1 Introduction
Transfinite is pleased to provide Ofcom with this response to the call for inputs (CFI):


We would be happy to provide further information in response to requests to clarify any point in this response. In addition, we would be grateful to be kept informed of any workshops or further developments within this strategic review.

2 Background
Transfinite is an independent UK company, with an excellent track record of consultancy support, study work and software development. We specialise in products and services to analyse compatibility between radiocommunications systems and their use of the radio spectrum. Our tools have a particular emphasis on interference analysis, spectrum management and frequency coordination. Our study work has encompassed a wide range of communications systems including both terrestrial and satellite services.

We have experience in a range of spectrum sharing techniques including:

- Propagation models, including P.452, P.1546, P.1812, P.2001 and Hata / COST 231. We have worked with the UK’s leading propagation experts to ensure our implementations are rigorously tested
- Interference analysis, including a very wide range of metrics (I, I/N, C/I, C/(N+I), EPFD, PFD, field strength etc.) and methodologies (static, dynamic, Monte Carlo, area, combinatorial etc.)
- Coverage prediction of a range of services including broadcasting and mobile and modelling of many others including fixed, satellite, radar, science, astronomy etc.
- Ofcom frequency assignment methodologies including fixed service (FS) links and business radio (BR) applications
- Development of interference analysis and coverage tools including optimisation, user interface design, testing, training and support
- Integration with GIS data including terrain and land use databases, including high resolution surface databases to model urban areas
- Area licences, including participating in an auction, winning a 28 GHz area licence, licence variation and sale.

We have also developed web based radio spectrum management tools including the Visualyse Spectrum Manager (SM). Visualyse SM provides all the necessary features to support issuing of licences including application, processing, search and display, technical analysis, management, reporting and engineering.

We have provided additional information on two projects undertaken for Ofcom in which Transfinite developed ideas relevant to this consultation, namely:

- The Generic Radio Modelling Tool (GRMT), in Section 4
- The N-Systems methodology, in Section 5.
3 Response to Consultation Questions

Question 1: Do you have any comments on the barriers to increased sharing that we have identified above? Which are the most significant and why? Are there others we should take into account?

Response

An additional barrier is availability of suitable licensing software solutions within Ofcom. The GRMT project (described below) would be a suitable basis to provide an enhanced licensed sharing environment with assured levels of protection.

Question 2: Have you experienced or are you experiencing the effects of these barriers? If so, in what circumstances and with what impact?

Response

We have undertaken studies in which we have been limited by the availability of data about licensed systems, in particular their technical parameters.

Question 3: Are the categories of information set out in paragraph 5.5 the right ones? Are there any areas here that you think we should prioritise? Are there other types of information that we should be improving?

Response

The primary requirement is for sufficient information to be able to undertake interference analysis. Models of example parameters and availability could be the approaches used by the ACMA & FCC. Additional technical parameters would allow more accurate assessments, and as shown by GRMT this can involve both in-band and adjacent band(s). The GRMT project also showed how templates (i.e. default values) can be used to reduce requirements to specify each individual licence by completing the definition of parameters.

Note that there are significant dangers in focussing only on monitored use rather than authorised: radio systems could be silent for a good reason (e.g. require extremely high likelihood of assured access to radio spectrum, be emergency back-up or be operating on low power). If a licensee pays for a radio spectrum licence then they should be taken into account during any technical assessment.

Licence database can be include permanent and also time dependent assignments. Key requirement is that to get in the database it is necessary to pay for licence to avoid blocking and cancelling (i.e. gaming the system).

Question 4: Do you think the information about spectrum characteristics described in paragraph 5.9 would be useful? What information would need to be included as a minimum to make it useful?

Response

In general, the more information the better, as described above. The GRMT database structure was designed to:

a) Capture all the parameters necessary to undertaken a technical assessment of interference (both into other systems and from other systems and both co-frequency and non-co-frequency)
b) In particular, the GRMT data dictionary also captured receiver characteristics including, relevant thresholds

c) Have templates to map Ofcom’s standard licensing products to this database in a way that reduced the data capture requirements.

The parameters required for a GRMT style assessment would also be sufficient to undertake the N-Systems methodology, described further below.

**Question 5**: Have we identified the relevant market enablers, or are there others we should take into account? For each one, what is the potential for it to facilitate sharing and what are the downsides? Are there any that you think would be particularly effective or problematic?

**Response**

This is an area that would benefit from Ofcom support. For example, Ofcom could manage a band with LSA or provide the support to the area licence holder to manage the LSA for them. In particular, Ofcom has ability to monitor spectrum usage and powers to enforce licence holders to switch off equipment.

**Question 6**: Have we identified the relevant technology enablers, or are there others we should take into account? For each one, what is the potential for it to facilitate sharing and what are the downsides? Are there any that you think would be particularly effective or problematic? What, if any, role should Ofcom play in helping to develop them?

**Response**

There are significant dangers in relying on spectrum sensing (e.g. listen before transmit) as they can miss receive only or low powered (e.g. satellite) systems or hidden nodes.

Improvements to spectrum sharing is feasible if have:

- More information: in particular the technical parameters giving detailed characteristics of radio systems
- Improved accuracy of station location: in particular, where they are in 3D (latitude, longitude, height above terrain or buildings)
- Better definition of the sharing environment: e.g. use of high resolution surface databases
- More accurate modelling methods: e.g. better propagation models and use of advanced techniques such as Monte Carlo models
- Licensing or authorisation systems that are able to handle liberalised spectrum scenarios which involve wide variety of spectrum products.

Propagation research is a key enabler for which Ofcom can play a leading role, in particular to develop computationally fast and accurate models of urban environments (e.g. using a surface database, potentially extending the model in Rec. ITU-R P.2001).

**Question 7**: Do you have any comments on the authorisation tools that we have identified above? Are there others we should take into account? For each one,
what is the potential for it to facilitate sharing and what are the downsides? Are there any that you think would be particularly effective or problematic?

Response

Tiered access a good way to manage primary / secondary rights, but it is also necessary to have authorisation systems that permit mixed use bands. Hence technology such as GRMT could be used to enable LSA. This LSA could either be via Ofcom managed bands or for Ofcom to provide a packaged license, where the primary owner would inform Ofcom of their usage and Ofcom manage the underlay on their behalf, keeping track of authorisations.

In such mixed usage bands it would be necessary to consider pricing and the N-Systems methodology can be used provide metrics that can assist in this process. The N-Systems methodology calculates the spectrum opportunity cost of a system of type A compared to type B. Note that the total licence price can include both fixed overheads costs and spectrum opportunity cost and that:

- In areas of low spectrum demand it might only be necessary to consider the fixed overhead costs
- In areas of high spectrum demand it would be necessary to consider both fixed overheads and spectrum opportunity costs.

The N-Systems methodology can also be used to determine maximum deployment densities and hence assess whether there is high or low spectrum demand.

Question 8: Are the characteristics of use we have identified sensible and sufficient to provide a high level indication of sharing potential? Are there other factors that we should expect to take into account? Are there any factors that you consider to be particularly significant? Are there any which we should attach less weight to?

Response

The parameters seem more useful for a high level assessment of spectrum usage than detailed technical analysis of interference, as discussed further above.

4 GRMT Project

This section gives an overview of the Generic Radio Modelling Tool developed for Ofcom by Transfinite. More information can be found in the project deliverables, in particular the:

- Final Report
- Final Report Annex A: Licensing, USMS, FS Planning, Spectrum Blocks and Interference Apportionment;
- Final Report Annex B: Propagation Studies;
- Algorithm Definition;
- Definition of the Spectrum Product Templates.

Transfinite would be happy to provide more information on GRMT and the derived Visualyse Spectrum Manager tool including presentations and / or demonstration.
4.1 Project Objectives

In a traditional “Command and Control” regime, the radio spectrum is divided into bands which are allocated to services, as in the figure below.

![Figure 1: Traditional Spectrum Management](image)

Ofcom is interested in introducing market forces to the management of the radio spectrum and to give users increased flexibility via trading and liberalisation.

Rather than having a single service in each band, there could be a range of scenarios that lead to a mixture of services within a band or in adjacent bands, including:

- A licensee in a band allocated to one service requests change of use (CoU) to another type of service;
- A band is in transition with migration of the existing service to higher frequencies. New entrants of a different service type wish to start operating prior to the band being fully cleared;
- A stakeholder approaches Ofcom wishing to gain a licence to operate a standard spectrum product in a band not currently allocated to that service type;
- A stakeholder approaches Ofcom wishing to gain a licence in a new type of system that is not easily categorised into one of the existing service types;
- A stakeholder approaches Ofcom wishes to gain a licence for a standard spectrum product in a band where there are a mix of service types – for example because there has been at least one CoU;
- Ofcom wish to increase spectrum efficiency by permitting licensing in the currently empty guard bands between allocations to two different services;
- Ofcom wish to allocate bands to services in a way that is different to that of the UK's geographic neighbours while ensuring they can be technically coordinated.

These scenarios have in common the need to be able to assess interference between nearly any combination of services at nearly any frequency band.

However it is likely to be difficult to analyse such scenarios using software tools designed to model one or at most two services.
The objective of the Generic Radio Modelling Tool (GRMT) was to provide Ofcom with an analysis and licensing tool that can undertake a technical assessment of the potential for interference between any of the main service types, and therefore manage the scenarios above.

The GRMT approach is summarised in the figure below.

In particular, three scenarios for use of GRMT by Ofcom were identified:

- Scenario 1: What-if studies
- Scenario 2: Assessment of CoU request against current Assignments
- Scenario 3: Management of a Liberalised Band

From these scenarios a set of twelve specific requirements were generated that are listed in section 2.4.5 of the Final Report, which were used to develop the software architecture and design.

4.2 GRMT Software

The project developed the GRMT software to meet the requirements identified above. It is based upon a client / server architecture, as shown below.
GRMT comprises the following key components:

**GRMT Online**

This is shown in a standard web browser. When used in conjunction with client management software on the GRMT Application server it can be used to create new or CoU licences, submit for examination, view status and results of examinations, and perform licence management tasks.

**GRMT Desktop**

This is a standard Windows desktop application that interfaces to the GRMT Application server. It uses a local database of licences in GRMT’s Technology Neutral Radio Parameters (TNRPs) format to allow complex “what-if” calculations. It can import licences from the central database or they can be created locally.

**GRMT Application Server**

This is the core of GRMT and runs on a dedicated Windows 2003 server. It undertakes queries of databases, performs the necessary computations for a licence technical examination, and interactions with potentially multiple users across the Ofcom Intranet.

**Support for Existing Licence Types**

While capable of managing generic formats of licences it is noted that the majority of licences are likely to be one of a standard set of spectrum products such as wide area business radio or point to point fixed link. To facilitate management of such spectrum products by GRMT the following features were included:

a) **Spectrum Product Templates**: the user interface has been designed to capture the essential parameters of a pre-defined set of typical systems;

b) **Fixed Service Planning Tool**: an interface has been included that undertakes the planning tasks required to introduce a point to point fixed link including calculation of EIRP and selection of frequencies to use;
4.3 Examination Process

At the heart of GRMT is its ability to undertake a technical examination of whether a new or CoU licence application should be approved or rejected.

An examination is based upon a series of tests, with the three main ones shown in the figure below.

A GRMT Examination comprises four tests:

1) Test whether the licence parameters are within the range permitted for its frequency block. In particular there can be thresholds to determine if it should be submitted for Site Clearance if its EIRP and antenna heights are above certain values. Note that this need not represent a failure of the licence application.

2) Test whether the new licence would cause harmful interference into existing licences;

3) Test whether the new licence would suffer harmful interference from existing licences.

In some bands there will be additional constraints that should be included in the examination, such as:

4) Test whether the new licence would result in PFD or field strengths on or beyond a boundary are above levels defined for that band. These constraints could be derived from Memorandum of Understanding (MoUs) with neighbouring countries or domestic constraints such as an aggregate receive power limit to protect the Fylingdales radar site.

The assessment of the impact of one licence on another is based upon the relevant emission rights and Spectrum Quality Benchmarks (SQBs). In GRMT
these technical parameters comprise the TNRPs of the licence, and are mapped onto TX Systems and RX Systems respectively.

Definition of the TNRPs is facilitated by the use of the spectrum templates, and hence the GRMT approach allows automatic interference analysis between different types of licence, as in the figure below.

![Figure 5: Analysis of interference from Licence A of type X to Licence B of type Y](image)

4.4 **GRMT Data Dictionary**

The licence and TX/RX systems fit into the overall structure of TNRP data elements developed by the GRMT project as shown in the figure below.

![Figure 6: GRMT TNRP Data Structure](image)

The key elements are:

**Licence Types:**

```
- Licence Owner: owns one or more Licence;
- Licence: contains one or more Systems, which can be any combination or number of TX Systems and/or RX systems. The Licence is issued by the Spectrum Block Holder;
- System: can be either TX, in which case it defines the emission rights, or RX, in which case it defines the requested levels of protect from interference. It is contained within a Spectrum Block. It uses an Antenna and Deployment;
- Antenna: which defines the antenna gain pattern and pointing angles;
- Deployment: which specifies the locations of the TX and/or RX Systems;

**Band Types:**
- Spectrum Block Owner: is responsible for one or more Spectrum Blocks;
- Spectrum Block: defines a blocks of spectrum extending geographically and in frequency. It contains a number of Systems and defines constraints such as transmit EIRP and received PFD limits.

There are two methods that a TX System can define its emissions:

a) Those defined by individual transmitter’s EIRP limits and either located either at a fixed point or randomly across a service area.

b) Those defined by PFD on boundary (used for in-band analysis) and EIRP plus fixed distance (used for out-of-band analysis);

RX Systems can be one of two types, with corresponding impact on the form of their SQB:

- Those defined at a single point, in which case the SQB is in the form:
  \[
  \text{Interference at the receiver within the receiver bandwidth should not exceed } X \text{ dBW for more than } Y \% \text{ of time}
  \]
- Those defined over an area, in which case the SQB is in the form:
  \[
  \text{Interference at the receiver within the receiver bandwidth should not exceed } X \text{ dBW for more than } Y \% \text{ of time at more than } Z \% \text{ of locations}
  \]

### 4.5 Interface to USMS

The Phase 2 version of GRMT was able to access current Ofcom assignments via a dedicated interface to the Unified Spectrum Management System (USMS) developed by LS Telcom. This provided read-only access to Fixed Service, Business Radio, and Satellite Earth Station assignments.

For Phase 2-5 data was imported directly into the GRMT database.

### 4.6 Relevance to Consultation

The GRMT project gives Ofcom the potential to introduce liberalisation into bands it manages while ensuring licensees have protection from harmful interference. It could therefore be used to support Ofcom in its goal as identified in its three vision statements:

1. Spectrum should be free of technology and usage constraints as far as possible. Policy constraints should only be used where they are justified.
2. It should be simple and transparent for licence holders to change the ownership and use of spectrum.

3. Rights of spectrum users should be clearly defined and users should feel comfortable that they will not be changed without good cause.

The key delivery of the project of relevance to this Consultation is the algorithm, database format and templates:

1) The GRMT Algorithm permitted an automated interference assessment of any of the principle spectrum products issued by Ofcom

2) The database format provided a parameter based method to capture the technical characteristics of any radio systems

3) In order to reduce the complexity of data capture, templates were created that defined default attributes of the main spectrum product types so that user entry was restricted to the minimal set of required parameters

The workflow could be mapped onto the standard Ofcom licensing process and permit:

- Time dependent licensing (e.g. like PMSE)
- Priority based licensing (e.g. with tiered access)
- Licensed shared access (LSA)
- Underlays managed by Ofcom of auctioned bands

It should be noted that the derived Visuallyse Spectrum Manager (SM) could handle a flexible licensing regime for C band that would permit licensing of:

- Satellite Earth stations
- Point to point fixed links
- Point to multi-point cells
- Mobile base stations (macro or small cell)
- Other services

An example screen show is shown below.

Visuallyse SM includes a first-come, first-serve (FCFS) workflow that would permit external organisations to undertake:

- Licence searches
- New licence application
- Process management, including checking on-line of the results of technical analysis
- Try before buy features
- Secure authentication
- Reporting
- Etc.
5 N-Systems Methodology

The N-Systems methodology was used during the Ofcom project:

- Evaluating spectrum percentage occupancy in licence-exempt allocations, Aegis, Transfinite.

The Final Report includes a description of the methodology which is reproduced below.

The methodology is also described in the following paper with results in the final section:


5.1 Introduction

All use of the radio spectrum has to some degree an impact on other users, as transmissions can not 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 imposition of restriction on one or both systems. A key question is how to quantify or cost the impact of one system using the radio spectrum 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 are made allocations to various services. Some allocations are made to single
services, to permit homogenous deployment of a single system in the space domain. For example mobile operators are given licenses 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 local busy hour. However capacity can always be increased by use of cell-splitting techniques, and so there is balance between cost and capacity.

Even for such situations where only a single service operates within a location in a certain band it must accept interference from other services (for example satellite, other bands, other locations, systems such as UWB that operate across many bands). This interference impacts on homogenous 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 limit area, rather than wide-scale homogenous 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 still 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 effected 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.

5.2 Model Description

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.
The method is built upon the concept of a system: while a system could involve one or more transmitters and receivers, to be applicable to the N-Systems method it 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.

Figure 8: Method to calculate N-Systems
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 number of trials 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 different sharing scenarios one derives different values of full occupancy. It is then possible to arrive at a comparative measure of spectrum occupancy.

5.3 Definition of environment / deployment

The first stage of the method is to define the environment to be considered. By this we mean:

- Select the frequency band to consider.
- Define the wanted system characteristics, e.g. antenna gain, noise temperature, interference criteria etc.
- Define the interfering system(s) characteristics, e.g. antenna gain, transmit power (including transmit power control), bandwidth etc.
- 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 introduced 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 a homogenous 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 as 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 those actual systems.
- Select the appropriate propagation model.

5.4 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 systems being deployed, but is likely to involve a check that interference levels are not exceeded. Interference can be between systems of the 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 available 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 systems 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 loss of clarity in the method and increased likelihood of errors.

A judgement will have to be made when implementing the N-Systems method as what is an 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: e.g. for some bands and services there are well defined I/N thresholds, while for others it might be BERs. These thresholds could also be defined to be 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 means 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 9: Interference paths for example FS-ES deployment](image)
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: BT into WLAN**

The figure below shows a simple deployment consisting of two WLAN networks and 7 BT systems, with both WLANs transmitting to devices within their service area.

![Graph showing interference paths](image)

**Figure 10: 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 the previous FS-ES example. For example it is likely to be necessary to sample from a set of WLAN service area locations (either at random or a grid within the service area or around its rim). At each of these points a 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 impact on throughput, which can be compared against requirements. A similar calculation could be performed on the uplink direction (i.e. into the WLAN AP).

5.5 **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 (which might be populated by other interfering systems) 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.

5.5.1 **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:

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

As $N_A$ is a mean, there would be a range of $P_O$ based upon mean +/- standard deviation.

5.5.2 **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:

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

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 to a specified density).

5.5.3 **Determine relative spectrum cost of one system compared to another**

The impact of introducing interfering Type B systems into the scenario is likely to be a reduction in number of Type A systems that can be introduced. As the number of Type B systems increases the number of Type A systems is likely to reduce.

In the case that there is a linear relationship between the relative cost of one system compared to another, namely:

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

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 of different types of system and service, and hence get a measure of how efficient each is. More complicated relationships could be considered when introducing multiple interfering systems, e.g.:

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

5.5.4 Determine relative spectrum cost of particular technologies

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

1. \( N_{A1} \) = number of Type A systems that can be introduced into a certain geographic area using modulation 1
2. \( N_{A2} \) = 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 (e.g. service area, BER requirement, traffic type etc.) then the impact of using the different modulations can be compared by the ratio:

\[ \beta_{12} = \frac{N_{A1}}{N_{A2}} \]

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 considering the two values of \( N_A \) and the two ratios \( \alpha_{AB} \).

5.6 Example Results

The results in the paper at the IEE were that the result of deployment satellite ES was to reduce the average density of point to point fixed links as per the following chart:
The data showed strong statistical significance with, for the system characteristics assumed for the study, the following ratio:

\[ N_{FS} = 33 - \frac{1}{93} N_{ES} \]

Hence in this case, the spectrum opportunity cost of an ES was 1/93rd that of a point to point fixed link.

### 5.7 Relevance to Consultation

The N-Systems methodology could be used to derive spectrum licensing prices that are based upon spectrum opportunity cost. Having price directly linked to how a system causes / is susceptible to interference would be a driver in ensuring efficient use of the radio spectrum.