Transfinite Systems and Spectrum Sharing Problems

Abstract: In this paper, we highlight some areas of our consultancy work that we believe will be of interest. In particular, we touch on aspects of our software modelling in *Visualyse Professional* including some detailed explanations. Our consultants set out to engage with spectrum engineering problems in a robust manner, aiming to take the lead on technical questions, strategy and tactics in the regulatory environment.

Spectrum Sharing Problems

Transfinite has contributed to several complex spectrum sharing problems over the past few years. In this paper, we touch on just some of the issues encountered with focus on aspects of the modelling and analyses developed by our consultants and software development experts using *Visualyse Professional.*

In general, we aim to use our expertise and experience to take a lead on modelling questions. In particular, we will propose progressive, non-conservative, approaches when addressing spectrum sharing problems.

We will support these ideas and proposals with detailed software simulation work including innovative solutions and software development. Occasionally, special software is developed for a project and we discuss an example in this paper.

Equivalent Objects

One feature encountered in some recent terrestrial sharing studies is the concept of a single victim receiver being exposed to interference sourced from a mass of randomly positioned interferers.

A typical example of this is where the study requires a victim Earth station to be located at the centre of a large-scale, somewhat abstract, model of an urban and rural mobile network deployment.

Figure 1 shows such a deployment in *Visualyse Professional* where the circular urban area, centred on the victim Earth station, is defined by a radius of 30 km and the rural area by an inner-radius of 30 km and outer-radius of 100 km. The base station inter-site distances are 1.732 km and 7 km respectively.

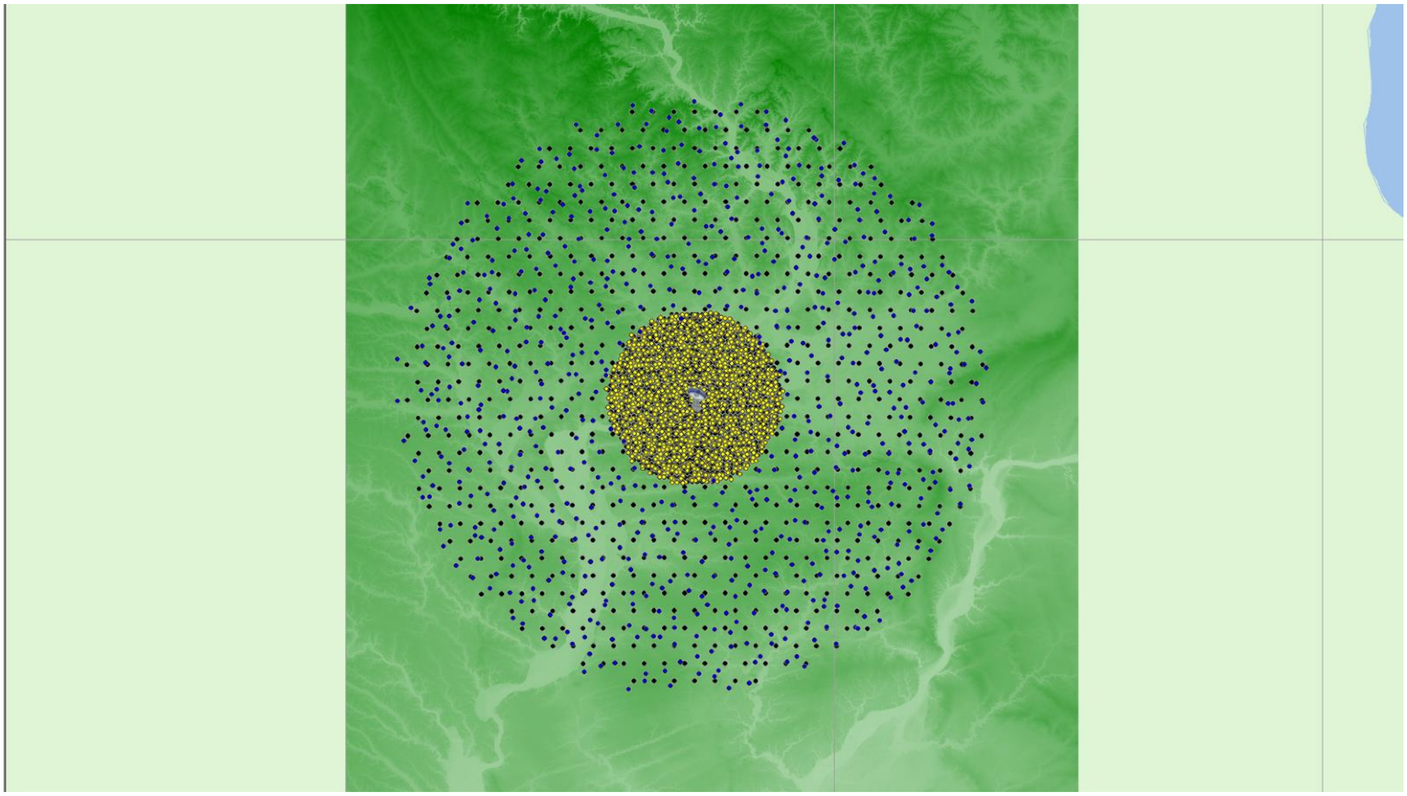


Figure 1 Mobile deployment

For computational efficiency, an important aspect of this model is the use of *equivalent objects* where one modelling object represents more than one interferer in the radio environment. With this study, each equivalent object represents all simultaneously active User Equipment (UEs) in the mobile cell area. In Figure 1, black markers represent hexagon cell centres while yellow and blue markers are equivalent objects in the urban and rural areas. In this case, 1,753 equivalent objects are deployed, representing 31,554 UEs; that is, each equivalent object represents 18 UEs.

Our equivalent objects require an EIRP representative of all UEs in the cell. This would be a simple summation of powers if the UEs were simultaneously transmitting at a fixed power level but in this study an EIRP distribution characterises UE emissions (a model for transmitter power control).

The EIRP distribution for an individual UE can be modelled as a Cumulative Distribution Function (CDF) in Visualyse. The following procedure was used to develop CDFs of aggregate EIRP for the equivalent objects:

1. Model a specified number of conventional UEs in an experimental cell
2. Specify the EIRP CDF for an individual UE
3. Model a test receiver
4. Specify omni-directional antennas at both ends of the communications link
5. Switch propagation modelling OFF
6. Plot the aggregate EIRP distribution incident to the test receiver
7. Use the plot data to develop an aggregate EIRP CDF
8. Model an equivalent object in the experimental cell
9. Associate the equivalent object with the aggregate EIRP CDF
10. Plot aggregate EIRP sourced from both conventional and equivalent models
11. Compare aggregate EIRP plots to ensure good correlation

Figure 2 shows graphs of the aggregate EIRP collected from 18 individual UEs and from an equivalent object.

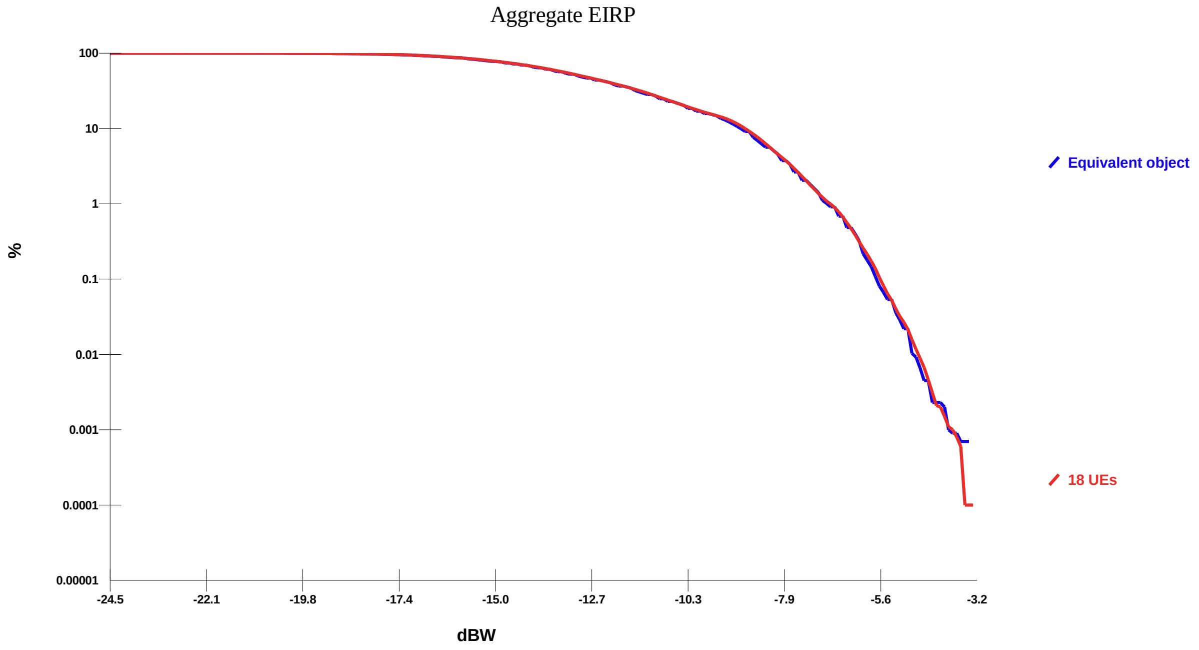


Figure 2 Comparing EIRP plots

In Figure 3 we show how a Traffic Model is configured in *Visualyse Professional* to specify a CDF of aggregate EIRP for the equivalent object.

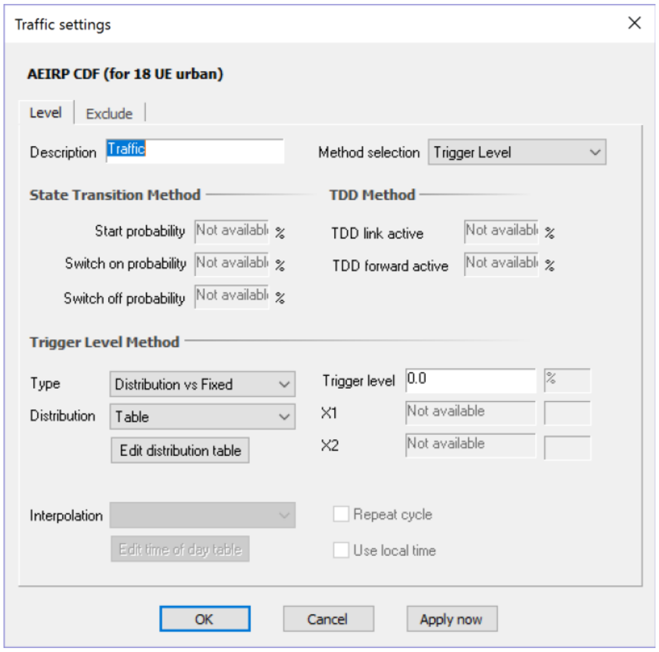
Figure 4 shows an extract from the aggregate EIRP CDF specified in the Traffic Model's *distribution table.* Each entry under *CDF* is a probability and each entry under *Variable* is aggregate EIRP expressed in Watts.

Here we use the *interval method* to implement the distribution. That is, there are two identical entries for each aggregate EIRP in the distribution and the corresponding entries under *CDF* give the probability P_i of the *ith* EIRP being selected during the simulation run where:

Equation 1

$$P_i = p_i^2 - p_i^1$$

and p_i^1 and p_i^2 are the first and second entries in the ordered list of probabilities associated with the *ith* EIRP.



Traffic settings

AEIRP CDF (for 18 UE urban)

Level | Exclude

Description: Traffic

Method selection: Trigger Level

State Transition Method

Start probability: Not availabl %

Switch on probability: Not availabl %

Switch off probability: Not availabl %

TDD Method

TDD link active: Not availabl %

TDD forward active: Not availabl %

Trigger Level Method

Type: Distribution vs Fixed

Distribution: Table

Trigger level: 0.0 %

X1: Not available

X2: Not available

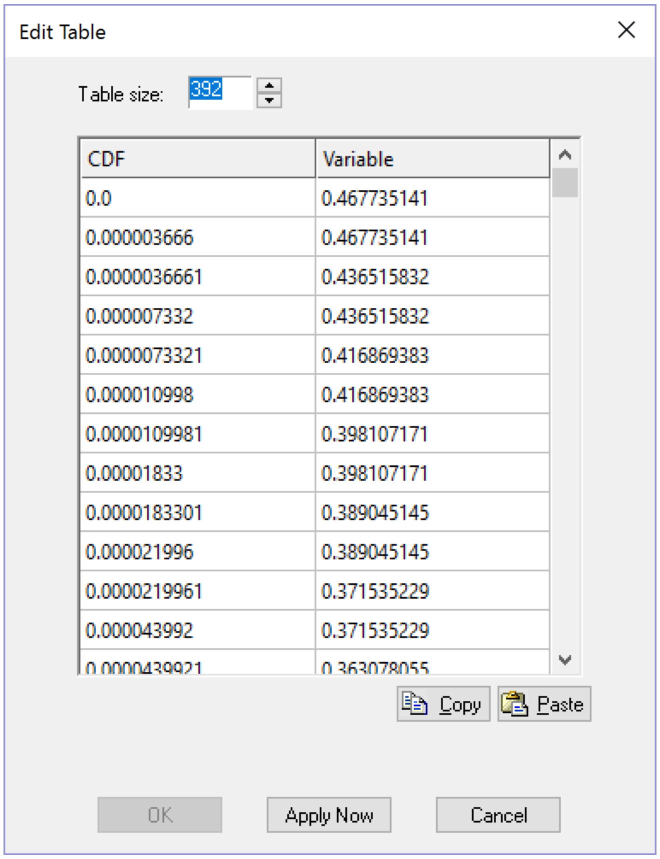
Interpolation:

☐ Repeat cycle

☐ Use local time

Figure 3 Traffic Model

The first two lines in the extract show that the CDF gives a probability P_i = 0.000003666 that EIRP = -3.3 dBW (converted from Watts) will be selected during the simulation.



Edit Table

Table size: 392

CDF	Variable
0.0	0.467735141
0.000003666	0.467735141
0.0000036661	0.436515832
0.000007332	0.436515832
0.0000073321	0.416869383
0.000010998	0.416869383
0.0000109981	0.398107171
0.00001833	0.398107171
0.0000183301	0.389045145
0.000021996	0.389045145
0.0000219961	0.371535229
0.000043992	0.371535229
0.0000439921	0.363078055

Figure 4 Aggregate EIRP CDF

We proceed with a large-scale deployment of equivalent objects using the aggregate EIRP CDFs.

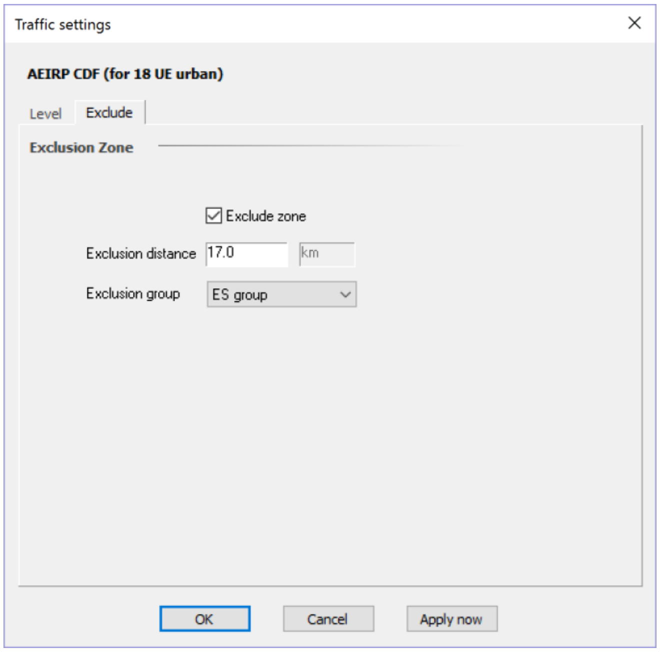
In this model, our equivalent object randomly locates within the cell area so replicating the random location of UEs.

Doughnuts

A routine procedure in sharing studies is calculation of a minimum separation distance between victim receiver and interferer. There are several ways of handling this with large-scale deployments.

In the study discussed above, the Traffic Models were used to define an *Exclusion Zone* around the victim Earth station. Figure 5 shows that the exclusion zone is set to 17 km for the urban deployment. Using the Traffic Model in this way means that all interference sourced from the urban deployment within a radius of 17 km of the victim receiver is disregarded. A second Traffic Model specifies the EIRP CDF and Exclusion Zone for the rural deployment. The Exclusion Zones can be adjusted until the interference criteria are satisfied.

The mobile UE deployments in this model (and illustrated in Figure 1) use *doughnuts*, or annuli, to define urban and rural areas via a special software tool developed for this work. This allows for the inner and outer radii of each doughnut, the inter-site distance between cell centres and the random location of stations within each cell to be specified.



AEIRP CDF (for 18 UE urban)

Exclusion Zone

☑ Exclude zone

Exclusion distance 17.0 km

Exclusion group ES group

Figure 5 **Exclusion Zone**

Doughnuts can also be used to determine minimum separation distance. Figure 6 illustrates an approach taken in another study, this time investigating interference into MSS user links from mobile UEs.

Here a smaller mobile deployment of 19 base stations serving 342 UEs in an urban environment is organised into doughnuts with a constant separation of 1 km between inner and outer radius. The UEs are our source of interference.

With this approach, the doughnuts are really *conceptual,* with each doughnut defined as a Transmit Link where all of the interferers associated with a doughnut are members of the Link's Station Group.

We can add or remove individual Transmit Links from the list of interferers on the Interference Path, effectively switching doughnuts on and off.
In this case, we were able to calculate minimum separation to a resolution of 1 km. However, a finer resolution could also be used.

Another important feature with this approach was the specification of propagation models for each doughnut.

Clutter loss was considered in the study and the doughnut method allowed for alternative assumptions to be made for different interference path lengths.

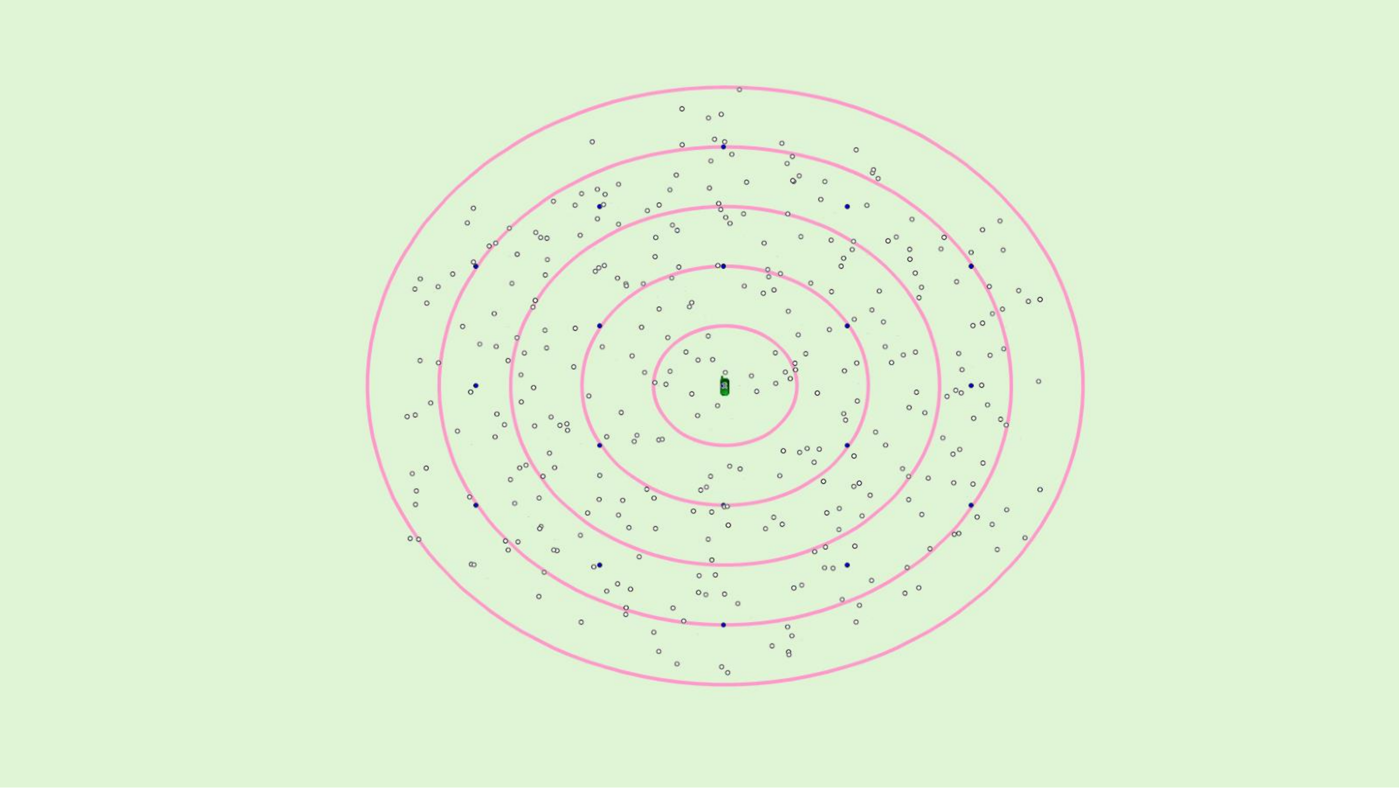
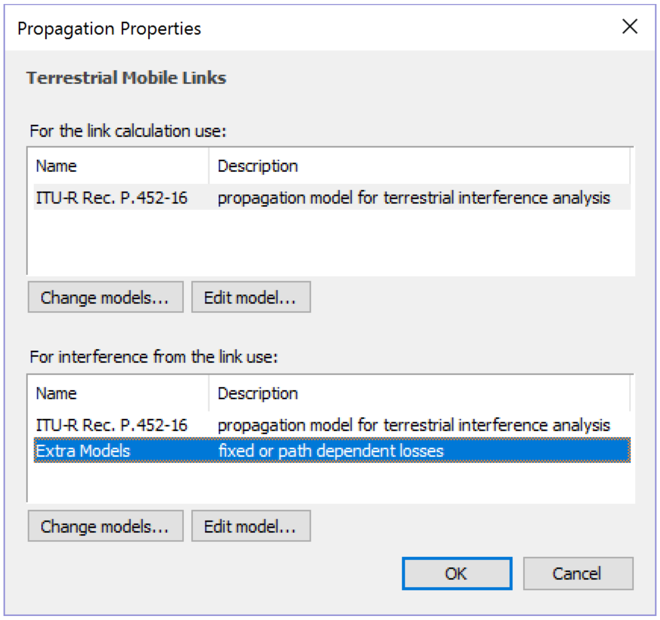


Figure 6 **Doughnuts (conceptual)**

Specifically, it seemed appropriate, in this urban environment, to assume clutter loss at UE locations but with the possibility of line-of-sight interference at shorter distances. One particular configuration allowed for all UE locations to be exposed to 20 dB clutter loss with the exception of the inner doughnut (inner radius = 0 km; outer radius = 1 km) where 0 dB was assumed.

Figures 7 and 8 show how this can be achieved by setting a Fixed Clutter Loss using Extra Models under Propagation Properties.



Propagation Properties

Terrestrial Mobile Links

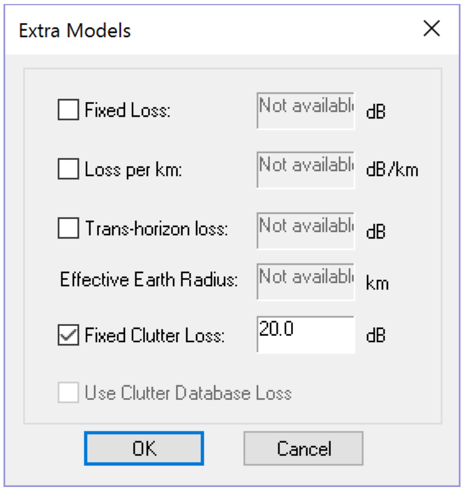
For the link calculation use:

Name	Description
ITU-R Rec. P.452-16	propagation model for terrestrial interference analysis

For interference from the link use:

Name	Description
ITU-R Rec. P.452-16	propagation model for terrestrial interference analysis
Extra Models	fixed or path dependent losses

Figure 7 **Propagation Models**

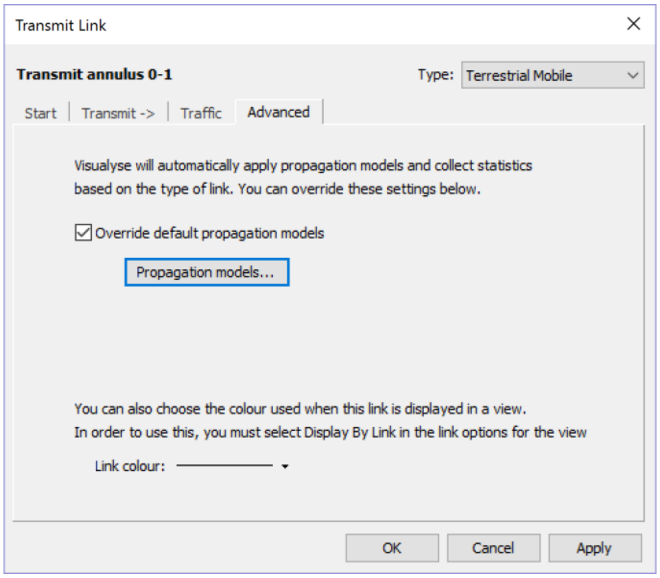


Extra Models

☐ Fixed Loss: Not available dB
☐ Loss per km: Not available dB/km
☐ Trans-horizon loss: Not available dB
Effective Earth Radius: Not available km
☑ Fixed Clutter Loss: 20.0 dB
☐ Use Clutter Database Loss

Figure 8 **Fixed Clutter Loss**

Figures 9 and 10 show how this can be overridden for a particular Transmit Link (doughnut), where 0 dB Clutter Loss is required, using the *Override default propagation models* option in the Transmit Link's Advanced tab and with Fixed Clutter Loss deselected for this link.



Transmit Link

Transmit annulus 0-1

Type: Terrestrial Mobile

Visualyse will automatically apply propagation models and collect statistics based on the type of link. You can override these settings below.

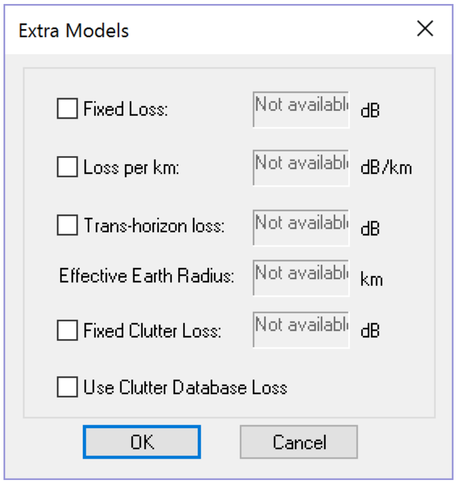
☑ Override default propagation models

You can also choose the colour used when this link is displayed in a view.
In order to use this, you must select Display By Link in the link options for the view

Link colour:

Figure 9 **Transmit Link Advanced Tab**

Doughnuts can also be specified in the Monte Carlo objects in *Visualyse Professional.* Here, it is possible to randomly locate a station or a group of stations within the bounds of a doughnut shape.



Extra Models

☐ Fixed Loss: Not available dB
☐ Loss per km: Not available dB/km
☐ Trans-horizon loss: Not available dB
Effective Earth Radius: Not available km
☐ Fixed Clutter Loss: Not available dB
☐ Use Clutter Database Loss

Figure 10 **Clutter Loss deselected**

Validity of Monte Carlo Simulations

Monte Carlo modelling is an approach often used to handle variations in the input parameters to a simulation.

Examples of input parameters that could vary include:

- Selecting the position of a mobile system's user terminal (UT) at random over a base station sector
- Selecting the transmit power to use at random from a distribution
- Switching a link on or off, as specified by a traffic model
- Selecting a frequency from a set of alternatives (e.g. in a channel plan)
- Selecting a percentage of time and / or percentage of locations in a propagation model etc.

A Monte Carlo analysis involves taking multiple snap-shots or trials. For each trial, the input parameters that vary are sampled at random, and the effect is to convolve their distributions together in the interference engine.

There is often some discussion around Monte Carlo modelling and recently some questions have been raised in relation to the validity of these simulations.

Monte Carlo modelling introduces a random element to simulations so that outputs are statistical in nature. These results will alter as the number of trials increases, typically stabilizing after a sufficient number of steps: but how many steps are required to achieve statistically valid results?

Figure 11 shows how the likelihood of a C/(N+I) threshold being exceeded varies by the number of trials.

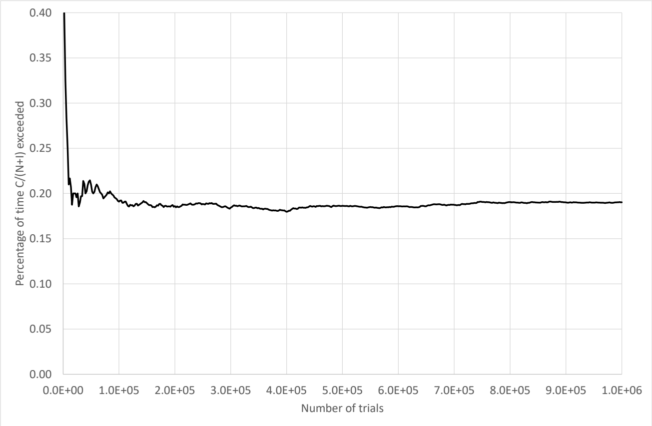


Figure 11 **Exceedance versus number of trials**

It can be seen that there is initially significant variation in this likelihood until the statistics stabilize. But how many trials are necessary?

One approach is to group the results and output the average over that group. It is then possible to calculate the standard deviation of the average and observe how this converges, as shown in Figure 12.

This leads to a confidence interval derived by a specified number of standard deviations either side of the mean.

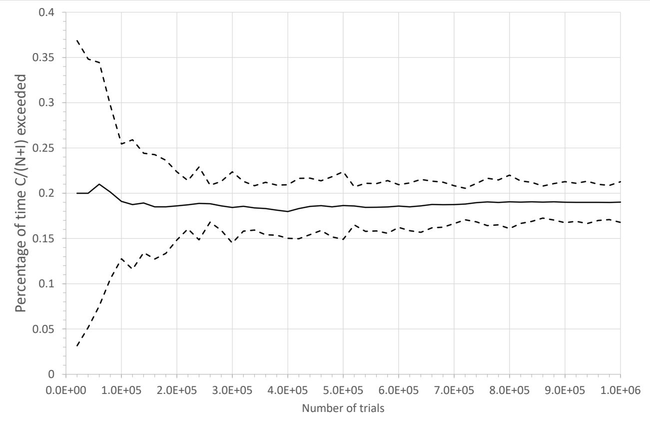


Figure 12 **Standard deviation**

Protection Criteria

The interference thresholds used in studies can make an enormous difference to outcomes and yet there is often cursory discussion around this topic.

Where there is discussion, those in favour of sharing, possibly emerging services with inadequate access to spectrum, will likely advocate non-conservative thresholds while the opposite is likely to be the case with incumbents. Transfinite's consultants contributed to some recent discussions regarding the protection criteria to be used for FSS in sharing studies with IMT.

ITU-R S.1432 apportions aggregate interference from all sources incident to a FSS satellite receiver such that the degradation of noise is 32% or 27% of the clear sky satellite system noise, dependent on frequency re-use. We denote this percentage increase in noise by $\Delta T/T$.

These criteria correspond to an interference margin of 1.21 dB or 1.04 dB since the interference margin M is given by:

Equation 2

$$M = 10.\log\left(1 + \left(\frac{\Delta T/T}{100}\right)\right).$$

If M is known, then $\Delta T/T$ can be calculated using:

Equation 3

$$\Delta T/T = 100 \cdot \left(10^{M/10} - 1\right).$$

The apportionments of the overall $\Delta T/T$ given in ITU-R S.1432 are as follows:

- 25% for all other FSS systems not practising frequency re-use
- 20% for all other FSS systems practising frequency re-use
- 6% for all other co-primary services
- 1% for all other sources

Following this scheme, if FSS and IMT were sharing a frequency band and no other co-primary services were involved, the aggregate interference from IMT would be limited by $\Delta T/T$ = 6%.

The interference margin for each of these apportionments can be calculated using equation 2 which, for $\Delta T/T$ = 6%, gives M = 0.25 dB; this maps to I/N = -12.2 dB using:

Equation 4

$$I/N = 10.\log(10^{(M/10)} - 1).$$

Although not discussed in ITU-R S.1432, The 0.25 dB interference margin available to co-primary services will often be subject to both *service* and *geographic* apportionments in the studies and it is here that simple, worst-case, assumptions and modelling can quickly come into play, radically reducing the criterion.

In general, the criterion is apportioned equally between services and geographic regions with detailed analyses neglected entirely.

There are some important questions in this discussion. We highlight a few here:

1. Can the FSS link accommodate an interference margin > 1.04 dB (assuming frequency re-use)? If so, then the apportionments of M can be adjusted accordingly. For example, if M is increased by just 0.13 dB then I/N for co-primary sharers could be relaxed to -10 dB.

2. If other co-primary sharers exist, what proportion of the co-primary apportionment will they use? A move away from arbitrary apportionment of the available margin is essential for efficient spectrum utilisation but requires detailed study.

3. If geographic apportionment is appropriate, are reasonable assumptions in play with regard to coverage? If we model aggregate interference sourced from a deployment in a particular region, is coverage and geographic apportionment based on realistic satellite beams rather than the point of view of the satellite from space? This can have a radical impact on results.

These are difficult questions that should be approached in a balanced manner and investigated with a clear and detailed understanding of the constraints on FSS operations.

Summary

This paper has set out, very briefly, some aspects of the software modelling initiatives and study work undertaken by our consultants in the recent period.

Our consultancy involves a wide range of spectrum engineering work including sharing studies, frequency coordination, regulatory compliance and special software development.

About Transfinite

We are one of the leading consultancy and simulation software companies in the field of radio communications.

Our consultants set out to engage with spectrum engineering problems in a robust manner, developing in-depth studies based on engineering, mathematical and scientific principles.

We aim to provide a lead on technical questions, strategy and tactics in the regulatory environment.

We develop and market the world leading Visualyse products:

- Visualyse Professional
- Visualyse GSO
- Visualyse Coordinate
- Visualyse EPFD

We also provide training courses in the use of our products including advanced training that can cover modelling of specific systems and scenarios. More information about these products and services is available at our web site:

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info@transfinite.com

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