results is d_0, the breakpoint in the path loss propagation model, which in this example is set to 100m. Three plots are shown in Figure 21; the simulated interference power, the interference power derived from our analytical interference model (Method 1), and the analytical interference power for a lower limit of integration of 1m (Method 2).

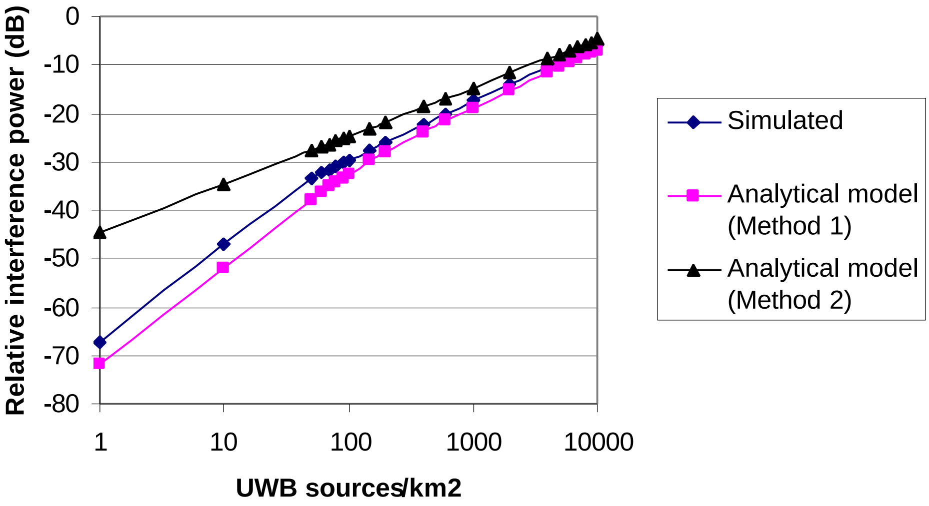

Figure 21 The UWB cumulative interference power evaluated by three methods. One method is based on a simulation and the other two are analytical methods.

Note that the simulated and analytical graphs are similar. On the other hand, decreasing the lower limit of integration to 1m, increases the interference at the victim receiver for low UWB densities. This happens because the integral unfairly weights the interference by the high received power close to the victim receiver, instead of treating the impact of the interference from close-in UWB sources proportional to the average inter-UWB device distance.

3.5.2.2 Interference on various avionics receivers

Returning to the review of published aggregate interference models, Time Domain Corporation [19] also modelled the interference of multiple UWB sources on various avionics receivers in aircraft flying low over urban areas. The interference calculations were performed using an analytical model, which represents various environments as cylinders. A cylinder can represent a tall building, a low building, or an entire populated area, depending on the cylinder's dimensions. A cylinder can also be split into wafers, with each wafer separated by an attenuating slab. This accounts for the attenuation of the floors and roof of a building. The interference model is similar to ours, except the density of UWB devices is per unit volume rather than area, and hence the model is three-dimensional instead of two-dimensional. The radio propagation model was derived from Okumura's measurements.

The main results show that thousands or tens of thousands of UWB devices can operate simultaneously without affecting either aircraft communications or navigation.

3.5.3 Arthur D Little Inc.

Arthur D Little Inc. [20] has developed an interference model that considers the cumulative impact of 2GHz bandwidth devices centred at 6.5GHz. The UWB devices were assumed to have a maximum power spectral density of 75nW/MHz, ie, FCC Part 15 unintentional radiator Class B limits. The following scenarios were considered as important:

1. Urban environment, with devices operating in buildings or in the street.
2. Sparse rural environment.
3. Roads that represent a build up of UWB devices in a non-random orientation.
4. Special cases, such as shopping malls.

Arthur D Little gave priority to looking at the interference of victim receivers in a busy street, and in aircraft at 500 to 1000m above an urban area.

The results showed that for low flying aircraft, the ratio of power received to thermal noise varies from –8dB to –6dB depending on the altitude of the aircraft. Radio users at street level are affected by channelling of device concentrations along the street. At high densities, noise may be degraded by up to 6dB compared to thermal noise. This is due to devices in LOS of the victim receiver, and not due to a large proliferation of devices elsewhere.

3.6 Different UWB source distributions

Our interference model considers the general case of uniformly distributed UWB sources, with the closest ones to the victim receiver being inversely proportional to the density of UWB sources. The merits of this model include its easy adaptation to different propagation environments. Of course the model does not consider every interference scenario, it is more of a general model, ie, on average the distance from the nearest UWB sources to a victim receiver is going to be a distance from the nearest UWB sources inversely proportional to the UWB source density. A victim receiver could sometimes be close enough to a UWB device for that single UWB device to cause significant interference to the victim receiver. Assuming free space propagation, we can calculate the minimum distance beyond which a victim receiver will have negligible interference from a single UWB source. We can assume that the UWB device has emission levels equivalent to the FCC’s Part 15 Class B unintentional radiator maximum emission levels, ie, 12nW/MHz and 75nW/MHz for frequencies less than 960MHz and more than 960MHz, respectively. Also we can assume that the victim receiver has a noise figure of 6dB. The distance between a UWB device and a victim receiver to cause a 1dB and 3dB degradation in receiver noise power is plotted as a function of receiver operating frequency in Figure 22. The peak in the curves at a frequency of 2000MHz is an anomaly caused by the transition from an emission level for frequencies below 960MHz and another enforced emission level for frequencies above 960MHz.

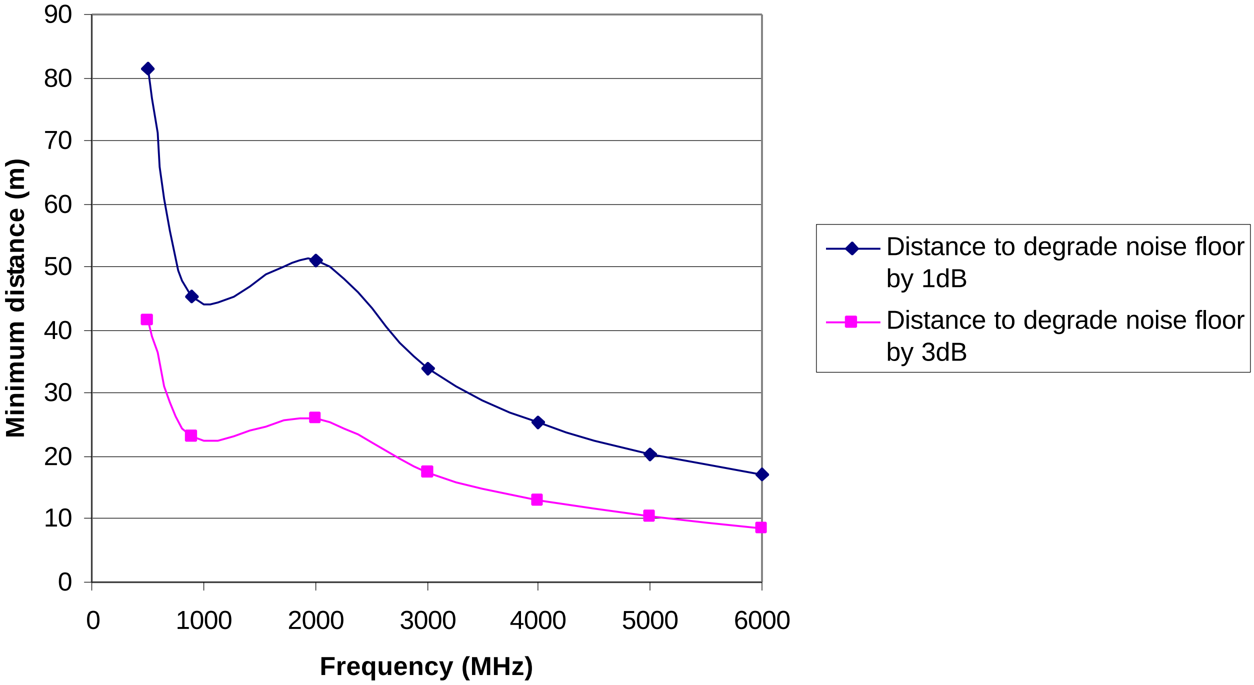

Figure 22 Graph of the distance between a UWB device and a victim receiver to cause a 1dB and 3dB degradation in receiver noise power plotted as a function of receiver operating frequency.

Most commentators have calculated the minimum distance based on the UWB interference power being equal to the noise power, which equates to a 3dB increase in noise power, ie, the curve in the figure above, labelled ‘distance to degrade noise floor by 3dB.’ To keep in line with our interference model that treats a 1dB degradation in noise power as significant, the curve labelled ‘distance to degrade noise floor by 1dB’ is more appropriate. For a frequency of 2GHz the distance at which the UWB interference becomes benign is approximately 50m. This means that a victim receiver will receive significant interference if it is within 50m of a UWB device that is in LOS of the victim receiver. It must be noted that this is the worst case scenario. A PC is restricted to identical emission levels and hence the distance between a PC and a victim receiver that degrades the receiver noise power by 1dB is also 50m, provided they are in LOS of each other. Currently the emission level from PCs is perceived as acceptable, but in some situations will cause significant interference to a mobile receiver. It is equivalent to consider the cumulative interference from unintentional radiators as from UWB devices.

When the unintentional radiator density is sufficiently high for a radiator to always be very close to a victim receiver, then the effect of increasing the unintentional radiator density will not degrade the interference further. However, the interference due to the close radiator in this case will be high anyway. Time Domain Corporation [19] has measured the emissions from a hairdryer, an electric shaver, and a Sun workstation and they are all at the levels expected of UWB devices.

It is often commented that mobile phones do not work very well inside buildings. This is either because the building is not sufficiently covered by the network, or the network suffers from capacity problems, or the building is sufficiently covered but the interference due to unintentional radiators that proliferate inside buildings degrades the noise floor of a mobile receiver, and in so doing decreases the signal to noise ratio below the minimum required, especially as the desired signal strength is generally low inside buildings. This lack of service inside buildings is usually attributed to the unpredictable nature of propagation into buildings, when perhaps it is really due to the environment being excessively noisy.

The situation that may occur in the future if UWB devices are allowed in an unregulated manner, is a noticeable degradation of network performance for mobiles located in streets caused by the noisy environment created by UWB devices.

We have shown that in the general case of UWB devices being distributed uniformly in rural or urban areas, typical UWB densities would not cause significant interference problems. However, the worst case scenario of a mobile receiver being close and in LOS of an UWB device will cause an interference problem. In this case the effect of the proliferation of devices is second order. The type of UWB systems that might cause these problems in urban streets could be wireless local loop (WLL), high capacity dense microcellular networks, and collision avoidance sensors in cars. It is not the cumulative interference of a high density of UWB devices that would cause the problem. Instead it is the increased likelihood of being in LOS of close UWB devices, which is of course proportional to the UWB density. For example, consider a rectilinear street grid in an urban area, and imagine a UWB device located at every street intersection. Assuming that a mobile receiver operating at 2GHz located in a street has a LOS view of its nearest BS, then anywhere in the street the receiver will have a noise floor degraded by at least 1dB. The UWB density for this scenario is 100 per square km.

It would seem that the current spurious emission levels would not be sufficient to regulate UWB devices. A lower level would have to be enforced. In Figure 23 the minimum LOS distance to cause negligible interference to a victim receiver is plotted for a UWB device that is transmitting at emission levels 10dB and 20dB below the current spurious emission levels.

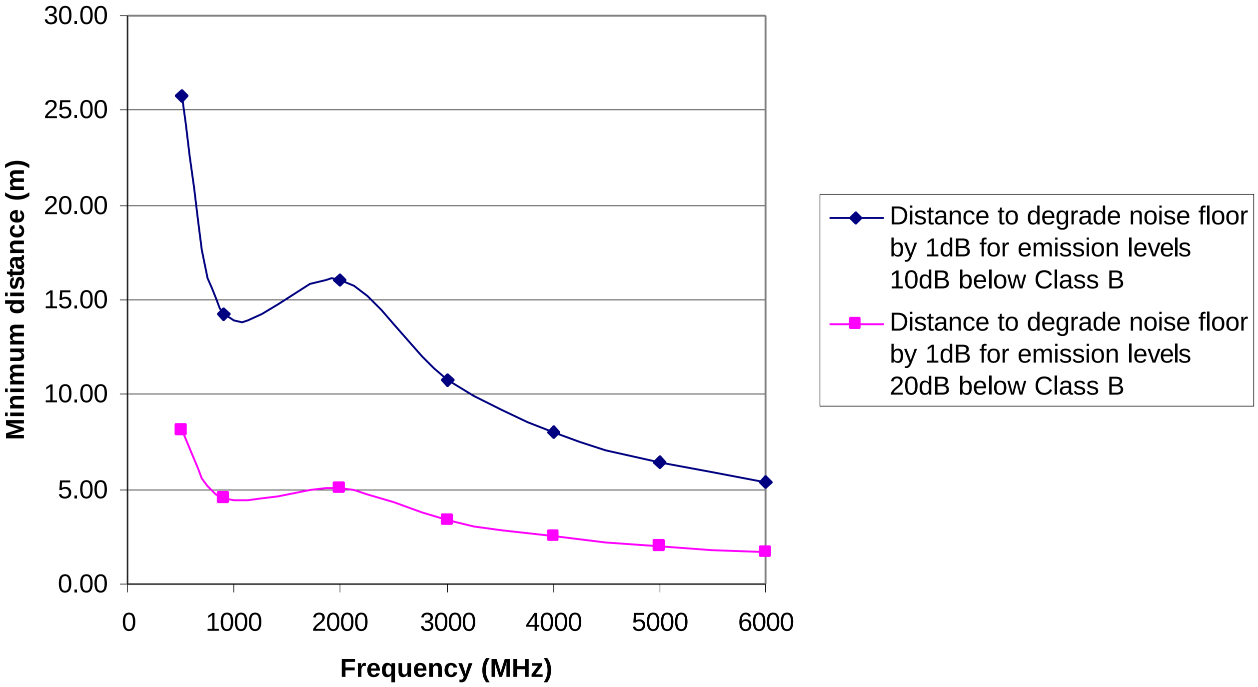

Figure 23 Graph of the distance between a UWB device and a victim receiver to cause a 1dB increase in receiver noise power plotted as a function of receiver operating frequency. The plots shown are for UWB emission levels 10dB and 20dB below the FCC Part 15 unintentional radiators limits**.**

Probably a realistic limit to enforce is 10dB below the current emission levels. In this case for a mobile receiver operating at 2GHz the minimum distance between a UWB device and the receiver to cause negligible interference is approximately 15m. This would allow UWB devices to proliferate in urban street areas, and only cause interference to other non-obstructed devices up to a distance of 15m away. There is a controversial issue of regulating UWB devices differently to unintentional radiators such as PCs. For example, let us revisit the in-building scenario, ie, of a large number of PCs located inside a building. These PCs are currently likely to be contributing to interference to cellular systems. It would be deemed legitimate to increase the number of PCs tenfold and increase the interference further by a significant amount, but not to introduce an equivalent number of UWB devices that have emissions regulated in the same manner. Instead if the UWB devices are to have their emissions limited to 10dB below the PC emission limits, this unfairly restricts the range of the UWB devices, and causes much less interference than the PCs. On the other hand, restricting all unintentional radiator emissions to 10dB below the current levels would be impractical, to say the least.

3.7 Summary of results

In this section we summarise the results of the interference from multiple UWB devices to various victim receiver types. For all but the GPS receiver and CDMA BS receiver, we define the maximum UWB PSD that degrades the receiver noise power by 1dB, where the noise power is either thermal noise or co-channel-interference-plus-noise power. The degradation in performance of a CDMA system is defined as an increase in MS transmit power of 1dB. For a GPS receiver, the maximum UWB PSD is that which causes the GPS receiver signal-to-noise ratio to fall below the minimum required.

3.7.1 Rural area, FDMA/TDMA noise limited or a CDMA system

One UWB source per square km allows a maximum UWB transmitter power of 0dBm for a 1GHz bandwidth transmission. For an emission level of –19.2dBm in 1GHz transmission bandwidth, which is equivalent to the current FCC Part 15 intentional radiator emission level, the maximum number of UWB sources per square km is approximately 50.

3.7.2 Urban area, CDMA system

One hundred UWB devices per square km allow a maximum UWB transmitter power of –20dBm, for a 1GHz transmission bandwidth. These results assume a propagation model of n and d_0 of 4 and 100m, respectively. A scenario that renders the urban propagation model inaccurate is when UWB devices are distributed in a rectilinear street grid environment, commonly found in American cities. Imagine a UWB microcellular or wireless local loop (WLL) system with transmitting antennas located at street level. For a victim receiver operating at 2GHz that is in LOS and within 50m of a UWB device, the noise power of the receiver is degraded by at least 1dB. Now, consider the case of having a UWB device at every street intersection of a 100m x 100m block size rectilinear street grid. In this case a victim receiver located in the streets will always receive interference from the UWB sources. This means that for high capacity dense microcellular UWB networks, and collision avoidance sensors mounted on cars, the interference is likely to be harmful to existing and future mobile phone operators. If the emission levels of UWB devices were to be forced to be 10dB below current spurious emission level limits then for a 2GHz victim receiver, interference problems are only likely to occur within 15m of a UWB device.

3.7.3 Urban area, FDMA/TDMA system (interference limited)

One hundred UWB sources per square km allow a maximum UWB transmitter power of 0dBm for a 1GHz transmission bandwidth. Enforcing the current FCC Part 15 unlicensed intentional radiator emission levels, then for 1GHz transmission bandwidth, 2500 UWB devices per square km would be allowed.

3.7.4 GPS receivers

We showed that a GPS receiver will generally not be affected by UWB devices in an urban or rural area, if the density of UWB devices is restricted to 300 and 100 per square km, respectively. This assumes the UWB devices are transmitting at current FCC Part 15 unlicensed intentional radiator emission levels, and a 1GHz UWB transmission bandwidth. The numbers quoted above are for a GPS receiver in acquistion mode. For a GPS receiver to keep track of satellites, the maximum density of UWB devices per square km is 1500 and 750, for urban and rural areas, respectively. Of course if you put a GPS receiver near an electronic device, which may be a UWB device, the GPS receiver is not likely to function. Note that GPS systems do not generally work very well in urban areas. So even if the interference from UWB devices is sometimes significant in urban areas, the GPS system would probably not work in the absence of the UWB devices anyway.

3.7.5 Television receivers

In a residential area, 1 UWB device per square km does not cause significant interference to a TV receiver. Another scenario tested is a TV antenna mounted on the roof of a single storey building having a floor space of 200 square metres. The number of UWB devices inside the building that can operate without causing significant interference to the TV receiver is five. We have not modelled the antenna pattern of the TV antenna, which is usually directional, and thus is likely to have very little gain in the direction of the UWB devices. Therefore, we would expect many more UWB devices to operate in a residential home without causing interference to a TV receiver. We are not aware of any reports of interference on a TV receiver from the many electronic devices found in houses, such as audio systems, PCs, microwaves, etc.

3.7.6 FDMA/TDMA noise-limited receivers in buildings

Considering a FDMA/TDMA victim receiver inside a large single storey building, such as a supermarket, the maximum number of UWB devices in a 100m x 100m area causing insignificant interference on the receiver was 150. However, reiterating once again, if the receiver is close to and in LOS of a UWB device, then it is likely to suffer from interference.

3.7.7 Navigation devices in aircraft

Published theoretical models appear to indicate that the interference from terrestrial UWB devices is not a significant problem.

3.7.8 General comments

There are two main points worth summarising. Firstly, if a victim receiver is not close to and in LOS of a UWB device, then it is important to consider the cumulative interference due to a proliferation of UWB devices. However, the results so far conclude that in such cases the cumulative interference for the assumed UWB densities is insignificant. Secondly, if a victim receiver is close to and in LOS of a UWB device then the cumulative impact of UWB devices is not significant. However, the effect of the close-in UWB device is not to be ignored and is going to cause significant interference to the victim receiver. The results of a published interference model showed that the effect of the proliferation of UWB devices is not important. However, the model always had a UWB device 1m away from the victim receiver, which is obviously going to cause harmful interference.

4 Likely UWB system parameters and services

In this section, the likely UWB system parameters and types of services UWB systems can support are examined. We also assess the potential commercial threat of UWB communication systems to current cellular and future third generation systems. Firstly, we present the parameters and services suggested by Time Domain Corporation.

4.1 Parameters and services suggested by Time Domain Corporation

Time Domain Corporation [19] predicted the transmitted power requirements of commercially viable time-modulated UWB (TM-UWB) systems. Time Domain Corporation split up the applications into three categories; those that require FCC Part 15 unintentional radiator Class A limits, Class B limits, and applications that require higher emission levels to operate. The applications were listed outlining the specifications to make them viable products. A link budget analysis was performed to calculate the required transmit power. The environments and the exact limits (Class A or B) were listed for each application. For full details of the results, refer to Appendix B of Reference [11]. In Table 1, the communications and geo-location systems that would operate under the proposed Class A or B limits are listed. In Table 2 the radar systems that would operate under the proposed Class A or B limits are listed.

System	Centre frequency (MHz)	Bit rate (kbps)	Desired range (m)
Navigational systems	3000	0.05	100
Mini-Cell RF asset ID and tracking	3000	100	25
Team comm., ID, and tracking	2000	64	25
Music quality microphone	2000	500	30
Long range voice microphone	2000	64	50
Precision automatic aircraft landing system	4500	0.05	3050
Medical telemetry	3000	100	40

Table 1 Time Domain Corporation's predicted applications for UWB communications and geo-location systems, that operate within FCC Part 15 Class A and B limits.

System	Centre frequency (MHz)	Desired range (m)
Runway and roadway inspection	4000	1
Building construction inspection imaging	8000	1
Law enforcement agency and emergency services motion detection	2000	10
Law enforcement agency and emergency services motion detection and tracking	4000	15
Security proximity detector	2000	10
Security fence	2000	150
Precision airbag deployment sensor	6000	1.5
Automotive backup safety sensor	2000	3

Table 2 Time Domain Corporation’s predicted applications for UWB radar systems, that operate within FCC Part 15 Class A and B limits.

The applications that would require higher field strength limits are public safety networks, very high speed wireless LANs, wireless business telephone systems, ad hoc wide-area networks, precision altimeters, obstacle warning for helicopters, airborne synthetic aperture radar (SAR) mapping, low frequency ground penetrating radar (GPR), and long range automotive collision avoidance.

4.2 Our comments

UWB devices are subject to interference over a very wide bandwidth. The sources of interference include high power cellular base stations, UHF TV transmitters, etc. However, a TD-UWB or CDMA UWB system offers very large processing gains, which to some extent counteracts the interference. It is beyond the scope of this short study to calculate the range and bit rates likely of possible UWB communication systems, by link budget analysis. The general consensus is that by limiting the transmitted power to FCC Part 15 limits, even with the inherent high processing gain of TD-UWB or CDMA UWB systems, the interference from other sources still limits the possible range of UWB devices. One potential area of further work is to theoretically evaluate the possible range and bit rates of UWB systems.

We can comment on Time Domain Corporation's results presented in Section 4.1 on likely UWB system parameters and services. The possible bit rates are generally low, ie, up to 100kbps, and the ranges generally less than 10m. There is an obvious trade off between range and bit rate. The lower the bit rate, the higher the processing gain in a given signal bandwidth, and thus the higher the range. If the emission levels are set to 10dB below the limits suggested by Time Domain Corporation and many other commentators, the range and bit rates will have to be reduced further. The likely centre frequencies can be concluded from the tables in the last section. Many of the centre frequencies are around 2GHz. For communication systems the only proven UWB modulation and multiple access method are encompassed in Time Domain Corporation's TM-UWB technology. Also the possible UWB bandwidths demonstrated by Time Domain Corporation are in the 1 to 2GHz range. It appears that beyond the applications suggested in the tables above, the possible communication services are going to be low data rate and short range. This means that cordless services could be supported by UWB technology. Therefore, there is likely to be very little threat to cellular and 3G services, and the only potential threat is to the cordless telephony market. Looking ahead, if the possible UWB bandwidth for communication systems can be increased to 10GHz, the range can be increased, benefiting from the increased processing gain. If this happens there is a possible threat to high capacity cellular networks.

5 Regulation issues

The regulation of emissions from UWB devices could be carried out differently depending on the type of UWB device. Ground penetrating radars could be regulated differently to other systems. GPRs are directed towards the ground, which means the emissions into free space are very low. Therefore, GPRs could be tested for emissions with a material simulating the ground beneath the GPR under test.

Comments were made on the emissions of UWB devices falling into restricted bands. The use of notch filtering to prevent the emissions was deemed by many to be both expensive and detrimental to the performance of UWB systems.

5.1 Method of measuring the emissions from UWB devices

The best method of measuring the emissions from UWB devices is to measure the power spectral density (PSD) of the emitted signal. This is a frequency domain measurement proposed by many organisations. Alternative techniques are based on time domain measurements, which will not work for UWB systems not employing impulse or short pulse technologies. The frequency domain technique is versatile enough for all UWB technologies.

A suitable frequency domain PSD measurement would be similar to current FCC Part 15 peak and average power measurements, which are measured over a 1MHz bandwidth, ie, PSD measurements. However, the measurement of PSD over one fixed bandwidth, does not adequately measure the potential interference from a UWB system. An analysis by WINForum [21] concluded that the bandwidth of the PSD measurement is important, and that PSD measurements should be performed for a variety of spectrum analyser resolution bandwidths. WINForum showed that the effective PSD depends on the pulse repetition rate and spectrum analyser resolution bandwidth, for a pulse UWB system. However, as highlighted by Time Domain Corporation [19], the measurement procedure would be too complicated, especially as measurements with spectrum analyser resolution bandwidths greater than 1 to 2MHz cannot currently be carried out, and instead details of the transmission system would have to be obtained from manufacturers and PSD calculations performed. Also WINForum's analysis assumed that UWB systems are based on pulse transmission techniques. In fact there are other possible transmission schemes, such as UWB CDMA, and swept or stepped frequency systems. Further equations would need to be derived for these other UWB systems to calculate the relationship between the PSD and the receiver bandwidth, for high receiver bandwidths. Also derivations would have to be made for all new UWB technologies. For practical reasons, the PSD measurements should be taken for just a few spectrum analyser resolution bandwidths, and the regulations structured in a manner to establish a PSD limit over the range of resolution bandwidths.

It would be prudent to carry out peak and average PSD measurements by adjusting the video bandwidth of the spectrum analyser. If the video bandwidth is greater than or equal to the resolution bandwidth, the analyser will record the peaking effects, whereas if the video bandwidth is much less than the resolution bandwidth, the filter averages the spectrum analyser intermediate frequency (IF) output. The resulting peak and average PSD measurements are useful for characterising the interference, giving the peak effects and average emissions over a bandwidth.

The current FCC Part 15 peak and average PSD limits for an unlicensed intentional radiator state that the peak emissions can be up to 20dB over the average limit (not the average measurement). The need for a peak limit is to prevent low duty cycle pulsed transmissions causing the front ends of victim receivers to become non-linear.

The precise PSD limits set by the regulatory authorities are debatable. Many organisations believe that the PSD limits should be set to the current FCC Part 15 unlicensed intentional radiator limits, which also equal the unintentional radiator Class B emission limits. Their argument is that millions of unintentional radiators currently generate emissions at Class B limits without any interference effects on other radio devices. The results of our interference modelling indicate that there are scenarios where the interference from UWB sources emitting at current emission levels is not insignificant. These are not unlikely scenarios and therefore it would be appropriate to set the PSD limits to at least 10dB below the Class B emission limits. Note that to regulate the UWB devices at such emission limits, low noise spectrum analysers would be required.

6 Conclusions

The cumulative interference from UWB sources was investigated using an analytical interference model. In rural areas, the interference on a noise-limited cellular system or a CDMA system was found to be negligible, ie, less than 1dB degradation, for UWB source densities of less than 50 per square km, assuming that the UWB transmitter powers will be limited to FCC Part 15 unintentional radiator emission levels. Similarly for urban areas, the interference on a CDMA system was found to be insignificant for UWB source densities of 100 per square km. For an interference limited FDMA/TDMA cellular system the maximum density of UWB sources in an urban area that causes negligible interference is up to 2500 sources per km.

The density of UWB devices in urban and rural areas can be even higher before the interference affects the operation of GPS receivers. Up to five UWB devices in a typically sized residential home are allowed before a TV receiver’s performance is degraded. This number is likely to be higher in practice due to the low antenna gain of a TV antenna in the direction of the UWB devices. One hundred and fifty UWB devices within a 100m x 100m area inside a large single-storey building inflict negligible interference on a noise limited receiver inside the building. Published theoretical models indicate that the interference from terrestrial UWB devices is harmless to navigational devices in aircraft.

All of the above results assumed that the UWB transmitter powers were at the current FCC Part 15 unintentional radiator emission levels. Interference problems from UWB sources will occur if the victim receiver is in close range and in LOS of at least one UWB device. However, in this case the cumulative impact of UWB devices is not significant. Generally though, if a victim receiver is not close to a UWB device, then the cumulative interference due to a proliferation of UWB devices cannot be ignored. An UWB microcellular system or wireless local loop system in an urban area could degrade the performance of cellular receivers in all street areas, because a cellular receiver is always within close range and in LOS of a UWB device. These scenarios are likely and therefore cannot be ignored, which means that it would be appropriate to set the PSD limits to at least 10dB below the Part 15 current limits. The most appropriate method of measuring the emissions from UWB devices is to measure the PSD in a similar manner to FCC Part 15 procedures.

The most promising technology for UWB systems is time modulated UWB (TM-UWB) developed by Time Domain Corporation. Low frequency range, 1 to 2GHz bandwidth systems are possible using TM-UWB technology. The main limiting factor in such a system is the antenna that acts as a filter.

Time Domain Corporation evaluated the ranges and bit rates of several UWB applications, assuming that the transmitter powers are limited to current FCC Part 15 limits. The results showed that only low bit rate, short range communication systems are feasible. This means that the commercial threat of UWB communication systems on current cellular or future third generation systems is minimal.

It was beyond the scope of the study to calculate the potential range and bit rates of UWB communication systems and this could form the basis of a more detailed follow-on study.

References

1. Comments of Pulson Medical Inc on the FCC Part 15 Notice of Inquiry, 7th December 1998, http://www.uwb.org/standards.htm.

2. Comments of Interval Research Corporation on the FCC Part 15 Notice of Inquiry, 7th December 1998, http://www.uwb.org/standards.htm.

3. Comments from Arthur D Little Inc on the FCC Part 15 Notice of Inquiry, 10th December 1998, http://www.uwb.org/standards.htm.

4. Comments of M/A-Com on the FCC Part 15 Notice of Inquiry, 7th December 1998, http://www.uwb.org/standards.htm.

5. Comments of Zircon Corporation on the FCC Part 15 Notice of Inquiry, 7th December 1998, http://www.uwb.org/standards.htm.

6. Comments of Geophysical Survey Systems Inc on the FCC Part 15 Notice of Inquiry, 7th December 1998, http://www.uwb.org/standards.htm.

7. Comments of SAAB Marine Electronics AB on the FCC Part 15 Notice of Inquiry, 4th December 1998, http://www.uwb.org/standards.htm.

8. Comments of Magnetrol International on the FCC Part 15 Notice of Inquiry, 7th December 1998, http://www.uwb.org/standards.htm.

9. Comments of Rosemount Measurement on the FCC Part 15 Notice of Inquiry, 7th December 1998, http://www.uwb.org/standards.htm.

10. Comments of Endress and Hauser GmbH & Co on the FCC Part 15 Notice of Inquiry, 7th December 1998, http://www.uwb.org/standards.htm.

11. Comments of Time Domain Corporation on the FCC Part 15 Notice of Inquiry, 7th December 1998, http://www.uwb.org/standards.htm.

12. Comments of Multispectral Solutions Inc. on the FCC Part 15 Notice of Inquiry, 7th December 1998, http://www.uwb.org/standards.htm.

13. Comments of Lawrence Livermore National Laboratory on the FCC Part 15 Notice of Inquiry, 7th December 1998, http://www.uwb.org/standards.htm.

14. Comments of TEM Innovations on the FCC Part 15 Notice of Inquiry, 4th December 1998, http://www.uwb.org/standards.htm.

15. A. M. Viterbi and A. J. Viterbi, "Erlang capacity of a Power Controlled CDMA system", IEEE Journal on Selected Areas of Communications, Vol 11, No 6, Aug 1993, pp 892-900.

16. Comments of Federal Aviation Administration on the FCC Part 15 Notice of Inquiry, 23rd October 1998, http://www.uwb.org/standards.htm.

17. Comments of the US GPS Industry Council on the FCC Part 15 Notice of Inquiry, 7th December 1998, http://www.uwb.org/standards.htm.

18. Reply comments of the U.S. GPS Industry Council, American Airlines, the General Aviation Manufacturers Association, Stanford University and United Airlines on the FCC Part 15 Notice of Inquiry, 3rd February 1999, http://www.uwb.org/standards.htm.

19. Reply comments of Time Domain Corporation on the FCC Part 15 Notice of Inquiry, 4th February 1999, http://www.uwb.org/standards.htm.

20. Reply comments from Arthur D Little Inc on the FCC Part 15 Notice of Inquiry, 3rd February 1999, http://www.uwb.org/standards.htm.

21. Comments by Wireless Information Networks Forum (WINForum) on the FCC Part 15 Notice of Inquiry, 7th December 1998, http://www.uwb.org/standards.htm.