Ultra Wide Band (UWB) compatibility

Final Report to the Radiocommunications Agency

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EXECUTIVE SUMMARY

As a consequence of an ever increasing demand, the issue of rational use, sharing and protection of the radio spectrum is becoming increasingly important. One consequence of the limited radio spectrum is the development of new technologies to increase the efficient use. Ultra Wide Band (UWB) systems combine wide bandwidths with low power spectral densities and it is claimed that this increases the utilisation of the radio frequencies.

UWB technology is based on the use of very narrow, baseband pulses (typically in order of nanoseconds) as a basic signal structure. These pulses result in spectral components covering a very wide bandwidth in the frequency domain. The impulsive nature of UWB emissions and the resultant spectral characteristics have caused concerns about the compatibility of these signals with existing radio systems.

The primary objective of this study was to perform a literature search of compatibility issues relating to the implications of UWB technology on the existing technologies and to identify areas where further investigation may be required. The work was required to be high level and wide ranging in order to enable areas that have not been addressed to be identified.

The literature survey has revealed that compatibility analyses of UWB technology with respect to other radio services has been undertaken to various degrees by employing both measurements and theoretical analysis. It is noted that compatibility with the Global Positioning System and the Aeronautical Services have been investigated extensively while the implications of UWB emissions into terrestrial fixed, mobile and broadcast services have been examined to some extent. It is also noted that compatibility with Satellite Services, Radioastronomy, Amateur Service, Military Service and Licence-exempt systems require further investigations.

Furthermore, key issues surrounding UWB compatibility are noted to be: interference being dominated by a single nearby device or an aggregation of devices in the vicinity of the victim, the assumption that UWB signals resemble Gaussian noise, the specification of emission limits and measurement techniques (i.e. the use of frequency domain or time domain measurements, the measurement capability of conventional spectrum analysers in characterising extremely wide band signals) and the analysis of electromagnetic compatibility of UWB devices.

LIST OF ABBREVIATIONS

CDMA	Code Division Multiple Access
CEPT	European Conference of Postal and Telecommunications Administrations
DME	Distance Measuring Equipment
DVB-T	Terrestrial Digital Video Broadcasting
ECC	Electronics Communications Committee
EIRP	Effective Isotropic Radiated Power
EMC	Electromagnetic Compatibility
ERO	European Radiocommunications Office
FCC	Federal Communications Commission
FDMA	Frequency Division Multiple Access
GPS	Global Positioning System
GSO	Geostationary Orbit
HEMP	High Altitude Electromagnetic Pulse
HPM	High Power Microwaves
ILS	Instrument Landing System
ITU-R	International Telecommunications Union Radiocommunications Section
LEO	Low Earth Orbit
LOS	Line of Sight
MAC	Multiple Access Communications Limited
MEO	Medium Earth Orbit
MSS	Mobile Satellite Service
NDB	Non-directional Beacons
NOI	Notice of Inquiry
NPRM	Notice of Proposed Rule Making
NTIA	National Telecommunications and Information Administration
PMP	Point to Multipoint
PPM	Pulse Position Modulation

PN	Pseudo-random Noise
RMS	Root Mean Square
RNSS	Radio Navigation Satellite Service
SARSAT	Search and Rescue Satellites
SE24	Spectrum Engineering Working Group
SSR	Secondary Surveillance Radar
T-DAB	Terrestrial Digital Audio Broadcasting
TD	Time Domain Corporation
TDMA	Time Division Multiple Access
TVRO	TV Receive Only
UWB	Ultra Wide Band
VHF	Very High Frequency
VOR	VHF Omnidirectional Range
UHF	Ultra High Frequency

1 INTRODUCTION

Ultra Wide Band (UWB) is a radio technology based on the generation of very short pulses of electromagnetic energy. These pulses, being short in the time domain, give rise to spectral components covering a very wide bandwidth in the frequency domain, hence the term Ultra Wide Band. It is claimed that the spectral components fall within existing regulations designed to control the unwanted emissions associated with conventional radio technologies and therefore should cause no problems to existing radio services.

UWB was initially used for radar in the 1940s with further significant developments taking place in the 1960s. However it is only recently that commercial applications have become prominent. This commercial interest has led to the Federal Communications Commission (FCC) in the US to initiate a process that may or may not result in a change to the regulations in order to allow the use of UWB devices.

1.1 FCC process

The FCC initiated an investigation into the possibility of permitting the operation of UWB systems on an unlicensed basis[1] through the publication of a Notice of Inquiry (NOI) in October 1998.

http://www.fcc.gov/Bureaus/Engineering_Technology/Notices/1998/fcc98208.txt

Subsequently, the FCC announced its plans for allowing the deployment of UWB devices through a Notice of Proposed Rule Making (NPRM) issued in May 2000.

http://hraunfoss.fcc.gov/edocs_public/attachmatch/FCC-00-163A1.pdf

Comments and reply comments relating to these two documents can be found using the FCC search engine at:

http://gullfoss2.fcc.gov/prod/ecfs/comsrch_v2.cgi

When accessing this search engine the Proceeding (first field) should be identified as 98-153.

As part of this FCC process three reports have been produced by the NTIA. The initial report characterises UWB signals.

http://www.its.bldrdoc.gov/pub/ntia-rpt/01-383/

The second of these reports addresses the compatibility of UWB with respect to selected federal systems and can be found at

http://www.ntia.doc.gov/osmhome/reports/uwb/uwb.pdf

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[1] Within the context of the Part 15 rules which can be found at: http://www.access.gpo.gov/nara/cfr/waisidx_01/47cfr15_01.html

The third NTIA report addresses the compatibility with respect to GPS receivers and can be found at the following locations (the second being an addendum)

http://www.its.bldrdoc.gov/pub/ntia-rpt/01-384/

http://www.its.bldrdoc.gov/pub/ntia-rpt/01-389/

1.2 European activities

The possibility of UWB use within Europe is also being addressed. The issue was raised through a workshop organised by the CEPT and held in March 2001. The content of this workshop is summarised on the ERO website at:

http://www.ero.dk/EROWEB/SRD/UWB/Agenda-presentations.htm

Subsequently, detailed work is being undertaken within the SE24 project team of the Spectrum Engineering Working Group. An ECC report is being prepared but no material is in the public domain yet. Reference is however made to working documents circulated within SE24.

1.3 Compatibility concerns.

Because of the impulsive nature of UWB signals (in the time domain) and the consequential bandwidth and spectral characteristics (in the frequency domain) concerns have been expressed about the compatibility of such signals with other users of the radio spectrum.

While it is claimed that with appropriate modulation techniques the signal can be made to appear noise-like, there are concerns that such a representation is not a true picture of the signal and consequently this may not enable the impact on other systems to be assessed correctly.

The bandwidth of narrow impulses (without any intentional filtering) is very wide and will therefore cover many frequency allocations used by a wide range of radio services. These will include safety services, TV broadcast, passive sensing (including radioastronomy), which uses sensitive receivers, and many others. Such services generally operate in their frequency bands on an authorised basis and are therefore afforded protection from interference. The effective introduction of licence-exempt devices across all frequency bands needs to be assessed carefully if disruption is to be avoided.

1.4 Remit of this study.

The overall objective of the study was to perform a literature survey of compatibility issues relating to UWB and to identify areas where further investigation may be required. The work was required to be high level and wide ranging in order to enable areas that have not been addressed to be identified.

The initial literature search identified over 370 potentially interesting references[2]. Of these less than 10% related in one way or another to compatibility issues. The references obtained as a result of the initial literature search identified other sources addressing UWB issues. However within the short timescale of the work it was not possible to pursue such leads to other references.

This work was undertaken by Aegis Systems Limited for the Radiocommunications Agency over a 4 week period during November / December 2001 (Contract Reference AY4166 / 510007833).

1.5 Structure of report.

The report firstly addresses the key characteristics of the UWB signal and key applications foreseen for this technology (Sections 2 and 3).

The middle part of the report (Section 4) looks at the compatibility issues that have been addressed and discusses some of the key issues surrounding UWB compatibility (Section 5).

As required by the remit of the work the report concludes (Section 6) by identifying areas that do not appear from the literature search to have been investigated.

1.6 Basis of opinion

This report presents the authors' best understanding of the situation as of December 2001. The material in this report is derived from a variety of sources in the public domain. Every effort has been made to present the information from those sources accurately. However, Aegis Systems Ltd cannot be held liable for any consequences arising from the use of information presented in this report.

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[2] Note that this figure is based on an INSPEC literature search and therefore does not include the approximately 800 comments filed with the FCC with respect to the UWB proceeding, or documents published directly by individual companies (i.e. not through journals or conference proceedings).

2 UWB TECHNOLOGY

Electromagnetic waves with instantaneous bandwidth greater than *25%* of the centre operating frequency or an absolute bandwidth of *1.5 GHz* or more are referred to be ultra wideband (UWB) signals. UWB radio systems with bandwidths more than *1.5 GHz* but an instantaneous bandwidth less than *25%* of the centre operating frequency can be designed using traditional RF components (antennas, frequency synthesisers, amplifiers and filters) which are reasonably straightforward to produce. On the other hand, UWB systems designed at lower frequencies (typically less than *3 GHz*) with an instantaneous bandwidth greater than *25%* of the centre operating frequency require a more novel approach [1-5].

A common approach employed by existing wireless systems is to generate and modulate a sinusoidal carrier signal to transmit information. This is used to ensure that the bandwidth of the emission is as narrow as possible, which, in turn allows sharing of the radio spectrum among diverse applications and users. UWB technology, on the other hand, is based on the use of very narrow, base band pulses (typically in order of nanoseconds) as a basic signal structure.

Figure 1 illustrates a regular (equally spaced) monocycle pulse train and its power spectrum [6].

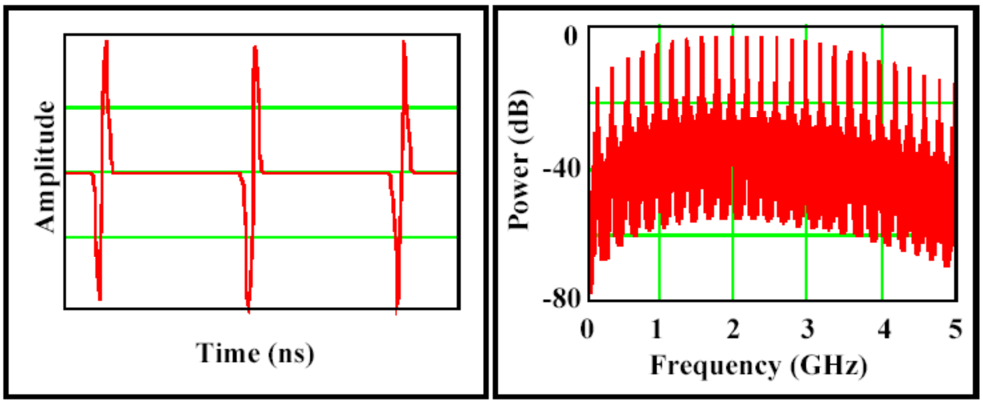

Figure 1 : Regular Pulse Train and its Power Spectrum (taken from [6])

As can be seen, the frequency domain response of the regular pulse train includes both continuous and discrete spikes (or spectral lines) at regular intervals. The primary impact of the spectral lines is the greater potential for interference into other systems operating within the transmission bandwidth of the UWB signal.

One way of carrying information using the above pulse train is to modify the pulse positions (i.e. pulse position modulation, PPM). Assuming that a data symbol is represented by a number of pulses, a small time shift is added to pulses corresponding to the data '*1*' while no time shift is applied when the data is '*0*'. It is argued that the application of PPM smoothes the spikes present in the power spectrum to some extent [1].

In addition to pulse position modulation, a channel code which is a pseudo-random noise (PN) sequence is applied to randomise the pulse position. This process is commonly referred as 'pulse dithering'. Assigning a channel code (i.e. a distinct periodic pulse shift pattern) to each user enables multiple user access to the same spectrum and, more importantly, the spectral lines are further reduced as shown in Figure 2 [6].

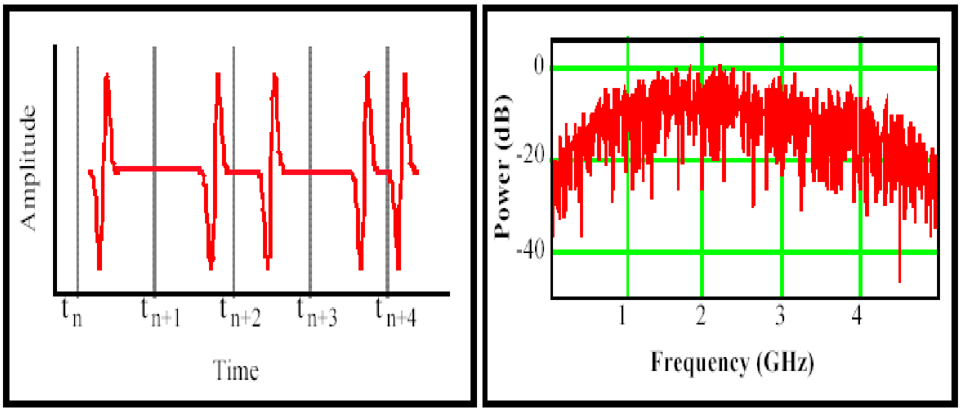

Figure 2 : Pulse Position Modulated and Randomised Pulse Train and its Power Spectrum (Taken from [6])

Comparison of Figure 1 & 2 indicates that when the pulse positions are not randomised the power spectrum is dominated by the spectral lines whereas the use of randomisation reduces the lines and the power spectrum is predominantly continuous. It should be noted that when the pulse time delay introduced due to modulation is relatively small compared with the time delay resulting from a pulse randomisation, the effects of pulse position modulation on the power spectrum are insignificant [4].

The frequency spacing between the consecutive spectral lines is determined by the pulse randomisation function and the UWB signal pulse repetition rate. For example, assuming that the pulse positions are randomised uniformly within *50%* of a pulse period (*T*), which is an inverse of the pulse repetition rate, and the pulse delay due to modulation is negligible, it can be shown that the frequency spectrum of the pulse randomisation function is $Sinc(\pi fT/2)$. This function has nulls at frequencies equal to $2k/T$ (where $k = \pm 1, \pm 2, \ldots$) and, therefore, the interval between the spectral lines is $2/T$ *MHz* (assuming T is in *microseconds*).

As far as UWB interference into a narrow band receiver is concerned, in line with the above discussions, when a UWB signal pulse repetition rate is greater than a receiver bandwidth, the receiver bandwidth may fall between the spectral lines. In such situations, the UWB signal (which is low power and its energy is spread across a large bandwidth) may approximate to a noise-like signal as none of the spectral lines appear within the victim receiver band [4].

It is worth noting that UWB signals are not limited to the modulated and randomised pulse trains of monocycles. The pulse shape can be any type of radiation where the signal energy is confined to a very short time duration. The modulation type can be an on/off keying modulation (where individual pulses are selectively turned off or eliminated to represent data bits) instead of a pulse position modulation. The pulse randomisation scheme may be based on an absolute-time (where the pulse spacing is varied according to the absolute clock) or a relative dithering (where the pulse spacing is varied relative to the previous pulse). A UWB signal may also comprise gated pulse groups where a UWB transmitter is turned on or off for a period of pulses, i.e. pulses are distributed in bursts by employing a programmed set of transmission periods [4, 5].

It should be noted that the choice of the pulse shape, modulation method and pulse randomisation scheme, gating will have significant impact on the power spectrum of the UWB signal [2-5].

As the use of narrow pulses as a basic signal structure implies an extremely wide emission bandwidth, these systems have the potential to affect a number of other existing radio systems simultaneously. This led the US Federal Communications Commission (FCC) to initiate investigations into the possibility of allowing UWB systems to operate on an unlicensed basis under Part 15 of its rules.

2.1 FCC Part 15 Rules

Part 15 defines regulations under which an intentional, unintentional, or incidental radiator may be operated without an individual license where the emission may occur in a part of the spectrum assigned for use by particular services. Limits are defined in the form of the maximum allowable signal transmit levels.

The regulations state that an unlicensed intentional radiation should not exceed *12 nW/MHz* for frequencies of less than *960 MHz*, and *75 nW/MHz* for frequencies above *960 MHz*. The unintentional radiation limits are specified for two classes of equipment. Class A devices are used in commercial, industrial or business environment while Class B equipment is for residential use. The Class A limits are *147 nW/MHz* for frequencies less than *960 MHz*, and *300 nW/MHz* for frequencies above *960 MHz*. The Class B limits are identical to those defined for the intentional radiation. The table below summarises the Part 15 emission limits.

		< 960 MHz	**> 960 MHz**
Intentional Radiation Limits		-49.2 dBm/MHz	-41.2 dBm/MHz
Unintentional Radiation Limits	**Class A**	-38.3 dBm/MHz	-35.2 dBm/MHz
	Class B	-49.2 dBm/MHz	-41.2 dBm/MHz

Table 1 : FCC Part 15 Limits

It is worth noting that intentional emissions from unlicensed devices are not allowed in any of the restricted bands because of interference potential into critical radio services. However, it is noted NTIA produced a document (Waiver of Part 15 Rules, 15 June 1999) outlining conditions under which UWB devices may be allowed to operate in these bands.

3 UWB APPLICATIONS

Although it is claimed that many exotic applications would benefit from UWB technology, the literature search revealed that there are two main potential UWB application areas: communications and radar/sensor. For both areas, the basic UWB system components include transmitter sources, modulators, RF pulse generators, detection receivers and wideband antennas.

There has been a significant amount of research into the development of UWB components over many years. It is suggested that the antenna design remains to be a significant challenge. The options being considered include loaded dipoles, TEM horns, biconicals and ridged horns, spiral and large current antennas, each with a variety of advantages and disadvantages [7-9].

It is worth noting that many of the current communications and radar/sensor devices are bandlimited due largely to the bandwidth limitations imposed by the antennas which act as band pass filters in UWB transmissions. More recent system proposals do not rely on bandlimited transmissions which, in turn, brings about the requirements for modification of the Part 15 rules.

The following sub-sections summarise the likely communications and radar/sensor applications.

3.1 Communications

It is argued that the types of potential communications devices to be deployed will largely be dictated by the emission limits enforced by regulatory authorities [1]. The maximum operating distance and the transmission rate will be the key parameters for the performance assessment of the UWB communications systems. Operational characteristics of some of the devices are outlined below [9].

- Handheld transceiver designed for full duplex voice and data transmissions up to *128 kbps*, operating at *1.5 GHz* with an instantaneous bandwidth of *400 MHz*. The peak output power is measured to be *2 Watts* and the LOS range is up to *2 km*. With small gain antennas, the range extends up to *32 km*.
- Ground wave communications system designed for non-LOS digital voice and data transmission up to *128 kbps*, operating in the *30-50 MHz* band over a range of *16 km* with a peak power of approximately *35 Watts*.
- Asymmetric, bi-directional video/command and control UWB transceivers designed to operate in the range *1.3-1.7 GHz* with transmission rates up to *25 Mbps* using *4 Watts* peak output power.
- Handheld transceivers designed for multichannel, full duplex, *32 kbps* digital voice transmissions over a range of *100 meters* in the band *1.2-1.8 GHz* on board a navy craft.

- Indoor short range communications device operating in the range *2.5-5 GHz* over a range of *50 m* providing data rates up to *60 Mbps*.

3.2 Radars/Sensors

The primary use of UWB radars is to provide target detection while the UWB sensors are used to obtain information concerning the target. The number of applications is extensive. These include ground penetration, position location, wall penetration, collision warning for avoidance, foilage penetration, fluid level detection, intruder detection and vehicle radar. New applications include distance and air-bag proximity measurements, road and runway inspection, heart monitoring, RF identification and camera auto focus. System characteristics of some of the radars/sensors are summarised below [8, 9].

- Vehicular Electronic Tagging and Alert System designed to relay the picture of the driver together with information on the driver and the vehicle to a roadside sensor in a police vehicle. The system operates in *1.4-1.65 GHz* region with a peak power of *0.25 Watt* over a range of *300 metres*.
- Geolocation system designed to provide three dimensional location information, operating in *1.3-1.7 GHz* region by utilising *2.5 nanoseconds*, *4 Watt* peak power UWB pulses. LOS range is *2 km* with omnidirectional antennas. Indoor range is up to *100 metres*.
- Precision altimeter and collision avoidance sensor designed to operate in the *5.4-5.9 GHz* range with peak output power of *0.2 Watt*.
- Backup sensor designed to detect objects behind large construction and mining vehicles, operating with *0.25 Watt* peak power in *5.4-5.9 GHz* region over a range up to *100 metres*.
- Electronic licence plate designed to provide both automobile collision avoidance and RF tagging for vehicle to roadside communications. Collision avoidance functions are provided using *0.2 Watt* peak power in *5.4-5.9 GHz* region over a *30 metre* range while the tagging functions are supported with a *0.3 Watt* peak power over a range *200 metres*.
- Military radar designed for very short range applications (less than *2 metre*) with an average power of *85 nanowatts* operating at *10 GHz* with a *2.5 GHz* bandwidth.

4 COMPATIBILITY WITH OTHER SERVICES

The high bandwidth nature of UWB signals means that UWB devices will effectively be operating across frequency allocations that have been made to all types of radio service. Consideration therefore has to be given to the potential impact of UWB devices on a very wide range of systems.

As compatibility issues are being considered here the range of systems can be broken down roughly in line with the sort of geometrical configurations[3] that will arise. Such a breakdown is merely for convenience and allows a systematic rather than random approach to looking at which situations have or have not been addressed. Having said that, there are of course systems that do not readily fit into the chosen general categories. These have been appended to the list as individual cases.

- Mainstream terrestrial services: Fixed (Point-to-point and Point-to-Multipoint), Mobile (various types of system) and Broadcast (TV and audio)
- Aeronautical services: aircraft and ground based equipment providing communications and navigation services (including GPS)
- Satellite services (GSO, MEO, LEO): supporting fixed and mobile communications links (including TT&C), broadcast services and remote sensing (active and passive radio sensors)
- Radionavigation / radiolocation and radar services not addressed under aeronautical services above
- Radioastronomy
- Licence-exempt services
- Amateur
- Military systems covering most of the above

4.1 Mainstream terrestrial services

4.1.1 Fixed

The SE24 Draft Report [10] analyses central stations associated with P-MP fixed wireless access type systems in association with base stations for cellular mobile systems (this is summarised in the next section). It also analyses point-to-point fixed service systems, albeit in the wider context of receivers operating with high gain antennas.

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[3] That is to say terrestrial systems generally with local coverage determined by the horizon, airborne systems having a much wider coverage and space based systems potentially having global coverage.

Initially it is demonstrated that interference sources between 1 and 10 km produce a significantly higher interference risk than sources in close vicinity to the receiver. It is shown that antenna gain is of small importance as any change in gain is compensated for by the change in main beam area and consequently the number of significant interferers. It is also shown that high antennas will suffer less interference than low antennas. It is concluded that the highest interference risk is due to the density of interferers.

There is however no apparent link between these results and the conclusion that for the process of definition of tolerable power spectral density levels of UWB devices, separation distances to Radio Service application operating with high gain antennas well below 1 m or below *[sic]* (0 dBi gain of victim receiver) should be applied, in order to protect these Services adequately against harmful interference from UWB devices.

Later in the SE24 Draft Report [10] there is a further analysis concerning the impact of a single UWB device on a 44 dBi point-to-point receive terminal operating in the 3400 - 4200 MHz band. The analysis is based on spherical Earth propagation (ITU-R Recommendation P.526-7) and includes a 6 dB margin for reflection and focussing effects.

The results indicate that a UWB device emitting -90 dBW/MHz can be tolerated at distances up to 3 km. At 50 km an EIRP of -50 dBW/MHz can be tolerated. It is however noted that the aggregation of several sources of interference should lead to significantly more stringent requirements.

4.1.2 Mobile

The compatibility study report [3] produced by *Multiple Access Communications Limited* examines the impact of UWB transmissions into cellular mobile receivers. In the report, an analytical expression is derived to calculate the aggregate interference from an equally spaced population of UWB transmitters as a function of average transmitter density and path loss.

This expression is then used to calculate maximum UWB power spectral density levels that would increase the noise power at a cellular receiver by a given margin. Both noise-limited and interference-limited environments are taken into consideration. Results are presented in the form of transmitter density vs. maximum power spectral density curves for cellular receivers operating at 900 & 1800 MHz. These curves are used to determine transmitter densities that would allow UWB operation within the existing Part 15 limits.

The results from the analysis indicate that in the rural case, for example, up to 50 transmitters /km^2 (each with 1 GHz transmission bandwidth) could be allowed if the Part 15 intentional radiator limits were met. In the case of an urban area CDMA system deployment, up to 100 transmitters /km^2 with the same transmission bandwidth could be allowed to operate. For an urban area FDMA/TDMA system deployment, the maximum density is calculated to be 2,500 transmitters /km^2.

Time Domain Corporation investigated the difference between a single entry and an aggregate interference using Monte Carlo analysis over an area of 100*100 metre and concluded that a single entry interference from a transmitter located at a 1 metre distance dominates the aggregate interference [11].

The *Multiple Access Communications* study [3] compares this analysis method against theirs and concludes that if there is always one UWB transmitter at a 1 metre distance, the increase in the UWB density does not have a significant effect on the aggregate interference. It is shown that when the transmitter density is increased from 1 to 10,000 / km^2 the aggregate interference increases by 5 dB.

It is worth noting that, in the analytical method used in the *Multiple Access Communications* study, the minimum distance between the receiver and the closest UWB transmitter is varied with the UWB density. The results show that the aggregate interference is 4 dB greater than that calculated for a single entry up to 50 transmitters/km^2 and the difference increases to 11 dB when the density is 10,000 transmitters/km^2.

It is argued that the second approach (where the minimum distance between the receiver and the closest UWB transmitter is varied with the UWB density) is more realistic and, therefore, it should be concluded that interference aggregation does have an impact on the aggregate interference.

The *SE24 Draft Report* [10] analyses the impact of different densities of UWB devices on cellular network base or central stations where these can be considered to exist not only in mobile networks but also in fixed wireless applications. In its current form the description of the analysis methodology and results is somewhat unclear.

Initially it is demonstrated that the isolation is almost constant up to approximately 2 km distance, assuming line-of-sight conditions. This implies that the distance between interfering transmitter and victim receiver is of less importance than might be assumed and that all sources of interference within the service area will contribute similar interference power independent of their geographic separation. It also shows that for low densities of interfering sources a significant variation in interference levels can be expected due to all the possible different locations. With increasing density, the variation decreases and becomes almost constant at densities above approximately 1000 devices per sq. km.

Once again there is no apparent link between these results and the conclusion that for the process of definition of tolerable power spectral density levels of UWB devices, separation distances to base and central stations in the order of 1 m or below (0 dBi gain of base / central station) should be applied, in order to protect base and central stations.

Later in the *SE24 Draft Report* [10] there is a further analysis concerning the impact of a single UWB device on a IMT-2000 base station based on spherical Earth propagation (ITU-R Recommendation P.526-7) and including a 6 dB margin for reflection and focussing effects. The results indicate that a UWB device emitting -110 dBW/MHz can be tolerated at 10 m. At 10 km an EIRP of -50 dBW/MHz can be tolerated. It is however noted that the aggregation of several sources of interference will lead to significantly more stringent requirements.

It is also pointed out that CDMA cellular systems rely on fast power control which is usually signalled over the radio interface using a few data bits that are not interleaved because of the need for a fast response time. It is suggested that these bits will be more susceptible to interference and the tolerable spectral power densities indicated above should be based on the peak power of the UWB emission.

With regard to user terminals, the *SE24 Draft Report* [10] analyses an outdoor scenario covering an area of 1 sq. km. with two perpendicular streets populated with 10,000 UWB devices per sq. km.

Monte Carlo results (using the street-canyon propagation model of ITU-R Recommendation P.1411-1) are presented. These show line-of-sight and non-line-of-sight interference entries and their aggregation. It is not clear however whether these results are significant as there is no explanation as to the values shown.

It can also be noted that the Radiocommunications Agency has undertaken measurements relating to the potential for interference into a GSM receiver. The results of these measurements have been submitted to SE24 but they have not yet been used to assess how significant the problem might be.

4.1.3 Broadcast

Time Domain Corporation considers the impact of cumulative interference from UWB emitters on licensed broadcast services [12]. The model has the same heritage as that used to determine the impact of multiple UWB emitters on various aircraft receivers (see following section).

In this case three environments were modelled:

- UWB devices outdoors throughout an urban environment
- UWB devices indoors in a low factory building
- UWB devices indoors throughout a 25 storey office building

The UWB emitters were assumed to transmit either 1 mW or 1 µW and have a bandwidth of 476 MHz centred about 1961 MHz.

There are no broadcast services in this band so a benchmark protection level was required. Existing FCC protection levels for broadcast services in other bands are shown in the following table, along with the performance of a Part 15 type device.

Service	Protected Field Intensity (dBµV/m)	Frequency (MHz)	Received Power (dBµW)
FM	60	100	-25.45
VHF - lo	47	88	-37.34
VHF - hi	56	216	-36.14
UHF	64	776	-39.25
Part 15 at 3 m	54	1961	-57.30

Table 2: Field intensities (in dBµV/m) and corresponding received power (in dBµW) for various licensed broadcast services. These signals must be protected according to FCC rules.

On the basis of the above figures an arbitrary level of -60 dBµW was chosen to protect hypothetical broadcast services in the band around 2 GHz. This provides at least 20 dB of protection to broadcast services in the band, although it is noted that the FCC would prefer about 40 dB of protection (i.e. -80 dBµW). In addition, the -60 dBµW level is roughly the same as the power delivered by a Part 15 device at 3 metres. Thus, if the noise power from multiple devices is no more than -60 dBµW, then they cumulatively interfere no more than a single UWB device.

For the different environments outlined above, the numbers of devices that could operate without exceeding the benchmark are shown in the following table.

	1 mW per transmitter		1 µW per transmitter	
Cumulative noise (dBµW)	-60	-80	-60	-80
Urban area	4,077	29	>1,000,000	36,178
Factory	0	0	89	0
Tall building	0	0	35	0

Table 3: Number of allowable transmitters, assuming either 1 milliwatt or 1 microwatt of power radiating from each, and assuming either 20 dB (-60 dBµW) or 40 dB (-80 dBµW) of protection for licensed services.

Alternatively, the space required by each transmitter (represented by a cube with the transmitter at the centre) gives an idea of the densities that can be tolerated. It can be seen (from the completely populated column) that the densities are of the same order between the three environments with the difference being due to the precise shape of each.

	1 mW per transmitter		1 µW per transmitter	
Cumulative Noise (dBµW)	-60	-80	-60	-80
Urban Area	135	701	21.5	65.2
Factory	∞	∞	9.7	∞
Tall Building	∞	∞	15.3	∞

Table 4: Dimension of cube (metres per side) surrounding each allowed transmitter, for various assumed radiated powers and degrees of protection for licensed broadcast services.

On the basis of the results obtained it is concluded that multiple UWB emitters can operate in the 1961 MHz band. It is also concluded that multiple UWB emitters could coexist with licensed broadcast services in the 787 MHz band, where radiowave propagation is more favourable. The link between the results and the conclusions is not at all clear and the situation in the real broadcast bands needs to be tested.

The *Multiple Access Communications* [3] sharing study briefly investigated the implications of aggregate interference from UWB transmitters into TV residential receivers by using the same analysis model used in the cellular receiver case (see previous section). Assuming that the maximum allowed degradation in the receiver noise floor is 1 dB, UWB density curves are derived as a function of the maximum UWB transmitter power for a number of transmitter bandwidths. It is argued that if the Part 15 Class B emission limits were to be complied with and the transmitter density were to be limited to 1 /km^2, there would not be an interference problem into TV receivers.

A simple analytical model is also developed to derive UWB transmitter power vs. UWB transmitter density curves concerning interference from indoor UWB transmitters into a residential TV antenna mounted at a rooftop. It is concluded that the Part 15 Class B emission limits will provide enough protection (i.e. the noise floor will not be degraded by more than 1 dB) if the number of UWB transmitters were to be limited to 5 assuming that the floor space of the building is 200 m^2.

Finally, it is suggested that UWB interference into digital TV receivers may be more problematic as the receivers are likely to be more sensitive. This is identified to be an area requiring further investigation. Since the *MAC* report was written, the Radiocommunications Agency has undertaken measurements relating to the potential for interference not only into DVB-T receivers but also into T-DAB receivers. The results of these measurements have been submitted to SE24 but they have not yet been used to assess how significant the problem might be.

4.2 Aeronautical services

As part of the current US regulatory process the NTIA published a report of a study into the compatibility of UWB devices and GPS receivers [5]. In the report, it is stated that the objective of the study was to define maximum UWB EIRP levels that could be tolerated by GPS receivers. Calculated EIRP levels are then compared to the Part 15 emission limits to determine if these limits provide adequate protection for the GPS receivers.

It is noted that GPS receiver interference threshold levels are measured for two performance criteria: break-lock (where the signal lock between a satellite and a GPS receiver is lost) and reacquisition (where a UWB transmitter causes an abrupt increase from the nominal reacquisition time). Measurements were conducted on 32 representative UWB signal structures with various pulse repetition, modulation and gating percentages. On the basis of the measured receiver interference threshold levels, interference analysis was performed to determine the maximum UWB EIRP levels that could be tolerated by GPS receivers used in various terrestrial, maritime navigation, railway operations, surveying and aviation applications.

The report concludes that the measured GPS receiver interference threshold levels are exceeded at EIRP levels well below the Part 15 emission limits for some of the UWB signal structures considered. The maximum tolerable EIRP levels calculated for dithered signals are higher than those corresponding to non-dithered signals as dithering reduces the spectral lines in the GPS band. Furthermore, it is suggested that when the dithered UWB signals are considered, the aggregate interference is the addition of individual signals. In the case of non-dithered signals, the aggregate interference is largely dominated by a single UWB signal and is the result of a UWB spectral line present in the GPS receiver band.

More recently (September 2001), the NTIA published a report providing additional information concerning interference from UWB devices into GPS receivers [13]. The report examines the implications of UWB signal characteristics (on-off keying, dithering, pulse repetition rate and gating) on the GPS receiver performance. It is argued that: ***on-off keying*** can have a significant impact on GPS receivers as it also results in a power spectrum with spectral lines, ***dithering*** can reduce the impact of UWB interference, higher ***pulse repetition rates*** cause greater power being gathered into each spectral line and also result in greater percentage of time for which the pulses are present, and ***gating*** reduces the impact of interference as the power of individual spectral lines is spread into multiple lines and the percentage of time for which pulses are present is reduced.

The *Multiple Access Communications* UWB/GPS sharing analysis [3] is based on the derivation of the path loss prediction curves (between uniformly distributed UWB transmitters and a GPS receiver) analytically as a function of a UWB density. The path loss prediction model is the same as that used in the cellular mobile interference analysis. These curves are compared against the required isolation (based on satisfying the GPS receiver minimum signal-to-noise ratio) to determine the maximum allowed transmitter densities. It is worth noting that the path loss prediction model is based on regularly spaced UWB transmitters interfering with the victim receiver. The distance between the closest UWB transmitters and the victim varies with the transmitter density.

It is shown that when the UWB densities are limited to 300 /km^2 in urban areas and 100 /km^2 in rural areas the GPS receiver will not be affected by UWB transmissions (operating within the Part 15 intentional radiator emission limits with a 1 GHz bandwidth). It is concluded that the maximum tolerable UWB densities are greater than those calculated for the cellular mobile case and, therefore, interference into the GPS receivers is less likely to be a problem.

A report on a UWB-GPS compatibility analysis was published by *The Johns Hopkins University* in March'01 [2]. The study is based on the application of a statistical analysis approach to the data collected from measurements conducted by Applied Research Laboratories at the University of Texas. The measurements were obtained using six GPS receivers and two UWB devices.

The theoretical analysis and the statistical data evaluation presented in the report suggest that 'properly' time coded UWB signals can produce spectrum similar to white noise within the GPS receiver bands. This is confirmed by the measurements obtained by the University of Texas from the UWB test devices. It is argued that the aggregate signal produced by more than one of these devices is also a white noise signal. However, some of the coding techniques are found to be producing non white noise UWB signals which may have a greater impact on the GPS receivers performance.

Based on the GPS receivers and UWB transmitters considered, it is concluded that the GPS receiver performance is subject to severe degradation when the separation is less than 3 metres.

The NTIA investigated the implications of UWB interference into a number of federal telecommunications systems [14]. Analytic interference modelling tools were developed to examine both single entry and aggregate interference. The victim receivers considered included air route surveillance radar, air traffic control radio beacon system, microwave landing system, airport surveillance radar, distance measuring equipment, S-band marine radar and SARSAT payload.

In the case of a single UWB transmitter, maximum permitted EIRP levels (assuming a relatively small separation distance) and minimum required separation distances (assuming transmitters operate at Part 15 emission limits) are calculated. The maximum EIRP calculations take account of relative height difference between the transmitter and receiver, receiver antenna gain pattern, receiver interference threshold and path loss. EIRP levels are then calculated at 10 metre increments in the distance range from 200 metres to 15 kilometres. The lowest calculated EIRP is considered to be the maximum allowable EIRP that does not exceed the receiver interference threshold. In addition to the maximum allowed EIRP, the required separation is determined when the UWB device is assumed to radiate at the Part 15 EIRP limits.

In order to model aggregate interference, a simple analytical model has been developed. In the analysis, UWB transmitters are assumed to be uniformly distributed geographically and transmit the same effective power in the direction of the victim receiver. The cumulative effects are assumed to be additive to the receiver noise. The aggregate interference is found to vary directly with the UWB EIRP, density and transmitter activity factor. It is claimed that, all other factors being fixed, there will be a UWB transmitter density figure where the aggregate interference will exceed that from a single UWB transmitter. Therefore, it is argued that claims of an aggregate interference not exceeding a single entry level is based on an unrealistically close distance between a single UWB transmitter and a victim receiver.

In the single entry interference analysis, a smooth Earth approximation is used to calculate the path loss. The receiver antenna radiation pattern and the transmitter/receiver heights are also taken into account. It is shown that a significant reduction (in order of 20 dB) in Part 15 emission limits would be required to protect the distance measuring equipment used for ground interrogators, air route surveillance radar and SARSAT land user terminal (all operating in the band 960-1610 MHz). Maritime radars (operating in the 2900-3100 MHz band) are found to be sensitive to the UWB emissions which may require limiting UWB EIRP below the Part 15 limits. In addition, the microwave landing system (operating in the band 5030-5091 MHz) is noted to be the most sensitive to non-dithered UWB signals.

In the aggregate interference analysis, the maximum EIRP curves are plotted as a function of active UWB transmitters. In addition, it is shown that the aggregate interference may be greater than the single entry level for densities as low as few transmitters per square kilometre. Additional factors needing to be considered are identified to be foliage, natural terrain irregularities, man made obstacles, building penetration losses and a UWB antenna directivity.

In addition to the analytical approach, measurements were carried out on the air route and airport surveillance radars to compare the calculated maximum allowed EIRP levels against those measured. It is noted that the measured EIRP levels are a few dB lower than the calculated ones due to the inclusion of terrain effects into the measurements and the differences in the assumed (for analytical calculations) and real (for the measurements) radar antenna elevation patterns.

Time Domain Corporation considers a range of aircraft based avionics receivers including [12]:

- 25 kHz bandwidth voice operating at 118 MHz
- 300 kHz bandwidth DME operating at 962 MHz
- 20 kHz bandwidth VOR operating at 108 MHz

- 12 kHz bandwidth NDB, ADF operating at 190 kHz
- 10 kHz bandwidth ILS Localiser operating at 108 MHz
- 34 kHz bandwidth ILS Glide Slope operating at 329 MHz
- 2 MHz bandwidth GPS (using C/A Code) operating at 1.6 GHz

Of these, voice, DME and GPS were chosen for analysis on basis that they are the three worst cases taking into account sensitivity and/or bandwidth.

Two environments were modelled with respect to the above three worst case receivers on board an aircraft flying at an altitude of 900 feet (1000 feet minimum clearance requirement less a 100 foot error):

- UWB devices outdoors throughout an urban environment with radius 8000 metres and height 50 metres.
- UWB devices indoors throughout a 25 storey office building

Propagation was modelled using the measurements of Okamura (VHF and UHF) and, in the case of the office building, the shielding effectiveness of floors and roofs reported by Owen and Pudney.

In addition two different emitter powers were considered; 50 microwatts and 200 microwatts radiated over a 2 GHz bandwidth. These correspond to Class B (consumer) and Class A (industrial) limits.

A summary of the results, in terms of the number of simultaneous emitters, as presented in the TD comments is shown in the table below:

Emitter Environment	Class of UWB Emitter	Voice Receiver	DME Receiver	GPS (Using C/A Code) Receiver
Open Urban Area	A (200 μW)	9,397	>10^6	23,899
	B (50 μW)	36,946	>10^6	100,000
25 Storey Building	A (200 μW)	5,367	>10^6	12,434
	B (50 μW)	23,899	>10^6	50,432

Table 5: Analysis Results

Time Domain Corporation [12] outlines the results of test and analysis carried out using a TD Part 15 qualifiable radar on a GPS receiver. It is stated that the measured results have been confirmed by FCC measurements and that for the FCC test the emissions from the radar prevented the GPS receiver from tracking when the separation distance was less than 1 foot and it prevented acquisition at a separation distance of less than 10 feet. It is claimed that similar GPS interference can be seen from testing devices such as pagers and Motorola’s popular walkie talkies.

The GPS unit was initially able to acquire 5 satellites (with the UWB transmitter located a significant distance away) and failure was considered to occur when lock could not be maintained on 3 satellites simultaneously. Lock was lost on the fifth satellite when the UWB device was 10 feet away and on the third satellite (= failure) when 4 feet (horizontal UWB polarisation) or 6 feet (vertical UWB polarisation) away.

A theoretical estimate of the range required to protect GPS from a UWB device (Class B) indicated 19.8 m (64 feet) and 7.1 m (23 feet) for acquisition, compared to the 1.8 / 1.2 m (6 / 4 feet) measured to be required to track 3 satellites. The discrepancy between measured and theoretical results is explained by:

- The satellites being at the beginning of their life and therefore transmitting 3 to 7 dB more power than specified
- The GPS receiver having acquired the signal requiring 8 dB less power to track it
- The UWB radar emissions being 1.8 dB below the Part 15 Class B limit to allow for electric field measurement error

Aiello et al [15] report on preliminary measurements of interactions between a controlled and calibrated UWB transmitter and GPS receivers, receiving signals from satellites under operational conditions. The measurement programme looked at the effects of varying UWB signal characteristics such as pulse shape, pulse repetition frequency, pulse dithering and pulse bursting. Several representative GPS receivers were used in the tests (narrow correlator, inexpensive hand-held, experimental, and survey grade). The interference criterion was considered to be the loss of any one satellite referenced to the number of satellites received with the UWB transmitter off.

Taking account of all the combinations of GPS receiver and UWB signals used in the tests a wide range of results was obtained. Separation distances between 1 and 100 metres were obtained, but note that these distances are based on measurements taken at 3 metres and then extrapolated using line-of-sight, $1/r^2$, loss.

It is concluded that it is difficult to pinpoint the range at which harmful interference occurs. However it is noted that the results indicate that GPS may require more protection than that afforded by the unintentional levels of Part 15.

At the *CEPT UWB Workshop* (2001)[4] it was claimed by Eurocontrol[5] that the minimum geographical separation required for primary radar with respect to a single UWB device operating at a height of 2 metres would be 5.5 km, and 15 km if the UWB device operated at a height of 30 metres [16]. Having indicated the risk posed

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[4] http://www.ero.dk/EROWEB/SRD/UWB/Agenda-presentations.htm

[5] http://www.ero.dk/EROWEB/SRD/UWB/Pelmoine.ppt

by a single device it was also noted that aggregate radiation from multiple devices will increase the risk further.

It was further noted that interference will also occur to other aviation systems such as DME and SSR, and, given the interference potential to GPS that has been noticed elsewhere, it has been deduced that UWB will also interfere with new RNSS developments including Galileo.

No technical material has been provided to support the separation requirements that have been stated. Further information and/or work is required to determine how appropriate these distances are.

It can be noted that there was a placeholder for Galileo in the draft SE24 report, although this has disappeared in the most recent draft.

4.3 Satellite services

A wide range of receivers exist here. Receivers on GSO, MEO and LEO spacecraft need to be considered as do the Earth stations on the ground.

4.3.1 Fixed and mobile satellite communications links

The NTIA study into the implications of UWB interference into a number of federal telecommunications systems included an FSS Earth station receiver operating at 3750 MHz [14].

In the single entry interference analysis, maximum allowed UWB EIRP levels are calculated for a range of UWB signals (dithered/non-dithered, pulse repetition factors within the range 0.001 to 500 MHz). A sensitivity analysis is carried out to examine the implications of the receiver antenna elevation, the peak and average transmitter power and the transmitter and receiver antenna heights. Single entry separation distances satisfying the current Part 15 limits are also calculated for each interference alignment.

It is concluded that the UWB device operating at -41.3 dBm/MHz (Part 15 limit) in the vicinity of FSS Earth station receiver will exceed the interference threshold in most cases.

In the aggregate interference analysis, a simple analytical model is used to aggregate interference from uniformly distributed UWB transmitters each assumed to be radiating the same effective power in the direction of the FSS receiver. Results are presented in the form of maximum EIRP vs. active UWB emitter density. They suggest that, for up to 100 active UWB emitters /km^2, the maximum allowed EIRP is -49 dBm/MHz for the FSS receiver operating at 5 degrees elevation and -34 dBm/MHz for the FSS receiver operating at 20 degrees elevation.

Apart from the above NTIA analysis very little work in the area of satellite communication systems was found. It is understood that the SE24 work has a placeholder for the Mobile Satellite Service (MSS) safety services, although this no longer appears in the most recent draft of their report.

4.3.2 Broadcast services

There is no evidence from the literature survey that TVRO terminals have been addressed.

4.3.3 Remote sensing

There is no evidence from the literature survey that active or passive sensors on board spacecraft have been addressed. It can be noted however that there was a placeholder for the Earth Exploration Satellite Service in the draft SE24 report, although this has disappeared in the most recent draft.

4.4 Other radionavigation / radiolocation and radar

The impact of UWB interference into weather radars and altimeters has been examined as part of NTIA's study into the implications of UWB interference into a number of federal telecommunications systems [14]. As explained earlier, in this study, both single entry and aggregate interference analyses have been carried out for various scenarios.

For the single interference entry, it is shown that the next generation weather radar operating in the band 2.7-2.9 GHz can tolerate UWB EIRP levels in the range -76 dBm/MHz to -39 dBm/MHz depending on the antenna heights, pulse repetition rate and whether pulse position randomisation is applied or not. It is also worth noting that a minimum separation of 200 metres is used in the process of calculating the maximum allowed EIRP. These levels are compared with the Part 15 limit of -41.3 dBm/MHz. For those scenarios where the Part 15 EIRP limit is exceeded, the minimum required separation distances are calculated to be between 1.4 km and 7.9 km. In addition, the maximum tolerable EIRP levels at 200 metres are calculated to be between -35 dBm/MHz and -63 dBm/MHz for the terminal Doppler weather radar operating at 5.6 GHz. The required separation is calculated to be 6 km to meet the Part 15 limit for the scenarios where the maximum allowed EIRP is -63 dBm/MHz. Using the same approach, the maximum allowed EIRP levels varying between 14 dBm/MHz and 25 dBm/MHz are calculated for the continuous wave and pulsed radar altimeters operating in the band 4.2-4.4 GHz, indicating that interference into altimeters is unlikely to be problem (as the tolerable EIRP levels are much higher than the Part 15 EIRP limit).

Using the analytical model developed for the aggregate interference analysis, maximum EIRP vs. UWB density plots have been derived for the next generation weather radar and the pulsed radar altimeter. For the weather radar, the results show that the maximum tolerable EIRP is reduced from -39 dBm/MHz to -75 dBm/MHz when the density is increased from 1 to 10,000 active transmitters / km^2. In the case of the altimeter, the EIRP range is between 18 dBm/MHz and -40 dBm/MHz.

4.5 Radioastronomy

As one of the more sensitive services it is somewhat surprising that the implications for radioastronomy have not been addressed. Some material on the protection required has been injected into the draft SE24 report but as yet there has been no analysis of the situation.

4.6 Licence-exempt services

The closest there is to addressing licence-exempt services is the consideration of an indoor scenario for user premises equipment put forward in the *SE24 Draft Report* [10]. It analyses an indoor scenario consisting of a 5 storey 50 m x 50 m office building populated with 100,000 UWB devices per sq. km.

Monte Carlo results (using the site-general propagation model of ITU-R Recommendation P.1238-2) are presented. These show interference entries from the different floors and their aggregation. As in the case of the outdoor scenario (mentioned under mobile services earlier) it is not clear whether the results presented are significant as there is no explanation as to the values shown.

It can also be noted that the Radiocommunications Agency has undertaken measurements relating to the potential for interference into Bluetooth. The results of these measurements have been submitted to SE24 but they have not yet been used to assess how significant the problem might be.

4.7 Amateur

No mention has been found of the implications of UWB deployment on amateur activities.

4.8 Military systems

The military establishment, and potentially other government agencies, already use UWB in one form or another. There is however no public domain evidence that the implications of widespread public use of UWB devices on military systems has been investigated.

5 SPECIFIC ISSUES

In addition to the compatibility issues associated with specific radio services, as addressed in the previous section, there are a number of other more general issues that are the subject of debate. The most important of these are addressed in the following sections.

5.1 Aggregate v. Single

There are several views on whether the impact of UWB devices on victim receivers is more likely to be dominated by a single nearby device or an aggregation of devices in the vicinity.

Time Domain Corporation states that there are a number of factors that limit the buildup of UWB emissions such that the cumulative impact should not be a concern [11].

Propagation - It is pointed out that foliage attenuation, absorptive soil, Fresnel attenuation, loss due to walls, people and structures, as well as blockages from buildings and hills limit the amount of aggregation. It is suggested that propagation exponents of 3.25 to 4 in various types of obstructed environment (as opposed to 2 for free space) should be taken into account.

User density – The separation among devices needs to be accounted for as they are spatially spread from one another and this reduces the overall emissions at any one point.

User duty cycle – The percentage of time that any one of the UWB devices will be operating limits the buildup of emissions as in the real world very few products will be operating simultaneously.

The results of a Monte Carlo modelling exercise are presented (taking account of user density but not propagation effects additional to free space path loss nor user duty cycles). The exercise was primarily designed to show the effect of aggregation with respect to the impact of a single UWB device.

A number of users (UWB devices) was randomly distributed over an area assuming (or ensuring) that there is always one transmitter 1 metre from the sample point. Free space propagation was assumed and no transmitter could be closer than 1 metre.

The number of users was distributed over a 100 m x 100 m area and at each step 81 cumulative field strengths were calculated over a regular grid of sampling points in a 50 m x 50 m area in the centre of the area over which the UWB devices are distributed. Each step gives 81 field strength samples and 1000 steps were executed therefore giving 81,000 data values.

From the data produced, results are presented in terms of mean value of the RMS field strength at the 81 sample points for all 1000 Monte Carlo simulations, i.e.

average over 81,000 data values. Also, for each of the 1000 random distributions, the largest RMS value from the 81 sampling points is selected and then the average value of these 1000 samples is determined.

On the basis of these results it is claimed that for 100 UWB devices the RMS field strength at the 81 measurement points is only 1.2 dB greater than for a single user, and the RMS of maximum values is less than 6 dB greater.

It should be noted that in terms of presentation much of the statistical information regarding the results has been lost. Two averaging processes have been used, firstly over the 81 measurement points and secondly over the 1000 Monte Carlo simulations. The first result (1.2 dB) is based on both of these. The second result (6 dB) is based on averaging the maximum values from the 81 measurement points over the 1000 Monte Carlo simulations.

Interval [17] provides an analysis of the aggregation of noise from multiple emitters with respect to a receiver at an altitude above the Earth's surface.

The first part of the analysis is the standard integration over the surface of the Earth as used extensively in ITU-R studies. Based on a flat earth assumption it demonstrates that if the power density (W/m^2) on the surface of the Earth is P then the power density at a receive antenna at the apex of a 45° cone (i.e. 90° solid angle at the apex and 45° elevation at the base) is 2.178P - not a significant aggregation. However when integrating to the horizon (where the curvature of the Earth is clearly involved), the result depends on the apex height. As an example, if the apex height is 100m the power density impinging on the receive antenna at the apex will be 34.75P. While this is a much more significant aggregation, it is suggested that signals will be "damped" through absorption. This absorption near the surface of the Earth is applied to all signal paths in the integration process. It is claimed that even small amounts of damping will reduce the aggregation of near horizontal signals, although quantifying by how much has been left somewhat open.

The analysis concentrates on comparing the power density (W/m^2) emitted from the surface of the Earth with the power density impinging on a receive antenna at the apex of a cone. While demonstrating that "damping" will reduce the aggregation effect it is not clear why it is claimed that the density of emitters is not an issue, only the spatial reuse. The power density emitted from the surface of the Earth will depend on multiple emitters reusing the same frequency and therefore implicitly represent a density of emitters.

XtremeSpectrum [18] also provides an analysis of the aggregation of UWB emitters with respect to a receiver at an altitude above the surface of the Earth (using 4/3 Earth radius to account for refraction).

The computation shows that as the altitude of the victim receiver goes up, the energy density at a victim receiver goes down. It concludes that the worst case receiver position is at ground level, but, as the victim receiver altitude approaches zero, a discrete model is needed because the assumption that a finite number of transmitters can be modelled as a uniform density, breaks down.

A discrete model based on a planar grid of emitters is also presented. It is concluded from results derived from the model that the power received is influenced most by the nearest transmitters and that this would be even more the case had other propagation considerations been taken into account (e.g. $1/R^4$ rather than the $1/R^2$ assumed). It can be noted that the analysis presented by XtremeSpectrum also took account of the activity level of the transmitters. 10% activity was used in addition to the worst case 100%.

5.2 Measurement techniques

Measurement techniques will play a significant role in allowing the introduction of UWB technology. As far as the compatibility with other systems is concerned, it is crucial to decide which parameters (for example, pulse width, pulse repetition factor, peak power, rise/fall time) should be used to limit UWB transmissions, what numeric values should apply and which techniques should be used to measure these limits.

The NTIA report on the temporal and spectral characteristics of UWB signals [4] states that measurements were carried out to capture individual pulses directly in the time domain by using a fast transient digitizer and, in some cases, a sampling oscilloscope. Measurements of the UWB signal power in various bandwidths (up to 20 MHz) were obtained using spectrum analysers.

It is argued that the field strength in a bandwidth derived from a Fast Fourier Transform of a full bandwidth pulse shape measurement matches the field strength shape measured in a narrower bandwidth by a spectrum analyser in general shape and absolute amplitude at the peak emission frequency. Therefore, narrowband spectral measurements with a spectrum analyser or other measurement receiver are claimed to provide accurate information to characterise the overall shape and absolute amplitude of the RF spectrum of UWB signals.

In the same report, it is noted that the measurement of the UWB signal amplitude probability distribution is important to assess whether the signal resembles Gaussian noise or very impulsive noise. A comparison of the amplitude probability distribution function of a Gaussian signal and an example UWB signal suggests that differences exist.

The report produced by *Multiple Access Communications Limited* [3] provides a brief overview of methods for measuring emissions from UWB devices. It is noted in the report that the best method of characterising UWB transmissions is to measure the power spectral density of the emitted signal. Alternative proposed methods include measuring time domain characteristics. It is argued that time domain measurements may not be appropriate when UWB systems do not employ impulse or short pulse technologies and, therefore, the frequency domain measurements are versatile enough for all UWB techniques.

The same document reports that the measurement of the power spectral density for a single fixed bandwidth does not adequately reflect the interference potential from a UWB system. Power spectral density measurements should be performed for a variety of spectrum analyser resolution bandwidths. It is shown that the power spectral density depends on pulse repetition rate and spectrum analyser resolution bandwidth. This is in line with the WINForum comments submitted to the FCC [19].

The report also suggests that, by adjusting the video bandwidth of the spectrum analyser, it should be possible to carry out peak and average power spectral density measurements. If the video bandwidth is greater than the spectrum analyser resolution bandwidth, the analyser will record the peaking effects. If the video bandwidth is much less than the resolution bandwidth the filter averages the spectrum analyser IF output.

Two papers [7, 8] providing information on the historic development of UWB technology argue that the concept of power spectral density is based on harmonic analysis and does not apply to single transient events (i.e. pulse transmissions) unless the sampling rate is large enough. Furthermore, it is claimed that the power spectral density is an even function of frequency and possesses no phase information about the signal. Pulsed signals are not an even function of frequency and a valid peak power measurement is critically dependent on the signal phase.

The same documents suggest that a matched filtered response of a dithered UWB pulse train shows that there is always a central peak in the power spectrum corresponding to energy/sampling time of the individual UWB pulse regardless of the extent of dithering. It is claimed that spectrum analysers do not sample fast enough to capture the peak power of the individual UWB pulse, and, therefore, misrepresent the energy and power in a UWB pulse train. It is also argued that pulse dithering does not reduce the UWB power to a flat spectrum and that these claims are based on inadequate sampling of the individual pulses within the pulse train. It is suggested that increasing the amount of dithering can narrow the central peak but the height (peak power) remains the same.

The same documents also state that a sample-and-hold oscilloscope with sampling rate >20 GHz will capture the peak power in an individual UWB pulse (applied repetitively) but not in aggregated pulses (resulting in a continuously changing, aperiodic and non-repeating signal) from different emitters. Furthermore, it is suggested that the emissions of an aggregate of disparate pulses at disparate pulse repetition frequencies with disparate superimposed temporal codes constitute a noise of aperiodic transients. These aggregate emissions can only be examined by real time oscilloscopes, for example a real time digital phosphor oscilloscope.

It is claimed that testing the effects of UWB emissions on conventional receivers is difficult because there is no generic UWB individual signal or pulse (different rise and fall times, harmonic modulated components), pulse repetition frequency and pulse dithering code.

A recent input paper to SE24 concerning the relationship between average and peak power and the implications of bandwidth shows that this issue is likely to be addressed as part of the SE24 report.

5.3 EMC

No references were found to the general EMC implications of UWB devices operating at power levels consistent with the US Part 15 rules.

The only obvious reference to this issue concerns the terrorism implications of high power UWB on an aircraft when applied from the outside of an aircraft [20]. This reference looks at High-altitude Electromagnetic Pulse (HEMP), High Power Microwaves (HPM) and UWB. In this instance UWB is considered to be based on a peak power at the antenna of a few GW to 20 GW giving rise to peak electric fields of 4 to 20 kV at 100m.

It is estimated that an overall attenuation of about -50 to -80 dB can be expected between an external threat and voltages induced on a circuit situated inside an aeroplane. An HPM source delivering a field of 30 - 300 kV/m at a distance between 100 m to 1 km and using the -80 dB transfer function would give rise to 3 - 30 V induced at the entry of electronic equipment which it is claimed represents a destructive disturbance for the electronics.

There are references that compare the emissions from other devices with those of a UWB device. In the first instance Appendix E of Time Domain Corporation's comments (7 December 1998) contains a time domain plot of an emission from a Pentium personal computer motherboard. It is not clear from the text but it can reasonably be assumed that the plot presented represents a single clock pulse, although it is not obvious from which part of the computer architecture it might have emanated. It is however clear that the shape of this pulse is very similar to one type of UWB waveform. There is however no direct comparison of power levels.

Secondly there are frequency domain plots that compare emission levels of various electrical devices with those of a UWB device.

Time Domain Corporation [12] Appendix C shows the peak and average field strengths (dBµV/m), measured at 1 metre and across the frequency range 1 to 3 GHz, for a Sun workstation motherboard, a Norelco razor, a CONAIR hairdryer and a Time Domain RadarVision UWB device. The measurements include ambient emissions such as PCS.

Interval [17] Exhibit 4 shows the power spectral density in dBm (based on a resolution bandwidth of 1 MHz and a video bandwidth of 1 MHz) across the frequency range 410 - 1410 MHz for background noise and for a 450 MHz Pentium and a UWB transmitter.

These measurements are designed to show that the level of UWB emissions are similar or less than electrical devices which are extensively deployed already.

5.4 Antennas

It is noted that the UWB antenna design remains to be the main challenge in the progress of UWB technology [1, 3]. This is primarily attributed to the fact that antennas act as a band pass filter and limit the transmission bandwidth. It is claimed that, as a rule of thumb, antennas with a bandwidth such that the ratio of the maximum to minimum frequency is more than two are not easy to build practically. A UWB signal spanning the frequency range 1 MHz to 10 GHz has a ratio of 10,000 and, therefore, an antenna providing this bandwidth is very difficult to construct.

From a compatibility point of view it would be useful to have information on the radiation patterns associated with UWB antennas. Little information on this was found in the references obtained, although the specific topic was not pursued in its own right. In many of the compatibility studies it is either assumed that the UWB devices radiate omnidirectionally or that their maximum radiated power is directed towards the victim receiver. In any event, if the regulations are couched in terms of maximum EIRP spectral density, needing to know the antenna pattern is no longer an issue.

6 CONCLUSIONS

From the literature search that formed the basis of the work reported here, it can be concluded that compatibility analyses of UWB with respect to other radio services has been undertaken to various degrees as follows:

- GPS and the aeronautical services have been investigated extensively.
- The terrestrial Fixed, Mobile and Broadcast services have all been investigated to a greater or lesser extent.
- The various satellite services have hardly been addressed at all. A single analysis of an earth station has been undertaken, but no analysis with respect to satellite receivers. It can be noted that there was a placeholder for the Earth Exploration Satellite Service in the initial draft SE24 report but it is no longer there in the most recent draft.
- Radioastronomy has not been addressed yet, although the protection criteria have been injected into the draft SE24 report.
- There is no evidence of the amateur service or military applications having been addressed.
- Licence-exempt systems have been touched on. Arguably the interference environment that licence-exempt systems generally have to deal with means that these systems need not be considered a priority.

It should be noted that the results presented in the various documents have not been subjected to the most detailed scrutiny because of the time available. Further investigation into the assumptions and methods made might be worthwhile in order to determine more particular areas that have not been addressed sufficiently.

Other conclusions that are not specific to particular services can be made as follows:

- There is a clear gap between the theoretical aggregation models and specific situations. For example, in some circumstances it is not the nearest devices that cause the highest levels of interference. It is therefore not always appropriate to ignore aggregation and assume that a single entry situation is the determining factor.
- It is necessary to take account of the propagation degradations likely to be experienced in the real world, particularly where aggregated effects are considered. In those instances where a single interference entry from a nearby device dominates, line-of-sight propagation is clearly appropriate but it should not be used indiscriminately.
- The specification of limits and the measurement techniques used to confirm that the limits are met need to be considered carefully. Recognising the particular nature of impulse signals in terms of their frequency domain signature, it is

important that limitations on the (frequency domain) spectral power density are specified sufficiently to protect existing services, bearing in mind that these services use many different bandwidths. Furthermore, once specified it is important that appropriate measurement techniques are used. There is still some disagreement on this area which needs to be resolved.

- It appears that there has not been much analysis on the EMC impact of UWB devices. There has been some comparison, in both the time and frequency domain, of UWB emissions with emissions from personal computers. The form of the emissions is found to be comparable.

  It should be noted however that the phase relationship between the different spectral components of a pulse may be maintained over short distances and therefore potentially have an impact on equipment in very close vicinity. The phase relationship is likely to be dispersed very rapidly with distance and/or through material.

- The amount of information on UWB compatibility is very disparate and often conclusions have not been drawn from the results presented as to whether sharing is possible or not. No clear picture will emerge until the results are pulled together and a view taken. This will require significant further work.

REFERENCES

[1] Mitchell, T.: 'Broad is the way', IEE Review, January 2001, pp. 35-39.

[2] 'UWB-GPS Compatibility Analysis Project', The Johns Hopkins University, March 2001.

[3] 'Investigation into the Potential Impact of UWB Transmission Systems', Multiple Access Communications Limited, February 2000.

[4] 'The Temporal and Spectral Characteristics of UWB Signals', NTIA Report, February 2001, http://www.its.bldrdoc.gov/pub/ntia-rpt/01-383/.

[5] 'Assessment of Compatibility Between UWB Systems and GPS Receivers', NTIA Report, February 2001, http://www.its.bldrdoc.gov/pub/ntia-rpt/01-384/.

[6] 'PulseOn Technology Overview', http://www.timedomain.com

[7] Barrett, T.W.: 'History of ultra wideband communications and radar Part I, UWB communications', Microwave Journal, Euro-Global Edition, Vol:44, No:1, January 2001, pp.22-56, Horizon House Publications, USA.

[8] Barrett T.W.: 'History of ultra wideband communications and radar Part II, UWB radars and sensors' Microwave Journal, Euro-Global Edition, Vol.44, No.2, February 2001, pp.22-52, Horizon House Publications, USA.

[9] Fontana, R.J. : 'Recent Applications of UWB Radar and Communications Systems', http://www.multispectral.com

[10] SE24 Draft ECC Report on UWB (Revision 2), Document Reference: SE24M13_21, 6 Dec 2001.

[11] 'Comments of Time Domain Corporation on the FCC Part 15 Notice of Inquiry', December 1998. See *Note* below

[12] 'Comments of Time Domain Corporation on the FCC Part 15 Notice of Inquiry', February 1998. See *Note* below

[13] 'Addendum to NTIA Report 01-384: Measurements to Determine Potential Interference to GPS Receivers from UWB Transmission Systems', NTIA Report, September 2001, http://www.its.bldrdoc.gov/pub/ntia-rpt/01-389/.

[14] 'Assessment of Compatibility Between UWB Devices and Selected Federal Systems', NTIA Report, January 2001, http://www.ntia.doc.gov/osmhome/reports/uwb/uwb.pdf.

[15] Aiello G.R., Rogerson G.D. & Enge P.: 'Assessing Interference of Ultra-wide Band Transmitters with the Global Positioning System - a cooperative study', Fantasma Networks Incorporated, 2000.

[16] Pelmoine C.: 'Ultra-Wide Band Technology - Impact on Aviation Systems', Ultra Wide Band Workshop, Mainz, 20 March 2001.

[17] ‘Comments of Interval Research Corporation on the FCC Part 15 Notice of Inquiry’, December 1998. See *Note* below

[18] ‘Comments of XtremeSpectrum Incorporated on the FCC Part 15 Notice of Inquiry’. See *Note* below

[19] ‘Comments of WINForum on the FCC Part 15 Notice of Inquiry’, December 1998. See *Note* below

[20] Lanoz M. & Wipf H.: ‘Modelling and Simulation Methods to Assess EM Terrorism Effects’, Asia-Pacific Conference on Environmental Electromagnetics, Shanghai, China, 3-7 May 2000.

Note. These documents can be found using the FCC search engine at:

http://gullfoss2.fcc.gov/prod/ecfs/comsrch_v2.cgi

When accessing this search engine the Proceeding (first field) should be identified as 98-153.