Evaluating spectrum percentage occupancy in licence-exempt allocations

Office of Communications (Ofcom)

Final Report

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1606/LEM/R/3

7 July 2004

Table of Contents

EXECUTIVE SUMMARY

Introduction

This study, undertaken by Aegis Systems Ltd and Transfinite Systems Ltd for the Office of Communications (Ofcom), outlines a general method for quantifying spectrum occupancy in licence-exempt frequency bands. The method has been applied to the 2.4 GHz band where it was assumed that the wanted service was a Wireless Local Area Network (WLAN). In addition, a limited programme of measurements has been undertaken in an attempt to make a connection between real systems and the modelled results.

The method

Ofcom has a responsibility for ensuring optimal use of the spectrum. One aspect of this would be a consideration of how efficiently the spectrum is being used. There is, however, no universal method for determining spectrum efficiency and it is therefore not possible to compare the efficiency of different types of service. We consider that the most appropriate method for assessing the utilisation of licence-exempt bands is to determine the spectrum occupancy of a band, and in particular what constitutes full occupancy.

We have proposed a method that introduces systems to an area until an unacceptable level of interference occurs. The point just before this occurs constitutes full occupancy based on interference between systems of the same type. The same process can be undertaken with the area pre-populated with other types of system acting as interferers. Full occupancy for the type of system being investigated will be somewhat less under these circumstances. Comparisons can then be made not only between different interference environments, thereby providing the equivalent utilisation of different technologies, but also between the situation in the field and that predicted by the method.

Issues

In applying the method to WLANs operating in the 2.4 GHz band it became clear that there are a number of interrelated factors that need to be addressed by the model implementation. It was considered that the assessment should be made at the RF level in terms of C/(N+I) and, bearing in mind the environment in which WLANs operate, it can be expected that there will be significant time and location variability in both the wanted signal (C) and interfering signals (I).

For the example we chose to model—WLAN access points covering a specified service area (cell)—it was necessary to specify the cell size, the propagation behaviour that applied to the wanted and interfering signals, and the criterion that determined whether the WLAN access point was providing an acceptable service. There is no generally recognised way for specifying this criterion and it is further complicated by the lack of any knowledge about user expectations, particularly when the service is supported by quality of service protocols. It is known, however, that the system throughput deteriorates rapidly once the packet error rate exceeds 10% and that this is broadly equivalent to a bit error rate of 1 in 10^5. In the absence of any information on a suitable criterion, and acknowledging signal variability, we chose to define the criterion as a requirement for a BER better than 1 in 10^5 for more than 90% of the time at more than 90% of locations in an access point service area.

Modelling results

The method was implemented in software with WLAN access points as the wanted system and Bluetooth devices, ENG/OB terminals and microwave ovens as the interference sources.

Runs were undertaken for a range of scenarios: with and without interferers, for different areas, different interference criteria, inside and outside. The results are detailed in the report. By way of example, it was found that on average 24.79 co-channel access points could co-exist in 1 km^2 and still meet the 90% criterion identified above. Relaxing the criterion to 80% time and area allowed 41.05 access points in the same area.

With 2000 Bluetooth devices operating in the 1 km^2 area, the number of WLAN access points was reduced from 24.79 to 9.82 (90% criterion). Results for intermediate numbers of Bluetooth devices showed a nearly linear relationship in equivalence between Bluetooth devices and WLAN access points at a rate of 7.5 WLANs for every 1000 Bluetooth devices.

Measurements

A limited programme of measurements was undertaken to assess the behaviour of WLANs in an interference environment. While it was not practical to deal with a multitude of devices in a large area, it was possible to assess devices on a smaller scale in order to validate the separation distances required and to compare these with the separation distances suggested by the model results. In the event, the measurement results indicate that the effect of protocols is more important, at least for the small-scale environment investigated, than the gradual change of signal strength with distance. This suggests that the BER criterion used in the modelling does not reflect device behaviour across the whole access point service area.

Conclusions

The method that has been proposed is general in nature and as such is considered to be very robust with respect to any situation where the deployment of systems is not co-ordinated. Applying the method to a particular example requires detailed consideration of a number of factors. In the case of WLANs and other devices operating in the 2.4 GHz band it has been found that the difficulty is in the detail. In the first instance there is no agreed definition of what constitutes an acceptable level of service for a WLAN. This makes it difficult to be precise about when a frequency band (or channel) is full (i.e. when no further WLANs can be deployed without suffering unacceptable performance degradation). This is further complicated by the adaptive nature of WLAN protocols.

The criterion we have used is based on link level bit error rate with a fixed throughput requirement. The throughput, as measurements have confirmed, is in fact adaptive—this will be satisfactory for some users but not for others. Our criterion reflects the situation where the entire throughput is required to be available for each WLAN network.

Further work needs to be carried out in this area if the method we have proposed is to be exploited successfully.

1 INTRODUCTION

This report describes the results of a study undertaken by Aegis Systems Ltd and Transfinite Systems Ltd for the Office of Communications (Ofcom) between January and June 2004. The study contracted by Ofcom was for the evaluation of spectrum percentage occupancy in licence-exempt allocations with a specific study at 2.4 GHz (AY4529).

1.1 Objective of the study

The remit of regulatory authorities responsible for managing the radio spectrum usually includes a requirement that attention should be paid to maximising spectrum efficiency. With this in mind, Ofcom has an interest in determining how efficiently licence-exempt bands are being used. It is therefore necessary to have some means of measuring the efficiency with which the spectrum is being used by licence-exempt devices. Traditional measures of spectrum efficiency do not lend themselves to the licence-exempt environment, so other means have to be considered. Ofcom has therefore posed the following questions:

- What makes a system spectrally efficient in a band?
- What different band-occupancy metrics are relevant for licence-exempt operation?
- How should the efficiency be measured for non-uniform traffic and within a mix of different propagation environments?
- Should a realistic deployment be defined for a licence-exempt network to which different technologies are measured?
- Can and should the efficiency of multiple access schemes be separated from the modulation efficiency in assessing a technology and if so how?
- How should relaying and *ad hoc* systems be assessed in comparison with centralised architectures?
- What criteria should be used to determine if a band is full?

In order to answer these questions the terms of reference for the study require the work to:

- Consider the range of parameters that will need to taken into account for each service in a band so as to develop a worthwhile technique for quantifying spectrum occupancy.
- Propose an appropriate technical measure that can be used to calculate the spectrum occupancy based on the relevant characteristics identified by the above.
- Apply the measure using typical data to show a result in the 2.4 GHz band assuming the wanted service is that of a WLAN.

- Measure WLAN performance in an interference environment and compare the measurements with the modelled results.

The remainder of the report is structured as follows:

Chapter 2 provides background on efficiency measures used elsewhere

Chapter 3 outlines the key characteristics of licence-exempt use

Chapter 4 summarises different approaches to modelling the coexistence of radiocommunication systems

Chapter 5 details the chosen method

Chapter 6 applies the method to the 2.4 GHz band

Chapter 7 presents the results from applying the method to the 2.4 GHz band

Chapter 8 describes the results of measurements used to investigate the behaviour of the model

Chapter 9 presents the conclusions drawn from the work

2 MEASURES OF EFFICIENCY

2.1 Background

There is a long history of efforts to define spectrum efficiency and yet there is no universally agreed method.

Methods developed in ITU-R and originating from the time when it was the CCIR have been continuously updated over the years with respect to different services. The most recent general material from ITU-R is contained in Recommendation ITU-R SM.1046-1, which will be addressed shortly.

More recently there has been a new interest in relating spectrum efficiency to other efficiency factors. The FCC Spectrum Policy Task Force Report, for example, identifies three efficiencies:

- “spectrum efficiency” occurs when the maximum amount of information is transmitted within the least amount of spectrum
- “technical efficiency” occurs when inputs, such as spectrum, equipment, capital, and labour, are deployed in a manner that generates the most output for the least cost
- “economic efficiency” occurs when all inputs are deployed in a manner that generates the most value for consumers.

Another source has suggested a slightly different breakdown: technical efficiency (bandwidth / frequency re-use / coverage), functional efficiency (reliability / quality / ease of use) and economic efficiency (revenue / profit / added value).

For the purposes of the remainder of this report only the technical issues associated with use of licence-exempt spectrum will be addressed.

2.2 Spectrum efficiency

Recommendation ITU-R SM.1046-1 defines spectrum utilisation (U) as:

$$U = B \times S \times T$$

where:

B = frequency bandwidth

S = geometric space (usually area)

T = time

These parameters represent the “space” denied to other users. This utilisation metric can be applied to transmitters and receivers as both deny other users “space”.

Spectrum utilisation efficiency (SUE), or spectrum efficiency, is then defined as:

$$SUE = M / U = M / (B \times S \times T)$$

where:

M = amount of information transferred over a distance

Relative Spectrum Efficiency (RSE) is simply $SUE_{actual\ system}$ / $SUE_{standard\ system}$ where likely candidates for standard systems are:

- the most theoretically efficient system
- a system that can be easily defined and understood
- a system that is widely used—a *de facto* industry standard.

While it is noted that spectrum efficiencies may be compared, it is also noted that such comparisons should be conducted with caution, especially when the systems being compared are very different. It is suggested that the comparison of spectrum efficiency should only be done between similar types of system that provide identical radiocommunication services or, for example, the same system over time (e.g. to see if there is any improvement).

In an annex to the recommendation the spectrum efficiency metric is applied to various examples, including:

- an indoor pico-cellular radio system
- land mobile radio systems
- radio-relay systems.

These cases highlight particular aspects of the spectrum efficiency metric. In the case of **indoor pico-cellular systems** the metric becomes:

$$\frac{Total\_traffic\_carried\_in\_an\_area}{Bandwidth\_used \times area}$$

which gives a result in Erlangs/MHz/km^2. The example uses the numbers of buildings in an area, the number of floors per building, the number of channels and the channel bandwidth as inputs. In addition, it is assumed that a number of Erlangs is carried per floor, the implicit assumption being the provision of voice at a particular grade of service. In the simplest case it is assumed that the traffic density and bandwidth re-use is uniform but this need not necessarily be true. Use of the formulation can be adapted up to a point to cater for variations in parameter values over an area but there will always remain some assumptions regarding uniformity even if they are at a lower level than the whole.

Similarly, for **land mobile radio systems** the spectrum efficiency metric is expressed as:

$$\frac{Total\_occupancy\_in\_area}{Total\_amount\_of\_spectrum \times area}$$

where occupancy is represented by the number of Erlangs carried[1]. The approach essentially takes the traffic generated by the different users on the same frequency in an overlapping area (where each user can be considered to support a number of Erlangs over a unit of time) and aggregates the traffic, implicitly assuming that the grade of service experienced by the different users is acceptable. The total occupancy is derived by examining the coverage of each real transmitter, taking account of transmitter and receiver characteristics and an appropriate propagation model. In addition, there is an interest in the denied spectrum, as adjacent channels of assigned frequencies cannot be used within a certain distance of the base station. The final result provides occupied and denied values of Erlangs/kHz/km^2 both averaged over an area (e.g. a whole city) and for arbitrary geographic elements (e.g. 2 km x 2 km) representing a district in a city.

In the case of **radio-relay systems** spectrum efficiency can be defined with regard to a single node (i.e. based on the number of branching links operating on the same frequency channel that can be deployed at a single site) or with regard to a network of radio relay links, whether in a radio-relay configuration or in a more random mesh deployment. Various examples are given whereby the basic spectrum efficiency metric can be used to demonstrate, among other things, that:

- digital systems are superior to analogue systems for links with smaller fade margins
- in high density random mesh networks the highest efficiency is achieved with low level modulation schemes (e.g. 4-PSK), whereas higher level modulation schemes (e.g. 8-PSK, 16-QAM) are more efficient when the network density is lower.

It is interesting to note that these radio-relay cases are good examples of the spectrum efficiency metric being used properly in comparisons (i.e. when the same functionality is being provided by different means). There is, however, a warning given in a further example looking at the relative efficiency of higher order modulations (16, 64 and 256-QAM), that it is not possible to say that modulations with higher transmission efficiencies (bps/Hz) use the spectrum more efficiently without taking account of all system design factors (antennas, signal processing, RF filters etc.).

Although the pico-cell example is based on voice traffic, there is no reason why it cannot be extended to data traffic such that the metric becomes bps/Hz/m^2 for example. It is interesting to note that a variation on this metric has been used recently in trying to demonstrate the superior performance of UWB communications

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[1] The formulation is effectively the same. Different terms have been used and there is a different treatment of the time dimension.

devices. One comparison indicates the spatial capacity (kbps/m^2) of four devices thus:

- 802.11b 1 kbps/m^2
- Bluetooth 1 30 kbps/m^2
- 802.11a 83 kbps/m^2
- UWB 1000 kbps/m^2

This comparison is flawed for two reasons. In the first instance it takes no account of the amount of bandwidth used and neither does it take account of the different link distances supported by the various technologies. It is difficult to make the necessary adjustment for bandwidth utilisation as it is not known what assumptions have been made in deriving the above figures (e.g. is the 802.11a spatial capacity based on one or more frequency channels?). The bandwidth used by UWB, as its name implies, is significantly larger than that used by the other technologies. Using the complete spectrum efficiency metric would undoubtedly make the comparison more balanced. However, returning to the link distance aspect, this comparison demonstrates why Rec. 1046 urges caution and suggests that the comparison of spectrum efficiency should only be done between similar types of system that provide identical radiocommunication services.

The difficulty in comparing radio spectrum efficiency is further illustrated by a consideration of broadcast services, where it has been suggested that a suitable metric for efficiency would be:

$$Data\_rate \times Area$$

This is the complete opposite of mobile services, where the efficiency is measured in terms of traffic per area (i.e. divided by area). It can be seen therefore that there is a conflict regarding a suitable metric for use in convergent scenarios.

It might reasonably be concluded that no absolute measure of spectrum efficiency exists, or should exist, as it is not sensible to compare different applications. However, it is sensible and possible to measure efficiency by way of comparison. That is to say, full occupancy (representing 100% efficiency) can be calculated and any other occupancy (calculated, measured or otherwise known) can be related to this in order to provide a percentage efficiency figure. Care needs to be taken that the external circumstances (e.g. the interference environment caused by other types of system) are the same in the full occupancy and partial occupancy cases.

3 LICENCE-EXEMPT USE

3.1 Deployment of devices

Licence-exempt devices are not completely uncontrolled. It is, however, important to distinguish what is and what is not controlled. Control is exercised over the emissions of licence-exempt devices through regulations that specify maximum power levels and sometimes other parameters that ensure that the potential to cause interference is minimised. Licence-exempt devices, however, are not allowed to claim protection from other radio systems and are not allowed to cause harmful interference into licensed radio services even when operating in accordance with the specified operating limits.

Most importantly, from the point of view of this work, these devices are not controlled in terms of their deployment, except when there may be an indoor-only restriction (e.g. some parts of the 5 GHz band).

The importance of this aspect to the modelling relates to the potential treatment of systems when deciding their location, and in particular to the difference between *ad hoc* systems and planned systems. Because of the absence of any knowledge about where a system will be deployed, it is appropriate to use random location techniques in the modelling. In the case of a planned system (i.e. one that consists of a number of cells in a particular configuration due to frequency sharing constraints) it is clearly not appropriate to randomise the locations of the different base stations or access points in the system. For a planned system, it will be the system that is randomly located rather than individual devices (as would be the case in an *ad hoc* network).

3.2 Other characteristics

It can be seen from the previous discussion on spectrum efficiency, as defined in Rec. 1046, that the utilisation aspect, which can also be regarded as denial to others, covers the three dimensions of frequency, space and time. These dimensions all need to be considered when looking at how the spectrum efficiency of licence-exempt devices can be determined. Some of the particular characteristics of licence-exempt devices relating to these dimensions are described below.

Frequency

Many systems have fixed channels that can be used and it will be necessary to determine the degree of frequency overlap and hence potential for interference. However, operation under licence-exempt conditions has led to so-called “polite” technologies becoming more common. In particular, the use of dynamic frequency assignment or selection is being implemented not only to facilitate sharing with other services but also to enable the coexistence of similar systems.

Space

Apart from the separation afforded by signal decay with distance, separation in the space dimension is mainly achieved through the use of antenna technologies. For the types of system likely to be deployed on a licence-exempt basis, it is also the case that frequency re-use will be aided by the nature of the applications (i.e. short range, low power and, when used in the indoor environment, by the isolating effects of walls, ceilings and other partitions—potentially frequency-selective surfaces in the future).

Time

In the time domain there are two different levels that need to be considered when trying to determine whether one device might interfere with another.

At the macro level there is the device activity, which is defined by the relationship between the amount of data that needs to be sent and the throughput provided by the system. For many applications, where relatively small amounts of data need to be sent, the activity will be 1% or less. For more intensive applications like video streaming, the activity could be significantly greater.

At the micro level there is the packetisation of data and the access and acknowledgement protocols that need to be considered. Collision avoidance techniques need to be considered as well. Overall, these protocols can lead to a reduction of up to 50% when comparing the throughput as seen by the user with the instantaneous transmit data rate.

Signal

Even when signals overlap each other in one or more of the frequency, space and time dimensions, there are a number of other techniques that can be used to mitigate the potential for interference. In the context of licence-exempt operations it is reasonable to expect some or all of these techniques to be used in order to make life easier in the inherently anarchic radio environment of licence-exempt spectrum.

- Spread spectrum (Frequency hopping / direct sequence / OFDM), which is used as a matter of course by most applications.
- Automatic power control.
- Adaptive modulation / FEC, whereby the throughput is adjusted to match the radio link quality.
- Multiple-In, Multiple-Out (MIMO), whereby signal processing is able to combine and/or discriminate between signals simultaneously.

4 APPROACHES TO MODELLING

This section presents a review of the various approaches that could be used to evaluate spectrum percentage occupancy, concluding with the model that we consider to be most applicable for licence-exempt allocations.

4.1 Modelling methods

Evaluation of spectrum occupancy using analytic methods can only be achieved in highly restricted and constrained scenarios. It is likely that the method to be developed will require an approach based upon a more general model.

A whole range of modelling methods have been used in previous studies. Each study has approached the problem in a slightly different way, but it is possible to group and classify them to gain an understanding of the choices made. Each choice involves some form of compromise—no study has modelled all aspects of the problem. One key choice is the type of output produced: for example, separation distance, level of interference, probability of interference, or locations free.

The figure below shows the most significant categories of model:

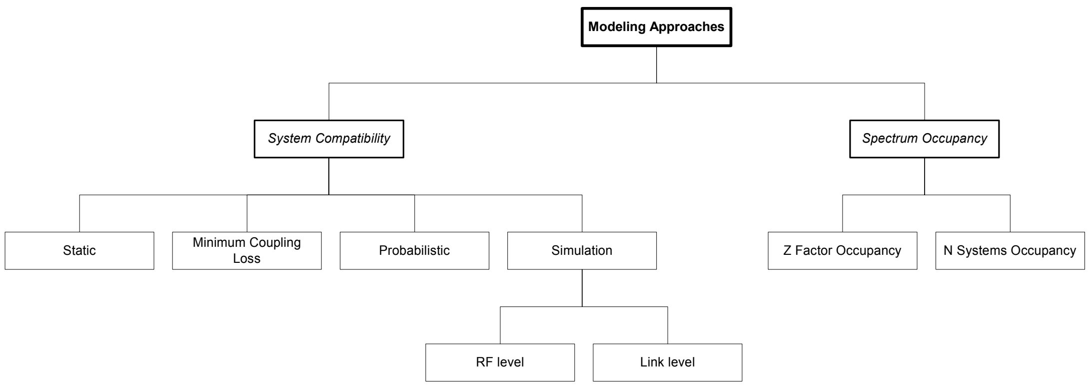

Figure 1: Types of modelling approach

At the top level these are split into two types:

> **System compatibility**: models used to determine whether two or more systems or types of system can operate simultaneously (either in-band or out-of-band) without causing unacceptable levels of interference.
>
> **Spectrum occupancy**: models used to determine whether spectrum is occupied.

While there have been system compatibility studies at 2.4 GHz, these have not produced information about spectrum occupancy. On the other hand, while there have been some spectrum occupancy studies, these have not been based on the 2.4 GHz band or have used systems that differ from those that typically operate in the band.

Therefore it is likely that any method will require aspects to be taken from both system compatibility and spectrum occupancy methods, which are discussed in more detail below.

4.1.1 Static

An example of the "static" approach is given in "Understanding Wireless LAN Performance Trade-offs" by Jung Yee and Hossain Pezeshki-Esfhani published in Communication System Design. This compares the performance of the 2.4 GHz 802.11b standard with the 5 GHz 802.11a standard using simple geometry to calculate the intra-system signal-to-noise ratio (i.e. between access points). Calculations are made at a single, static, worst-case location within a set of cells based upon constants such as transmit power and out-of-band attenuation.

For both the wanted and receiving signal, the strength is calculated using:

$$S_{RX} = S_{TX} - L_p$$

where:

S_{RX} = signal power at the receiver (dB)

S_{TX} = transmit power or EIRP (dB)

L_p = path loss (dB)

As the output is the C/(N+I) for the worst case, it can be compared against the threshold level needed to achieve a BER < 10^{-5} for various modulations, using standard graphs of BER vs E_b/N_o to determine whether or not the required data rate would be available for all locations.

This approach has the benefit of simplicity, but requires significant assumptions that would make it difficult to extend to general scenarios.

4.1.2 Minimum Coupling Loss

The Minimum Coupling Loss (MCL) approach calculates the required loss to protect a receiver of one system from the transmitter of another, as in the equation below:

$$MCL = P_{RAD} - P_{RX} + C/I$$

where:

P_{RAD} = Radiated power (EIRP) for interfering transmitter (dB)

P_{RX} = Wanted system received power (dB)

C/I = Carrier to interference ratio required for wanted system (dB)

Other factors can also be included (gains, feeder losses, bandwidth factors etc.).

This loss can be converted into the separation distance and/or frequency offset required to avoid such interference.

An example of the MCL approach is given in ERC Report 109, "Compatibility of Bluetooth with other existing and proposed radiocommunication systems in the

2.45 GHz Frequency band". For various sharing scenarios involving Bluetooth and other systems, distances are calculated based upon required C/I values for co-channel or adjacent channel operation.

As with the static approach, while there are benefits in its simplicity, there are significant limitations, such as the difficulty of including multiple transmitters, and the calculation of other measures of the impact of interference (including the probability of interference).

4.1.3 Probabilistic Method

The use of probabilistic methods to assess the efficiency of spectrum utilisation is promoted by **Recommendation ITU-R SM.1271**. However, the two examples contained in the recommendation do not really give a full indication of probabilistic methods that can be used. A good example of one of the more common techniques used, whereby Monte Carlo sampling is applied to one or more distributions, is the CEPT SEAMCAT software.

The probabilistic method can be used to extend the scope of the MCL approach described above, as shown in ERC Report 109. A distance is calculated by the MCL technique, beyond which it is assumed transmissions from other systems would not cause interference. The number of possible interfering transmitters is then calculated using, for example, a uniform density over the area of a circle with a radius of the specified distance.

The probability of interference is then derived by combining the probability of various overlaps in time, geography and frequency. For example:

P_{OL_TIME}: unwanted transmitter active at the same time as the wanted receiver

P_{OL_GEOG}: coupling between main beams (where there is significant antenna directivity)

P_{OL_FREQ}: bandwidth overlap between wanted and unwanted systems.

The total probability of interference is then calculated using:

$$P_{INF\_TOT} = 1 - \prod_{N_{INT}} \left(1 - P_{OL\_TIME} P_{OL\_GEOG} P_{OL\_FREQ}\right)$$

where N_{INT} is the number of interferers calculated to be within the distance derived using the MCL method.

These factors (in particular, the probability of overlaps in time and frequency) will depend upon the data unit being measured—bit, packet, or a higher level unit such as a file transfer. So, an example output could be "probability of packet error".

From these statistics ERC Report 109 suggests that other variables can be deduced. For example, the relative impact on throughput will be affected by the probability of packet loss for the data packet and the ACK packet, and hence calculation of the probability of success involves squaring the $(1–P_{err})$ term.

A suitable formula is then:

$$R = P_{on}\left(1 - P_{err}\right)^2$$

where:

R = throughput ratio

P_{on} = probability that the interferer is active (duty cycle)

P_{err} = average packet error due during on time

Note: this equation includes the probability that the repeated ACK is also errored and so on, as the equation includes a series summation.

A similar approach was used in the paper "Reliability of IEEE 802.11 Hi Rate DSSS WLANs in a High Density Bluetooth Environment", Zyren, Intersil Corporation. This document does not describe the equation used to calculate impact on throughput, but it appears only to consider the probability of interference into the ACK packet not the data packet, i.e.:

$$R = \left(1 - P_{err}\right)$$

The probabilistic method approach is limited because:

- it ignores the aggregate affect of transmitters outside the MCL distance
- the probability of packet error will depend on the packet size, and data packets and ACK packets are not likely to be the same size
- it assumes that all interferers have the same characteristics (e.g. degree of main-beam antenna alignment)
- it is difficult to include a range of effects (e.g. the in-band MCL distance is likely to be different from the out-of-band MCL distance, which makes it hard to include both simultaneously)
- it generates only a single point on the interference vs probability curve.

4.1.4 Simulations

The limitations with the methods described above have led many to consider detailed simulations of sharing scenarios. These attempt to describe the actual behaviour of the radio systems under consideration in as much detail as considered necessary.

Two approaches are often used in simulations:

Monte Carlo: in which input parameters are defined by a distribution of possible values which is repeatedly sampled during the simulation, and often implies lack of information about the state of the simulation at a previous sample. An example would be location of mobiles within a base station sector.

Time sequence: in which events at each sample depend upon the state of the simulation at a previous sample. An example would be modelling a data transfer, where a station must continue to transmit until the required number of packets has been sent.

These are often combined and layered. For example, there could be random sampling of the service area (Monte Carlo) and at each sample point a time sequence simulation is performed to calculate interference vs probability of interference at that location.

A large number of simulations have been done at 2.4 GHz and related bands that provide lessons on how to model such systems. A key factor is the level of detail to be considered, which typically means whether a communication system is described solely at the radio-frequency (RF) level or includes link level information (for example at the MAC level).

Components and examples of these two are described in the following subsections.

4.1.4.1 RF level

An RF level simulation calculates the impact of interference at the receiver from potentially multiple sources, taking account of factors such as:

- station locations
- transmitter power
- transmitter gain patterns
- transmitter locations
- power control and limits (if used)
- propagation model
- environment such as clutter
- feeder losses
- receiver gain patterns
- receiver noise temperature.

From factors such as this, link budgets are derived for wanted and interfering signals, which are combined with interference adjustment factors such as:

- coding gains
- bandwidth adjustments
- polarisation adjustments
- filter masks
- out-of-band power mask.

Interference can then be measured in terms of I, I/N, C/I, or C/(N+I) or converted into BER using standard curves for the modulation involved.

By repeating this process many times (whether using Monte Carlo or time sequence techniques) a distribution of interference vs probability can be generated and compared against requirements. The time sequence approach can operate at the level of milliseconds, modelling bursts and packet exchange or over longer periods, modelling station motion.

Examples of this approach include:

- ITU-R TG 1-8/18: “The effects of UWB on UMTS Operating in Localised (Hot Spot) environments”. This paper includes two methods, the first being an RF level model, which includes a detailed description of an office environment and then randomises the UMTS location and UWB activity between samples based upon probability distributions.
- IEEE 802.15-00/308r0: “BT and 802.11 PHY Model (Stage 0)”, which analyses interference between 802.11b devices and Bluetooth. Interference is calculated in terms of C/(N+I) and then converted into BER using equations such as:

$$BER = \sum Q\left(\sqrt{2.SNIR.R_c.W_m}\right)$$

The statistics of BER can be the primary output, or instantaneous BER can be used in a higher link level simulation to assess whether the model should switch a bit, as in the figure below.

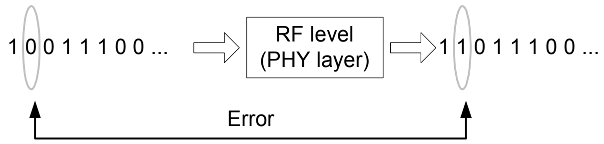

Figure 2: PHY layer bit error model

- “Compatibility between radiocommunication & ISM systems in the 2.4 GHz frequency band”, by Aegis Systems for the Radiocommunications Agency. This derived cumulative distribution functions of interference for a range of sharing scenarios using Monte Carlo techniques such as randomly distributing user terminals.

Some higher level properties can be deduced. For example, it is possible to derive the PER from a distribution of BERs, and determine how the PER impacts the throughput. This can be used to provide an insight into the impact of interference on higher level measures, such as throughput, while undertaking analysis at the radio level.

This approach is generally very successful in analysing compatibility issues. The only reservation is that the introduction of complexity reduces the ease of use of the model, and the degree to which higher levels of a protocol impact the results needs to be carefully analysed. The latter issue is described further in the following section.

4.1.4.2 Link level

Link level analysis takes account of elements of the protocol stack above the RF level, such as the signalling exchanges required to transfer data. This can build upon a lower level RF simulation, or be based upon various assumptions about error rates. Working at a higher level allows network concepts like jitter to be used as measures of performance.

For example, the study “Interference Evaluation of Bluetooth and IEEE 802.11b Systems” by Golmie et al. of the National Institute of Standards and Technology builds upon the PHY model described in the previous section to model the impact of interference on the data and signalling packets. The principal output in this study is the probability of packet loss under such circumstances.

Another model is described in “Study into the Effects of Ultra Wide Band Technology on Third Generation Telecommunications”, by Mason Communications for the Radiocommunications Agency. This used a 3G planning tool to perform a Monte Carlo analysis that derived QoS statistics such as Block Error Rates and probability of success.

While the link level approach can be very powerful, the level of detail required makes models extremely scenario specific, and generalisation would require significant levels of resources.

4.1.5 Z Factor Occupancy

An algorithm to determine spectrum occupancy is given in ITU-R Recommendation SM.1599, “Determination of the geographical and frequency distribution of the spectrum utilization factor for frequency planning purposes”. The objective of the method is to determine the likelihood that it would be possible to introduce a new system within a defined area without causing or suffering unacceptable levels of interference.

This is done by sampling points across the area and at each point determining if a new system could be introduced at that location. The metric, Z, is then the ratio of those points for which it would not be possible to introduce a new system to the total number of points considered. This can be done by frequency band, or averaged over all frequency bands to get an aggregate value.

Hence:

$$Z_i = \frac{M_i}{N_p}$$

where:

M_i = number of test points for which interference would be above the given threshold for frequency “i”

N_p = number of test points considered

Z_i = probability that a new system could not be introduced in the test area with frequency "i"

This can then be averaged over all frequencies using:

$$Z = \frac{1}{N_f}\sum_i Z_i = \frac{1}{N_f N_p}\sum_i M_i$$

where:

M_i = number of test points for which interference would be above the given threshold for frequency "i"

N_p = number of test points considered

N_f = number of frequency bands considered

Z = probability that a new system could not be introduced in the test area

Full occupancy is reached when Z = 1, which is when it is not possible to add any more systems at any location at any frequency band.

An example is given of introducing a PMR system as in the figure below, where the test points are shown as crosses and existing PMR systems are shown as dots. The area under consideration is the rectangle at the bottom left of the larger area.

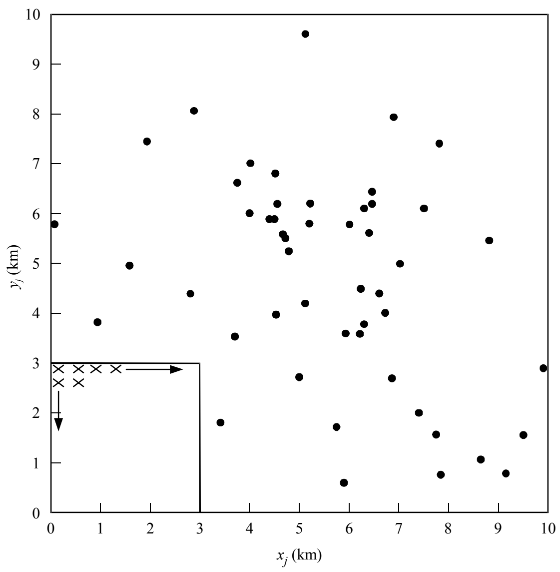

Figure 3: Sampling locations using algorithm in Rec. 1599

It should be noted that this method does not define how to determine whether a specified location and frequency would suffer acceptable or unacceptable levels of interference, though reference is made to ITU-R Recommendation SM.337, "Frequency and distance separations". Hence the method could in principle be applied to many types of system.

4.1.6 N-Systems Occupancy

The Z Factor Occupancy method described above gives a metric, Z, as follows:

Given: A known deployment of existing systems

An area of interest

Derive: Z = likelihood of not being able to introduce one new system into that area

A band is therefore fully occupied when no more systems can be introduced. However, this method has as its input a deployment of existing systems, and is therefore less useful for unplanned bands where system locations are not known.

A method to determine what would constitute full occupancy of a band is described in a paper presented to the IEE, "Analysis of the spectrum efficiency of sharing between terrestrial and satellite services", Pahl. This method is also based upon an area of interest, but systems continue to be added at random until no further locations can be found for which interference levels in any direction are acceptable. The result is then N_A, the total number of Type A systems that could be introduced, based upon initial conditions, which can include the existence of other systems.

If systems are added at random, then the outcome of each run can be different. The result of a set of runs becomes a distribution, with mean and variation, as shown in the figure below.

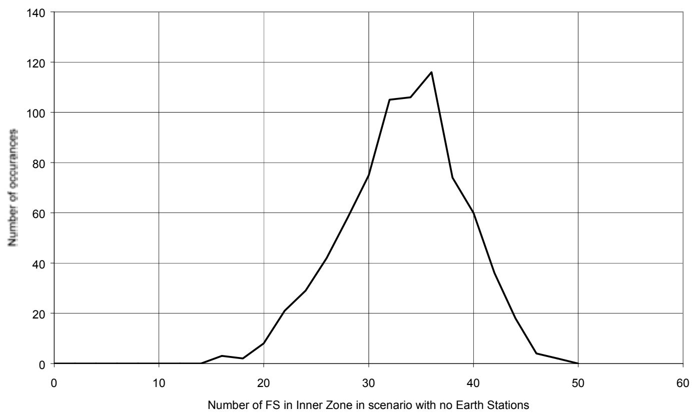

Figure 4: Histogram of number of FS introduced

The method includes a concept of inner and outer zones, where only the number of systems in the inner zone contributes to the answer, with the outer-zone systems being included to avoid bias due to the beneficial effects of lower interference at the edge of simulation zones[2]. These zones are shown in the figure below, for an example based upon sharing between point-to-point FS and receiving Earth Stations.

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[2] Alternatively the wrap-around method, commonly used for UMTS simulations, could be employed. This would also avoid edge effects and potentially save on processing.

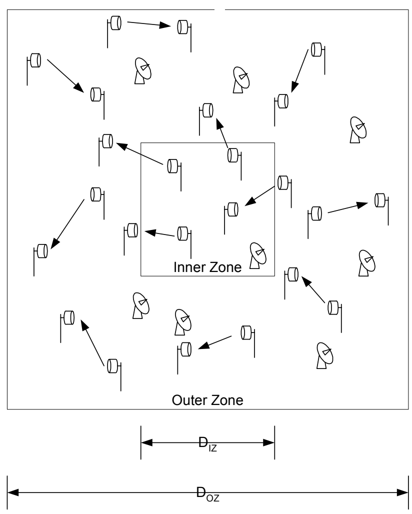

Figure 5: Example of inner and outer zones

By adding into the initial conditions N_B systems of another type (i.e. Type B) then the need to protect them and avoid unacceptable interference from them reduces the locations at which new Type A systems can be introduced. Therefore the mean number of Type A systems, N_A, is reduced, and the paper suggests there could be a relationship such as:

$$N_A(N_B) = N_A(0) - k_{AB} N_B$$

In other words, the impact of adding N_B Type B systems is that the mean number of Type A systems that can be introduced is reduced by $k_{AB}N_B$.

This approach would allow the comparison of spectrum efficiency in an environment populated by a number of other types of system by comparing various values of N.

4.2 Conclusions

This section has reviewed a number of methods of determining spectrum occupancy and simulating sharing scenarios for the bands under consideration. Of the two methods identified for determining spectrum occupancy the N-Systems approach is considered more applicable to this study as it:

- is general—almost any type of system can be modelled
- is flexible—the level of detail used in analysis can be selected as required
- can include multiple sources of interference, including intra-system and inter-system, in-band and out-of-band
- allows measures of both occupancy and efficiency to be derived.

For these reasons, the N-Systems method was selected for further consideration.

As noted above, the N-Systems approach includes analysis of compatibility, and so a modelling approach must also be selected from the system compatibility methods identified earlier in this section.

5 THE N-SYSTEMS METHOD

All use of the radio spectrum has to some degree an impact on other users, as transmissions cannot be stopped, only attenuated by separations in the dimensions of time, space, frequency and code. This impact usually results in a degree of degradation or the imposition of a restriction on one or both systems. A key question is how to quantify or cost the impact of one system upon another.

One way to manage use of the radio spectrum to facilitate operation of different radio systems is to split the frequency domain into bands, within which allocations to various services are made. Some allocations are made to single services, to permit homogeneous deployment of a single system in the space domain. For example, mobile operators are given licences to deploy base stations as required to provide the necessary coverage and service levels. Such systems are planned, with a density of base stations that varies depending upon the predicted levels of traffic. A well-designed network can be fully loaded at any cell, and as such could be thought to have full spectrum occupancy at the local busy hour. However, capacity can always be increased by the use of cell-splitting techniques, and so there is balance between cost and capacity.

Even for situations where only a single service operates at a location in a certain band the service must accept interference from other services (e.g. satellite, other bands, other locations and systems such as UWB that operate across many bands). This interference impacts on homogeneous services by reducing the capacity and/or coverage or requiring additional base stations. There is therefore a cost that can be derived from permitting certain levels of interference.

The situation is different in bands where systems are deployed in a non-homogeneous way. For example, PMR systems are deployed where there is a request for a licence and where it can be issued without impacting existing licensees. Each system requires access to a specific limited area, rather than wide-scale homogeneous coverage.

The licence-exempt or unplanned bands are similar: users will install and operate equipment at almost any location without consultation with any other user of the spectrum in order to provide a local service. It is a key characteristic of licence-exempt bands that the equipment approved for operation should be limited in power to provide a short-range service. This allows significant re-use in the geographic domain in those frequency bands allocated to such services. Within a particular location and at a specified frequency there can also be re-use in the time and code dimensions.

The impact of interference is that users will be unable to operate over the required coverage area, and hence fewer systems will be able to operate within a specified area. This will result in an opportunity cost—the number of Type A systems that can be introduced will be affected by the number of other systems (Type B, C, D etc.) that exist within a defined environment.

Therefore in frequency bands where systems are restricted by licence constraints to operate within a limited area or only over a short range it is possible to analyse whether a band is occupied within a geographic region by determining how many systems can be deployed successfully. A band and geographical area is fully occupied when no further systems can be deployed. The number of systems of different types that can be deployed can then be compared, and the relative efficiency in their use of spectrum determined.

This approach, the N-Systems method, has been selected as the basis of this study as being most applicable to the licence-exempt bands.

5.1 Model Description

Section 4.1.6 above describes an approach that can be used to determine spectrum occupancy in licence-exempt bands. In this section we describe the method in more detail and show how it would be applied to a typical scenario.

The figure below shows a flow chart of the N-Systems method.

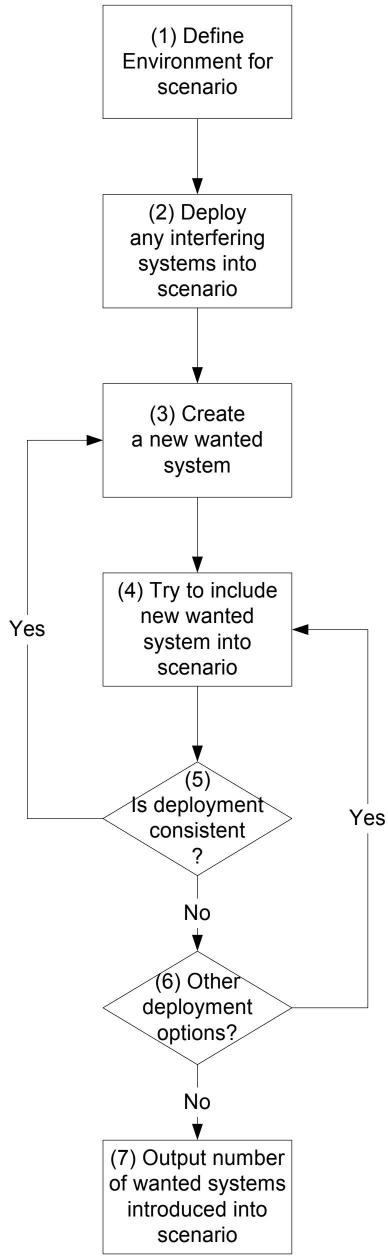

Figure 6: Method to calculate N-Systems

The method is built upon the concept of a system, which could involve one or more transmitters and receivers; to be applicable to the N-Systems method the system should be limited in geographic extent.

The method is based on the following key stages:

1) Define the environment to be considered (i.e. the frequency band, the systems to be analysed, the geographic area of interest and the propagation model).

2) Deploy a set of interfering stations, located and pointed at random. Ensure that the deployment is consistent.

3) Create a new wanted system and deploy it according to the required deployment scenario.

4) Calculate the interference from all other systems into the new wanted system and update the aggregate interference into other wanted systems. If no wanted system suffers interference then continue to try to add wanted systems.

5) When interference into any of the wanted systems exceeds the threshold try another location for the new wanted system.

6) If after a fixed number of attempts it was not possible to find a location for which the interference threshold is not exceeded then the algorithm terminates and the number of wanted systems introduced (N_{sys}) is obtained.

The result is the total number of wanted systems that could be introduced co-frequency with other systems operating at a particular location. The method can be repeated to generate a set of values for a required number of trials.

By applying the method to a range of sharing scenarios different values of full occupancy are derived. It is then possible to arrive at a comparative measure of spectrum occupancy.

5.1.1 Definition of environment / deployment

The first stage of the method is to define the environment to be considered:

- Select the frequency band to consider.
- Define the wanted system characteristics (e.g. antenna gain, noise temperature, interference criteria).
- Define the interfering system(s) characteristics (e.g. antenna gain, transmit power—including transmit power control—and bandwidth).
- Define the deployment scenario for both wanted and interfering system(s). Stages (2) and (4) of the method require systems(s) to be deployed into the model. Systems can be placed at any location within the area of interest independently of any other system. This implies a random, or quasi-random deployment, rather than a planned or systematic approach to provide homogeneous coverage.

  Random deployment can mean either that all locations are equally likely to be selected, or to include a bias towards certain locations. In other words the probability density function of the likelihood of deployment could be uniform across the required area or vary depending upon factors such as population density. When considering systems within an area it is important to avoid edge effects (discussed in Annex A).

The N-Systems model could also be used to analyse the occupancy in a band where systems have already been deployed. In this case, the stations could be initially deployed based on actual system locations and, after that, deployment could then be random or quasi-random. For example, to determine occupancy in a PMR band that is already partially used, the first set of systems deployed could have the characteristics of the existing systems.

- Select the appropriate propagation model.

5.1.2 Consistency / compatibility check

Step (5) of the model involves a check that the systems have been deployed in a way that is consistent with all the requirements of all systems in the model. This will vary depending upon the type(s) of system being deployed, but is likely to involve a check that interference levels are not exceeded. Interference can be between systems of a different type (inter-system interference) or between systems of the same type (intra-system interference). This interference can come from in-band and/or out-of-band emissions.

Two choices must be made to calculate the interference levels:

1) the modelling approach to use

2) the level of detail required

Some options for modelling sharing system compatibility were discussed in Section 4.1. Of those considered the most appropriate is the simulation approach, as it has as its input system characteristics such as deployment location, which is also used in the N-Systems method.

The level of detail required to determine whether the deployment is consistent—i.e. that interference levels are acceptable—will vary depending upon the types of system involved and the degree of detail required. While in general more detail is beneficial, there are always resource constraints on any study, and excessive detail can lead to a loss of clarity in the method and an increased likelihood of errors.

A judgement will have to be made when implementing the N-Systems method as to the appropriate level of detail, e.g. whether based upon I/N, C/I, C/(N+I), or higher level characteristics of the communication protocols used. The decision can be aided by considering what would be suitable thresholds for interference: for example, for some bands and services there are well defined I/N thresholds, whereas for others the criterion might be BER. These thresholds could also be defined as single entry or aggregate interference thresholds.

Consistency could also include other factors such as minimum separation distance between stations. In practice, physical constraints such as equipment size and location mean that there will be a minimal separation between interfering transmitter and wanted receiver, which must be enforced within the model.

Some examples of how to decide on consistency are given below.

Example 1: HD-FS sharing with HD-FSS ES

The figure below shows a simple deployment with two FS systems and three ESs.

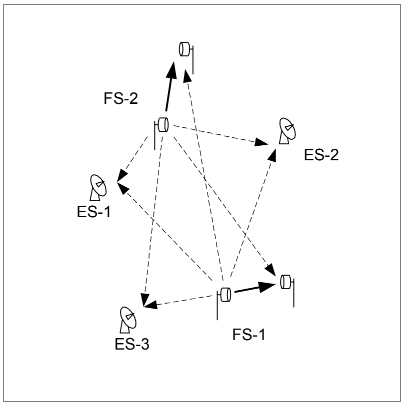

Figure 7: Interference paths for example FS-ES deployment

It can be seen that there are two types of interference paths:

a) from all FS into each ES

b) from all other FS into each FS

The aggregate interference limit in both cases is I/N = –10 dB, and so simulation is done to check consistency by calculating the aggregate interference for path a) and for path b) and then comparing against the threshold. As all transmitters and receivers can be active 100% of the time there is no need to model in the time or code dimensions and so the simulation only needs to derive a single aggregate I/N for each receiver.

Example 2: Bluetooth into WLAN

The figure below shows a simple deployment with two WLAN networks and 7 Bluetooth systems; both WLANs are transmitting to devices in their service areas.

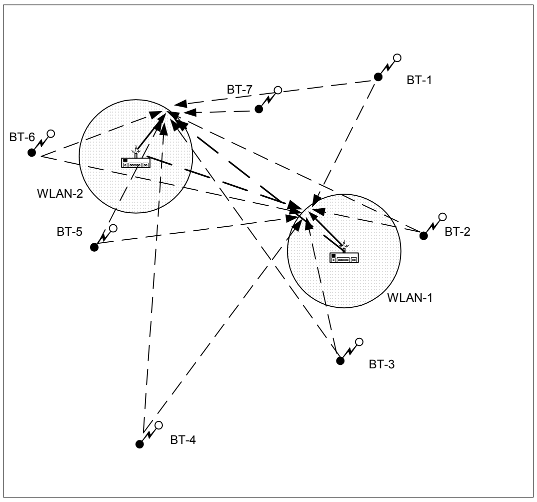

Figure 8: Interference paths for example WLAN-BT deployment

In this example there is a single type of interference path:

a) aggregate of interference into any point in any of the WLAN service areas from all the BTs and from all the other WLANs

Simulation is likely to require more analysis than for the previous FS-ES case. For example, it is likely to be necessary to sample from a set of WLAN service area locations (either at random or on a grid within the service area or around its rim). At each of these points the simulation is required to determine if the test point is usable. This could involve a single calculation of aggregate I/N or a more detailed determination of the aggregate C/(N+I) from all BTs and the other WLAN, taking account of:

- activity ratios (percentage of time device transmits)
- frequency hopping (how often BT is co-frequency with WLAN)
- path losses
- power control (if used)
- EIRPs.

The resulting C/(N+I) distribution could then be used to derive PER and hence the impact on throughput, which can be compared against requirements. A similar calculation could be performed on the uplink direction (i.e. into the WLAN access point).

5.1.3 Output from the model

The result of the N-Systems method is the number of systems that can be introduced into a given geographic area in a way that is consistent with their operating requirements. As deployment is random, the result could vary depending upon the sequence of random numbers generated. Therefore the output is likely to be a mean and distribution, rather than single number.

This information can be used in a number of ways, as described below.

5.1.3.1 Determine percentage spectrum occupancy

The output from the model is N_A, the mean number of Type A systems that can be deployed in an area without suffering interference. Thus if the number, n, of actual systems within a particular area is known, then the percentage occupancy, P_O, can be calculated as:

$$P_O = 100.\frac{n}{N_A}$$

As N_A is the mean of a distribution, P_O also has a range determined by the standard deviation of N_A.

5.1.3.2 Determine percentage spectrum occupancy in presence of interference

A similar calculation of the percentage spectrum occupancy can be derived that takes account of the fact that Type A systems are being deployed in an environment where there is interference:

$$P_O' = 100.\frac{n}{N_A'}$$

where N_A' is the mean number of Type A systems that could be introduced into an area in the presence of a defined deployment of interfering systems (e.g. BT devices at a specified density).

5.1.3.3 Determine relative spectrum cost of one system compared to another

The impact of adding interfering Type B systems into the initial conditions of a scenario is likely to be a reduction in the number of Type A systems that can be introduced.

If there is a linear relationship between the relative cost of one system compared to another, then:

$$N_A(N_B) = N_A(0) - N_B\alpha_{AB}$$

i.e.

$$\alpha_{AB} = \frac{N_A(0) - N_A(N_B)}{N_B}$$

This ratio gives the relative cost of Type B systems using the spectrum in terms of Type A systems.

This is a measure that can be used to compare the cost of spectrum used by different types of system and service, and hence get a measure of efficiency.

More complicated relationships could be considered when introducing multiple interfering systems, e.g.:

$$N_A(N_B, N_C) = N_A(0) - N_B\alpha_{AB} - N_C\alpha_{AC}$$

5.1.3.4 Determine relative spectrum cost of particular technologies

The spectrum cost of a particular technology (modulation, antenna etc.) can be derived by comparing the number of systems that can be introduced into the specified geographic area with and without the technology. For example, suppose:

N_{A_1} = number of Type A systems that can be introduced into a certain geographic area using modulation 1

N_{A_2} = number of Type A systems that can be introduced into a certain geographic area using modulation 2

Assuming that all other aspects of each system are kept constant (service area, BER requirement, traffic type etc.) then the impact of using the different modulations can be compared by the ratio:

$$\beta_{12} = \frac{N_{A_1}}{N_{A_2}}$$

This can be used as a measure of the efficiency in the absence of interference, where "efficient" is taken to mean that more systems can be introduced in a consistent way into a given area.

The efficiency in the presence of interference can be determined by comparing the values of N_A and α_{AB} for the two technologies.

5.2 Example application—WLAN deployment scenario

This example shows how the N-Systems method would be applied to assess the impact on a WLAN of the deployment of other devices, in other words to derive the reduction in the number of WLAN devices that can be deployed due to interference from systems such as Bluetooth and Outside Broadcast[3].

Hence:

- Wanted system: WLAN
- Interfering systems: Bluetooth (BT) and Outside Broadcast (OB)

In this example we are considering only the interference from BT and OB into WLAN, and hence other interference paths (e.g. from WLAN into BT and between OB and BT) are ignored.

5.2.1 Run with no interferers

The first stage is to determine the number of WLAN systems that could be deployed if there were no other systems using the band, i.e. $N_{WLAN}(0)$.

Stage 1—Define environment for scenario

The size of the area needs to be chosen to represent the types of deployment of interest and at the same time ensure statistically meaningful numbers.

It is also necessary to define the propagation conditions within the scenario both for the wanted links and the interfering paths, where the propagation conditions may or may not be different.

Stage 2—Deploy interfering systems

No action required in this run, as only the wanted system is being considered.

[3] An example application to a PMR scenario is given in Annex B.

Stage 3—Create a new wanted system

For the purposes of the simulation, a WLAN system is defined with characteristics such as:

- a central access point (AP) with defined EIRP, power control characteristics, bandwidth, frequency etc.
- a number of receivers having characteristics such as gain, noise temperature
- service characteristics such as coverage and performance requirements.

While two link directions are feasible (downlink from AP to user and uplink from user to AP) only the downlink direction is considered further in this example.

Note: WLAN technology can also be used to create an *ad hoc* network between two computers. This would be defined with different characteristics: for example, there would be two station locations instead of a service area and hence a different $N_{adhoc}(0)$ would be calculated.

Stage 4—Try to include wanted system into scenario

It is assumed that users deploy WLAN systems at random, with no planning involved as this is an unlicensed band. Hence the result after deploying eleven WLAN networks could be similar to the figure below.

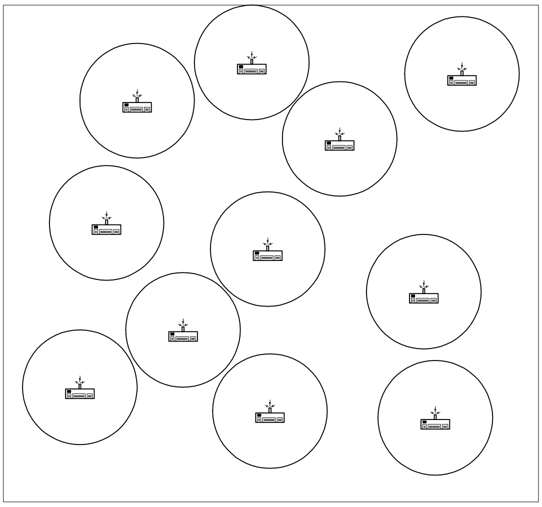

Figure 9: Random deployment of WLANs

Stage 5—Is deployment consistent?

In this case the issue is whether the systems can operate without intra-system interference. This could require detailed simulation of interference paths between WLAN networks taking into account issues such as:

- service area over which reception must be ensured
- EIRP, bandwidths, frequencies etc.

- activity ratios
- power control (if used)
- interference reduction.

The interference threshold could be a simple C/I > 10 dB or a more complicated measure, such as:

C/(N+I) > X dB for Y% of time for at least Z% of locations

Or a higher level measure, such as:

PER < Q % for at least Z% of locations

Stage 6—Are more locations feasible?

If a position has been selected for which the deployment would not be consistent (as at least one WLAN would suffer interference) then another position could be selected at random across the area. However, after a certain number of locations are tried without success (for example 20 or 100 locations) then it can be concluded that it is not possible to introduce more WLAN devices.

Stage 7—Count number of wanted systems introduced

This would be the total number of WLAN systems operating on a particular frequency that have been introduced into the environment without intra-system interference and maintaining the desired quality of service across the required cell size, i.e. $N_{WLAN}(0)$.

5.2.2 Run with BT and OB interferers

The next runs are to determine the number of WLAN systems that could be introduced if other systems are already deployed in the band—N_{WLAN}(2 OB, 20 BT), for example. Apart from the addition of other systems to the scenario, all other aspects of the model should be unchanged (system characteristics, interference thresholds etc.).

Stage 1—Define environment for scenario

This should be unchanged from the run with no interferers, using the same area and propagation models.

Stage 2—Deploy interfering systems

A number of OB masts and BT networks are deployed across the scenario, for example as shown in the figure below.

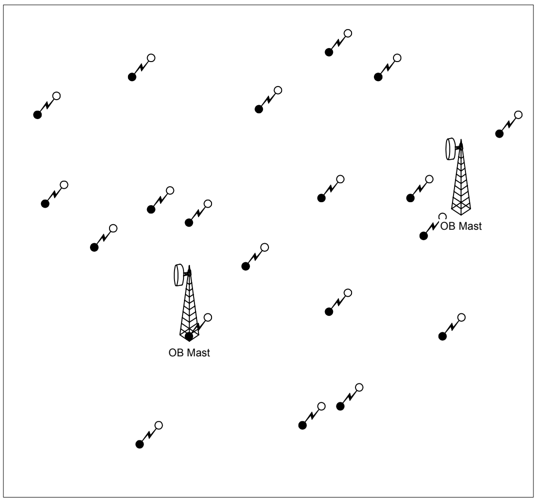

Figure 10: Deployment of interfering BT and OB systems

Stage 3—Create a new wanted system

The WLAN system should be defined in the same form as for the first run.

Stage 4—Try to include wanted system into scenario

WLAN systems are introduced at random into the scenario, as shown in the figure below.

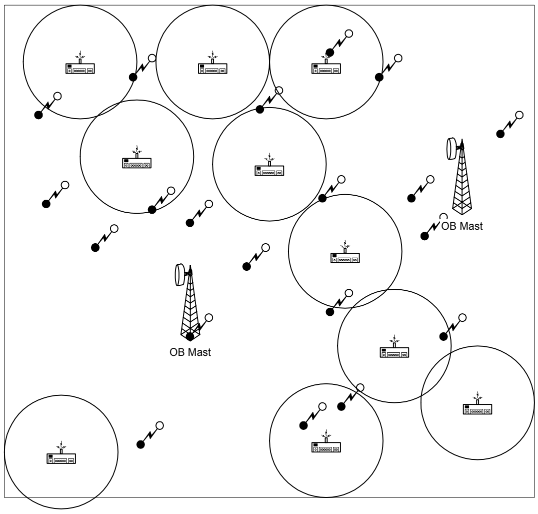

Figure 11: WLANs with interfering BTs and OB

Some minor adjustment might be required (e.g. to force a minimum separation distance between systems).

Stage 5—Is deployment consistent?

In this case the issue is whether the WLAN systems operate without interference across their deployment area. This requires interference calculations with a sufficient level of detail to model the BT and OB transmitters and their impact on the WLAN receivers across the wanted service area.

The same measure of interference should be used, but the calculation will have to be updated to include all sources of interference, including the newly added BT and OB transmitters.

Stage 6—Are more locations feasible?

An identical approach to determine whether more locations are feasible (e.g. try 20 or 100 times to find a new location selected at random) should be used as for the first run.

Stage 7—Count number of wanted systems introduced

This would be the total number of WLAN systems operating on a particular frequency that have been introduced into the environment while avoiding interference and maintaining a useful cell size, namely N_{WLAN}(2 OB, 20 BT).

5.2.3 Use of results

The two runs give an indication of the relative cost of spectrum for the introduction of 2 OB stations and 20 BT devices. If there is a linear relationship between numbers of different types of system then this gives the equation:

$$N_{WLAN}(2,20) = N_{WLAN}(0) - 2\alpha_{WLAN,OB} - 20\alpha_{WLAN,BT}$$

From a number of other runs the α factors can then be derived for WLAN and OB and for WLAN and BT.

Further measures of spectrum occupancy and efficiency could be derived, as described in the section above.

6 APPLICATION OF THE N-SYSTEMS METHOD TO 2.4 GHZ

6.1 Key issues

Before applying the N-Systems method to the 2.4 GHz licence-exempt band, in particular considering WLANs as victim systems, there are some important issues that have to be addressed in detail. The most important of these are the interference criterion that is used for the consistency check and the modelling of the propagation environment, both of which are inextricably related.

6.1.1 Propagation

In a wireless environment, the propagation effects can be classified into large scale, medium scale and small scale.

At the largest scale, path loss will increase as the wavefront spreads. In free space, this would be represented by a d^2 law. However, in real environments, a law with a different exponent is generally observed. A common expression used to model these effects is:

$$PL(d) = PL_{BP} + 10\ n \log (d / d_{BP})$$

where:

PL(d) is the path loss at a distance d

n is the path loss exponent

PL_{BP} is the path loss at the break-point distance d_{BP}. If free-space path loss is assumed to apply up to d_{BP}, then:

$$PL_{BP} = 20 \log (4\ \pi\ d_{BP} / \lambda)$$

The above technique can be extended to include multiple breakpoints[4].

Medium-scale effects correspond to large-scale random fluctuations in the path loss due to shadowing from objects in the environment. The log-normal distribution has often been used to model such shadowing effects. The probability density function of the log-normal distribution is given by:

$$P(x) = [\ 1 / (\sigma \sqrt{2\pi})\ ]\ \exp \{ -1/2\ [\ (x - \mu) / \sigma\ ]^2 \}$$

where:

x is the variable representing loss (dB)

σ is the standard deviation (dB)

μ is the mean (dB).

[4] To continue with free-space losses, assume an arbitrary break point (e.g. d_{BP} = 1 m) and use n = 2.

Small-scale effects correspond to fast random fluctuations in the path loss due to the vector summation of fields reflected by multiple scatterers. If the scatterers are moving (e.g. people) then fast temporal fading will occur. A well-accepted model for fast-fading effects is the Rayleigh distribution. The probability density function of the Rayleigh distribution is given by:

$$P(r) = (2 r / b^2) \ \exp (-r^2 / b^2)$$

where:

r is the variable representing loss in numeric amplitude terms

b is the RMS value of "r" (and is μ / 0.886 in numeric terms)

μ is the mean in numeric terms.

The Rayleigh amplitude fading results in a negative exponential power fading. For the above Rayleigh fading amplitude distribution, the corresponding probability density function of the negative exponential distribution is given by:

$$P(z) = [1 / (b^2/2)] \ \exp [-z / (b^2/2)]$$

where $b^2/2$ is the mean of the distribution in numeric terms (1 for Rayleigh fading).

For a scenario where indoor WLANs are considered, the above propagation effects can be applied as follows.

An access point (AP) is located randomly in the simulation area. A sample user location in the AP service area is selected randomly. Using the distance between the AP and the sample user location, a distance-dependent average path loss, L_1, (in dB) is calculated from a user-defined loss model where breakpoint(s) and path loss exponents are specified.

A shadowing loss value, L_2 (in dB, determined by sampling a log-normal distribution with a zero mean (dB) and a user-defined standard deviation (dB)), is added to the average path loss to reflect the location-dependent loss variation due to fixed obstructions.

For each combination of AP and user location, C/(N+I) and BER distributions are calculated from a number of Monte Carlo trials (e.g. 1000). In each trial, a shadowing loss, L_3 (dB), and a fast-fading loss, L_4 (determined by sampling a negative exponential distribution with unity mean and then converting to dB), are calculated and added to ($L_1 + L_2$) when calculating a received power at the user location point. L_3 and L_4 reflect the time-dependent loss variation due to object and people movements[5].

The process is repeated for other sample user location points.

[5] The simulator (see Section 6.3.1) enables the user to turn the shadowing and fast fading losses on and off as appropriate.

A significant amount of data has been published regarding indoor propagation. A review paper published in Proceedings of the IEEE ("The Indoor Radio Propagation Channel" by H. Hashemi, July 1993) states that, in the 2.4 GHz band, the reported values of the path loss exponent "n" are in the range 1.5–5.2. For various residential and commercial environments, path loss exponent values in the range 1.8–3.3 are also reported together with a log-normal shadowing model with standard deviation values in the range 3–14 dB (Wireless Communications, T.S. Rappaport, 1996).

A two-slope path loss model proposed by Kamerman ("Coexistence between Bluetooth and IEEE 802.11 CCK Solutions to Avoid Mutual Interference", Lucent Technologies Bell Labs, January 1999) has been widely used in sharing studies involving indoor IEEE 802.11 and Bluetooth devices. This model assumes line-of-sight propagation for the first 8 m and, beyond this point, the path loss exponent is assumed to be 3.3. Another breakpoint model proposed for use in the 2.4 GHz band assumes that the path loss exponent is 2 up to 5 m and 3.5 beyond this distance (Presentation by Radionet on the "2.4 GHz WLAN Radio Interface", October 2002, http://www.radionet.com/265374.shtml). A white paper on issues concerning IEEE 802.11g networks suggests that the indoor shadowing effects can be modelled using a log-normal distribution with an 8 dB standard deviation. It is further suggested that a two-slope model where the path loss exponent is 2 up to 10 m and 3.2 beyond 10 m can be used to model average path loss ("A Detailed Examination of the Environmental and Protocol Parameters that Affect 802.11g Network Performance", Proxim Corporation, 2003, http://www.proxim.com).

An extensive indoor residential measurement campaign by Intel Corporation ("A Path Loss Comparison Between the 5 GHz UNII Band and the 2.4 GHz ISM Band", January 2002) suggests that the path loss exponent is 3.73 for non-line-of-sight paths and 1.91 for line-of-sight paths. The same study reports that, for shadowing effects, the standard deviation is 4.35 dB for non-line-of-sight paths and 3.15 dB for line-of-sight paths.

At 2.4 GHz, in line with the studies mentioned above, an example set of values for the user input parameters can be assumed to be:

- Mean Path Loss:

    Breakpoint = 5 m

    Path Loss Exponent Up to Breakpoint = 2

    Path Loss Exponent Beyond Breakpoint = 3

- Shadowing (Log-normal Distribution):

    Standard Deviation = 3 dB

The following figures illustrate shadowing, fast fading and combined shadowing and fast-fading statistics obtained from the simulation model for 10,000 samples.

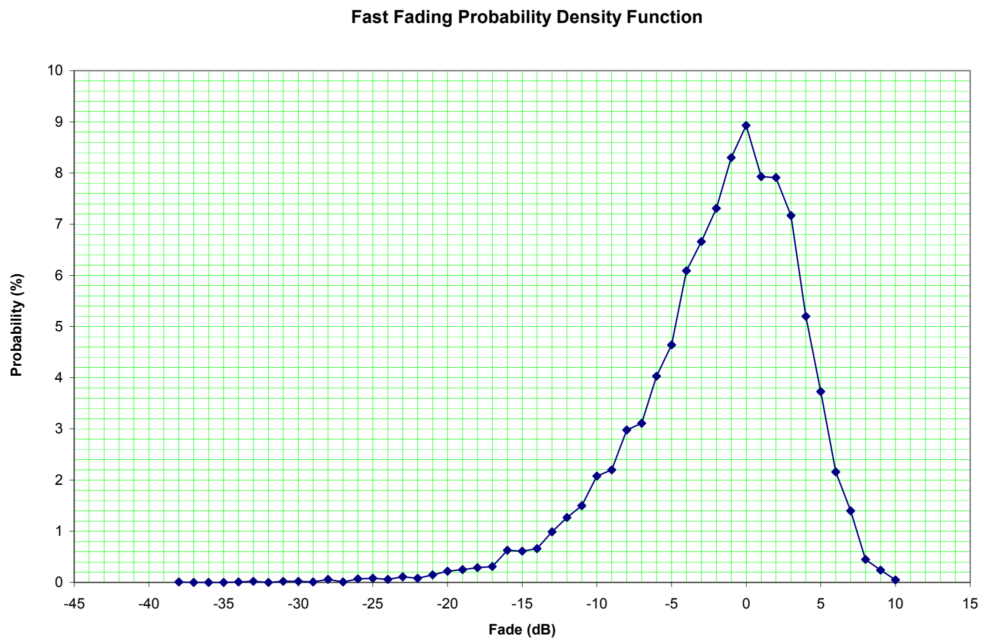

Figure 12: Fast-fading Probability Density Function (dB)

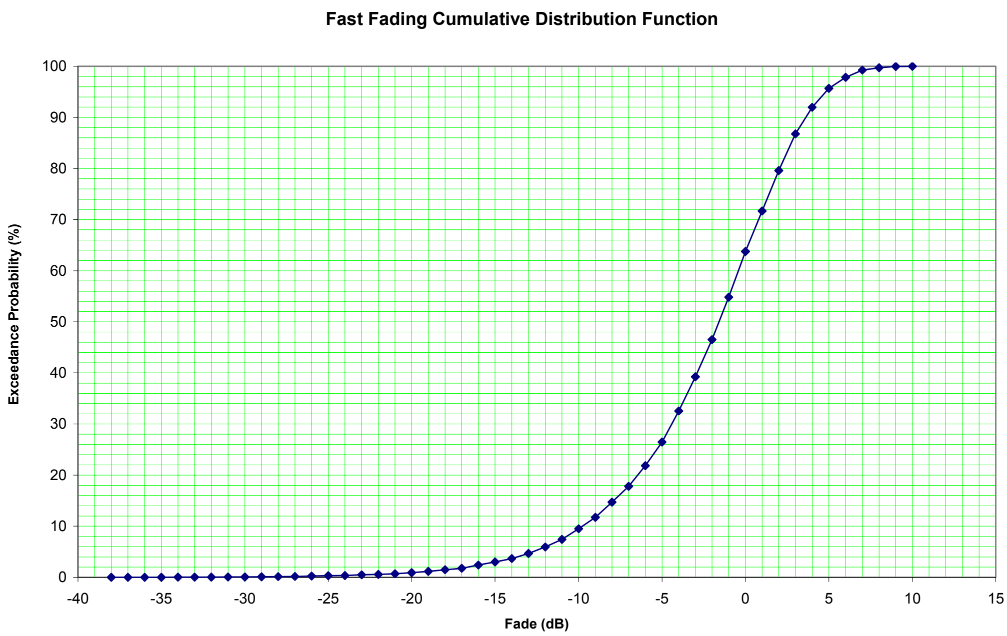

Figure 13: Fast-fading Cumulative Distribution Function (dB)

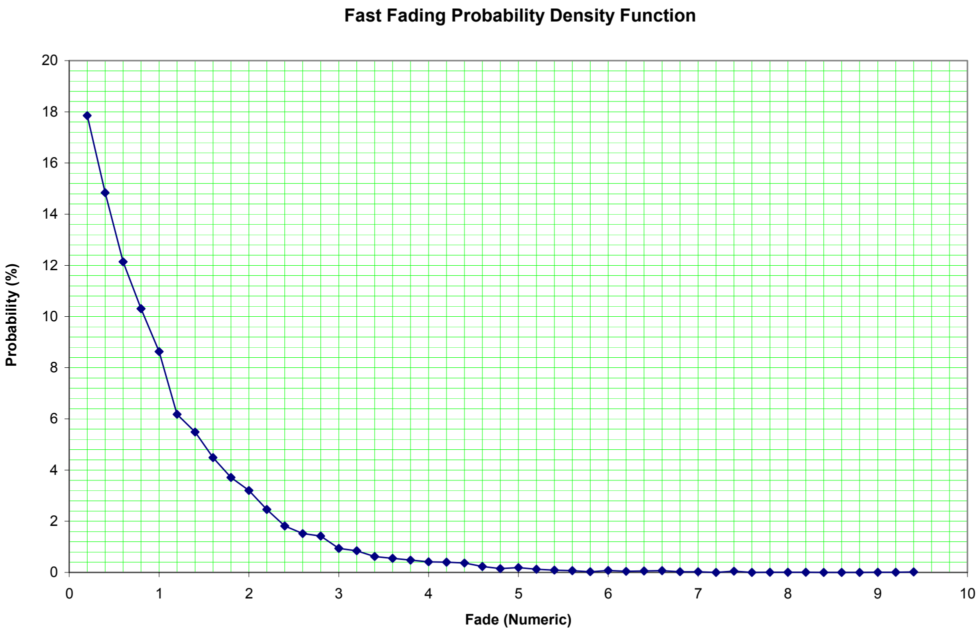

Figure 14: Fast-fading Probability Density Function (Numeric)

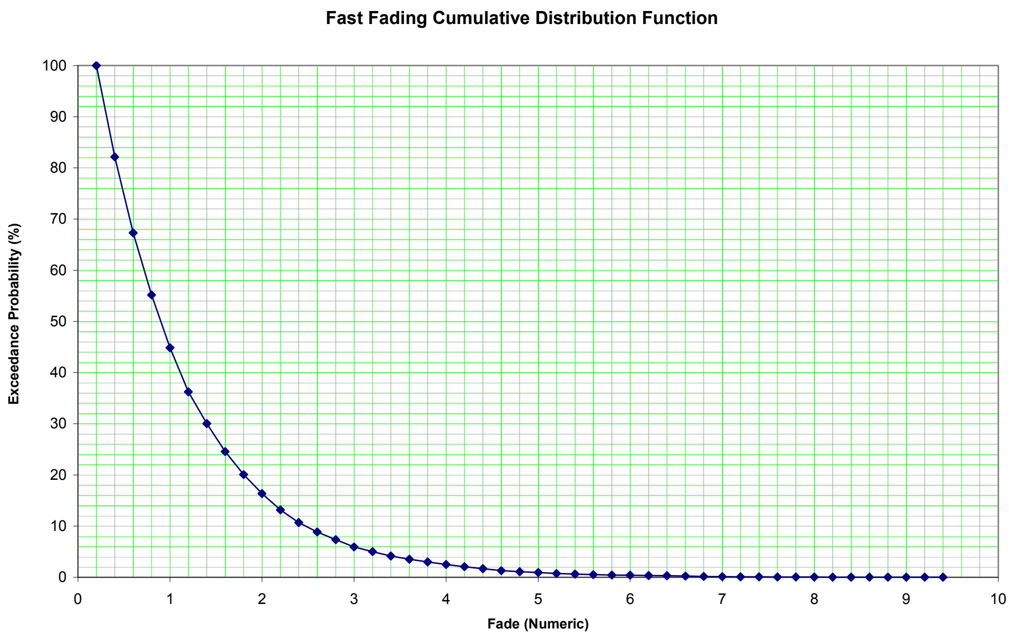

Figure 15: Fast-fading Cumulative Distribution Function (Numeric)

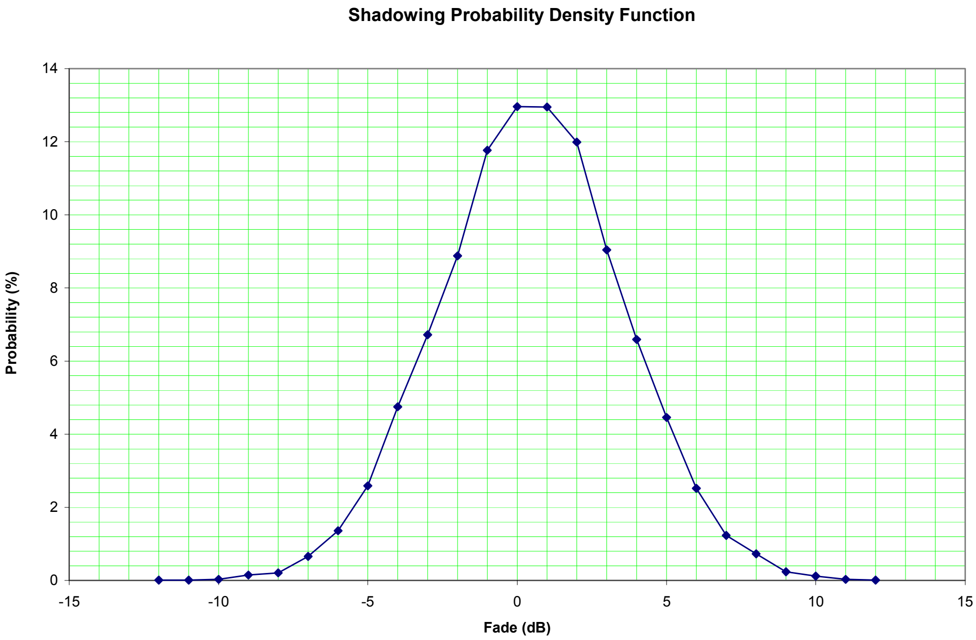

Figure 16: Shadowing Probability Density Function (dB)

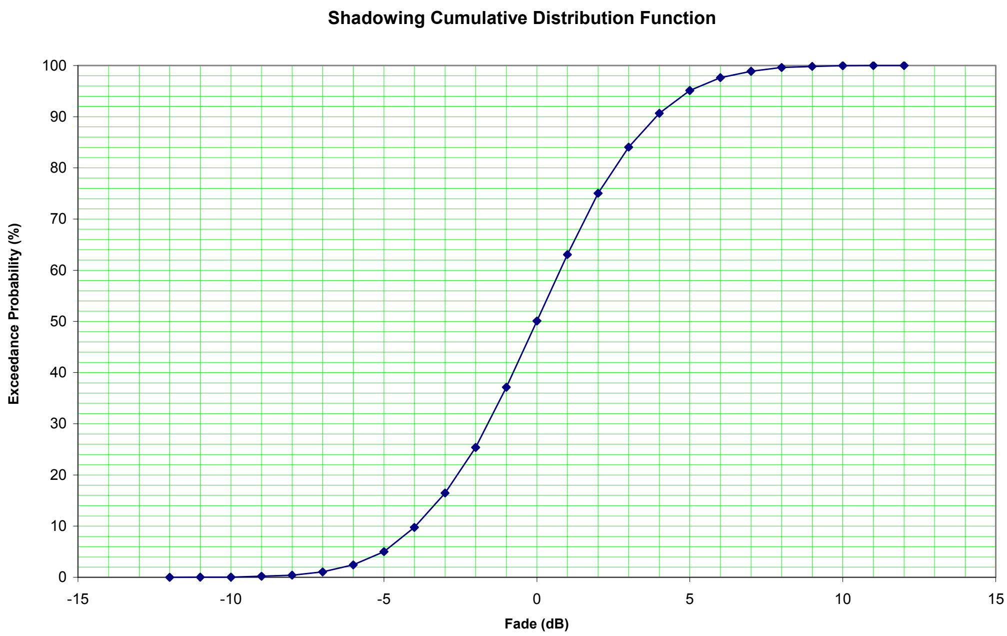

Figure 17: Shadowing Cumulative Distribution Function (dB)

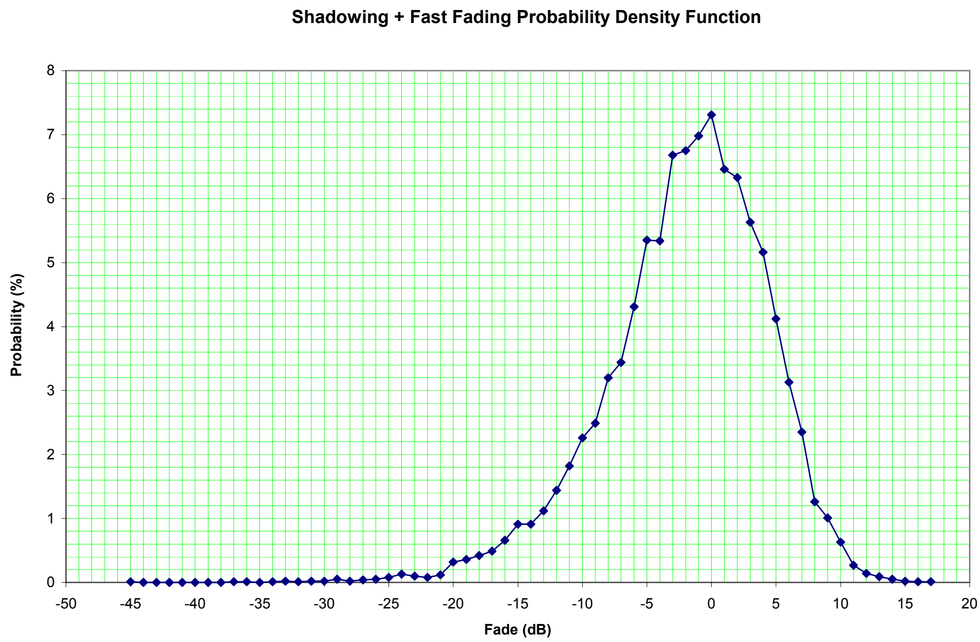

Figure 18: Fast-fading and shadowing Probability Density Function (dB)

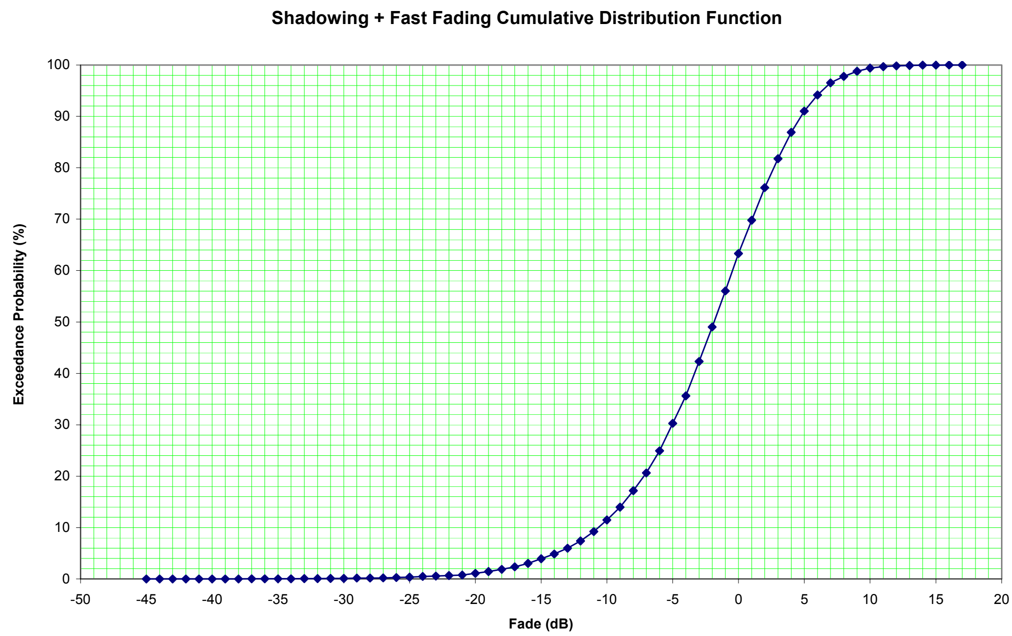

Figure 19: Fast-fading and shadowing Cumulative Distribution Function (dB)

As expected, the numeric fast-fading probability density function (PDF) is exponential with a unity mean and the shadowing PDF is normal with a zero mean and 3 dB standard deviation. The combined fast fading and shadowing PDF has an average value of –2.5 dB and a 6.2 dB standard deviation.

For outdoor-to-indoor paths, in addition to the above-mentioned effects, losses due to building penetration need to be considered. Using domestic sites in England, empirical measurements of building penetration loss have been carried out by Aegis at 1.3, 2.4 and 5.7 GHz ("Measurement of Building Penetration Loss", a S@TCOM study for BNSC by Aegis Systems Ltd, November 2002). The mean values of measured penetration loss are 9.2 dB at 1.3 GHz, 11.2 dB at 2.4 GHz and 12.7 dB at 5.7 GHz. Of particular relevance, loss values up to 30 dB have been measured at 2.4 GHz over all locations and path elevation angles considered. In simulations, a building penetration loss value of 10 dB is assumed.

6.1.2 Interference criterion

A criterion to be used in compatibility studies addressing licence-exempt devices has not been formalised as, by their very nature, licence-exempt devices are not generally entitled to protection. However, in the light of the recent frequency allocations to wireless access devices (including WLANs) at 5 GHz, there are moves afoot to put in place a protection requirement with respect to possible future services sharing the same allocations.

The rapporteur's report of the most recent meeting of JRG 8A-9B contains a working document toward a Preliminary Draft New Recommendation (PDNR) on "Protection criteria for wireless access systems, including radio local area networks, operating in the mobile service in the bands 5150–5250 MHz, 5250–5350 MHz and 5470–5725 MHz". This PDNR is based on a proposal emanating from IEEE 802 as follows:

WAS/RLAN systems operating under the provisions of Resolution 229 (WRC-03) should not suffer significant data rate and range impairments as a result of interference from services or applications with lower, or no, regulatory status. In order to not suffer such unacceptable interference, a protection criterion of –6 dB I/N worst case (aggregate or individual interferer) in the victim WAS/RLAN receiver's bandwidth should be tentatively proposed for discussion, subject to further study. Preliminary estimates indicate that this would result in approximately a 1 dB degradation in received SNR, which is expected to equate to approximately a 5% reduction in the range at which an IEEE 802.11a RLAN system could maintain its maximum link data rate of 54 Mb/s.

Apart from this formal protection requirement (albeit in draft form) it is necessary to look at other work that has examined system degradations under various interference scenarios in order to obtain an idea of what could be used to define an acceptable level of degradation. A summary of some of the work in this area is contained in Annex C and the following key points have been noted from that work:

- A range of metrics have been used in sharing analyses. These include BER vs C/I, PER vs C/I, Packet Loss vs C/I, PER vs Packet Size and Effective Throughput vs C/I.

- Using these metrics, the feasibility of coexistence has been assessed on the basis of a number of assumed sharing criteria. PERs of 1%, 8% and 10% and a BER of 10^{-5} are commonly used as criteria. In addition, a C/I of 10 dB and I = N are also assumed in some studies.

Rather than using the traditional type of interference criterion specified at the RF level it appears that a criterion based on PER or loss in throughput would be more appropriate. There is, however, a difficulty associated with defining the criterion at this level: it is not entirely clear how to define user expectations. For example, a user might accept a degraded service (i.e. a PER or throughput degradation greater than a certain value) for 1 second every minute but not 1 minute every hour. This implies that knowledge of interference event durations is required.

The Monte Carlo approach that has been proposed for the model does not allow information about time sequences to be obtained. We therefore consider that each Monte Carlo sample represents what is happening to a single bit and that, as far as a user is concerned, the average performance is of most interest (with re-transmission protocols implicitly dealing with those occasions when performance is worse than average). It might be considered sufficient to aim for an average BER, for example, of 10^{-5}. However, in a dynamic propagation environment it can be expected that the average will be dramatically distorted by a single bad sample[6]. It is therefore necessary to make an allowance for the time and location variability of signals if a sensible criterion is to be defined. We should consider the situation from a user's point of view and a service provider's point of view. If, for example, we consider a user arriving in an airport lounge and wanting to make a connection with an access point, what will that user be expecting and what will the service provider be offering in terms of service quality? It is suggested that service provision could be defined as *more than X% of locations achieving a Bit Error Rate of less than Y for more than Z% of the time*.

Furthermore, there is a difficulty in defining what the user would regard as acceptable performance when adaptive modulation is used. 802.11a devices, for example, back down in steps from 54 Mbps to 6 Mbps as the signal-to-noise ratio decreases and lower-order modulation / coding schemes have to be used. In a malign environment (except the very worst) the device might operate continuously at 6 Mbps, but this is unlikely to satisfy a user as a long-term prospect. For the purposes of this work it will be necessary to set a minimum average acceptable data rate and consequently a minimum average signal-to-noise (and interference) ratio which provides a required BER for the modulation / coding used for that data rate.

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[6] If the BER criterion is 10^{-5} then 1 sample with a BER of 10^{-2} and 999 samples with a BER of 10^{-10} will fail the test.

With regard to 802.11b devices, various modulation modes are implemented depending on the data rate:

- Differential Binary Phase Shift Keying (DBPSK) for 1 Mbps
- Differential Quaternary Phase Shift Keying (DQPSK) for 2 Mbps
- Complementary Code Keying (CCK) for 5.5 and 11 Mbps.

The following figure illustrates the E_b/N_o-BER performance curves in an Additive White Gaussian Noise (AWGN) channel. For DBPSK and DQPSK, it is assumed that the demodulation is based on phase comparison detection and the phase states follow a Gray code (Communication Systems, A. Bruce Carlson, McGraw Hill, 1986). For CCK, the curves are based on information provided in a DSSS baseband processor data sheet (HFA 3863) produced by Intersil Corporation (now called Conexant) and a paper titled “Modelling Multipath in 802.11 Systems” written by S. M. Nabritt of the University of Central Florida (www.commsdesign.com, October 2002).

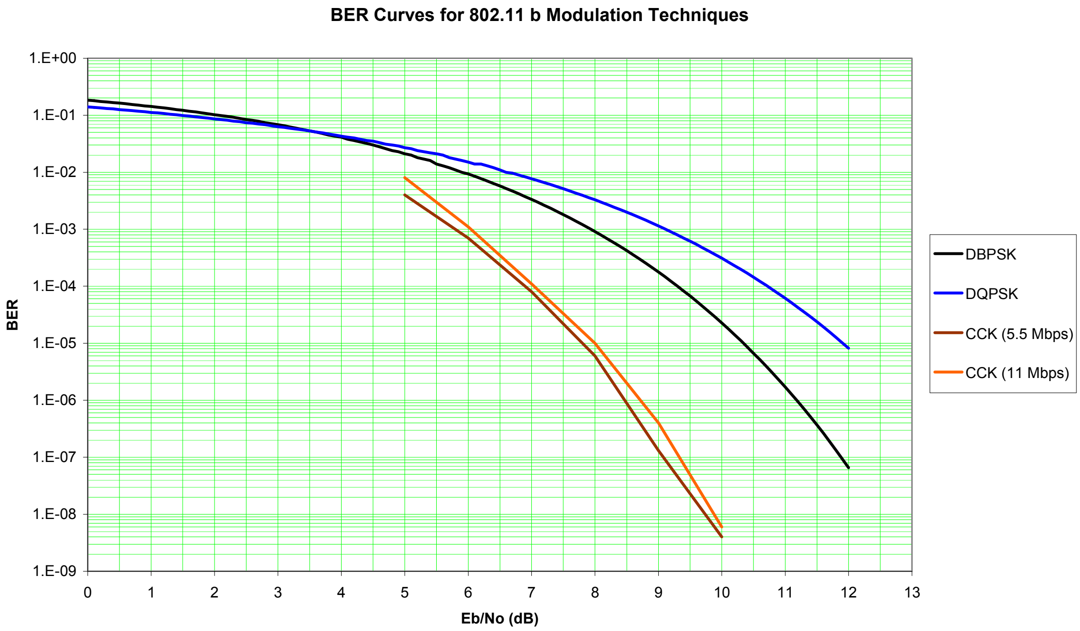

Figure 20: BER performance for 802.11b modulation techniques

As the above performance curves are theoretical, for a given BER, a modem implementation loss needs to be added to a corresponding E_b/N_o level. A paper titled “Troubleshooting Dual-Band WLAN Radios” written by R.L. Abrahams (Wireless Systems Design, www.wsdmag.com, March 2003) discusses practical issues related to WLAN systems and assumes a 2 dB implementation loss. Theoretical and measured modem curves provided in the HFA 3863 data sheet (802.11b) suggest that the implementation loss varies between 1 and 4 dB depending on the modulation type and BER. In addition, the implementation loss for an 802.11b modem produced by NewLogic (www.newlogic.com) is 1.3 dB. In line with these figures, in our analysis, a 2 dB implementation loss is assumed to be representative.

The C/N performance criterion associated with a WLAN user terminal test point is dependent on an assumed BER, transmission rate, bandwidth, modulation and implementation loss. The following steps summarise the derivation of a C/N criterion for an 802.11b DSSS link operating at 11 Mbps.

- Assume the required BER is 10^{-5}.
- For BER = 10^{-5}, the minimum required E_b/N_o is 8 dB (11 Mbps, CCK Modulation).
- Assuming the implementation loss is 2 dB, the minimum required E_b/N_o is 10 dB

$$C/N = (E_b/N_o)\ (\text{Bit Rate / Bandwidth})$$

$$C/N = 10\ \text{dB} + 10 \log (11\ \text{Mbps} / 22\ \text{MHz}) = 7\ \text{dB}$$

Initially, it was assumed that, for a user terminal test point, the average BER calculated from 1000 Monte Carlo trials should not exceed the criterion of BER $\leq 10^{-5}$. Test runs have indicated that this criterion is too stringent, as a single bad C/N resulting in a high BER (e.g. 10^{-2}) makes almost all test points unusable. In real applications, packet re-transmissions would overcome such situations without significantly affecting user perceptions. It has therefore been decided that, as a baseline figure, 90% of 1000 Monte Carlo trials should satisfy the minimum BER of 10^{-5}. This criterion aims to cater for time-dependent effects (i.e. people and object movements in the simulation area).

The relationship between BER and PER depends on a number of factors including packet size and protocols. As a rule of thumb, however, the BER of 10^{-5} we have chosen to use can be roughly translated into PER after making an assumption about packet size. If it is assumed that the packet size is large, 1000 bytes, then a BER of 10^{-5} translates into a PER of $1000 \times 8 \times 10^{-5} = 0.08$ (or 8%), which is a value commonly used by those addressing performance at a packet level.

Initially, it was also assumed that a WLAN system can be successfully located in the simulation area if all user terminal test points (assumed to be 50 over an area of 30 m radius) satisfy the above criterion. Test runs have proved that this location dependent criterion is also too stringent. In real applications, 100% coverage is not achieved. Therefore, it has been decided that, as a baseline figure, 90% of the user terminal test points need to satisfy the criterion of *90% of 1000 Monte Carlo trials satisfying the minimum BER of* 10^{-5}.

In summary, in a baseline scenario, it is assumed that the BER needs to be less than or equal to 10^{-5} for 90% of Monte Carlo trials at 90% of the tested user terminal locations for a WLAN system to be successfully located in the simulation area. It should be noted that the simulator attempts to insert a WLAN system a number of times (assumed to be 20) before deciding that the scenario is “full”.

6.1.3 Other issues

Recalling the separation dimensions outlined in Section 3.2 it is also possible to indicate how some of the distinctive characteristics of licence-exempt devices will be addressed.

Frequency separation: Conventional modelling of frequency overlap will be undertaken. Where Dynamic Frequency Selection (DFS) is concerned it can be assumed that the model will address a single channel at a time. It is not seen that modelling all channels together will provide additional information on occupancy. The population of devices that can be accommodated in a frequency band supporting a number of DFS channels can reasonably be assumed to be the sum of the devices supported by each channel.

Space separation: Conventional modelling of signal decay with distance, and taking account of antenna directivities where appropriate, will be undertaken. In the most general case, office environments will be represented by a decay greater than free space after a certain distance. Consideration also needs to be given to walls and partitions, the effect of which may or may not be taken into account by the increased signal decay exponent. Signal variability with location and time[7] needs to be addressed but the scale at which the variability will be taken into account depends on the application. Furthermore, diversity techniques are commonly used to mitigate this type of signal degradation. The propagation effects that have been taken into account in the modelling are described in Section 6.1.1 above.

Time separation: The characteristics of many licence-exempt devices mean that particular attention has to be paid to the time dependency of the interference. They can be characterised in terms of their (macro) activity and (micro) packetisation. For the purposes of this model these two factors give rise to an instantaneous probability of transmitting. When the instantaneous probabilities are aggregated this leads to the variability in the interference environment.

Signal separation: There are four aspects that need to be addressed here:

- Frequency Hopping Spread Spectrum (FHSS)—this will effectively be addressed by a combination of frequency separation and time separation considerations such that the degree of frequency overlap will introduce another probability factor to add to the instantaneous probability of transmitting within the channel bandwidth of interest.
- Automatic Transmitter Power Control (ATPC)—this has the potential to reduce the overall level of interference and increase the possibility of frequency re-use (i.e. occupancy). However, it is not as widely used as it might be because its use negates the effectiveness of collision avoidance protocols.

[7] Due to standing waves and their disturbance arising from the movement of people in the area.

- Adaptive modulation / FEC—this effectively changes the bitrate supported by a channel depending on the quality of the radio channel. The algorithm for determining when the bitrate is changed has not been standardised, resulting in differing performance between vendors' devices which are ostensibly the same. The channel bandwidth and the transmitted power remain the same. The level of interference (in terms of spectral power density) generated by the device broadly remains the same but the probability of a device transmitting may well increase, contention allowing, in order to maintain the user throughput required. From the modelling point of view we have specified a minimum acceptable data rate for the user as discussed in Section 6.1.2 above.
- Multiple-In, Multiple-Out (MIMO) is a wide-ranging term whereby signal processing techniques allow signals to be combined in order to provide an enhanced performance and / or discriminate against unwanted signals. In its most rudimentary form, selecting the better signal from a pair of diversity antennas can be viewed as MIMO. However, more sophisticated techniques such as antenna shaping and steering are envisaged for the future. Until these techniques are closer to being present in the field it is difficult to accommodate them fully in the model. It is not felt that future MIMO capabilities change the framework of the proposed occupancy model but it is possible that they will change the way in which the system compatibility part of the model is assessed. This part of the model can be modified once the MIMO techniques have been realised in the marketplace.

6.2 Overall process

The compatibility assessment carried out within the N-Systems occupancy method can be summarised as follows, assuming for this example that we are dealing with interference into the downlink of users being served by a WLAN access point:

- Locate an access point (AP) randomly in the simulation area.
- Select a random point within an AP coverage area (user terminal test point).
- For the AP-User Terminal test point pair, calculate C/(N+I) and BER over a user-defined number of Monte Carlo (MC) trials (the AP-User Terminal test point distance is the same in each trial but propagation loss varies from trial to trial due to time-dependent effects—shadowing and Rayleigh fading—corresponding to people and object movements in the simulation area).

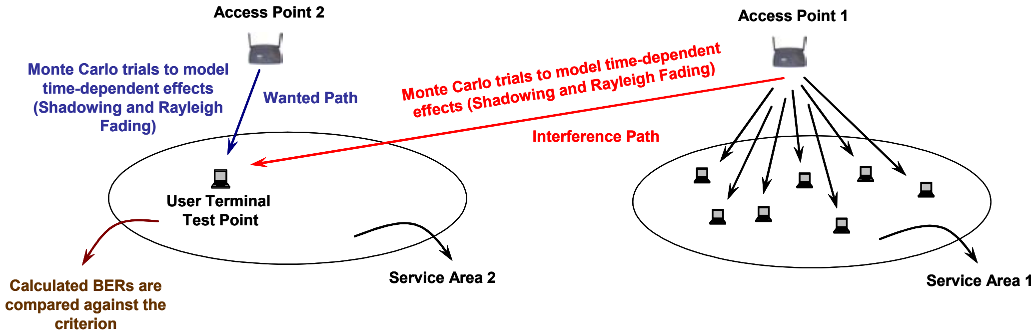

Figure 21: Example scenario

- Compare the calculated BERs against a criterion of "at least X% of MC trials should result in BER ≤ Y".
- If the criterion is satisfied, count the test point as a "successful" test point, otherwise count it as a "failed" test point.
- Repeat the above process for all user terminal test points (the number of user terminal test points is a user-defined input parameter).
- Compare the calculated number of "successful" and "failed" test points against a criterion of "at least Z% of user terminal test points should be successful" (this criterion aims to accommodate location-dependent variations, i.e. coverage requirements).

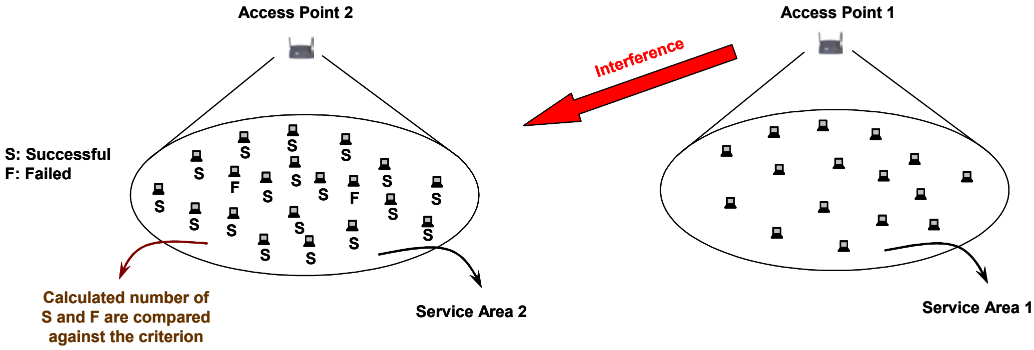

Figure 22: Location dependency

- If the criterion is satisfied, the WLAN system is assumed to be located successfully in the simulation area.
- If the criterion is not satisfied, another AP location is selected randomly and the whole process is repeated.
- The simulation area is assumed to be filled if the number of attempts to introduce a new AP reaches the user-defined maximum value.
- A simulation run finishes when the simulation area is filled; the total number of successfully located WLANs is then calculated for the run.

- For each simulation model, a user-defined number of simulation runs are completed and the average number of successfully located WLANs is then calculated.

6.3 Implementation of method

6.3.1 Software tool

The modelling method was implemented in a software tool based upon existing C++ source code available to Transfinite and Aegis. No significant problems were encountered, which suggests it would be relatively straight-forward to use the method in other situations provided that suitable libraries were available (for geometry, antenna patterns, propagation, link budget, performance/BER etc.). In particular, no changes were required to the logic described by the flow diagram in Figure 6.

6.3.2 Performance

It was noted that runs required significant processing. For example, a lower bound on the number of signal paths to be considered can be computed for a scenario with the parameters in the following table.

Number of Bluetooth devices	1000
Number of WLANs in test area	20
Number of user terminal locations (test points in AP service area)	50
Number of tries for introducing a new AP	20
Number of Monte Carlo samples at each test point	1000
Number of times a scenario is filled (i.e. number of runs)	100

Table 1: Scenario parameters

In this case, the numbers of wanted devices and interferers are:

[No. Wanted] = [No. of WLANS] * [No. of test points]

= 1000

[No. Interferers] = [No. BT] + [No. WLAN] – 1

~ 1000

Each of the 100 runs will end when 20 attempts have been made to introduce a new access point and have failed. This stage alone will therefore require the following number of signal paths to be considered:

[No. paths] = [No. Wanted] * [No. Interferers] *

[No. Tries for a new AP] * [No. MC Samples] * [No. Runs]

= 1000 * 1000 * 20 * 1000 * 100

$$= \quad 2 * 10^{12}$$

This figure represents a lower bound and the total number of paths required to be considered is likely to be higher.

While this represents a significant requirement, run times on a standard PC were found to be between a few hours and a few days. This was achieved without undertaking extensive optimisation, except that the tool pre-computed the fixed signal strengths. Further potential optimisations were identified but not implemented.

While the method can require significant computation, performance and run times were not found to be a major issue in this study.

6.3.3 Consistency check

A key stage in the method is the check that a scenario into which devices have been introduced is "consistent". This consistency check will depend upon the systems and scenario being modelled and, as explained earlier, it was decided that the check should be based upon the following:

a) all WLAN systems should operate within their performance requirement, which was taken to be a BER < 10^{-5} for 90% of the time for 90% of locations

b) no station should be separated by less than 5 cm from any other.

To check that the WLAN system meets its performance requirement, Monte Carlo simulations were done in which the BER was calculated taking account of:

- geometrical distribution of stations
- their gain patterns
- suitable propagation models including fading and shadowing effects
- traffic models in the form of activity ratios for each station
- models of C/(N+I) to BER performance for the WLAN carrier.

This was undertaken for the WLAN downlink direction (i.e. assuming users are receiving data from their AP and suffering interference from the AP of other networks). The consistency check could in principle be extended to analyse other interference paths.

6.3.4 Test simulation

Intermediate values were dumped to file during a run to provide further insight into the calculations. To improve comprehension, the run was limited to a 500 x 500 m test zone, considering only WLAN systems and only one Monte Carlo (MC) sample.

It should be noted that using only a single MC sample can lead to untypical results as the calculations are more susceptible to the particular sequence of random numbers used. However, such a limitation was considered to be acceptable in this particular case as it allowed insight into the simulation state.

The final distribution of WLAN Access Points (AP) and user test points for a cell of 50 m radius was as shown in the figure below.

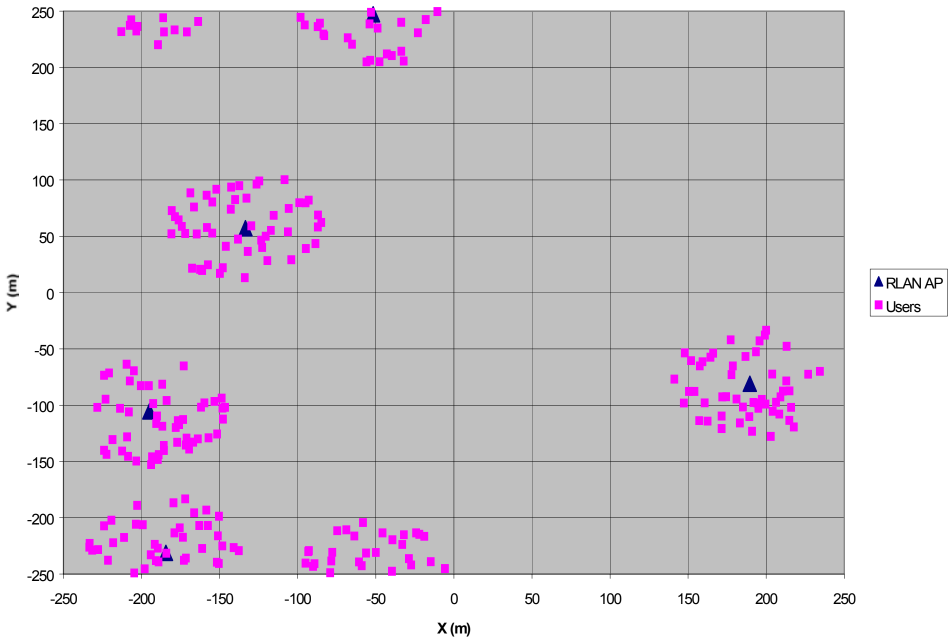

Figure 23: Distribution of WLAN access points and users

The impact of wrap-around geometry is clearly demonstrated in the distribution of users near the edge of the test zone.

A large sector of the zone (top right) was not deployed with WLANs: this could be either because it was tested and the trial resulted in too high interference or the random selection of trial locations did not sample that area.

The table below gives the positions of the WLAN APs.

Station	X	Y
WLAN 1	–133.5	57.11
WLAN 2	–194.94	–105.6
WLAN 3	–184.39	–231.18
WLAN 4	–51.75	247.07
WLAN 5	189.49	–80.85

Table 2: WLAN test locations

WLAN 2 is particularly close to WLAN 3 and 5 and therefore further investigation was considered useful.

The wanted and interfering signals for a single Monte Carlo sample for the WLAN 2 are shown in the table below. Note that all values are referenced to 1 MHz.

The various columns are:

- User: the reference number of the user for this particular row.

- C: this shows the wanted signal in the absence of time-variable fading and shadowing.
- C-fade: this shows the time-variable fading and shadowing for the MC sample, which is added to C to get the wanted signal for this sample.
- Noise: this shows the receiver noise corresponding to a noise figure of 10 dB.
- I-n: Interference from WLAN-n access point in the absence of time-variable fading and shadowing where n = 1, 3, 4 and 5. Where the entry is “off” this access point is considered to be idle for this sample.
- I-n-Fade: this shows the time-variable fading and shadowing for the MC sample, which is added to the I-n to get the interference for this sample.
- C/(N+I) is the resulting figure calculated from the preceding values.

Five values of C/(N+I) are below the 7 dB criterion, namely: –4.36, –2.66, 3.46, 6.84, and 6.9 dB. These are typically for the following reasons:

- either WLAN-3 or WLAN-5 active
- the interfering signal path from WLAN-3 or WLAN-5 is either not significantly faded or is enhanced
- the user is towards the edge of the coverage area and/or the wanted signal is significantly faded.

It is likely that if further MC samples had been taken then this location would have been rejected. However, for this particular sample, 90% of the users were above the BER = 10^{-5} threshold and therefore the WLAN-2 location was correctly considered as acceptable.

User	C	C-fade	Noise	I-1	I-1-Fade	I-3	I-3-Fade	I-4	I-4-Fade	I-5	I-5-Fade	C/(N+I)
0	-115.51	-7.5	-133.98	-126.65	-9.16	off	off	off	off	off	off	8.77
1	-105.52	-18.58	-133.98	-131.99	-2.06	off	off	off	off	off	off	6.9
2	-112.47	-1.38	-133.98	off	off	off	off	off	off	off	off	20.12
3	-105.4	7.25	-133.98	off	off	off	off	-124.87	-7.94	off	off	32.2
4	-113.41	0.92	-133.98	-124.35	-4.63	off	off	-131.28	1.54	off	off	13.16
5	-86.41	1.7	-133.98	-128.69	4.06	off	off	-130.45	-5.27	off	off	39.15
6	-94.22	1.44	-133.98	off	off	-124.3	-1.61	-129.13	4.18	off	off	29.32
7	-105.02	-3.92	-133.98	-135.05	-9.77	-119.97	-1.12	-130.2	-3.49	off	off	11.7
8	-111.06	-7.13	-133.98	off	off	-132.65	-2.53	off	off	-119.42	5.53	-4.36
9	-101.19	-6.47	-133.98	off	off	-130.3	-0.91	off	off	off	off	21.71
10	-112.91	-4.67	-133.98	off	off	off	off	-128.81	-8.77	-127.27	-1.74	9.8
11	-108.84	0.05	-133.98	-130.35	-3.14	off	off	off	off	off	off	21.93
12	-111.91	-7.08	-133.98	off	off	off	off	-128.75	-1.5	off	off	9.74
13	-102.1	-0.89	-133.98	off	off	off	off	off	off	-125.39	9.52	12.81
14	-98.65	-6.93	-133.98	off	off	off	off	off	off	off	off	28.4
15	-102.55	3.53	-133.98	-123.67	8.23	off	off	off	off	off	off	16.36
16	-103.83	-7.9	-133.98	off	off	off	off	-135.28	2.55	-126.08	-2.44	14.58
17	-113.63	5.97	-133.98	-127.5	2.4	off	off	off	off	off	off	16.91
18	-106.5	4.66	-133.98	off	off	off	off	-125.2	-4.82	off	off	26.72
19	-108.58	1.4	-133.98	off	off	-122.95	-7.49	off	off	off	off	21.66
20	-101.02	-2.03	-133.98	-131.43	-9.36	-126.01	-5.47	off	off	off	off	26.17
21	-102.91	-2.69	-133.98	off	off	-126.45	3.52	-126.32	2.33	off	off	14.62
22	-110.21	-6.91	-133.98	off	off	-122.24	-10.45	off	off	off	off	13.15
23	-115.23	-7.45	-133.98	-128.31	-5.17	off	off	off	off	off	off	8.03
24	-103.16	4.06	-133.98	off	off	off	off	off	off	off	off	34.88
25	-111.33	2.24	-133.98	off	off	-123.2	-0.94	-125.14	3.34	-121.99	-8.32	10.19
26	-90.09	-15.72	-133.98	-125.49	-5.93	off	off	-132.34	-7.2	off	off	23.29
27	-99.46	-3.07	-133.98	off	off	-124.72	7.97	-131.93	4.81	off	off	13.77
28	-106.94	4.06	-133.98	off	off	off	off	-128.18	1.57	off	off	23
29	-103.17	-5.7	-133.98	off	off	off	off	-127.18	5.22	-126.37	-1.45	11.88
30	-104.42	-6.39	-133.98	-125.74	1.68	-123.19	-4.5	off	off	-121.81	2.29	6.84
31	-99.58	0.33	-133.98	off	off	off	off	-132.46	-11.7	-122.62	-4.14	26.69
32	-101.57	-2.36	-133.98	-130.19	1.72	off	off	off	off	off	off	23.47
33	-93.36	-5.71	-133.98	off	off	-128.82	1.53	off	off	-124.75	-6.57	26.15
34	-107.34	8.07	-133.98	off	off	off	off	-126.89	2.24	off	off	24.9
35	-105.13	4.33	-133.98	off	off	off	off	off	off	off	off	33.18
36	-113.96	1.59	-133.98	off	off	-115.37	5.59	off	off	-127.31	-1.08	-2.66
37	-103.33	-8.03	-133.98	-129.78	2.28	off	off	off	off	-128.94	0.1	13.22
38	-108.92	3.28	-133.98	off	off	off	off	off	off	off	off	28.34
39	-106.18	-2.67	-133.98	off	off	off	off	off	off	off	off	25.12
40	-109.8	-10.11	-133.98	off	off	off	off	-128.79	-11.8	-127.32	-11	12.06
41	-89.31	-0.2	-133.98	off	off	off	off	off	off	off	off	44.46
42	-102.65	-9.77	-133.98	off	off	-117.16	-6.21	off	off	off	off	10.59
43	-106.74	-0.53	-133.98	off	off	off	off	off	off	-123.61	4.4	11.79
44	-112.54	3.81	-133.98	off	off	off	off	off	off	-120.05	-1.48	12.56
45	-106.21	2.26	-133.98	off	off	off	off	-127.69	1.05	off	off	21.95
46	-104.9	-3.58	-133.98	off	off	off	off	off	off	off	off	25.49
47	-115.67	-7.39	-133.98	off	off	off	off	-132.38	-16.79	-126.75	-0.66	3.46
48	-113.6	6.14	-133.98	-123.64	-11.25	off	off	off	off	-116.54	-3.1	11.89
49	-109.55	-3.66	-133.98	off	off	off	off	off	off	-127.94	-5.19	17.32

Table 3: Test results

6.3.5 Example WLAN deployment

As noted above, the distribution of WLANs in Figure 23 was untypical as it was based upon a single Monte Carlo sample. A more representative result based upon a full 1000 sample simulation for a cell of radius of 30 m is shown in the figure below.

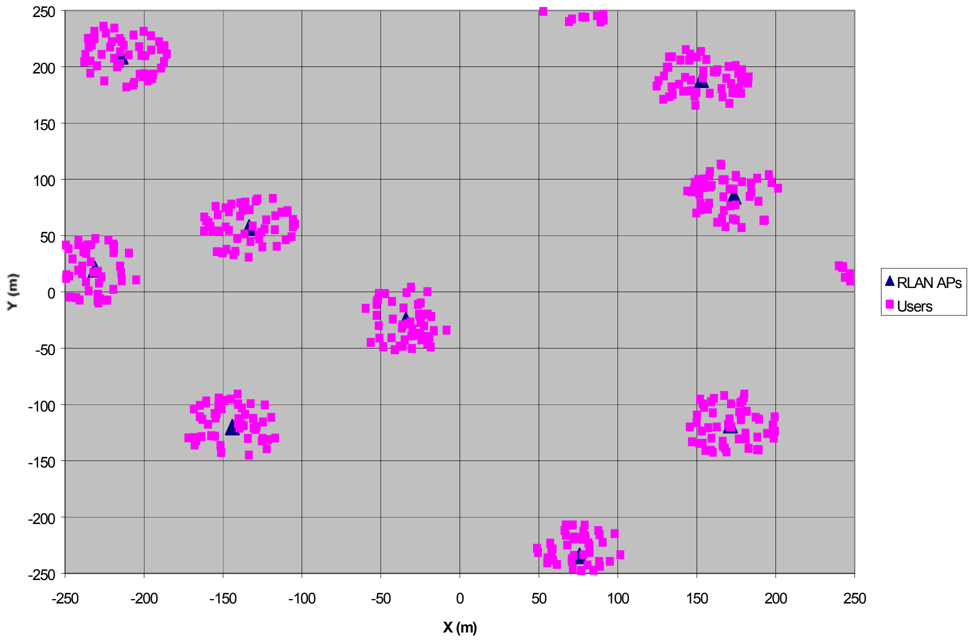

Figure 24: Typical distribution of WLAN access points and users

7 MODELLING RESULTS

7.1 Basic system parameters

From data sheets, it is assumed that the 802.11b access point (AP) has an EIRP of 15 dBm in a 22 MHz bandwidth (i.e. EIRP = –28.4 dBW/MHz) with a coverage range up to 50 m. The activity factor associated with each AP is assumed to be 30%. For user test points, it is assumed that the noise figure is 10 dB, which is in line with the range of values stated in literature(7–14 dB).

The Bluetooth EIRP is taken to be 1 mW in a 1 MHz band. An activity factor of 5% is assumed for Bluetooth interferers. This value has been adjusted to account for the assumed 1/3 of activity that will be in the victim WLAN receive band (i.e. the effective Bluetooth activity = 1.67%).

Extensive measurements carried out by the US NTIA have indicated that the average EIRP from microwave ovens is 5 dBm/3 MHz in the band 2.4–2.5 GHz. In interference analyses, microwave ovens are therefore modelled as isotropic emitters with an EIRP of –29.8 dBW/MHz and an assumed activity factor of 10%.

For ENG/OB systems, two types of transmit terminals are considered:

- **TX1**: 20 W / 20 MHz TX on pneumatic vehicle mast with 0.6 m parabolic dish (21 dBi) at 10 m height
- **TX2**: 1 W / 20 MHz handheld TX camera with omnidirectional antenna at 2 m height and 5 dBi maximum gain.

7.2 Scenarios modelled

Initial modelling has examined the implications of indoor WLAN intra-system interference. A baseline indoor simulation model has been developed and simulation runs have been carried out using the model. In each run, the simulation area is populated with WLAN systems by taking account of propagation effects and interference.

In line with the frequency separation discussion of Section 6.1.3, it should be noted that all the following results are with respect to a single WLAN channel.

The following parameters have been assumed for the baseline model.

Scenario	Indoor WLAN intra-system interference
AP EIRP (dBW/MHz)	–28.4 (32 mW in 22 MHz)
AP Activity Ratio (Interfering APs only)	0.3
AP Height (m)	3
User Terminal Height (m)	1
AP Cell Radius (m)	50
User Terminal System Noise Temp. (K)	2900 (NF = 10 dB)
User Terminal Max. Antenna Gain (dBi)	0
Data Rate (Mbps)	11
Implementation Loss (dB)	2
Modulation	CCK
AP Antenna Pattern	Isotropic
User Terminal Antenna Pattern	Isotropic
Propagation Model	Dual Slope n = 2 up to d = 5 m n = 3 for d > 5 m Log-Normal Shadowing Fixed Shadowing Std Dev. = 3 dB Variable Shadowing Std Dev. = 3 dB Rayleigh Fast Fading
Simulation Area (m^2)	500 x 500
Performance Criteria	BER ≤ 10^{-5} for 90% of Monte Carlo trials (time dependence) 90% of User Terminal locations should satisfy the above criterion (location dependence)
Number of Times a Scenario is Filled	100
Number of Monte Carlo Samples at Each Test Point	1000
Number of Tries for Introducing a New AP	20
Number of User Terminal Locations (Test Points in AP Service Area)	20

Table 4: Baseline model for indoor WLAN intra-system interference

After the initial simulation run with the baseline model, further runs have been implemented with modified baseline parameters. The simulation results (average number of WLAN systems) are shown in the following table together with the modifications.

Model	***Average Number of WLANs***	***Comment***
Baseline	2.62	A small number of WLANs are able to operate in the baseline model.
No shadowing, no Rayleigh fading	9.02	Average number of WLANs has increased from 2.62 to 9.02 when shadowing and fast fading have been excluded.
AP Cell Radius = 30 m Number of User Terminal Locations = 50 Propagation Model: Dual Slope n = 2 up to d = 30 m n = 3.5 for d > 30 m	8.35	Increase in the fade margin (due to reduced cell radius) and reduction in interference (due to increased path loss exponent and breakpoint at cell radius) have increased the number of average WLANs from 2.62 to 8.35.
AP Cell Radius = 30 m Number of User Terminal Locations = 50 Propagation Model: Dual Slope n = 2 up to d = 30 m n = 3.5 for d > 30 m No shadowing, no Rayleigh fading	23.46	Average number of WLANs has increased from 8.35 to 23.46 when shadowing and fast fading have been excluded.
AP Cell Radius = 30 m Number of User Terminal Locations = 50 Propagation Model: Dual Slope n = 2 up to d = 30 m n = 3.5 for d > 30 m Performance Criteria: BER $\leq 10^{-5}$ for 80% of Monte Carlo trials (time dependence) 80% of User Terminal Locations should satisfy the above criterion (location dependence)	14.11	Average number of WLANs has increased from 8.35 to 14.11 when the criterion has been relaxed.

AP Cell Radius = 30 m Simulation Area = 1000 x 1000 m^2 Number of User Terminal Locations = 50 Propagation Model: Dual Slope n = 2 up to d = 30 m n = 3.5 for d > 30 m	24.79	Average number of WLANs has increased from 8.35 to 24.79 when the area size has been increased from 500 x 500 m^2 to 1000 x 1000 m^2.
AP Cell Radius = 30 m Simulation Area = 1000 x 1000 m^2 Number of User Terminal Locations = 50 Propagation Model: Dual Slope n = 2 up to d = 30 m n = 3.5 for d > 30 m Performance Criteria: BER ≤ 10^{-5} for 80% of Monte Carlo trials (time dependence) 80% of User Terminal Locations should satisfy the above criterion (location dependence)	41.05	More relaxed performance criteria have increased the average number of WLANs from 24.79 to 41.05.
AP Cell Radius = 30 m Simulation Area = 1500 x 1500 m^2 Number of User Terminal Locations = 50 Propagation Model: Dual Slope n = 2 up to d = 30 m n = 3.5 for d > 30 m	43.84	Average number of WLANs has increased from 24.79 to 43.84 when the area size has been increased from 1000 x 1000 m^2 to 1500 x 1500 m^2.
AP Cell Radius = 30 m Simulation Area = 2000 x 2000 m^2 Number of User Terminal Locations = 50 Propagation Model: Dual Slope n = 2 up to d = 30 m n = 3.5 for d > 30 m	66.51	Average number of WLANs has increased from 43.84 to 66.51 when the area size has been increased from 1500 x 1500 m^2 to 2000 x 2000 m^2.

Table 5: Simulation results (indoor WLAN intra-system interference)

The number of devices that can be placed successfully in an area does not scale linearly with area (i.e. constant density) because there are more interfering sources aggregating in effect at each victim receiver. This can be seen from the following results (taken from Table 5):

Area (m x m)	Area (km^2)	Number of APs	Density of APs (per km^2)
500 x 500	0.25	8.35	33.4
1000 x 1000	1	24.79	24.79
1500 x 1500	2.25	43.84	19.48
2000 x 2000	4	66.51	16.63

Table 6: Area scaling results

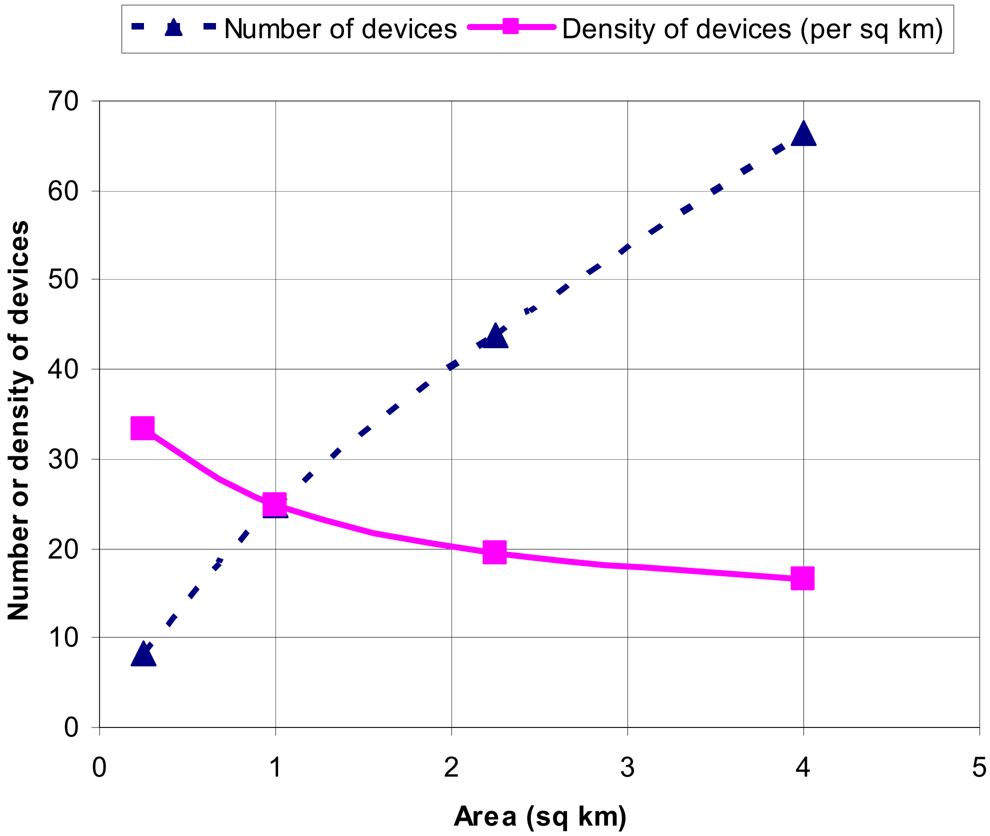

Figure 25: Number or density of WLANs with area

As the area is increased there comes a point at which the effect of distant interfering sources becomes insignificant. This is reflected by the density against area being asymptotic to some value—in this case, and on the basis of the results available as displayed in the graph above, it might be reasonable to estimate that the asymptotic value is around 15 devices per km^2.

The next set of runs covers the impact of interference from Bluetooth (BT) devices into WLAN systems. The following parameters have been assumed for the baseline model.

Scenario	Indoor Bluetooth into indoor WLAN
BT EIRP (dBW/MHz)	–30
BT Activity Ratio	0.0167 (Assume an overall activity ratio of 0.05 for which 1/3 of the time BT is active in a given WLAN system operating band)
BT Antenna Pattern	Isotropic
BT Height (m)	1
Number of BT Devices	500
AP EIRP (dBW/MHz)	–28.4 (32 mW in 22 MHz)
AP Activity Ratio (Interfering APs only)	0.3
AP Height (m)	3
User Terminal Height (m)	1
AP Cell Radius (m)	30
User Terminal System Noise Temp. (K)	2900 (NF = 10 dB)
User Terminal Max. Antenna Gain (dBi)	0
Data Rate (Mbps)	11
Implementation Loss (dB)	2
Modulation	CCK
AP Antenna Pattern	Isotropic
User Terminal Antenna Pattern	Isotropic
Propagation Model	Dual Slope n = 2 up to d = 30 m n = 3.5 for d > 30 m Log-Normal Shadowing Fixed Shadowing Std Dev. = 3 dB Variable Shadowing Std Dev. = 3 dB Rayleigh Fast Fading
Simulation Area (m^2)	1000 x 1000
Performance Criteria	BER ≤ 10^{-5} for 90% of Monte Carlo trials (time dependence) 90% of User Terminal locations should satisfy the above criterion (location dependence)
Number of Times a Scenario is Filled	100
Number of Monte Carlo Samples at Each Test Point	1000
Number of Tries for Introducing a New AP	20
Number of User Terminal Locations (Test Points in AP Service Area)	50

Table 7: Baseline model for BT interference into WLAN systems

As before, an initial simulation run with the baseline model has been implemented. This is followed by further runs with modified baseline parameters. The modifications and the simulation results are shown in the following table.

Model	***Average Number of WLANs***	***Comment***
Baseline (Number of BT Devices = 500)	20.67	With no interferers, the calculated number was 24.79 (see Table 5).
Number of BT Devices = 1000	18.13	Increase in interferers has resulted in a reduction in the average number of WLANs.
Number of BT Devices = 1500	13.91	
Number of BT Devices = 2000	9.82	

Table 8: Simulation results (BT interference into WLAN systems)

The following figure shows the sensitivity of the results to the choice of random number seed—as can be seen, the variation is not significant.

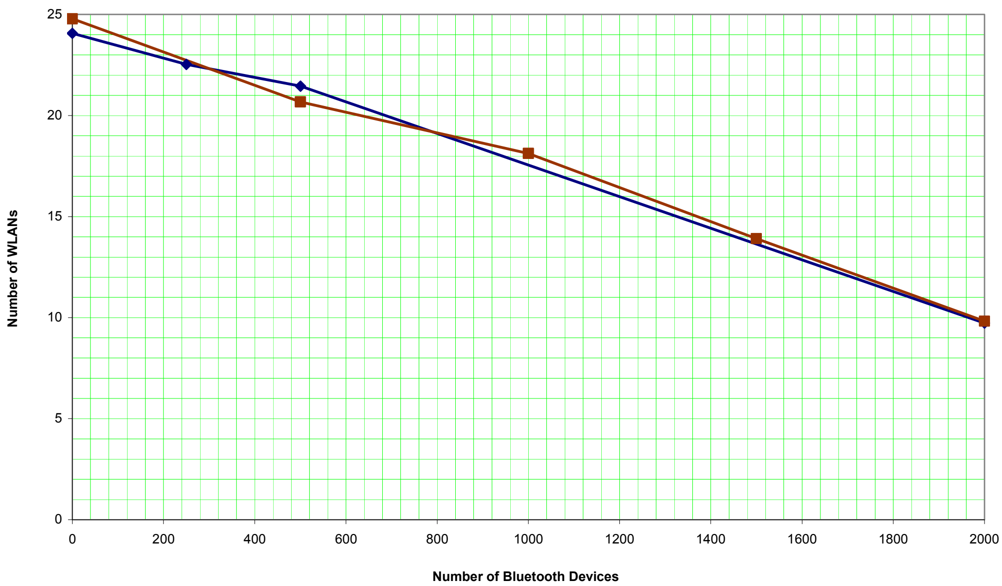

Figure 26: Number of WLANs vs number of Bluetooth devices

The impact of microwave oven interference has been examined using the baseline parameter values shown in the following table. It should be noted that the microwave oven EIRP is an average value based on the NTIA experiments, where a number of ovens and measurement frequencies in the band 2.4–2.5 GHz were used. The NTIA measurements show that EIRP does not vary significantly over a large portion of the band for most of the ovens considered. A study conducted on behalf of Ofcom (“2.4 GHz Monitoring Exercise”, Sept 2003, Mass Consultants) suggests that EIRP is higher in the upper part of the band.

Scenario	Indoor Microwave Oven into indoor WLAN
Microwave Oven EIRP (dBW/MHz)	–29.8 (Based on average emission of 5 dBm/3 MHz measured by the US NTIA)
Microwave Oven Activity Ratio	0.1
Microwave Oven Antenna Pattern	Isotropic
Microwave Oven Height (m)	1
Number of Microwave Ovens	500

Table 9: Baseline model for microwave oven interference into WLAN systems

The remaining simulation parameters are assumed to be the same as those used in the Bluetooth baseline model.

The following table summarises the simulation results.

Model	***Average Number of WLANs***	***Comment***
Baseline (Number of Ovens = 500)	0	Aggregate interference from 500 microwave ovens has not allowed any WLAN operation in the simulation area of 1000 x 1000 m^2.
Number of Ovens = 100	4.45	Reduction in the number of ovens has increased the average WLANs.
Number of Ovens = 100 Oven Activity Ratio = 0.05	10.45	Reduction in the oven activity has increased the average WLANs.

Table 10: Simulation results (microwave oven interference into WLAN systems)

The impact of ENG/OB interference has been examined using the following baseline model parameters.

Scenario	Outdoor ENG/OB into indoor WLAN
ENG/OB Max. EIRP (dBW/MHz)	21 (TX1) –8 (TX2)
ENG/OB Max. Antenna Gain (dBi)	21 (TX1) 5 (TX2)
ENG/OB Antenna Pattern	Rec. 699 (TX1) Omni (TX2)
ENG/OB Height (m)	10 (TX1) 2 (TX2)
Number of ENG/OB TXs	1
Outdoor to Indoor Penetration Loss (dB)	10

Table 11: Baseline model for ENG/OB interference into WLAN systems

The remaining simulation parameters are assumed to be the same as those used in the Bluetooth baseline model.

The calculated average WLAN systems are shown in the following table.

Model	Average Number of WLANs	Comment
Baseline (TX1)	3.45	Interference from a pneumatic vehicle mast allows an average 3.45 WLANs to operate in the simulation area of 1000 x 1000 m^2.
Baseline (TX2)	19.78	Interference from a handheld camera allows an average 19.78 WLANs to operate in the simulation area of 1000 x 1000 m^2.

Table 12: Simulation results (ENG/OB interference into WLAN systems)

The final set of runs examined the implications of outdoor WLAN intra-system interference. The following parameters have been assumed for the baseline model.

Scenario	Outdoor WLAN intra-system interference
AP EIRP (dBW/MHz)	–28.4 (32 mW in 22 MHz)
AP Activity Ratio (Interfering APs only)	0.3
AP Height (m)	10
User Terminal Height (m)	1
AP Cell Radius (m)	100
User Terminal System Noise Temp. (K)	2900 (NF = 10 dB)
User Terminal Max. Antenna Gain (dBi)	0
Data Rate (Mbps)	11
Implementation Loss (dB)	2
Modulation	CCK
AP Antenna Pattern	Isotropic
User Terminal Antenna Pattern	Isotropic
Propagation Model	Dual Slope n = 2 up to d = 100 m n = 3.5 for d > 100 m Log-Normal Shadowing Fixed Shadowing Std Dev. = 3 dB Variable Shadowing Std Dev. = 3 dB Rayleigh Fast Fading
Simulation Area (m^2)	2000 x 2000
Performance Criteria	BER ≤ 10^{-5} for 90% of Monte Carlo trials (time dependence) 90% of User Terminal locations should satisfy the above criterion (location dependence)
Number of Times a Scenario is Filled	100
Number of Monte Carlo Samples at Each Test Point	1000
Number of Tries for Introducing a New AP	20
Number of User Terminal Locations (Test Points in AP Service Area)	20

Table 13: Baseline model for outdoor WLAN intra-system interference

As before, further runs have been implemented with modified baseline parameters. The calculated average number of WLANs is shown in the following table together with the modifications.

Model	***Average Number of WLANs***	***Comment***
Baseline (AP Cell Radius = 100 m)	9.74	
AP Cell Radius = 50 m	19.76	Average number of WLANs has increased when AP cell radius is decreased.
AP Cell Radius = 30 m	30.37	
AP Cell Radius = 30 m Simulation Area = 1500 * 1500 m^2	19.6	Average number of WLANs has decreased when simulation area is reduced.
AP Cell Radius = 30 m Simulation Area = 1000 * 1000 m^2	10.72	

Table 14: Simulation results (outdoor WLAN intra-system interference)

7.3 Analysis of results

The raw results above were analysed to determine the sharing metrics described in Section 5.1.3. The summary results are shown in the tables below.

Number BTs	**Number of WLANs**
0	24.67
500	20.67
1000	18.13
1500	13.91
2000	9.82

Table 15: Overview of results of Bluetooth runs

Number Microwave Ovens (MO)	**WLANS (MO activity = 0.05)**	**WLANS (MO activity = 0.1)**
0	24.67	24.67
100	10.45	4.45

Table 16: Overview of results of microwave oven runs

Number of ENGs	**WLANS (ENG type 1)**	**WLANS (ENG type 2)**
0	24.67	24.67
1	3.45	19.78

Table 17: Overview of results of ENG runs

A hypothesis was proposed that the number of Type A systems would be (at least initially) linearly dependent upon the number of Type B systems that were present, and hence there would be a relationship as follows:

$$N_A(N_B) = N_A(0) - \alpha_{AB} N_B$$

The value $N_A(0)$ is the number of WLANs without interference, which for this case is 24.67 within an area of 1,000 x 1,000 m (i.e. a density of 24.67 WLANs/km^2).

This hypothesis was tested using linear regression tools on the values in Table 14 above. It was found that the regression correlation factor r = 0.997, which suggests there is extremely strong correlation.

For the cases above, the α terms were derived as shown in the table below, assuming that the other cases have as strong a correlation as the BT case.

Interfering system	α	Units
BT	0.007	WLAN/BT/km^2
MO(0.05)	0.142	WLAN/MO/km^2
MO(0.1)	0.202	WLAN/MO/km^2
ENG-2	4.890	WLAN/ENG/km^2
ENG-1	21.220	WLAN/ENG/km^2

Table 18: α values derived

These values show the comparative impact or opportunity cost of spectrum for various types of system with respect to a single WLAN system. Note that these values are only applicable for the environment used to derive these numbers.

It can be seen that the α for BT is significantly lower than that for ENG type 1 (i.e. BT has a much lower interference impact). Similarly, the impact of using a microwave oven with higher activity ratio can be seen by the difference in α value.

There was thus evidence that there is a linear relationship between the number of Type B systems added to an environment dominated by Type A systems and the number of Type A systems. In other words, for each N_B Type B systems added the number of Type A systems is reduced by α_{AB} N_B.

The runs did not cover the full range from “all Type A systems” to “all Type B systems”. For example, the WLAN vs BT runs covered the range from about 25 to 10 WLAN devices, and did not explore the range where there were extremely large numbers of BTs and very small numbers of WLANs. For this range it is likely that interference from BT devices will become the most significant factor. One approach for this range could be to reverse the process, and see how many BTs can be introduced in an area where a small number of WLANs have been deployed.

Some initial results suggest that the situation is indeed reversed when the environment becomes dominated by Type B systems—this is expected, as the behaviour should be symmetric between system A and system B. Note, however, that the slope could potentially be different, in other words $\alpha_{BA} \neq \alpha_{AB}$, but further work is required to clarify this for a range of scenarios.

The behaviour in the intermediate area where neither Type A or Type B systems dominate has not been analysed and further work is required.

The following section on the interpretation of results is based on the assumption that plotting the N-Systems statistic for two systems resembles the following graph.

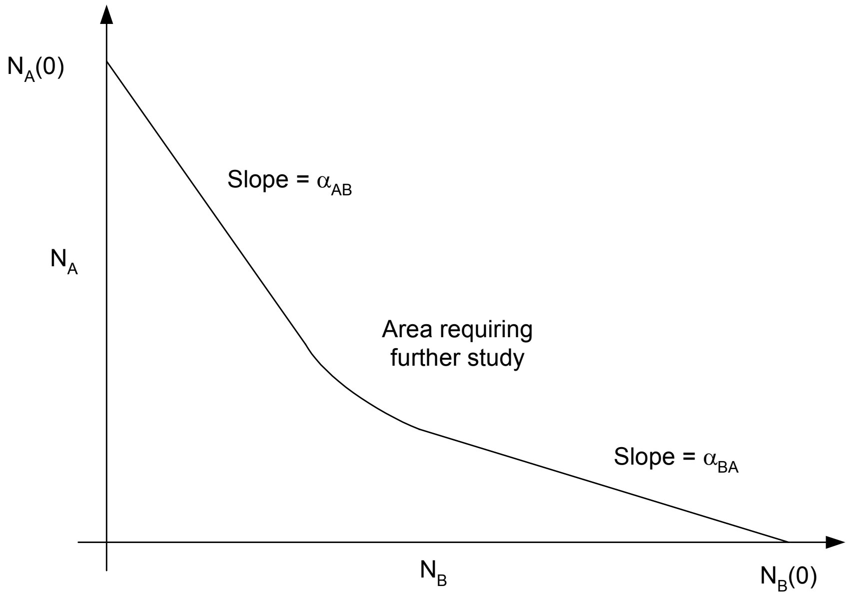

Figure 27: Shape of graph plotting N_A vs N_B

7.4 Interpretation of results

The section above has shown how the method can be used to derive two values:

N: the mean number of systems that can operate in a scenario that defines propagation and interference effects while meeting service requirements

α_{AB}: which relates the number of Type A systems that can be introduced against those of Type B, in a defined environment.

This section describes how these parameters can be used to derive measures of occupancy and efficiency, using the results obtained as an example (rounding to the nearest integer where appropriate).

7.4.1 Spectrum Occupancy

The N measure represents "mean full occupancy" of a band—the point at which the method was unable to introduce any additional systems into a particular scenario (which could include deployment of systems of other types). This can then be compared against actual deployment densities to give a measure of how occupied a band has become.

As noted, the method selected test points using random or quasi-random methods. Therefore there was not a single result but a distribution representing the result each time a scenario is completely filled. Therefore an additional measure is to determine the likelihood that a particular actual deployment density has reached full occupancy.

Alternatively, rather than comparing against an actual deployment density the measure could be compared against a forecast density to assist in determining spectrum requirements.

Example

If the method suggests that the mean number of WLANS that can be deployed in a 1 km^2 area is 25, and observations indicate that the actual value in a hot-spot of that size is 20, then the mean occupancy is 80%.

Alternatively, the distribution of runs can be examined as in the figure below and those for which the number of systems deployed was 20 or less counted. The probability that this location has reached full occupancy can then be derived, which in this case was p = 0.21.

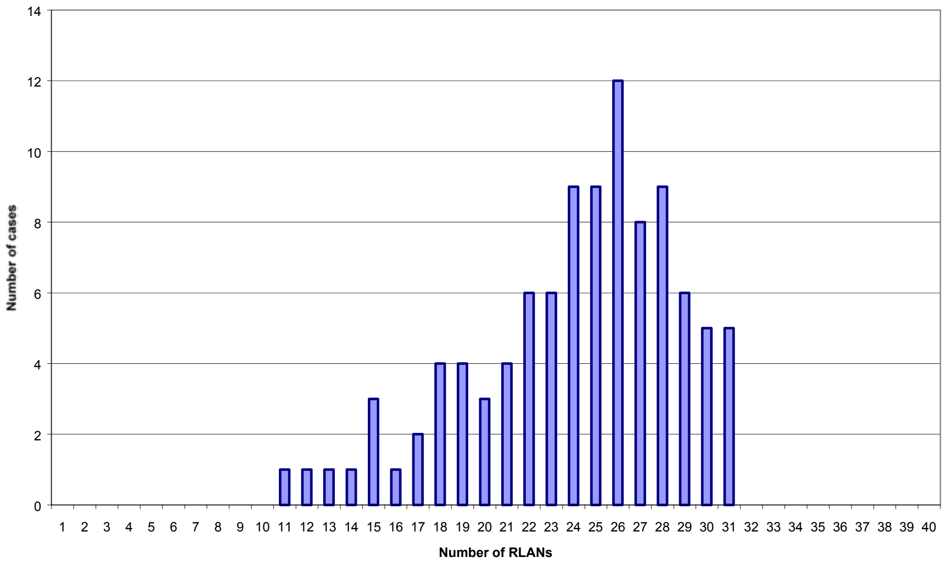

Figure 28: Histogram of number of WLANs / run

7.4.2 Relative Technical Efficiency

It is not in general possible to identify what is most efficient in all circumstances as there will be a dependency upon required service types, propagation environments, and the ability to facilitate sharing with other systems. A high N is not sufficient on its own—for example, it would imply that, for the systems considered, BT would be more efficient than WLANs or ENG devices, yet in practice BT would be unable to offer the same services.

Nor is it sufficient to say that for a given service a high N for a scenario without any interferers is an indicator of efficiency, as it is also necessary to take account of how a system might react to interference.

For example, the figure below shows a plot of the number of Type A systems against the number of Type B systems. If system A is modified in such a way as to increase the number of systems that can be deployed in an environment without any other types of system, it could become more susceptible to interference. Hence for an environment containing more than a critical number of Type B systems it could be said to be less efficient.

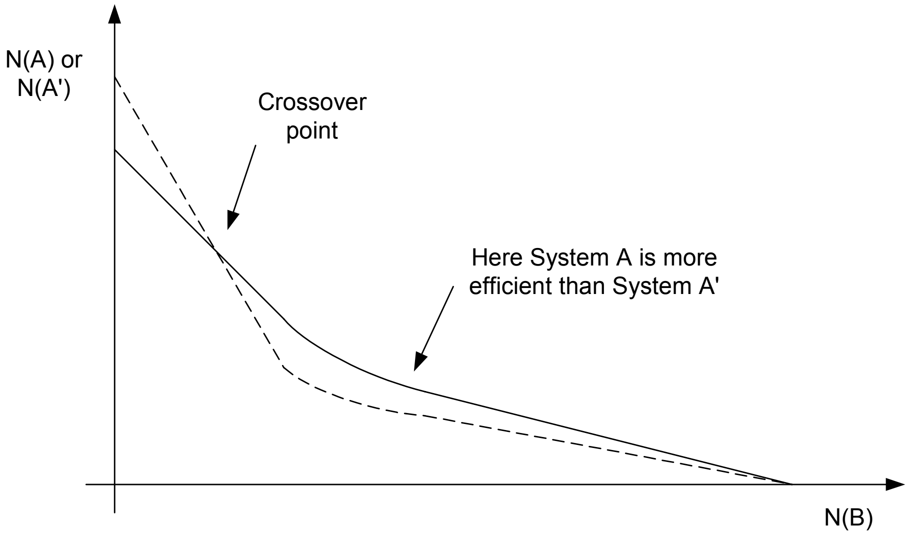

Figure 29: Conditional efficiency gain from change in System A

However, for a given scenario it is possible to identify what is *relatively* more efficient. So, in the example above, the original design can be said to be more efficient in some regions and less efficient in others.

The modification could result in a higher N_A for any N_B, as in the figures below.

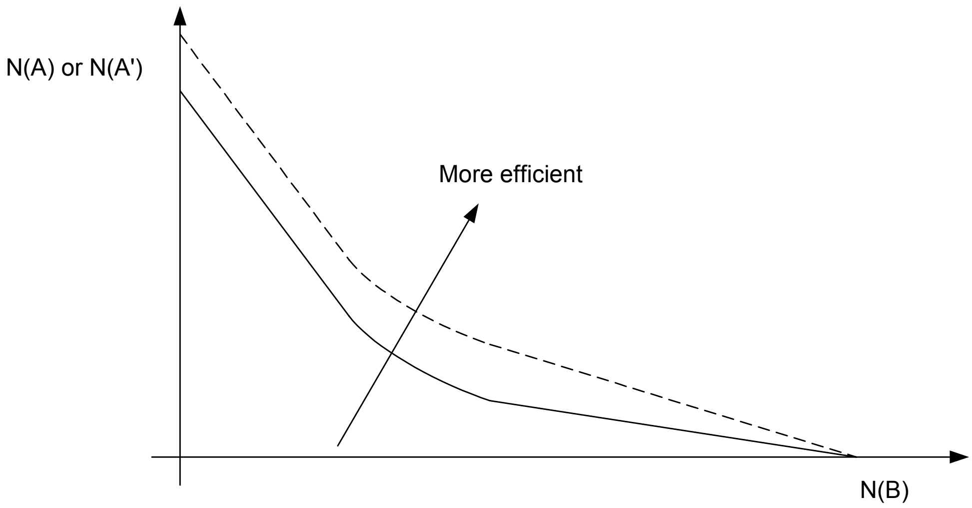

Figure 30: Efficiency gain from change in System A

This could also come from a change in system B that reduces its interference potential, facilitating sharing with system A.

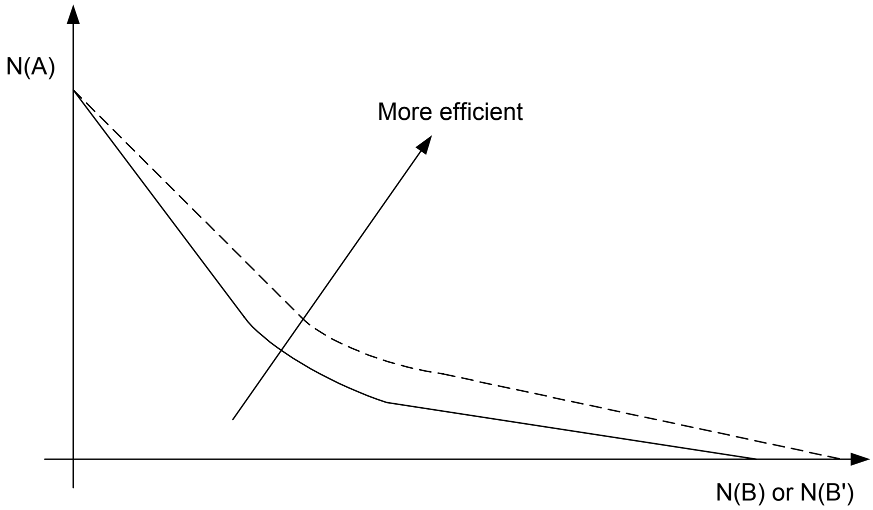

Figure 31: Efficiency gain from change in System B

In these situations it can be said that the modification to the system can increase or decrease relative efficiency. Note that this effect could vary between environments—for example, if the propagation characteristics were different.

Example

No runs were done to compare the impact on N of changing a system's characteristics while retaining its service requirements. However, this approach can be demonstrated by comparing the two runs that used different microwave oven activation factors. By changing this parameter from 0.1 to 0.05 the number of WLANs that could be introduced within the unit area of 1 km^2 was increased from 4 to 10. Hence if that change had maintained the service provided by the microwave ovens, then it could be considered to have increased spectral efficiency.

7.4.3 Value Based Efficiency

The α_{AB} factor identifies how many Type A systems can be deployed compared to the deployment of a single Type B system. This parameter can be used to generate a plot of the total number of systems in a range of scenarios from "all Type A" to "all Type B", as in the figure below.

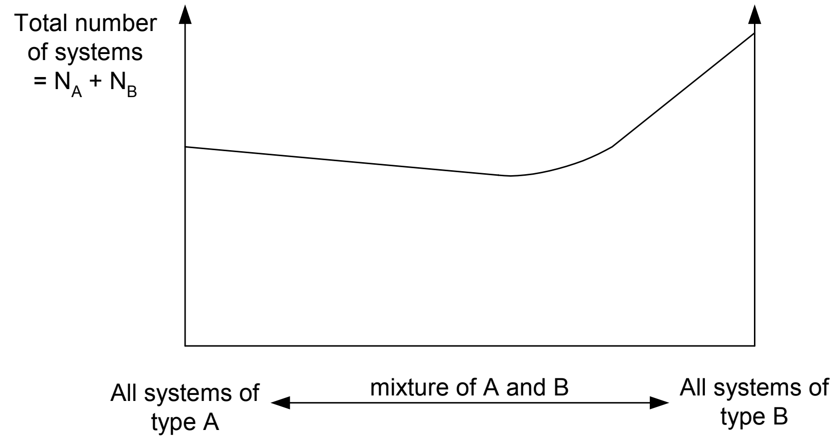

Figure 32: Total number of systems against type of system

As noted previously, this on its own is insufficient to make a judgement as different users will have different requirements for services, and therefore could value a Type A system higher than a Type B system.

However, by incorporating a measure of the value of each type of system—i.e. V_A, V_B—an assessment of the comparative value of spectrum can be made. If this value is based upon economic measures, then this would identify the most economically efficient use of spectrum. Using this information, the plot could change, as in the figure below.

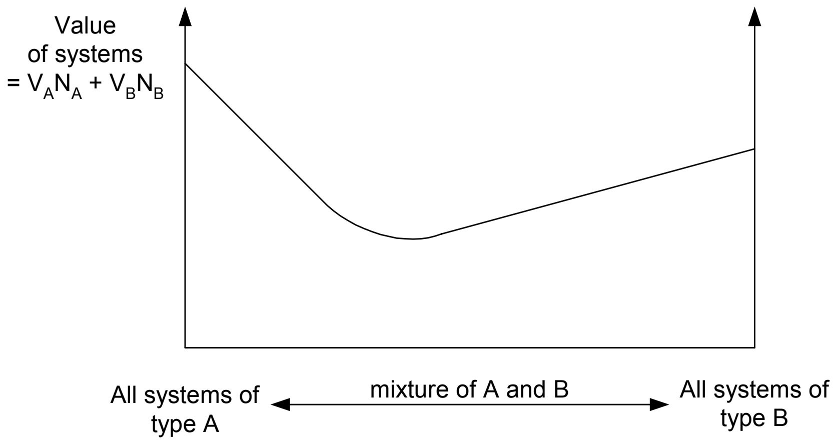

Figure 33: Value of systems against type of system

It is likely that different users will assign different values to each type of system and could therefore produce different judgements on what is more efficient for them to deploy.

This approach could be generalised to consider more than two types of system.

Example

The total number of WLANs that could be deployed in a 1 km^2 area was decreased by 4 after adding a single ENG of type 1. However, if the economic value of the ENG-1 was more than 4 times that of an WLAN (for example, 5 times) then it would be beneficial to allow ENGs to operate.

8 MEASUREMENTS

In considering the practicality of the developed method a short measurement campaign, aimed at comparing the results of the method against measured values, has been undertaken. A range of WLAN and PLAN devices has been procured, networked and operated in an office environment.

It should be noted that the scope of this work package is to compare a few results from the spectrum efficiency calculation method against measured values. The comparison is an example, as it is not practical to compare all situations that the method is capable of representing. In order to keep equipment levels within practical and cost effective limits a relatively small number of WLAN and PLAN devices have been procured. The devices are operated to ensure that unacceptable interference arises at some point in order to know when full occupancy occurs. The operating parameter values that lead to this situation will be inputs to the spectrum efficiency calculation, thereby linking measurement and method.

8.1 Design considerations

The aim of the experiments is to determine objective measurements of network performance in the presence of interference. Although the scenarios to be investigated cannot be exhaustive, and the definition of user acceptability is qualitative, the experiment is designed to recover unbiased, basic statistics from each test. The monitoring equipment should be capable of measuring effective data rate and bit error rate.

Application-oriented data rates (i.e. as perceived by the user) are relatively easily determined by using a real protocol, such as Web browsing, file transfer or streaming media. Web browsing is unlikely to be sufficiently sensitive to network performance unless the downloaded material is quite substantial, in which case the service is, in effect, file transfer. Although streaming services provide good diagnostics on network performance (and user acceptability), they are technically difficult to integrate into an automated measurement system, where a client interface is required in the measurement software; in addition, streaming services are normally accessible only via the Internet, which introduces an unknown performance element into any experiment, and may be subject to quality of service constraints. In summary therefore, file transfer is the most attractive option, as it provides high activity levels and requires simple client software and readily available server software. Data rate is then measured by timing the transfer of a file of known size.

There are a number of approaches to measuring bit error rate:

1. Given access to network interface hardware, it is possible to log the bit stream sent and received. Comparison of the two data sets then leads directly to a true BER estimate (i.e. including bit errors in protocol data as

well as application data). However, only specialist equipment provides such a low-level interface.

2. With a purpose-built packet interface using an unreliable protocol, it is possible to count packet errors by simply counting the packets missing from a sequenced stream.
3. The majority of commercial wireless routers and access points provide a management interface that gives basic statistics, such as packet counts, packet checksum errors and byte counts. It is not generally possible, however, to obtain direct estimates of bit error rates.

Using the management interface of a commercial-grade access point is a simple method for obtaining the required statistics, on the assumption that the bit error rate is calculated from the number of packet errors and the number of bytes transferred (which should be adequate for low bit error rates).

A further possible experiment dimension that could be explored is the variation in performance with different types of equipment (e.g. interoperability between devices from the same and different manufacturers). However, the purpose of the measurement campaign is to validate the proposed model rather than explore sensitivity issues: as a result, compatibility should be maximised by using a small number of manufacturers and a small range of equipment types.

8.2 Monitoring equipment

Aegis has developed an instrument control and data logging package, which has been used to log data from a range of experiments including balloon-based building penetration losses, location variability and various broadcast measurements. The software interfaces to a spectrum analyser, a GPS device, serial and parallel ports; it also has FTP and HTTP client interfaces, which provide a suitable basis for driving file transfer operations and monitoring access point statistics.

An additional measurement objective is to assess area coverage. To do this manually is quite laborious: however, a computer-controlled, rail-mounted antenna fixing was available from a previous experimental campaign and this was used to assess distance-dependent performance.

The final experimental configuration is shown in the following figure, as applied to a Bluetooth interferer.

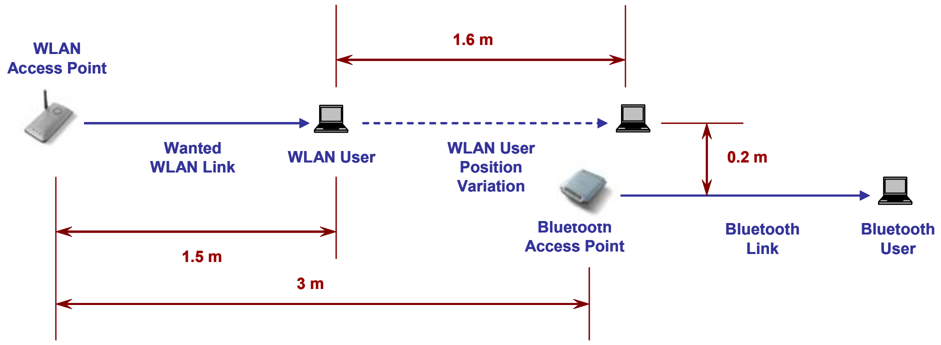

Figure 34: Experimental configuration

The following figure shows results from an example experiment, in which the WLAN "user" antenna is moved in 20 cm steps along the rail, starting 1.5 m from the WLAN access point and ending 3.1 m from the access point (no other system is operating); at each antenna position, ten trials are performed to assess the throughput; using FTP, each trial copies five different 1 MB files (i.e. a total of 5.10^6 bytes) from the access point to the user (each file contains random numbers).

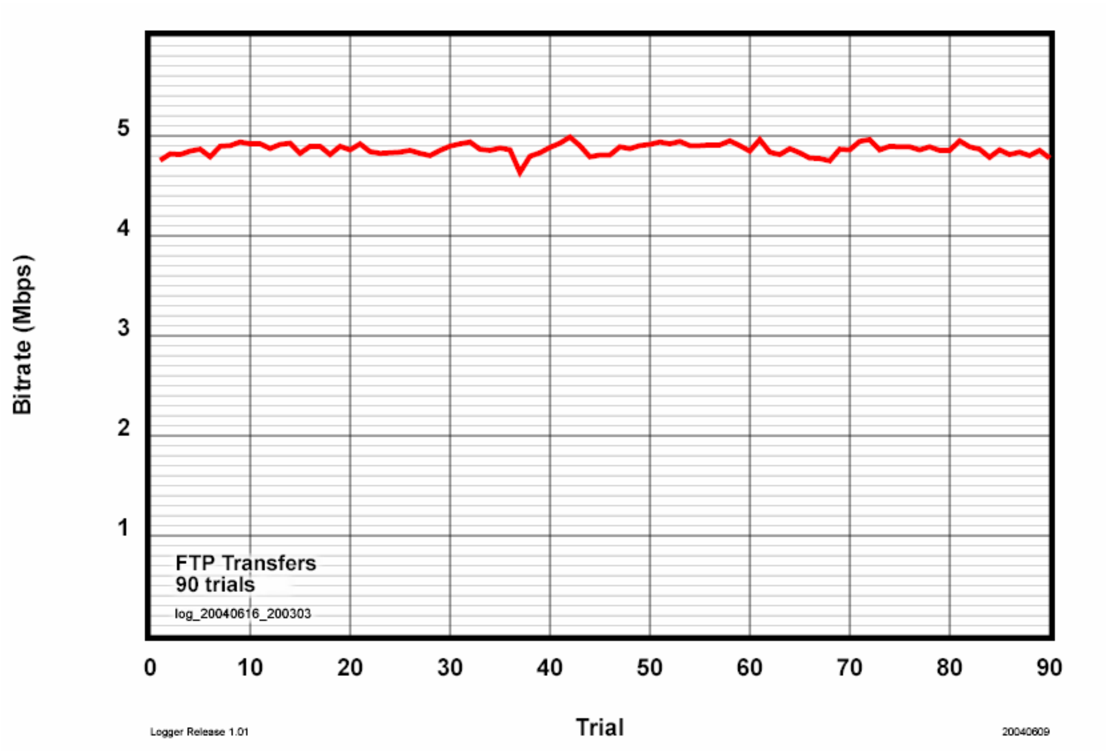

Figure 35: Measured throughput in 802.11b

8.3 Equipment under test

An equipment database has been collated containing capability, price and technical information (including data sheets) for over one hundred devices, including access points, network adapters and composite products such as wireless routers. The devices are for use in a corporate, small office or home environment—equipment for providing public networks is not included. The purpose of the database is to identify equipment that is suitable for use in an automated measurement programme. Specifically, the presence of a management interface for a device makes it possible to automatically obtain statistical data (typically Web or SNMP); also, Bluetooth devices have widely varying capabilities and care needs to be taken in procurement in order to ensure sufficiently high activity levels. A by-product of the data collection exercise has been to obtain information on typical equipment characteristics (e.g. EIRP), which has been used in determining simulation parameters.

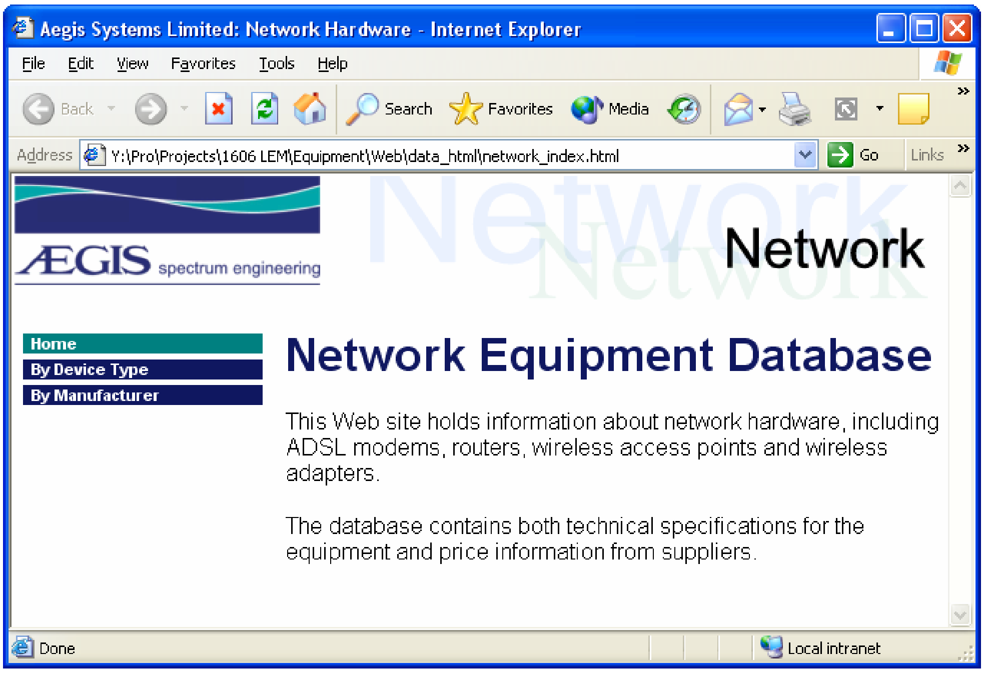

Figure 36: Equipment database

Another desirable feature for candidate equipment is the ability to control power levels, so that experiments can be run at low power in the hope that the results could be scaled up to larger areas. An ideal device would also include an interface that exposes measured power levels (most network adapters provide utility software with a power level indication).

8.3.1 802.11 equipment

Access points and network adapters from D-Link have been purchased to implement the 802.11 part of the experiments. The chosen 802.11g access point provides both HTTP and SNMP interfaces and has controllable power levels. The network adapter is designed for compatibility with the access point and supports a full range of 802.11g and 802.11b data rates and can be switched into an 802.11b-only mode.

Name	Number	Description
D-Link *DWL-2100AP*	3	802.11g/b access point with Ethernet interface.
D-Link *DWL-G520*	3	802.11g/b network adapter supplied as a PCI card.

Table 19: 802.11 equipment

8.3.2 Bluetooth equipment

Bluetooth devices are typically used in pairs. In order to generate sufficient activity is it desirable to connect a number of network adapters to a single access point and load the network with a file transfer task, as with 802.11. A small number of Bluetooth access points have been identified in the network equipment database: the D-Link device has been purchased.

Name	Number	Description
D-Link *DBT-900AP*	1	Bluetooth access point with Ethernet interface, supporting the PAN profile.
D-Link *DI-604*	1	Broadband Ethernet router, required for DBT-900AP.
TDK *go blue Bluetooth USB Adaptor*	1	Bluetooth network adapter supplied as a USB device.

Table 20: Bluetooth equipment

8.4 Calibration

A number of experiments were performed to assess the ability of each of the six test PCs to deliver an adequate data stream to the wireless network. It was immediately observed that, though all machines could load an 802.11b link, the throughput showed a significant dependence on file size. This dependence is a feature of the radio link, the PC and FTP: the following figure shows the results of an experiment conducted on a single machine in which each step results from a 10-fold increase in file size (starting at 1 kB and ending at 100 MB).

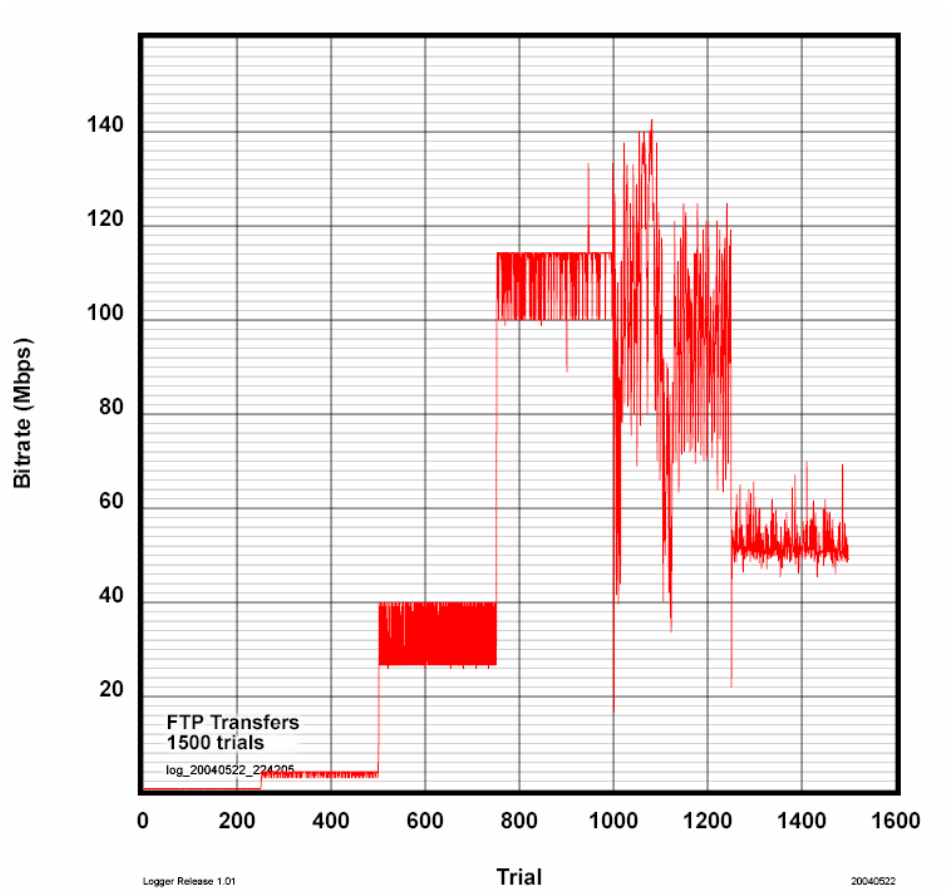

Figure 37: FTP performance and file size

It was also noticed that FTP failures sometimes occurred for large files (100 MB). The implications for the experiment are:

- small file sizes improve the time resolution of the results and reduce the elapse time of the experiment but may not give an accurate measure of throughput
- large file sizes improve the sensitivity of the experiment in detecting low bit error rates but multiple file copies may be more reliable.

The sensitivity of throughput to file size is shown in the following figure for various network types; the tests were performed on two machines—Test1 and Test4—and no significant dependence on machine is apparent.

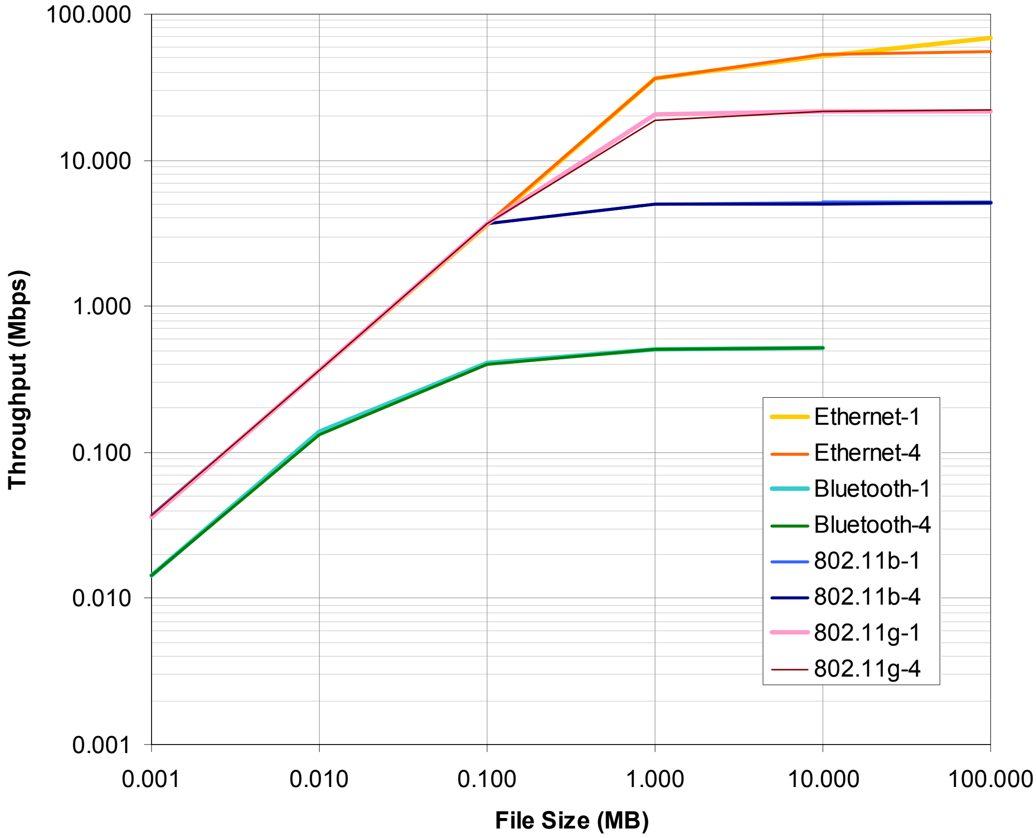

Figure 38: FTP throughput

For the final experiments it was concluded that:

- FTP caching (and writing to cache) must be disabled
- each trial should consist of multiple files (five)
- 1 MB files are adequate throughput measures for 802.11b and Bluetooth
- all test machines were adequate and unbiased for 802.11b and Bluetooth.

If 802.11g performance were to be measured then lower speed PCs (e.g. 200 MHz Pentium) should not be used, as the wireless link would not be fully loaded.

8.5 Results

The results presented here were obtained from the rail-mounted user configuration described previously. In each of the graphs, the x-axis broadly represents distance along the line joining the wanted and unwanted access points.

8.5.1 802.11b network sharing

The first series of experiments examined the performance of an 802.11b network without any other systems operating (“clear”) and then additional networks were introduced with the effect on the performance of the “wanted” network recorded. Each of the additional networks is itself copying files continuously with FTP.

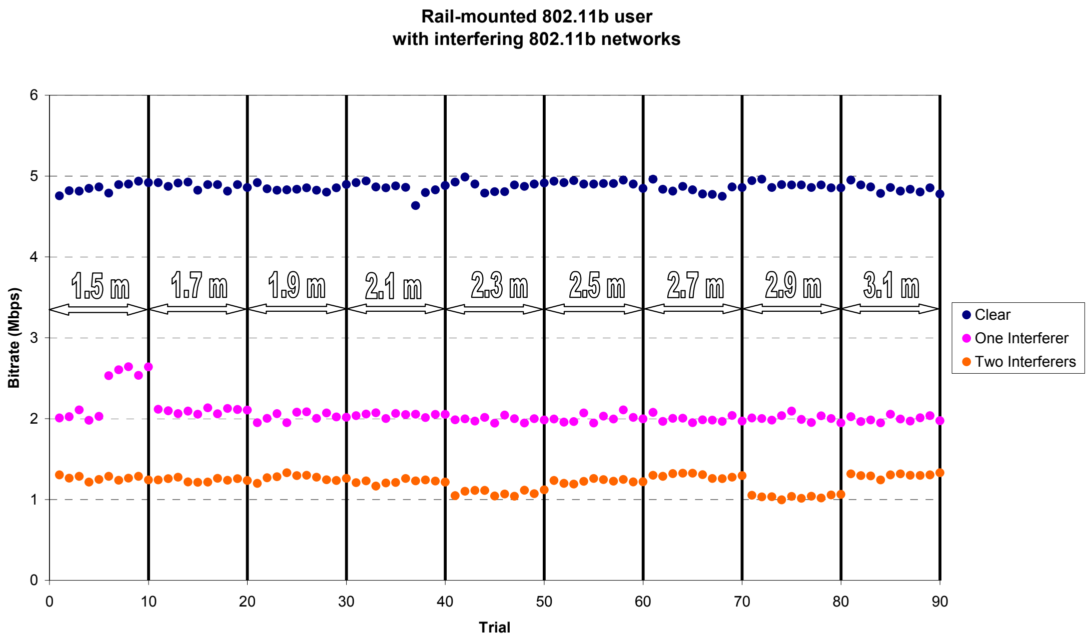

Figure 39: Effect of adding interfering 802.11b networks

Note that the first interfering 802.11b access point was located 3 m from the wanted 802.11b access point (along the rail, but offset 20 cm); the second interfering access point was 3 m from the wanted access point (perpendicular to the rail).

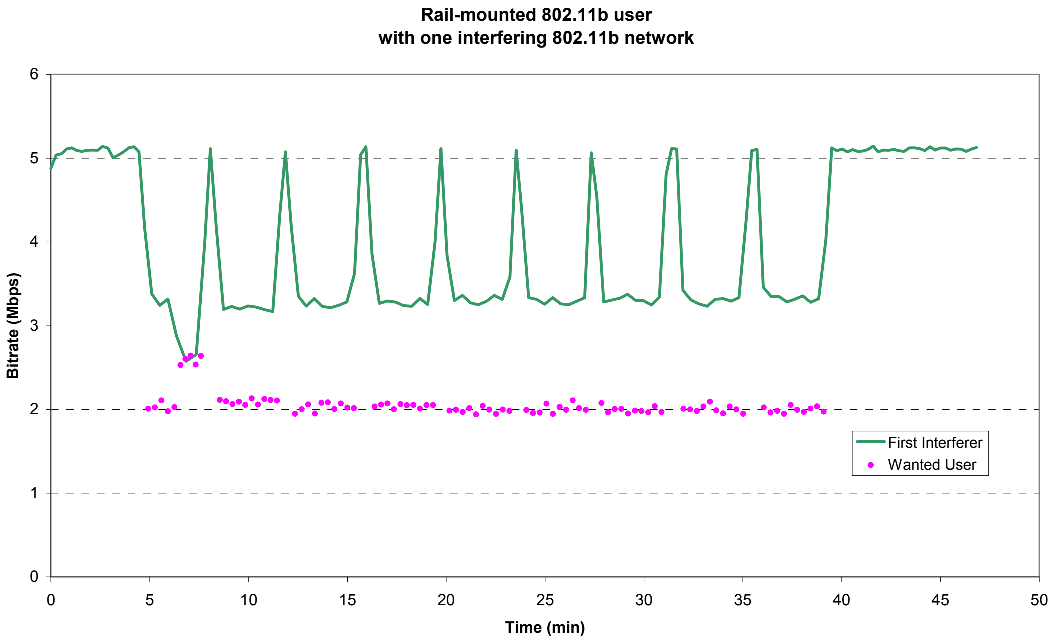

Figure 40: Throughput variation with time (one 802.11b interferer)

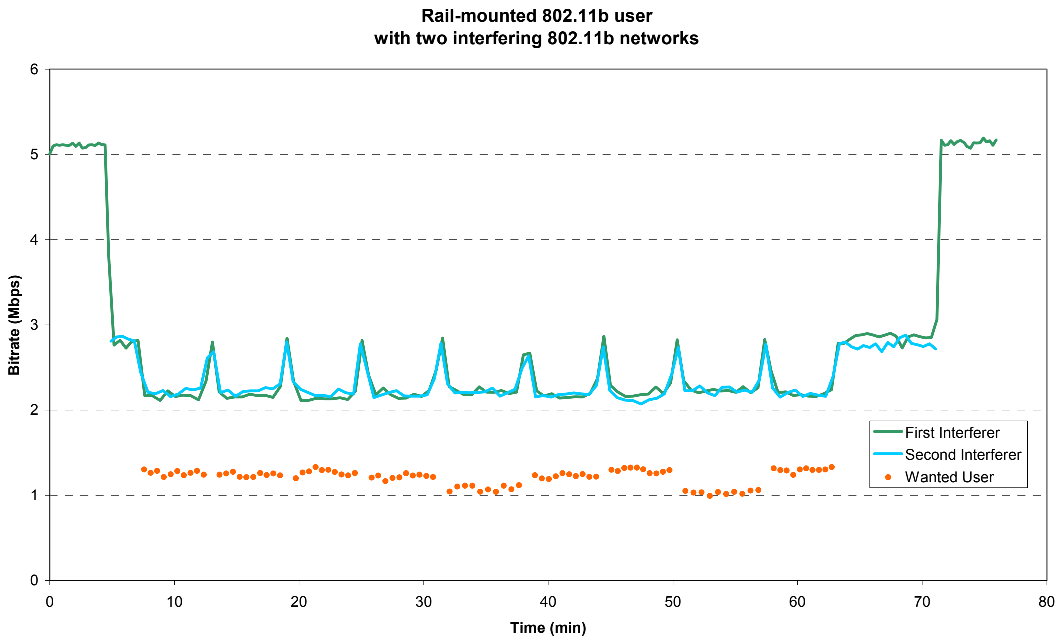

Figure 41: Throughput variation with time (two 802.11b interferers)

The spikes in the latter two figures arise from the motion of the "user" antenna: no data is transferred on the wanted link during the 20 cm travel and the available bandwidth is then taken up by competing networks.

The results show:

- no systematic variation with user position
- bandwidth sharing between all 802.11b networks.

The conclusion of the experiment is that 802.11b networks based on CSMA/CA are remarkably efficient at sharing the available bandwidth—at least, over short distances.

Note that all devices transmitted at 11 Mbps throughout the experiments. It is also noted that packet errors were recorded during (contended) RTS exchanges, but not during other data traffic.

8.5.2 802.11b and Bluetooth network sharing

A similar set of experiments was performed with a Bluetooth system being added as the "interferer". The Bluetooth link was configured to create a Network Access service that provided file sharing between the two test PCs; the link was then loaded with continuous FTP file copying.

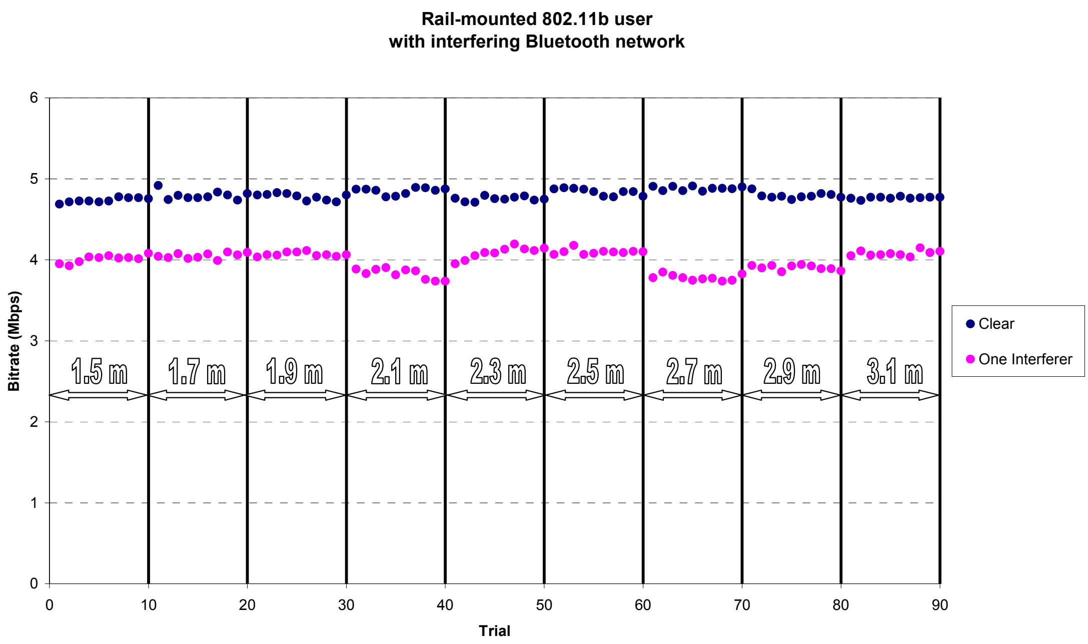

Figure 42: Effect of adding interfering Bluetooth network

Note that the interfering Bluetooth access point was located 3 m from the wanted 802.11b access point (along the rail, but offset 20 cm).

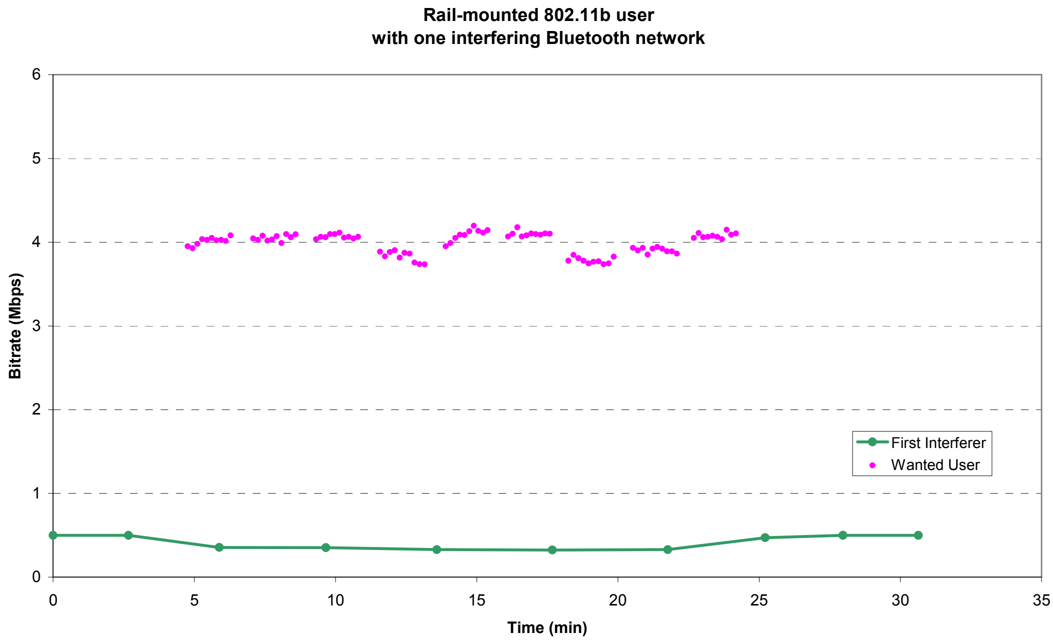

Figure 43: Throughput variation with time (one Bluetooth interferer)

Note that there are no spikes in the Bluetooth throughput when the antenna moves along the rail: this is because each Bluetooth file copy takes longer than the break period in the 802.11 transmissions.

The results show:

- no systematic variation with user position
- bandwidth sharing between 802.11b and Bluetooth networks[8]
- a reduction in 802.11b throughput by 16.9%
- a reduction in Bluetooth throughput by 32.9%.

The conclusion of the experiment is that 802.11b networks co-exist well with Bluetooth.

8.6 Measurements vs criterion

In effect, the criterion selected for the simulations primarily addressed link behaviour at the PHY (Physical) level. The measurements undertaken in a small-scale environment, however, indicate that the access protocols of the MAC layer dominate the overall link performance to the extent that any PHY level collisions are insignificant or non-existent. The efficacy of the MAC in sharing the available

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[8] Were the experiment to be repeated with high-activity 802.11b systems above and below the test channel (i.e. the default *ad hoc* channel, 6), then the Bluetooth link might well suffer a catastrophic degradation in performance: however, it is the performance of an 802.11 victim that is to be investigated here. It should also be noted that the activity factor of the experimental Bluetooth system is much higher than for typical Bluetooth applications.

capacity between devices means that C/I events (and hence bit errors) do not occur, at least for proximate devices.

Two important points arise from this comparison of the criterion used (BER, % time, % area) in the simulations and the measurement results:

- The measurements were undertaken in an environment that resulted in signal levels well above (by many tens of dBs) the noise floor. This allowed the carrier sense protocols to work very effectively. In the situation where two access points are more distant and signal levels are much lower, it might be expected that the carrier sense mechanism would cease to function perfectly and collisions would occur. In this circumstance the C/I and resulting BER would become relevant.
- The criterion used for the simulations was predicated on a minimum acceptable throughput. Although the dominance of the MAC behaviour is not directly reflected in the criterion proposed, the comparison between criterion and measurements is not completely inconsistent. The throughput of a device is automatically reduced when the carrier sense mechanism operates. This reduction in throughput would not meet the requirement of the criterion used in the simulations (i.e. for the entire throughput to be available for each WLAN network) even though the device continues to operate. In order to avoid a reduction in throughput due to the carrier sense mechanism, an interfering WLAN would have to be a sufficient distance away for it not to be detected. This distance is likely to be similar to the distance that would be required in order to satisfy the BER or C/(N+I) criterion.

9 CONCLUSIONS

There is no universal measure of spectrum efficiency and it is therefore not appropriate to compare the spectrum efficiency of systems offering different services. It is, however, quite proper to compare different systems offering the same service.

Operation in licence-exempt bands is characterised by the random placement of systems and the use of many different types of system. Although these systems are not controlled to the same extent as licensed systems, there are emission limits and standards so the systems can be characterised for the purposes of modelling.

In the absence of any universal measure of spectrum efficiency, and taking account of the generally random deployment of licence-exempt devices, we consider that the most appropriate measure against which spectrum utilisation can be judged is occupancy. A particular level of occupancy can be related to full occupancy and might be regarded as a measure of efficiency, or perhaps more appropriately utilisation. Full occupancy is determined by the random introduction of new systems to a scenario until no more can be added (the point at which a predetermined consistency check fails).

We have proposed a method (N-Systems occupancy) which allows the full occupancy of a frequency band or channel to be ascertained under different circumstances. There are two aspects to this method. Firstly, the overall approach to determining full occupancy and how this measure can be used, and secondly the consistency check that is used to determine the point at which full occupancy occurs.

We consider that the overall approach is very robust in terms of accommodating different licence-exempt radio systems. The sole requirement is that radio devices or systems are deployed without co-ordination, although the method does allow for real systems to be placed in a scenario and can accommodate planned systems where transceivers are specifically placed in relation to one another.

As noted above, the application of the method requires a consistency check that is effectively a system compatibility analysis. This raises the question as to what criterion to use as part of the compatibility analysis. The criterion can, of course, be very different for different services and frequency bands. The issues raised by the compatibility analysis were examined in relation to WLANs operating in the 2.4 GHz band.

It was found that there is no recognised criterion that specifies acceptable WLAN performance from the user or service provider's point of view. This is hardly surprising as it is difficult to specify an all-encompassing criterion when user expectations are not known, QoS protocols correct for lost packets and devices adjust their behaviour depending on the environment. Furthermore, the propagation environment influencing all this is likely to be dynamic in the situations where these devices are used (e.g. shadowing and fading). For the example of a WLAN access point and its service area we have therefore proposed the criterion as a requirement for a BER better than 1 in 10^5 for more than 90% of the time at more than 90% of locations within the access point service area. A simulator was implemented in software according to the method described in this report. In the implementation, it has been assumed that the victim system is an 802.11b WLAN running at 11 Mbps. The simulator was used to examine the implications of WLAN intra-system interference and interference into WLANs from Bluetooth devices, microwave ovens and ENG/OB systems, and behaved as expected. For example, an increase in the number of interferers and/or the introduction of variable losses (shadowing and Rayleigh) reduces the average number of WLANs whereas a relaxation in the criterion results in an increase in the average number of WLANs.

The measurement programme has identified and purchased suitable equipment and configured it for integration with network monitoring software. The original intention was to relate average separation distances (derived from the numbers of devices in a simulated area) to measured separation distances in a scaled-down environment. For the small-scale environment investigated, the measurement results indicate that the effect of protocols is more important than the gradual change of signal strength with distance. This suggests that the BER criterion used in the modelling may only be appropriate when signal levels are low (e.g. at the edge of an access point service area) and that a different type of criterion (e.g. related to protocols) might be appropriate when higher signal levels exist.

As an overall conclusion of the work it can be said that a robust method has been proposed, which enables spectrum occupancy and hence relative efficiency to be determined. The method was exercised successfully with respect to WLAN systems operating in the 2.4 GHz band and it is felt that the method would be equally successful with respect to licence-exempt systems operating in other parts of the spectrum.

The limited measurement programme does, however, raise the possibility that the proposed criterion used to determine whether a WLAN system can be introduced to a scenario may not be appropriate. A more extensive measurement programme including measurements representative of much larger distances would be needed to confirm this aspect of the work.

9.1 Revisiting the seven questions

The terms of reference for the study described in this document posed seven questions (as noted in the introduction). In the light of the work undertaken it is worth revisiting those questions.

1. What makes a system spectrally efficient in a band?

There is no universal measure of spectrum efficiency and it is therefore not appropriate to compare the efficiencies of different services and / or systems[9]. However, for a given type of system it is possible to determine what constitutes full occupancy in a frequency band / channel taking account of a particular interference environment generated by other types of system. By comparing full occupancy levels between systems that both provide the same level of service in a similar interference environment it is possible to determine which is more technically efficient relative to the other.

Another measure from the method is the relationship between what constitutes full occupancy between two different types of system. If it is possible to assign a value to each type of system (such as economic benefit) then the value of using the band for each can be calculated and hence the relative economic efficiency assessed.

2. What different band-occupancy metrics are relevant for licence-exempt operation?

The key characteristic of licence-exempt operation is that the placement of devices is random.

Having considered various approaches we consider that the proposed N-Systems occupancy method provides the most appropriate measure of band occupancy for licence-exempt bands. The method is robust and can be used in all cases where devices, or more precisely systems, are placed randomly. Planned systems, where devices are specifically located in relation to one another, therefore have to be treated as a single item when it comes to the random placement part of the method.

As long as the transmit / receive behaviour of devices and the environment can be characterised, along with a criterion that defines whether the performance of a device is acceptable or unacceptable, the overall method provides a measure of full occupancy against which other levels of occupancy can be compared.

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[9] Remembering that it is, however, quite proper to compare different systems offering the same service.

3. How should the efficiency be measured for non-uniform traffic and within a mix of different propagation environments?

The proposed method addresses device traffic in terms of an activity factor which represents the instantaneous probability of a device transmitting and therefore being a source of interference. This is one element that gives rise to time variability in the interference environment.

Time and location variability associated with propagation also needs to be taken into account. For the 2.4 GHz WLAN case modelled in detail and described earlier in this report, several aspects of propagation behaviour have been taken into account (e.g. static and time-varying shadowing and Rayleigh fading).

The key implication of time and location variability in signals is that the criterion needs to take account of this variability bearing in mind the fact that quality of service protocols allow for some signal degradation to be accommodated.

4. Should a realistic deployment be defined for a licence-exempt network to which different technologies are measured?

The proposed method measures full occupancy in terms of the number of systems that can be introduced to a given environment on the basis of a specified acceptability criterion. The given environment may contain a number of other systems or none at all. Furthermore, any of the existing systems may be randomly placed or may be located to represent real systems.

Technologies are modelled through the system transmit / receive characteristics and the interference criterion. The use of different technologies will then be reflected in different numbers of devices representing full occupancy in an area.

It is therefore possible to make a comparison of occupancy for different technologies with respect to real deployments (i.e. where there are existing systems) and/or random deployments. Use of the term “realistic deployment” presumes a representation of reality. While it would be entirely possible to base the modelling on a “realistic deployment”, defining such a representation is not easy to do and is open to dispute. It is therefore considered more appropriate to base the modelling on real and/or random cases.

5. Can and should the efficiency of multiple access schemes be separated from the modulation efficiency in assessing a technology and if so how?

The key test in the method that has been proposed is the consistency check as to whether an additional system can or cannot be introduced to a scenario. In exercising the model we have chosen to undertake the consistency check by specifying a criterion in terms of BER which is directly related to the RF environment through modem curves. Modulation efficiency is therefore implicitly taken into account—the interference sensitivity of a modulation technique is addressed within the model and the spectral efficiency (bps/Hz) is a consideration outside the model (where the bandwidth being examined is specified and the result will be a number of devices carrying a particular bitrate).

The impact of access schemes could be modelled but with increased difficulty. It would probably require a time sequence approach within the modelling, which does not sit well with the Monte Carlo style of model we have proposed. In the event that access schemes can be accommodated within the model it would be possible to separate the impact of modulation and access schemes on efficiency by looking at the relative efficiency of systems that are identical apart from one characteristic (e.g. just a change in the modulation or just a change in the access scheme).

6. How should relaying, and *ad hoc* systems be assessed in comparison with centralised architectures?

As identified above, the key characteristic of licence-exempt systems is their random placement. This is directly reflected in the occupancy method that has been proposed. *Ad hoc* systems are therefore easily accommodated by the method. Centralised systems based on a single access point, for example, are also easily accommodated when individual access points are independently placed. For a planned system (e.g. several access points arranged to achieve efficient frequency re-use) the method requires that the system is treated as a whole for random placement.

In the case of relaying, similar considerations apply. If the relay link is formed on a planned basis then the whole relay has to be treated as a single system for placement purposes. If, on the other hand, the relay is formed on an *ad hoc* basis, then each element of the relay should be treated independently, at the same time checking that end-to-end connectivity can be supported.

7. What criteria should be used to determine if a band is full?

As noted above, it is possible to determine what constitutes full occupancy in a band. It has been proposed that this is done by determining the point at which an additional system cannot be introduced to a particular scenario. Whether a system can or cannot be introduced is determined with respect to an appropriate interference criterion.

Defining this interference criterion will depend on the systems being considered. In the case of the 2.4 GHz WLANs that were modelled in detail it is clear that the definition of this criterion has a significant impact on the results. In the absence of any agreed criterion or any material concerning user expectations we have used a criterion that specifies a requirement for a BER better than 1 in 10^5 for more than 90% of the time at more than 90% of locations in an access point service area.

Determining whether a band is full is done by comparing the number of systems actually deployed against the mean number of systems predicted by the method or the distribution of values. By varying the scenario modelled (in terms of other interfering systems), it is also possible to see the trade-off between systems in terms of a reduction in full occupancy for Type A systems as Type B systems are added, for example.

It was not possible to fully relate the criterion used in the modelling to the behaviour of devices found during the limited set of small-scale measurements, because of the dominating effect of access protocols. While this does not invalidate the criterion used in the modelling, it is clear that further work is required to arrive at a practical criterion.

9.2 Recommendations

In the light of the results of this study it is recommended that further work is undertaken in the following areas:

1. System measurements that are representative of longer distances.
2. Further consideration of the most appropriate criterion to use in determining acceptable performance in WLAN and other licence-exempt systems.
3. Modification and optimisation of the software to accommodate more devices and to reduce run times.
4. Further runs to explore the validity of the efficiency metrics.
5. Additional runs to explore further the scaling of devices with area.

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- "The interference of Bluetooth and IEEE 802.11b Wireless Technologies in the 2.4 GHz ISM Band", S. Hollar et al, April 2003

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- “Error Rate Results of OFDM from Bluetooth Interference”, John Terry, Nokia Research Centre, Irving TX
- “Performance Evaluation and Modelling of Wireless Personal Area Networks”, N. Golmie et al, National Institute of Standards and Technology, Gaithersburg, MD
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A ANNEX A: AVOIDING EDGE EFFECTS IN SIMULATIONS

When simulating sharing between terrestrial systems it is important to avoid the "edge effect", whereby systems deployed towards the edge of any area considered could have an artificially lower interference environment than those at the centre.

Two approaches can be considered to avoid this:

- wrap-around geometry
- dual zones.

The wrap-around geometry approach is shown in the example below, where a test area is populated by two systems each of two stations. The test area is replicated across the plane, and then for each station the area to use is centred upon it.

In this example, while the two systems appear in opposite corners of the test area, by wrapping the geometry around, they will appear much closer. Each station will appear to be at the centre of a zone of size equal to the test area.

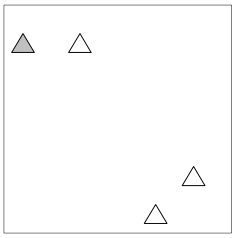


Figure A1: Test area and deployed systems

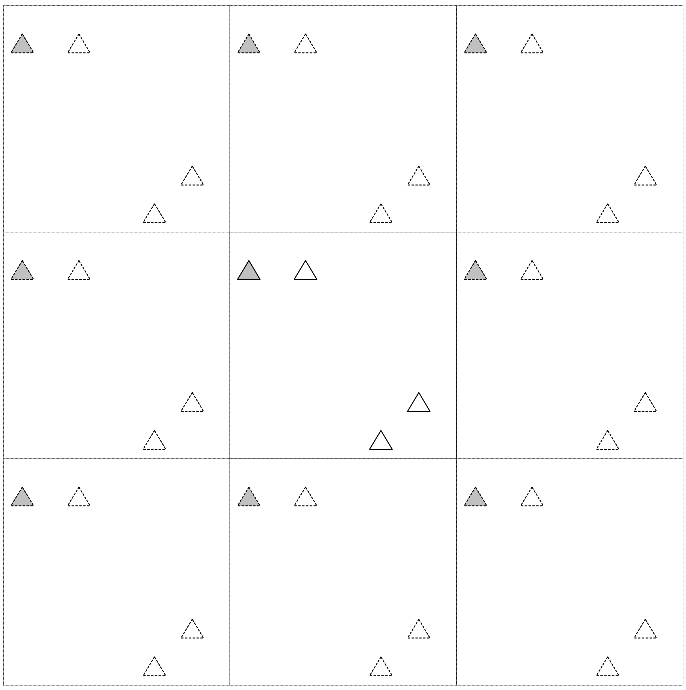


Figure A2: Multiplying the test area across the plane

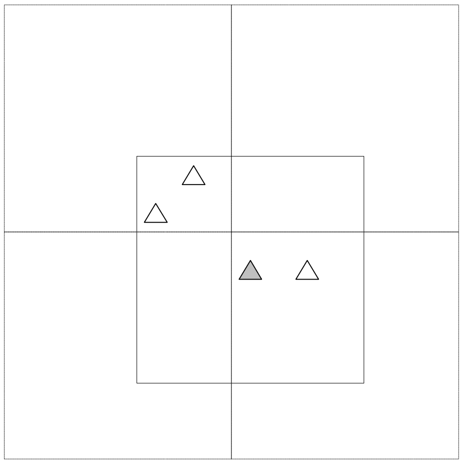


Figure A3: Using test area centred on test station

For the two zone case all analysis is done with a larger outer zone but only those systems within a smaller inner zone are counted towards the statistics.

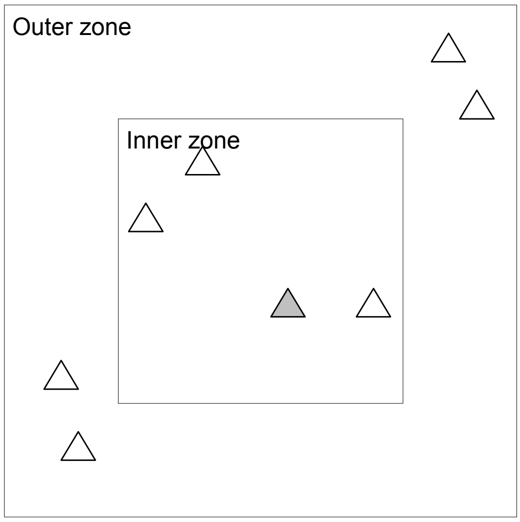


Figure A4: Dual-zone approach

In the analysis the wrap-around geometry approach was considered as:

a) it has been more extensively used in prior studies

b) it should require fewer stations to produce the same statistics and hence be more computationally efficient.

B ANNEX B: EXAMPLE APPLICATION—PMR DEPLOYMENT SCENARIO

This example considers the deployment of PMR in a band where GSM transmissions could cause interference.

Hence:

- PMR = wanted
- Unlicensed GSM = interferer

Different interference scenarios would be examined depending upon whether the regulatory environment required the PMR to protect the GSM or not. In this case we assume the GSM does not need protection.

Note that edge effects would also have to be addressed as discussed in Annex A.

B.1 Run with no interferers

Stage 1—Define environment for scenario

Define the environment e.g.:

- Area of interest = area 40 km square
- Propagation model = as required

Stage 2—Deploy interfering systems

- No action required in this run as it's for wanted only

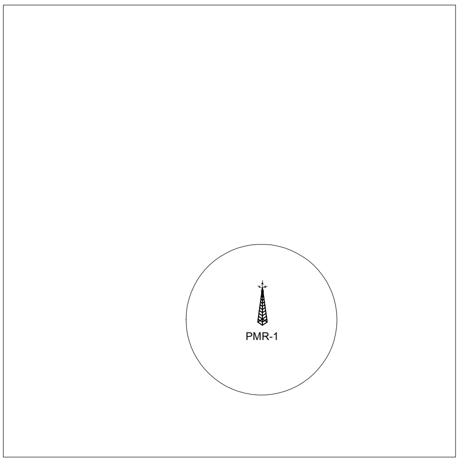
Stage 3—Create a new wanted system

System =

- transmitter with characteristics such as height, EIRP, frequency, bandwidth
- receiver characteristics such as gain, noise temperature
- service characteristics such as coverage and performance requirements

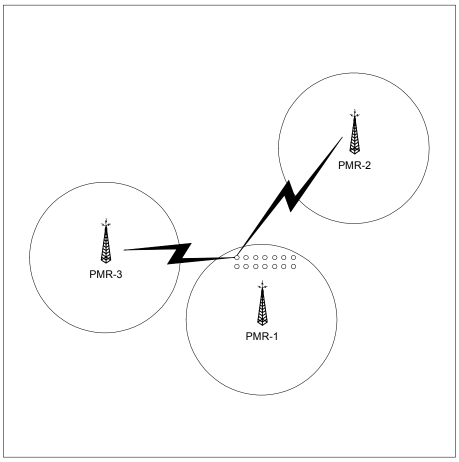
Stage 4—Try to include wanted system into scenario

The system is located at random (as PMR could be requested anywhere) within the area, as shown in figure below:



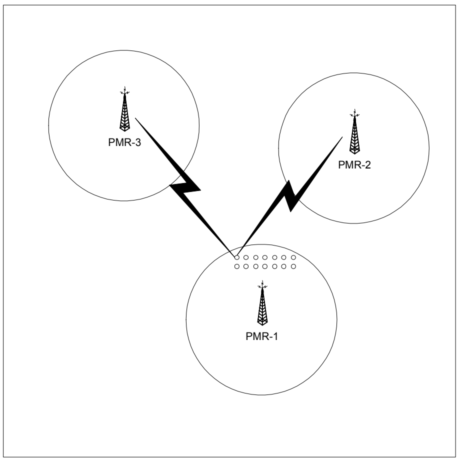
Stage 5—Is deployment consistent?

When there are multiple PMRs in the scenario then interference analysis must be performed. In this case it involves checking that, for each PMR coverage, the aggregate interference is below the required level at each point.



Stage 6—Are more locations feasible?

If, in the example above, PMR-3 is too close and causes unacceptable interference into a test point in the PMR-1 service area, then alternative locations can be considered as the deployment is random. Hence the algorithm can loop back to Stage 4 and try another deployment such as the one below.



Stage 7—Count number of wanted systems introduced

When no more locations can be found (either as a planned deployment or because sufficient random locations have been tried), then the algorithm terminates. The output is the number of systems introduced into the scenario, in this case: 3.

As the system involves a random element, a number of runs would be required and the mean and standard deviation calculated.

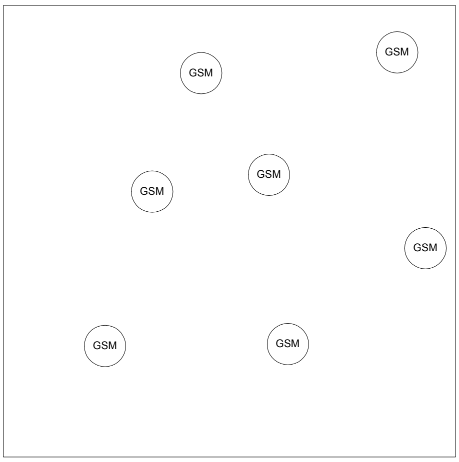
B.2 Run with GSM interferers

Stage 1—Define environment for scenario

- This should be unchanged from the run with no interferers

Stage 2—Deploy interfering systems

- A number of private GSM networks are deployed across the scenario, as in the figure below.



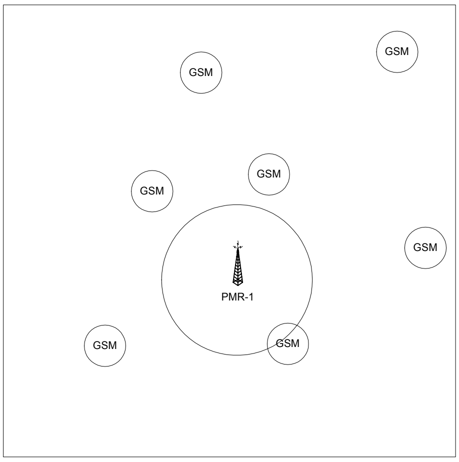
Stage 3—Create a new wanted system

System =

- transmitter with characteristics such as height, EIRP, frequency, bandwidth
- receiver characteristics such as gain, noise temperature
- service characteristics such as coverage and performance requirements

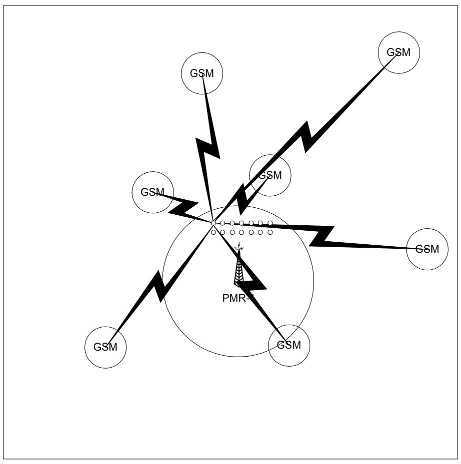
Stage 4—Try to include wanted system into scenario

The system is located at random (as PMR could be requested anywhere) within the area, as shown in figure below:



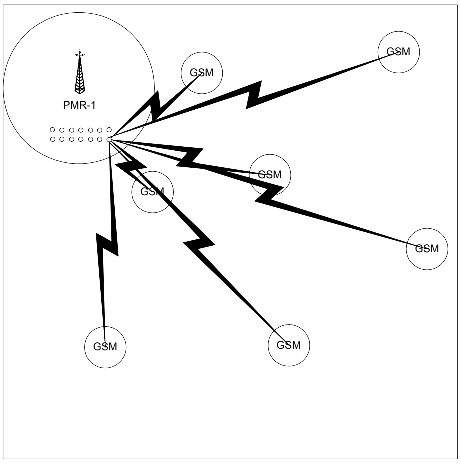
Stage 5—Is deployment consistent?

In this case there are interference paths to consider even if there is a single PMR network deployed, i.e. from all the GSM networks to any point in the PMR coverage. If the GSM networks required protection then there would be more interference paths.



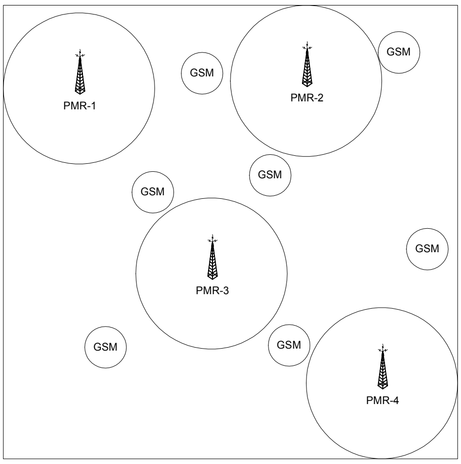
Stage 6—Are more locations feasible?

If in the example above, PMR-1 is too close to one of the GSM networks and suffers unacceptable interference, then alternative locations can be considered as the deployment is random. Hence the algorithm can loop back to Stage 4 and try another deployment such as the one below.



Stage 7—Count number of wanted systems introduced

When no more locations can be found (either as a planned deployment or because sufficient random locations have been tried), then the algorithm terminates. The output is the number of systems introduced into the area, in this case: 4.



As the system involves a random element, a number of runs would be required and the mean and standard deviation calculated.

C ANNEX C: PREVIOUS WORK

Experimental Results for Interference Between Bluetooth and IEEE 802.11b DSSS Systems (Ratish J. Punnoose, Richard S. Tseng and Daniel D. Stancil) (Dept. of Electrical and Computer Engineering Carnegie Mellon University, Pittsburgh PA)

The paper presents experimental results of interference measurements between a sample Bluetooth TX/RX pair and an IEEE 802.11b DSSS TX/RX pair. Performance degradations of both types of devices due to mutual interference are measured in a large outdoor open space (football stadium) and an indoor lab environment. For measurements, laptops with 802.11b and Bluetooth PC cards are used as transmitters and receivers. System parameters specified include power outputs, data rates and antenna patterns.

In outdoor experiments, an audio connection is set-up between Bluetooth cards to provide a steady traffic stream. Interference from this connection to an 802.11b link is measured. The victim 802.11b link uses client manager software which initiates packet transmissions and provides statistics of S/I and the number of lost packets as observed by the RX. For an assumed 802.11b TX/RX distance (35 yards), the measurement results are presented in the form of the percentage of successful packet transmissions vs distance (between the 802.11b RX and Bluetooth TX).
In addition, S/I vs distance curves are provided.

In laboratory measurements, signal attenuators, power splitters and directional couplers are used to experiment with different wanted signal and interference powers. Interference into both 802.11b and Bluetooth RXs is measured.

For measurements concerning interference into an 802.11b RX, a fairly active Bluetooth link is used where audio packets are sent once every two time slots. The victim 802.11b link is set-up for the 11 Mbps data rate without using Auto Fallback (which allows the PC card to switch to a lower data rate when transmission conditions become difficult). Each transmitted packet contains 1470 bytes of user data (generated at a rate of 5 Mbps) plus overheads corresponding to User Datagram Protocol (UDP), IP and MAC. In each measurement, 100 MB of data is sent from the 802.11b TX to RX using the *iperf* network performance measurement program. Statistics of lost packets and effective throughput are collected at the 802.11b RX. The effective throughput corresponds to the ratio of the throughput achieved under interference conditions to that achieved without interference, for a given transmission rate.

For measurements concerning interference into a Bluetooth RX, an IP-based connection is set-up between the Bluetooth TX and RX to transfer UDP data using the *iperf* program. Each packet contains 289 bytes of user data (which are generated at a rate of 250 kbps). For each measurement 10 MB of data is sent across the Bluetooth link. Interference is provided by an 802.11b TX sending UDP traffic at 5 Mbps. Statistics of lost packets and effective throughput are collected at the Bluetooth RX.

Comparison of results examining interference into 11 Mbps and 2 Mbps 802.11b links indicate that the 2 Mbps connection does worse than the 11 Mbps transmission, contrary to intuition. This is based on the fact that the time taken to transmit a single packet using a 2 Mbps 802.11b system is 5.5 times that taken to transmit it using an 11 Mbps system. The increased transmit duration increases the vulnerable period for a Bluetooth collision. Since the loss of any part of the packet causes the loss of the entire packet, the packet loss rate is higher with the 2 Mbps system.

The results also indicate that as Bluetooth interference increases the decrease in the effective throughput of the 802.11b systems is disproportionately greater than the increase in the packet loss rate. This is due to the fact that packet losses are not the only form of performance degradation. The MAC protocol of the 802.11b devices requires positive acknowledgement of all directed traffic. If a frame is not acknowledged, it is retransmitted. This causes the forced delay of other frames until a frame has been successfully acknowledged or until it has been retransmitted the requisite number of times. This causes significant degradation in performance even when the packet loss rate is relatively low. In the experiments, the implications of interference on the operation of the 802.11b transmitter are not considered when calculating the effective throughput. It is argued that, in practice, the 802.11b transmitter using physical carrier sense may conclude that the channel is busy and may defer transmissions, reducing the effective throughput even further.

In the case of Bluetooth RXs, it is argued that since there is no requirement for acknowledgements and retransmissions, and the Bluetooth TX does not perform carrier sensing before transmission, the achieved throughput is directly related to the percentage of lost packets (i.e. a packet loss rate of 20% results in a throughput of 80% of the maximum). It should be noted that Bluetooth connections do not use acknowledgements and re-transmissions for voice links. In the case of data links, acknowledgements and re-transmissions are used.

The interference of Bluetooth and IEEE 802.11b Wireless Technologies in the 2.4 GHz ISM Band (April 2003) (Stephen Hollar, Hatem Mohamed, Jeff Swearingen and Paul Suh)

The paper largely reports on measurements carried out in an indoor environment. The measurements are based on monitoring traffic with and without interference. The implications of interference between single and multiple Bluetooth piconets and 802.11b WLAN networks are examined. The system parameters specified include data rate, transmit power and maximum antenna gain. As with the previous paper, two metrics are measured: throughput and packet loss. The measurement results are presented in the forms of:

- Single Bluetooth piconet (or WLAN network) throughput vs distance between a Bluetooth device and an access point (or a WLAN station and an access point) in the presence of interference.
- Percentage of re-transmissions within a Bluetooth piconet (or a WLAN network) vs distance between a Bluetooth device and an access point (or a WLAN station and an access point) in the presence of interference.
- Percentage of re-transmissions within a Bluetooth piconet (or a WLAN network) when 1, 2 or 3 WLAN networks (or Bluetooth piconets) are present.
- Percentage of throughput reduction (compared to the “no interference” case) within a Bluetooth piconet (or a WLAN network) when 1, 2 or 3 WLAN networks (or Bluetooth piconets) are present.

It is noted that a simple probabilistic analytic method is developed to calculate predicted throughput reductions. The method takes account of the probabilities of frequency and time overlap. In the document, calculated and measured reductions are shown to be in good agreement.

Co-existence of 802.11g WLANs with Bluetooth (K.K. Wong and T.O. Farrell) (School of Electronic and Electrical Engineering, University Of Leeds, UK)

The paper presents a simulation-based analysis concerning interference from a Bluetooth device into an 802.11g RX. The simulation model is based on examining the disruption of the 802.11g packets by Bluetooth data bits. Simulation parameters specified include symbol durations, data rates, time-slot durations, packet lengths, modulation techniques, transmit powers and coding.

It is argued that the 802.11g OFDM signal (20 MHz) sees the Bluetooth signal (1 MHz) as narrowband interference mainly affecting a small number of sub-carriers. On the basis of this argument, the analysis aims to show the improvements obtained from replacing 802.11g data symbols corresponding to sub-carriers with low C/I ratios by erasures. Simulation results are expressed in terms of Packet Error Rate vs E_b/N_o for a given SIR and a number of erasures.

It is shown that, for example, the SIR required is reduced from 15 dB to –7 dB (to achieve PER of 1%) when 9 erasures are used in a 24 Mbps 802.11g connection operating in the presence of Bluetooth interference.

Error Rate Results of OFDM from Bluetooth Interference (Presentation by John Terry, Nokia Research Centre, Irving TX)

The presentation outlines simulation analysis conducted with a view to examining the impact of single and multiple Bluetooth interferers on 802.11a RXs. The

Bluetooth interferers are modelled as using GFSK modulation and operating at 1 Mbps with 1,600 hops/sec. The Bluetooth transmission slot is 625 μs and data is transmitted during the first 366 μs. In the simulations where erasures are used, a total of 11 erasures (each with a 312.5 kHz bandwidth) is employed. The 802.11a simulation parameters include 24/48 Mbps data rates, 16/48-QAM and convolutional coding with rates of 1/2 and 2/3. Simulation results (with and without erasures) are presented in the form of Packet Error Rate vs SNR for a given SIR. It is suggested that Bluetooth interference severely degrades the PER performance of OFDM systems for SIR < 10 dB. It is also stated that when all receiver data correction algorithms are used erasures provide very little additional protection.

Performance Evaluation and Modelling of Wireless Personal Area Networks (Presentation by N. Golmie, D. Cypher, R.E.V. Dyck, A. Soltanian, I. El Bakkouri, N. Chevrollier and H. Roelofs, National Institute of Standards and Technology, Gaithersburg, MD)

The document presents the analysis of mutual interference between a Bluetooth TX/RX pair and an 802.11b TX/RX pair. The analysis is based on a detailed software implementation of link protocols. In addition, a DSP-based implementation of TX/RX is used in the modelling. The propagation channel is assumed to be Additive White Gaussian Noise and the path loss is modelled as following:

$$Loss = 20 \log (4\pi d/\lambda) \qquad \text{when } d < 8 \text{ m}$$

$$Loss = 58.3 + 33 \log (d / 8) \qquad \text{otherwise}$$

Transmitted packet sizes are sampled from a geometric distribution with a mean of 368 bytes. The results are presented in the form of probability of packet loss vs distance of RX (Bluetooth / 802.11b) from the interference source (802.11b / Bluetooth). Similarly, the impact of interference on MAC access delay is presented in the form of mean access delay vs distance of RX (Bluetooth / 802.11b) from the interference source (802.11b / Bluetooth). Although not quantified, the presentation concludes that Bluetooth and 802.11b can cause significant interference to each other.

Reliability of IEEE 802.11 Hi Rate DSSS WLANs in a High Density Bluetooth Environment (Jim Zyren, Intersil Corporation, June 1999)

The document outlines an analytical approach to examine interference from Bluetooth TXs into 802.11 DSSS RXs. It is noted that the path loss model is the same as used in the preceding document.

In the analysis, initially, exclusion distances are calculated assuming that an 11 Mbps 802.11 RX station is located 4, 10 and 20 m from an access point. It is also assumed that the access point TX power is 20 dBm, the Bluetooth TX power is 0 dBm and the criterion is C/I = 10 dB. Using these assumptions, it is shown that the radius of an exclusion area varies between 1.3 and 10 m when the 802.11 RX station is 4–10 m away from its access point.

It is then argued that, even if there is a Bluetooth TX within an exclusion area, it is still possible that the 802.11 RX may avoid interference since there must be an overlap in time and frequency for a Bluetooth TX to disrupt an 802.11 packet. Based on this argument, the probability of collision between Bluetooth and 802.11 DSSS packets is calculated analytically. The calculation process makes use of the following parameters:

- *Bandwidth Overlap:* 802.11 DSSS BW = 20 MHz, Bluetooth BW = 1 MHz and there are 79 Bluetooth bands for hopping. Therefore, the probability that an active TX will be in the 802.11 RX band is approximately 25%.
- *Time Profile of Bluetooth Signal:* Dwell period = 625 μs and active time within dwell period = 366 μs.
- *802.11 Packet Size:* The largest allowable packet size is 1,500 bytes (12,000 bits). To transmit these packets (including header and preamble), 1210 μs is required.
- *Start of 802.11 Transmission (Relative to Bluetooth Hop Times):* Assumed to be uniform random variable within the range of the Bluetooth duty cycle (625 μs).
- *Bluetooth Load Factor:* This parameter varies with the application. A figure of 33% is calculated for a full-duplex phone link using an HV3 packet format (i.e. to support a single voice conversation, a transmission on every third time slot within the Bluetooth link is required). A load figure of 100% is used for e-mail applications using a DH1 packet format.

Using the above parameters, it is shown that the probability of collision with the packets of a Bluetooth TX operating in the exclusion area is 19%.

The above probabilistic approach is improved to take account of the possibility of collisions with 802.11 ACK packets and the network overhead associated with re-contention in the event that the TX fails to receive an ACK. The impact of interference is examined computationally by including these effects. Results are presented as Packet Payload vs Throughput for a number of assumed Bluetooth Load Factors (or user scenarios) and for single and multiple Bluetooth interferers. The document concludes that 802.11 systems show good reliability even in a fairly dense environment of Bluetooth piconets.

Bluetooth Voice and Data Performance in 802.11 DS W-LAN Environment (J.C. Haartsen and S. Zurbes, Ericsson, June 1999)

In the document, the impact of interference from 802.11 DSSS TXs (11 Mbps) into Bluetooth RXs is examined. Interference from both WLAN terminals and access points is calculated assuming a fixed TX power of 20 dBm in a 17 MHz bandwidth.

It is argued that the performance of the Bluetooth connection is dependent on the ratio of wanted power and interference. The Bluetooth TX power is assumed to be fixed at 0 dBm in a 1 MHz bandwidth. In calculations, mutual interference between Bluetooth devices is ignored. The propagation model is the same as that used in the preceding two documents.

The study differentiates between the impact on the Bluetooth data and voice connections. The following points summarise assumed time profiles for WLAN, Bluetooth data and Bluetooth voice connections.

- 802.11 WLAN: TX Data Packet (1210 µs), Delay (10 µs), RX ACK (106 µs), Delay (350 µs) followed by the same structure.
- Bluetooth Data: TX Packet (DH1, 366 µs), Delay (259 µs), RX Packet (DH1, 366 µs), Delay (259 µs) followed by the same structure. Load Factor = 366 µs / 625 µs = 58%.
- Bluetooth Voice: TX Packet (HV3, 366 µs), Delay (259 µs), RX Packet (HV3, 366 µs), Delay (259 µs). This structure is repeated every six time slots (where time slot is 625 µs). Load Factor = (2 x 366) / (6 x 625) = 20%.

It is noted that each Bluetooth packet is transmitted at a different hop frequency (i.e. TXs hop at the packet rate). Bluetooth performance thresholds are expressed in terms of Packet Erasure Rate (PER). It is assumed that PER < 10% for Bluetooth data connections and PER < 1% for Bluetooth voice connections. The argument behind the assumption of different thresholds for data and voice connections is that the Bluetooth data channel uses re-transmission protocols and, therefore, can cope with a higher PER. It is suggested that these thresholds should be used with care since the time period that interference lasts is important from a user point of view. For example, 2% PER for 10 seconds may be more annoying than 10% PER for 100 milliseconds in a voice connection.

Initial analysis is directed towards determining how close an 802.11 TX and a Bluetooth RX can operate using the above-mentioned time profiles, power levels and performance thresholds. It is noted that the analysis used differentiates between 802.11 data and ACK packets and different minimum distances are calculated for data and ACK packets.

Using exclusion areas (defined by the calculated minimum distances) and assumed density figures of uniformly distributed WLAN terminals and access points, the total numbers of potential interferers within the exclusion areas are calculated. These numbers are then used in an analytical probabilistic model developed to examine the probability of the PER exceeding the threshold for various assumed Bluetooth wanted path distances. In addition to the total number of TXs, the probabilistic model takes account of various 802.11 traffic patterns.

The study concludes that the Bluetooth voice user will not be affected (i.e. PER <1%) by WLAN interference so long as there is a minimum 2 m distance. For the Bluetooth data user, it is concluded that a throughput reduction of more than 10% occurs with 24% probability at an operating distance of 10 m.

Interference in the 2.4 GHz ISM Band: Impact on the Bluetooth Access Control Performance (Nada Golmie and Frederic Mouveaux, National Institute of Standards and Technology)

The paper presents analytic and simulation analyses examining the performance of Bluetooth in the presence of WLAN interference (both Frequency Hopping and Direct Sequence systems).

The analytic method developed is based on the calculation of the probability that a Bluetooth packet overlaps a WLAN packet in time and frequency. It is noted that this probability depends on the position of the WLAN packet with respect to the Bluetooth packet and the transmission frequencies of the Bluetooth and WLAN systems. In the analysis, these two factors are represented by random variables. It is stated that collisions are detected at the Bluetooth RX in the form of C/I which depends on the power transmitted, distance travelled and the path loss model used. The C/I then translates into a BER according to the modulation and the RX implementation used.

The metric used in the analytic method is the probability that a packet containing at least one error is received at the Bluetooth RX (prior to applying error correction). The analytic expression derived for the packet error probability is a function of the probability density functions of the above-mentioned two random variables, the interval between two WLAN packets, the packet overlap time interval, the number of overlapping channels and the BER.

In order to validate the analytical interference model, a simulation model is developed using OPNET where WLAN and Bluetooth protocols are implemented. Simulations are carried out to examine the impact of an 802.11 DSSS 1 Mbps connection on Bluetooth voice and data traffic. In the simulations, a specific geometry is modelled (in which the Bluetooth wanted link is 1 m and the interference path is 15 cm). Two metrics are used to evaluate the impact of interference: the packet loss (the number of packets discarded due to uncorrected errors in the packet divided by the total number of packets transmitted) and the packet error (the number of packets received with at least one error prior to applying error correction on the packet and deciding whether to keep or drop it).

The simulation results are presented in the form of WLAN Packet Size vs Probability of Packet Errors (and Packet Loss) and WLAN Offered Load vs Probability of Packet Errors (and Packet Loss) for Bluetooth voice and data links. The study does not define a PER criterion for Bluetooth RXs. It is noted that the packet loss curves obtained from the simulations and the analytic method are very close to each other.

Coexistence Metric (IEEE Contribution, IEEE P802.19-02/010r0, Coexistence TAG, November 2002)

The document proposes a metric for quantifying the coexistence between wireless TX/RX pairs and interfering TXs operating in the 2.4 GHz ISM band. The metric aims to determine "how close can an interferer come to a receiver while the RX maintains a reasonable packet error rate". In other words, coexistence is quantified as the minimum distance between a victim RX and an interfering TX that results in acceptable error rates at the RX.

The proposed calculation method is simple and takes account of the *RX wanted power* (assumed to be 10 dB greater than the minimum sensitivity of the RX), *interference power* (calculated by using a TX power, a path loss model [free space up to 8 m and a path loss exponent of 3.3 for distances > 8 m] and a spectral coupling [where the impact of overlap between a transmitter spectral mask and a receiver input filter is considered]), *BER* (a function of the C/I via modem curves) and PER (function of BER and average bits per packet). It is noted that no PER threshold value is defined in the document.

Compatibility of Bluetooth with Other Existing and Proposed Radiocommunications Systems in the 2.45 GHz Frequency Band (ERC Report, October 2001)

The interference analysis method is based on the calculation of the minimum coupling loss (MCL) defined as:

$$MCL = EIRP - P_{RX} + C/I$$

where:

EIRP is the interfering transmitter EIRP (dBm)

P_{RX} is the received interference power (dBm)

C/I is the carrier-to-interference ratio specified for the receiver (dB)

Using an appropriate path loss model, the calculated MCL is translated into a minimum interference range for a single interferer. For an interferer outside this range, C/I exceeds the threshold and, therefore, it can be assumed that received packets are error-free. For an interferer located at a distance less than the minimum interference range, the throughput reduction due to interference is examined by taking account of the implications of frequency hopping, dwell time and duty cycle.

In order to examine interference from multiple transmitters, a probabilistic method is developed. The method is based on determining an interference area (which is an area with a radius equal to the minimum interference range). Within the interference area, the total number of potential interferers is calculated for an assumed interferer spatial distribution. The probability of becoming a victim of any one of the potential interferers in the area is then calculated using the expressions derived for the probabilities of antenna beam alignment, frequency overlap and time collision.

D ANNEX D: CHARACTERISTICS OF TYPICAL 2.4 GHZ SYSTEMS

D.1 Wireless Local Area Networks (WLANs)

WLANs use radio frequencies to transmit and receive data. They can be configured in a variety of ways. Examples include: an *ad hoc* network (where all nodes are connected directly one another), an infrastructure network (where WLAN nodes connect to a corporate network through a wireless access point) and hotspots (where users are provided with a WLAN service in a wide variety of public meeting areas).

In an *ad hoc* network, several wireless nodes (for example, computers with wireless adapters) join together to establish peer-to-peer communication. *Ad hoc* mode is designed such that only nodes within transmission range (within the same cell) of each other can communicate. If a node in an *ad hoc* network wishes to communicate outside of the cell, a member of the cell must operate as a gateway and perform routing. *Ad hoc* networks typically require no administration. Networked nodes share their resources without a central server.

In a WLAN with infrastructure, there is a high-speed wired or wireless backbone. Wireless nodes access the wired backbone through access points. In general, an access point is a small box with one or two antennas. It allows the wireless nodes to share the available network resources efficiently. Prior to communicating data, wireless nodes and access points establish a relationship, or an association, through the use of networking protocols defined in the WLAN standards. Only after an association is established can the two wireless stations exchange data.

Whereas an access point connects a WLAN to multiple users, point-to-point or point-to-multipoint bridges can be used to connect multiple WLANs. For example, two buildings can be interconnected using a point-to-point WLAN bridge.

In a public hotspot, users with compatible wireless network devices such as PDAs, cell phones and laptops can connect to the Internet or a private intranet, to send and receive e-mail and download files.

The predominant standards for WLANs have been developed by the IEEE. These standards define system characteristics for both physical (PHY) and medium access control (MAC) layers. The PHY layer parameters include operating frequencies, power, transmission rates, antenna gain, modulation and coding. The MAC layer defines protocols to co-ordinate the communications between wireless nodes and control the behaviour of users trying to access the network.

IEEE 802.11 was the first standard, finalised in 1997. This base standard allowed data transmission of up to 2 Mbps in the licence-exempt 2.4 GHz ISM band. In 1999, the IEEE published two supplements to the initial 802.11 standard: 802.11a and 802.11b (which is often referred to as "Wi-Fi"). The 802.11a standard specifies operation in the 5 GHz band with data rates up to 54 Mbps whereas the 802.11b standard defines operation in the 2.4 GHz band with data rates up to 11 Mbps. The 2.4 GHz WLAN data rates were further enhanced in 2003 by the ratification of the 802.11g standard, which specifies operation in the 2.4 GHz band with a maximum data rate of 54 Mbps.

IEEE 802.11 standards use common MAC layer specifications. The MAC layer is contention-based (i.e. the medium is free for all—a station senses the free medium and occupies it as long as a data packet requires). The default MAC operation is based on Carrier Sense Multiple Access, Collision Avoidance (CSMA/CA).

In CSMA/CA, if a station has data to send, it waits for the channel to be idle. If the medium is sensed idle for a period greater than a DCF inter-frame space (DIFS), the station goes into a back-off procedure before it sends its frame. Upon the successful reception of a frame, the destination station returns an ACK frame after a short inter-frame space (SIFS). The back-off window is based on a random value uniformly distributed in the interval [0,CW] where CW represents the Contention Window parameter and is varied between CW_{min} and CW_{max}. If the medium is determined busy at any time during the back-off slot, the back-off procedure is suspended. It is resumed after the medium has been idle for the duration of the DIFS period. If an ACK is not received within an ACK timeout interval, the station assumes that either the data frame or the ACK was lost and needs to re-transmit its data frame by repeating the basic access procedure. It is suggested that the overhead of MAC layer reduces the WLAN throughput by 40-50%.

An optional virtual carrier sense mechanism is provided at the MAC layer. This mechanism uses the request-to-send (RTS) and clear-to-send (CTS) message exchange to make predictions of future traffic on the medium and updates the network allocation vector available in stations. Communication is established when one of the wireless nodes sends a short RTS frame. The receiving station issues a CTS frame that echoes the sender's address. If the CTS frame is not received, it is assumed that a collision occurred and the RTS process starts again.

In order to prevent unauthorised access to WLANs, various schemes have been incorporated into the basic WLAN industry security standard. These include Service Set Identifier (where nodes use a common key to access the network), Media Access Control (where node addresses are filtered and access to the network is restricted to those on a list of nodes) and Wired Equivalent Privacy (where data streams are encrypted). Flaws in the basic security standard have been identified and advanced protection mechanisms have been designed.

The following table summarises the key 802.11 specifications.

	802.11	***802.11a***	***802.11b (Wi-Fi)***	***802.11g***
Frequency Band (GHz)	2.4–2.4835	5.15–5.35 (low band) 5.725–5.825 (high band)	2.4–2.4835	2.4–2.4835
Data Rates (Mbps)	1, 2	6, 9, 12, 18, 24, 36, 48, 54 (Auto Rate Shifting)	1, 2, 5.5, 11 (Auto Rate Shifting)	6, 9, 12, 18, 24, 36, 48, 54 (Auto Rate Shifting)
Wireless Medium	FHSS (79 channels of 1 MHz) (TX 3-dB BW = 0.35 MHz) DSSS (13 overlapping channels of 22 MHz) (3 non-overlapping) (RX Noise Bandwidth 15 MHz) (TX 3-dB Bandwidth 15 MHz)	OFDM (8 non-overlapping 20 MHz channels in low band) (4 non-overlapping 20 MHz channels in high band) (Each channel comprises 52 sub-carriers of 300 kHz)	DSSS (13 overlapping channels of 22 MHz) (3 non-overlapping) (RX Noise Bandwidth 15 MHz) (TX 3-dB Bandwidth 15 MHz) (PN sequence : 11-chip Barker Code or 8-chip Complementary Code Keying)	OFDM (3 non-overlapping 22 MHz channels in high band)
Modulation	GFSK (FHSS) BPSK / QPSK (DSSS)	BPSK, QPSK, 16-QAM, 64-QAM	DQPSK, DBPSK,CCK	BPSK, QPSK, 16-QAM, 64-QAM
Coding		Convolutional (1/2, 2/3, 3/4)		Convolutional (1/2, 2/3, 3/4)
Max. TX Power (mW)	100	50 / 250 (low band) 1000 (high band)	100	
Typical Indoor Range (m)		12 at 54 Mbps 90 at 6 Mbps	30 at 11 Mbps 90 at 1 Mbps	30 at 54 Mbps 90 at 1 Mbps
Typical Outdoor Range (LOS) (m)		30 at 54 Mbps 300 at 6 Mbps	120 at 11 Mbps 460 at 1 Mbps	120 at 54 Mbps 460 at 1 Mbps
Max. Antenna Gain (dBi)	2 (omni-directional)		2 (omni-directional), 6	
Multiple Access	CSMA/CA	CSMA/CA	CSMA/CA	CSMA/CA
Min. RX Sensitivity (dBm)	-90		-90	
Duplex Method	TDD	TDD	TDD	TDD

Table D1: 802.11 specifications

D.1.1 Antennas

Antenna data sheets obtained from various antenna manufacturers' Web sites (www.worldproducts.com, www.sparklan.com, www.etenna.com and www.skycross.com) indicate that dipole and ceramic chip antennas are widely used in unlicensed band applications (e.g. IEEE 802.11 a/b/g and Bluetooth).

The radiation patterns of ceramic chip antennas designed for wireless clients (e.g. handsets, PDAs and laptops) can be approximated to that of an isotropic radiator with an average gain in the range –3 to 0 dBi at 2.4 GHz. It is also noted that omnidirectional (i.e. doughnut shape) antennas are designed for laptops. A typical gain value for the horizontal plane is 0 dBi for all azimuths and a typical maximum gain for the vertical plane is 2 dBi.

The radiation patterns of dipole antennas used for access points are omnidirectional. In the horizontal plane, patterns can be assumed to have fixed gain in the range 0–3 dBi for all azimuths. In the vertical plane (i.e. elevation plane), typical peak gain values are also in the range 0–3 dBi. It is noted that antennas with directional elevation patterns are also designed for access points.

The following table provides example 2.4 GHz elevation patterns.

Elevation Angle (degrees) (0 deg ceiling, 180 deg floor)	**Pattern 1 (dBi) (Omni)**	**Pattern 2 (dBi) (Directional with HPBW 90 degrees)**	**Pattern 3 (dBi) (Omni)**
0	–11	–20	–30
15	–7	–16	–15
30	–3	–17	–7
45	–1	–13	–2
60	–1	–10	1
75	0	–7	3
90	0	–6	3
105	–1	–5	1
120	–2	–4	1
135	–4	–2	–1
150	–6	–1	–3
165	–9	0	–8
180	–12	1	–30

Table D2: Example patterns

D.2 Bluetooth

Bluetooth is an industry specification for short-range RF-based connectivity for portable personal devices. It aims to replace non-interoperable proprietary cables that connect phones, laptops, PDAs and other portable devices. Bluetooth specifications were released in 1999 by the Bluetooth Special Interest Group (SIG).

Bluetooth uses 79 RF channels of 1 MHz bandwidth within the band 2.400 and 2.4835 GHz. Although the air interface is based on three transmit power levels (1, 2.5 and 100 mW), an antenna power of 1 mW (0 dBi gain) is used in the majority of devices. With a 1 mW transmit power, a transmission range of approximately 10 m is achieved. For 100 mW Bluetooth devices, there is a mandatory power control requirement (between the power levels of 2.5 mW and 100 mW). The signal is modulated using binary Gaussian Frequency Shift Keying (GFSK). The total data rate is defined at 1 Mbps. A Time Division Multiplexing (TDM) technique divides the channel into 625 µs slots. Each packet is transmitted on a different hop frequency with a maximum frequency hopping rate of 1600 hops/sec.

A piconet is formed when two or more Bluetooth units communicate on the same channel. In piconets, one unit operates as a master and the others (a maximum of seven active at the same time) act as slaves. A channel is defined as a unique pseudo-random frequency hopping sequence derived from the master device's 48-bit address and its Bluetooth clock value. Slaves in the piconet synchronize their timing and frequency hopping to the master. In the connection mode, the master controls access to the channel. Two or more piconets connected together form a scatternet.

Two types of link connections can be established between a master and a slave: the Synchronous Connection-Oriented (SCO) and the Asynchronous Connection-Less (ACL) link.

The SCO link is a circuit-switched, symmetric point-to-point connection between a master and a slave where the master sends an SCO packet in one TX slot at regular time intervals (T_{SCO}). The slave responds with an SCO packet at the next TX opportunity. T_{SCO} is set to either 2, 4 or 6 time slots for HV1, HV2, or HV3 packet formats, respectively. All three formats of SCO packets are defined to carry 64 kbps of voice traffic. There is no re-transmission in case of packet loss or error.

The ACL link is an asymmetric point-to-point connection between a master and active slaves in the piconet. Packet formats defined for the ACL link are DM1, DM2 and DM3. These occupy 1, 3 and 5 time slots, respectively. An Automatic Repeat Request (ARQ) procedure is applied to ACL packets, where packets are re-transmitted in case of loss until a positive acknowledgement (ACK) is received at the TX. A maximum data rate of 723 kbps is supported.

For some SCO and ACL packets, Forward Error Correction (FEC) is used to correct errors and reduce the number of re-transmissions.

The following table summarises the key Bluetooth specifications.

Frequency Band (GHz)	2.400–2.4835
RF Channels	f = 2402 + k (where k = 0, 1, … 78)
Data Rates (Mbps)	Up to 723 kbps
Wireless Medium	FHSS (79 channels of 1 MHz) (Maximum hopping rate = 1600 / sec)
Modulation	GFSK
Max. TX Power (mW)	1, 2.5 and 100
Typical Range (m)	10 m (1 mW) 100 m (100 mW)
Max. Antenna Gain (dBi)	0
Min. RX Sensitivity (dBm)	-70
Duplex Method	TDM/TDD

Table D3: Bluetooth specifications

D.3 Electronic News Gathering / Outside Broadcast (ENG/OB)

ENG/OB system characteristics outlined in this report are based on the information given in the following documents:

- ERC Report 38 (“Handbook on Radio Equipment and Systems Video Links for ENG/OB Use”, May 1995)
- “MSS Sharing with ENG/OB Use at 2 GHz” (study carried out by Aegis for RA, March 1998)
- ERC Report 109 (“Compatibility of Bluetooth with Other Existing and Proposed Radiocommunications Systems in the 2.45 GHz Frequency Band”, October 2001).

In broad terms, ENG/OB links can be categorised into three groups:

- temporary point-to-point links
- short-range links, from a mobile camera to a fixed point
- air-to-ground / ground-to-air links.

An example of a temporary point-to-point link might be a link established from a parabolic antenna mounted on the roof of a vehicle at a race-course to a similar antenna on a “midpoint” vehicle on a hilltop some 10–20 km distant. The midpoint vehicle might then relay the signal to a permanent receiver site at a studio centre or transmitter. The link would be characterised by fairly high-gain antennas at both ends, and a line-of-sight path. A typical example for the second application would be that of a handheld camera at a football match, relaying pictures over a few hundred metres to a fixed receive point. The camera antenna will normally be omni-directional, and may operate to a directional receive antenna which is manually tracked. Airborne link examples include a helicopter-mounted camera following a motor racing event, and relaying the pictures to a ground receiver, or a camera mounted in a racing car, transmitting to a helicopter "midpoint", which then re-transmits the pictures.

Typical TX and RX characteristics for analogue (FM) ENG/OB links are summarised in the following table.

Type	Antenna Gain @ 2.5 GHz	Height (a.g.l.)
Tripod-mounted, 0.6 m parabolic dish receiving from a radio camera at < 500 m distance	21 dBi	1.8 m
Vehicle roof-mounted, directional helical antenna receiving from a helicopter at < 2 km distance	17 dBi	3 m
Helicopter-mounted, omni-directional antenna receiving from mobile radio camera at < 500 m distance	4 dBi	200 m
1.2 m parabolic dish antenna (assumed to be one end of temporary fixed link) on transmitter mast, receiving from roving vehicle at 30 km distance	27 dBi	50 m
1 W handheld camera TX with Lindenblad antenna linking to tripod-mounted, 0.6 m parabolic dish RX	5 dBi	2 m
200 W helicopter-mounted TX with wilted dipole antenna providing lower hemispherical coverage to link to vehicle roof-mounted, "Golden Rod" RX antenna	3 dBi	200 m
20 W TX on pneumatic vehicle mast with 0.6 m parabolic dish used to link roving vehicle to fixed insertion point at 30 km distance	21 dBi	10 m
20 W TX on transmitter mast with 1.2 m parabolic dish used to link fixed insertion point to roving vehicle at 30 km	27 dBi	50 m

Table D4: ENG/OB characteristics

For all links, the carrier bandwidth may be assumed to be 20 MHz. ERC Report 38 uses an effective noise temperature of 32 dBK (Antenna + Receiver with NF = 7 dB). For the Aegis study ("MSS Sharing with ENG/OB Use at 2 GHz"), a typical receive system noise temperature is assumed to be 360 K, which is based on commercially available receivers. For transmitters, ERC Report 38 defines the following spectral mask.

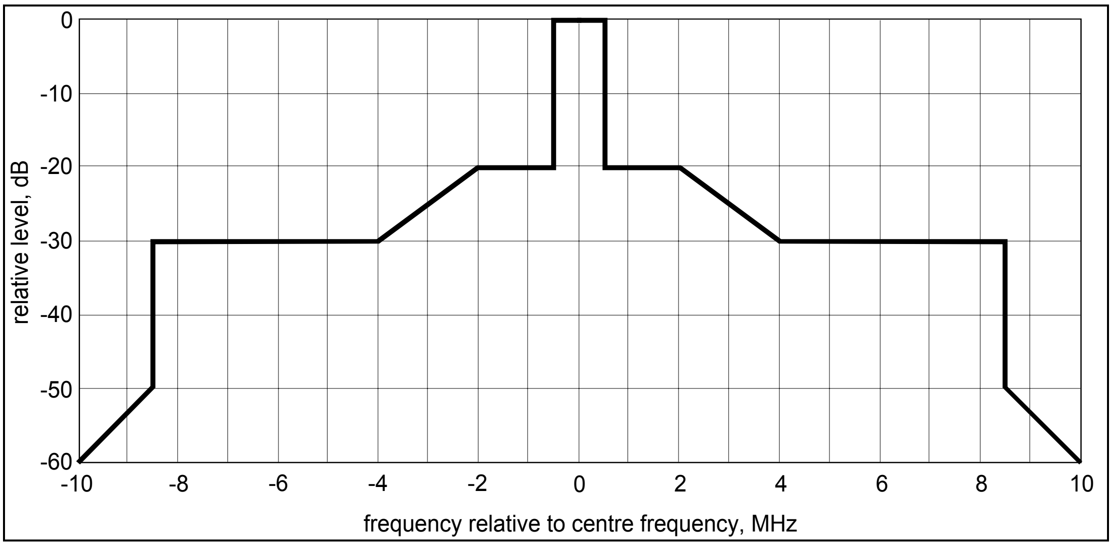


Figure D1: Representative spectrum mask for analogue ENG/OB video links

In the case of digital ENG/OB systems, the DVB-T standard defined for terrestrial digital TV broadcasting in Europe is used. The digital ENG/OB transmission method is based on COFDM where 1,704 carriers are modulated with either QPSK, 16-QAM, or 64-QAM. The transmission rates are 5–30 Mbps and forward error-correcting coding is employed at rates of 1/2, 2/3, 3/4, 5/6 or 7/8 depending on the modulation used. The receiver noise bandwidth is 7.61 MHz.

As far as the interference criterion is concerned, no formal performance targets are set, and fade margins may be very great (in the case, for instance, of a radio-camera operating over a few yards) or non-existent (an ENG vehicle establishing an unscheduled link to a studio at short notice over a diffracted path). Therefore, in the Aegis study, interference was assessed with respect to an assumed long-term limit of *receiver noise – 10 dB*.

For analogue ENG/OB links, ERC Report 38 argues that a minimum C/N of 29 dB is necessary to satisfy the performance requirement of a video link. In addition, ERC Report 109 indicates that the maximum short-term interference should be 30 dB below the carrier level (i.e. C/I = 30 dB). These two figures, in turn, suggest that the maximum allowed short-term interference could be approximately the same level as the ENG/OB receiver noise power.

For digital ENG/OB links, ERC Report 109 proposes a short-term criterion of I/N of +20 dB, which seems surprisingly relaxed. This may be based on the assumption that the transmit power levels for analogue and digital ENG/OB links are comparable. This assumption may not be appropriate as digital ENG/OB links may be employing lower transmit powers (due to their resilience to noise). If this is the case, C/N ratios (and hence the maximum allowed interference levels) should be similar for both types of links.

A further set of system parameters is provided in a document titled "ENG/OB parameters for 5 GHz sharing study" by JFMG Ltd (Paul Gill, Dec. 2002). It is stated that all ENG/OB equipment in the 5 GHz band uses analogue modulation (FM). For the protection requirements, the document refers to wanted-to-unwanted (W/U) ratios derived from measurements carried out by the RA's Radio Compatibility and Technology Group (RTCG). It is noted that while the measurements are based on the use of equipment operating in the 2.5 GHz and 3.5 GHz bands, the equipment is also typical of that used at 5 GHz. The following figure shows measured W/U ratios with CW interference.

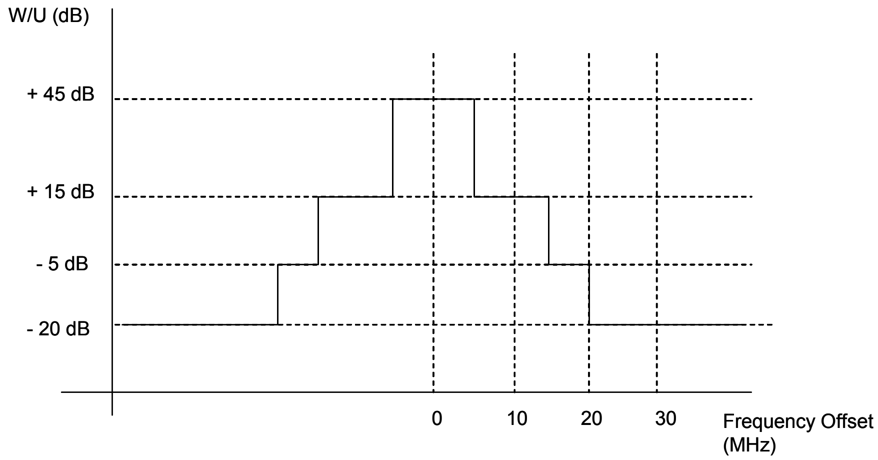


Figure D2: W/U for analogue FM RX with CW interference

For deployment characteristics and the transmitter spectrum mask, the document refers to ERC Report 38. The following table is based on tailoring ERC Report 38 to suit UK operations in the 5 GHz band (Carrier BW = 20 MHz).

	Max. EIRP	TX Antenna Gain and Type	TX Antenna Height (a.g.l.)	RX Antenna Gain and Type	RX Antenna Height (a.g.l.)	Description
Cordless Camera	6 dBW	6 dBi Omni	2 m	27 dBi 0.6 m dish	10 m	Handheld camera with integrated transmitter, power pack and antenna.
Portable Link	16 dBW	13 dBi Axial helix	3 m	27 dBi 0.6 m dish	30 m	Handheld camera but with separate body-worn transmitter, power pack and antenna.
Mobile Link (Ground RX)	26 dBW	13 dBi Axial helix	2 m	27 dBi 0.6 m dish	30 m	Mounted in motorcycles, pedal cycles, cars, racing cars and boats.
Mobile Link (Ground-to-air)	6 dBW	6 dBi Patch	2 m	6 dBi Co-linear	800 m	For airborne relay to fixed terminal (see below).
Mobile Link (Air-to-ground)	13 dBW	6 dBi Co-linear	800 m	27 dBi 0.6 m dish	30 m	For airborne camera or airborne relay of mobile TX on motorcycle, car etc.
Temporary Point-to-point OB Link	40 dBW	27 dBi 0.6 m dish	30 m	27 dBi 0.6 m dish	150 m	TX terminals are mounted on tripods, temporary platforms, purpose-built vehicles or hydraulic hoists. RX terminal is a masthead-mounted, steerable antenna.
Temporary Point-to-point ENG Link	40 dBW	27 dBi 0.6 m dish	20 m	27 dBi 0.6 m dish	150 m	TX terminal is on a vehicle-mounted pneumatic mast. RX terminal is a masthead-mounted, steerable antenna.

Table D5: Profile of typical 5 GHz ENG/OB operations

D.4 Radio Frequency Identification (RFID)

RFID system characteristics outlined in this report are based on the information provided in ERC Report 109, ERC Recommendation 70-03 and documents obtained from the following Web sites:

- Automatic Identification Manufacturers (AIM) (http://www.aimglobal.org)
- The UK-based (Oxfordshire) Blueleaf Limited (http://www.blueleaf.co.uk)
- Intermec Technologies Corporation (http://www.intermec.com)
- The US-based (Texas) TransCore (http://www.transcore.com)

A basic RFID system comprises a reader/writer and a tag. A reader/writer emits radio signals to activate a tag and read/write data from/to it.

There are two types of tags: active and passive. Active tags are battery-powered devices which transmit a signal either at a pre-set interval or when queried by a reader/writer. Active tags are typically read/write—tag data can be re-written and/or modified while in service. Passive tags obtain operating power from the radio signal received from a reader/writer. They are typically read-only devices containing a set of data that is programmed before operation. Due to the power limitation, passive tags operate over smaller ranges (approx. 1/3 of the range of an active tag).

The reader/writers differ considerably in complexity depending on the type of tags being supported and the functions to be implemented. Typically, a reader/writer unit comprises an antenna, RF module, tag decoder and power supply. The overall function of a reader/writer is to provide the means of communicating with the tags and to facilitate data transfer. The reader/writers may be portable or stationary and, in general, are controlled by a host computer.

In a typical operation, a reader/writer transmits a query through its RF module and antenna. When operating passively, the tag receives the signal and reflects a modulated signal back to the reader/writer antenna. The return signal is modulated in a way that tag data can be read from it. When operating actively, a signal of a different frequency can be generated, modulated and transmitted back to the reader/writer antenna. At the reader/writer, the received signal is demodulated to recover the tag data, which is then transmitted to a local security panel or a host computer for processing.

There are several frequency bands allocated to RFID operations. Low (100–500 kHz) and intermediate (10–15 MHz) frequency devices are inexpensive and operate over distances < 1 m. Typical applications include access control, inventory control, smart cards and car immobilisation. High frequency devices operate (or are planned) for the 915 MHz (in the US), 2.4 GHz (in Europe and Japan) and 5.8 GHz bands. These devices are widely used in transportation applications including toll collection for roads and bridges and controlled access to vehicles and areas.

An example of a 2.4 GHz system is the “Intellitag” RFID produced by Intermec Technologies and supplied in the UK by Blueleaf Ltd. It is noted that the reader/writer devices are either handheld or fixed with a maximum read range of 2.5 m. The data transfer rate is 8 bytes in 12 ms to read and 1 byte in 25 ms to write. The tags offer 1024 bits of storage: 96 bits are used for system addressing and control and 928 bits are available to be programmed for data storage.

Further examples of 2.4 GHz RFID devices are those produced by TransCore. It is noted that the 2.4 GHz tags offer up to 120 bits data capacity and their working range is 1.5–11 m. The reader/writers generate 50 and 300 mW nominal RF powers and use 10 dBi nominal gain antennas.

ERC Recommendation 70-03 states that the EIRP levels for RFID applications operating in the band 2.446–2.454 GHz should be limited to 500 mW and 4 W. It is noted that EIRP levels above 500 mW are restricted to in-building applications. In such cases, the duty cycle is specified as <15% in any 200 ms period. For enforcement purposes, any RFID emissions measured outside a building at a 10 m distance should not exceed the equivalent field strength of a 500 mW device mounted outside the building when measured at the same distance. It is suggested that FHSS should be used to mitigate interference when the EIRP is >500 mW. In addition, mobile RFID devices operating with an EIRP of >500 mW should be fitted with an automatic power control to reduce their emissions below 500 mW when they operate outdoors. RFID antenna radiation patterns need to have a horizontal beamwidth of <45 degrees and the sidelobe attenuation should be >15 dB.

The same recommendation indicates that emissions from RFID systems specifically intended for use in railway applications should be limited to an EIRP of 500 mW. These devices are allowed to transmit only in the presence of trains on five channels (each 1.5 MHz wide) within the band 2.446–2.454 GHz.

The following table shows representative RFID system parameters (primarily based on ERC Report 109 and ERC Recommendation 70-03).

EIRP	36 dBm (indoor) 27 dBm (indoor/outdoor)
Antenna Gain	6, 8 and 10 dBi (sidelobe attenuation >15 dB)
Antenna Beamwidth	< 45 degrees (ERC Rec. 70-03) < 90 degrees (ERC Report 109)
Duty Cycle	< 100% (for 27 dBm devices) < 15% (for 36 dBm devices)
Typical Range	< 11 m
3-dB Bandwidth	350 kHz (Frequency Hopping) (Hop Increment = 350 kHz, No of Frequencies = 20 Total BW = 7 MHz, Hop Rate = 5 hops/sec, ASK Modulated with Pulse Rate = Hop Rate) 100 kHz (Narrowband) (Channel Spacing = 600 kHz)
RX Noise Level	–93 dBm/350 kHz (Frequency Hopping) –121 dBm/100 kHz (Narrowband)

Table D6: RFID specifications

D.5 Microwave ovens

One of the main occupants of the 2.4 GHz band is microwave ovens. Information provided in this section is primarily based on detailed radio spectrum measurements of individual microwave ovens carried out by the US NTIA (Report 94-303).

Different microwave ovens are used in the NTIA measurements. Their rated powers are 700–1000 W. Although the nominal operating frequency is assumed to be 2450 MHz it is stated that all microwave ovens shift in frequency during operation and their peak levels are generally between 2450 and 2480 MHz.

Measurements include frequency spectrum characteristics and time waveforms covering the frequency range 2300–2600 MHz. The measurement configuration is based on a microwave oven placed at a height of 1 m on a wooden table and a calibrated horn antenna located at a distance of 3 m at the height of the centre of the oven. In the frequency domain, the received power (dBm) is measured as a function of frequency for each oven in a measurement bandwidth of 3 MHz. The measurement method is based on the use of a spectrum analyser by stepping from one frequency to another in increments equal to the measurement bandwidth. It is argued that this approach is more efficient in terms of time required to perform measurements as compared to the swept measurement approach where the spectrum analyser is sweep-tuned continuously across a desired frequency range.

Using the measured power levels together with the antenna gain correction and the 3 m path loss, the field strengths and the EIRP from the ovens are calculated and plotted as a function of frequency. In time domain measurements, time waveforms and amplitude probability distributions (APDs) are obtained at a number of single frequencies. APDs are used for determining the total percentage of time that emissions exceed given amplitudes.

Prior to the main measurement campaign, sensitivity measurements are carried out to examine the implications of a number of factors. These include oven temperature (at the start of measurements), oven orientation, oven load (i.e. material being cooked) and measurement antenna polarization. The results of sensitivity measurements indicate that spectral emission characteristics do not vary significantly with these parameters. On the basis of the sensitivity results, it is stated that measurements should be based on a warm oven (used 5 minutes prior to measurements), an oven load of 1 litre water and a measurement antenna aimed at the oven door. It is further stated that both vertical and horizontal measurement antenna polarisation should be used in compliance testing.

In microwave ovens, the source producing the microwave energy is a magnetron tube. All magnetrons operate at their rated power regardless of the oven power setting, which only regulates the percentage of time that the magnetron is operating. The spectrum emission characteristics for any oven are created during the periods when the magnetron is on and are the same for all power settings. Therefore, no sensitivity measurements are implemented for the oven power setting and all measurements are conducted in the full power mode.

In the main measurement campaign, the peak signal levels are recorded using the stepped measurement approach. The spectrum graphs represent the peak EIRP (and field strength) derived from the measured power levels at every 3 MHz over the band 2300–2600 MHz for each oven. It is stated that a dwell time of 0.9 second is spent at each frequency and, during each dwell period, the level of the strongest received signal is stored. It is noted that each oven produces a unique set of characteristics and the fundamental frequency on most of the ovens drifts. The rate and extent of the drifts vary from oven to oven. The mean EIRPs obtained by averaging over all ovens and measurement frequencies in three sub-bands are shown in the following table.

Frequency Band (MHz)	Mean EIRP (dBm / 3 MHz)
2300–2400	–16
2400–2500	5
2500–2600	–25

Table D7: Microwave oven emissions

A further document (thesis submitted to Virginia Polytechnic Institute and State University by Mark D’Souza) provides the results of an oven radiation measurement procedure based on the use of a spectrum analyser continuously sweeping the band 2400–2480 MHz. It is stated that each recorded measurement corresponds to a 100 kHz resolution bandwidth centred around measurement points spaced at 200 kHz. The results are presented for four ovens in the form of 3D plots, where received power levels (at an antenna of 0 dBi gain located at 1 m distance) are plotted as a function of frequency and measurement time. It is noted that each oven has a different radiation pattern and transmits high power levels at frequencies other than the centre frequency of 2450 MHz. The results indicate that the received power levels are in the range –70 to –20 dBm/100 kHz.

D.6 Other devices

The UK Radio Interference Requirement document for short-range devices defines a number of applications allowed to operate within 2.4 GHz band. These are shown in the following table.

Type	Frequency Band (MHz)	Max. EIRP (mW)	Channel Bandwidth (MHz)	Music or Speech Permitted
General Telemetry and Telecommand	2400–2483.5	10	≤ 20	N
Industrial/Commercial Telemetry and Telecommand	2445–2455	100	-	N
Short-Range Indoor Data Links	2445–2455	100	-	N
Railway Applications	2447–2453	500	≤ 1.5	N
Detection of Movement and Alert	2445–2455	100	-	N
Tagging and Identification	2445–2455	500 (outdoor) 4000 (indoor)	-	N
Wireless Audio	2400–2483.5	10	≤ 0.3	Y
Wireless Video Cameras (Non-broadcasting)	2400–2483.5	10	20	Y

Table D8: Short-range devices (2.4 GHz)

The UK short-range devices information sheet (RA 114) states that ERC Recommendation 70-03 aims to harmonise the use of short-range devices throughout Europe. It is also stated that the recommendation has not been fully adopted in the UK.

According to information provided in ERC Recommendation 70-03, equipment for detecting movement and equipment for alert are allowed to operate in the band 2.445–2.455 GHz in the UK. The EIRP of these devices is limited to 25 mW with no restriction on duty cycles. In addition, non-specific short-range devices are allowed to operate in the band 2.4–2.4835 GHz with a maximum EIRP level of 10 mW and a minimum channel spacing of 20 MHz.