Prediction Study of LTE Received Signal Strengths at Short Distances from Base Stations

Delivery Report

Version 1.3

Receiver

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Updates

VERSION	DATE	REDACTOR	OBJECT
1.0	29/11/2013	Vincent WEIS	Initial version
1.1	17/12/2013	Vincent WEIS	Modifications
1.2	23/12/2013	Vincent WEIS	Modifications
1.3	07/01/2013	Vincent WEIS	Modifications
1.4	04/02/2014	Vincent WEIS	Executive summary and conclusion additional comments

Executive Summary

OFCOM wishes to conduct a prediction study for an LTE model network deployed in dense urban environments. The aim of this study is to determine the distribution of received signal strength under practical conditions at short distances (<500 m) from base stations. This is required for use in interference analysis for protection of systems in adjacent frequency bands to mobile networks.

This project is all about the likely interference that an LTE network may cause to WiFi networks (indoor\outdoor) in adjacent bands once the 2.3 GHz band is released for mobile networks in near future (meanwhile only 800MHz and 2.6 GHz spectrum have been granted to carriers). The objective is to produce signal strength plots for a small scale LTE network deployed in dense urban environment in London, United Kingdom. The small scale LTE network to be studied is based on the assumption of the most likely deployment of LTE base stations in London at 2.3 GHz.

Ray tracing propagation models make the best use of finer map data details of such built-up areas and can provide greater prediction accuracy than empirical models. OFCOM therefore wish to understand what received signal-levels are likely to be achieved by using ray tracing predictions in conjunction with high quality map data, especially within close proximity of base stations. This will help OFCOM to perform better gap analysis between ray tracing and empirical predictions.

To meet with OFCOM requirements, SIRADEL proposed a comprehensive solution based on its off-the-shelf data (3D high resolution geo data of London, CW measurement data) and in-house simulation tools Volcano Lab and Smart City Explorer, leading not only to a study based on theoretical assumptions but on operational real-network use case at the end.

SIRADEL used off-the-shelf CW measurement data collected in London (more than 80.000 measurement outdoor locations, from 10 different transmitter locations) in order to calibrate Volcano URBAN propagation model and better match with the project constraints (environment, transmitter topology, frequency…). Finally, model key performance indicators show a global mean error of 0dB, a standard deviation error lower than 6dB and especially a very good mean error dispersion across London area (lower than 1dB), highlighting the reliability of the model from one area to another.

3D capabilities of the Volcano URBAN model combined with SIRADEL 3D high resolution London geographical data led to accurate and reliable simulations for the required scenarios, mixing outdoor-everywhere and outdoor-indoor disctintion.

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1. Introduction

SIRADEL technical scope of work to tackle with OFCOM requirements relies on the standard turn-key solutions schemas including:

- The use of SIRADEL home-produced 3D High resolution map data,
- The use of SIRADEL Volcano RF propagation models based on ray-tracing,
- The use of SIRADEL off-the-shelf CW measurement data collected across London
- The experience of SIRADEL for model calibration
- The use of internal simulation tools for predictions.

Next sections will describe in details the inputs that were used for the study (geo data, RF propagation model…) and explain the methodology and settings that were applied in order to carry out the simulations.

Besides this report, all required outputs have been delivered through a secured FTP site.

2. Geographical data

2.1. Introduction

Map data owned by OFCOM do not enable the use of ray-tracing models since it does not include 3D building polygon vector data. Besides, the format is not compliant to SIRADEL propagation models. Therefore, it was not used in the framework of that study. Instead, SIRADEL used its own off-the-shelf geo database of London as described in next sections.

SIRADEL produced and owns 3D high resolution geo data in London based on sources images (aerial pictures) from 2008. The total area covers a great part of London area. The area available is described by the black polygon below with total size 593 km². The Area of Interest (AOI) of OFCOM is presented as a circle area below. Please see the red polygon as below which was used for the predictions.

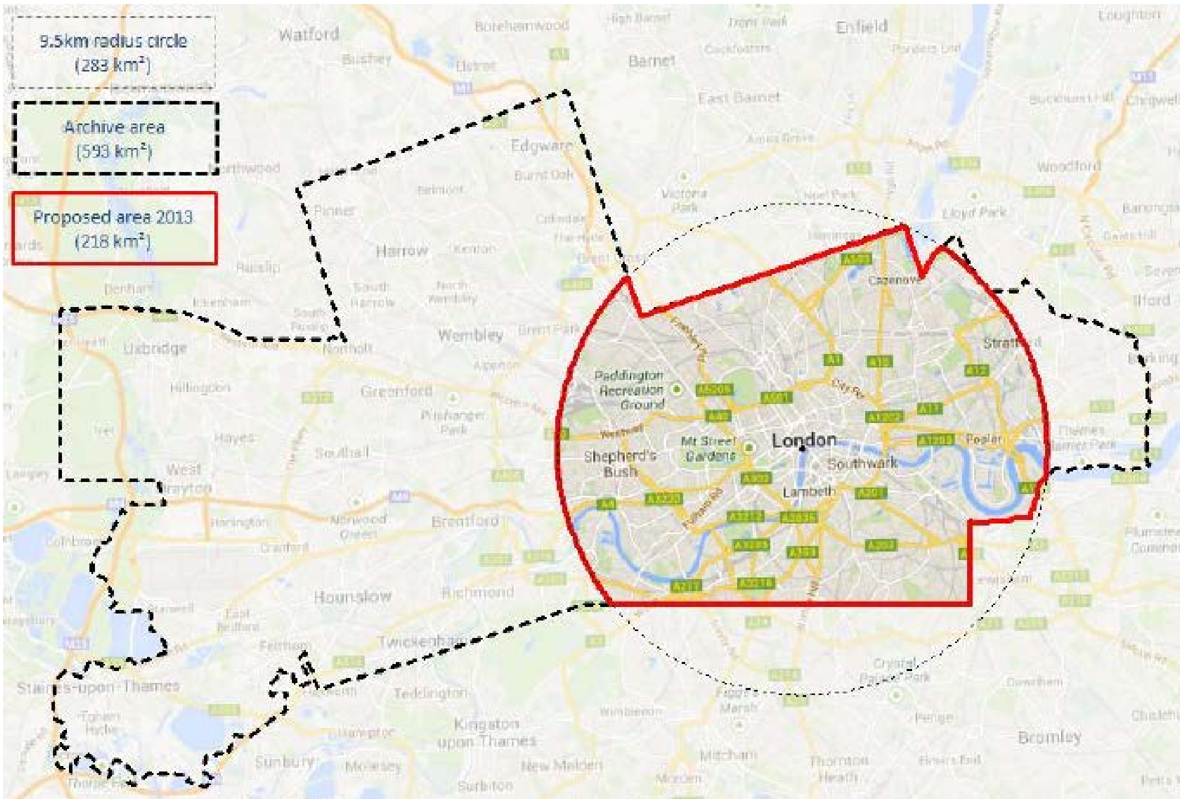


Figure 1: Off-the-shelf SIRADEL 3D data versus OFCOM area of interest

The total size is around 283 km². So, there is around 218 km² SIRADEL's off the shelf data inside OFCOM's Area Of Interest (AOI) which represents about 77% of the initial AOI. It was considered as acceptable by OFCOM although 7 sites of the original list were located outside the maps and therefore discarded from the study.

2.2. 3D high Resolution Geographical Data

2.2.1. Introduction

The best available geo data with sub-metric accuracy, the highly-accurate HR-3D product is specifically designed to increase confidence in radio coverage within challenging dense urban environments for multipath simulations. Produced from high-resolution stereo images, this product provides an extensive 3D description of the urban environment, including buildings (habitation, monuments, industry…), bridges, and vegetation.

Main specifications are:

- **Available layers:**
  - Digital Terrain Model (DTM raster data)
  - Digital Height Model (DHM raster data)
  - Digital Land Use (DLU raster data)
  - 3D-vector polygons
- **Data sources:** high resolution stereoscopic imagery
- **Accuracy:** [1m] RMS in XYZ
- **Resolution:** delivered at [1m or 5m]

2.2.2. DTM Raster Data

DTM (Altitude) describes the ground level in meters above mean sea level. DTM raster data used for this study is described as 5m resolution [x, y] raster data.

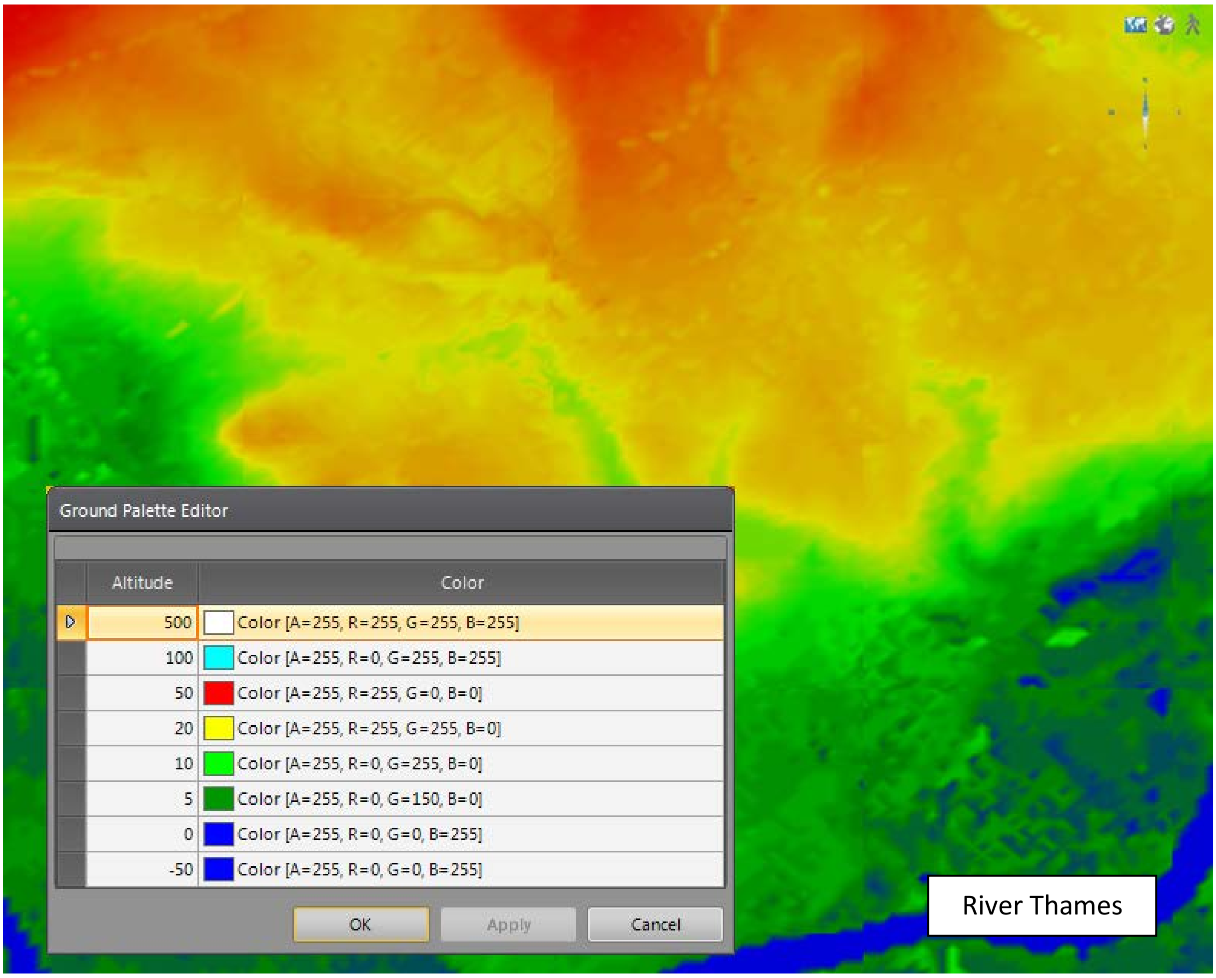


Figure 2: DTM (altitude) raster data in Smart City Explorer™ by SIRADEL

2.2.3. DLU Raster Data

DLU (land use, also known as clutter types) describes for each pixel the type of land use. DLU raster data used for this study is described as 5m resolution [x, y] raster data.

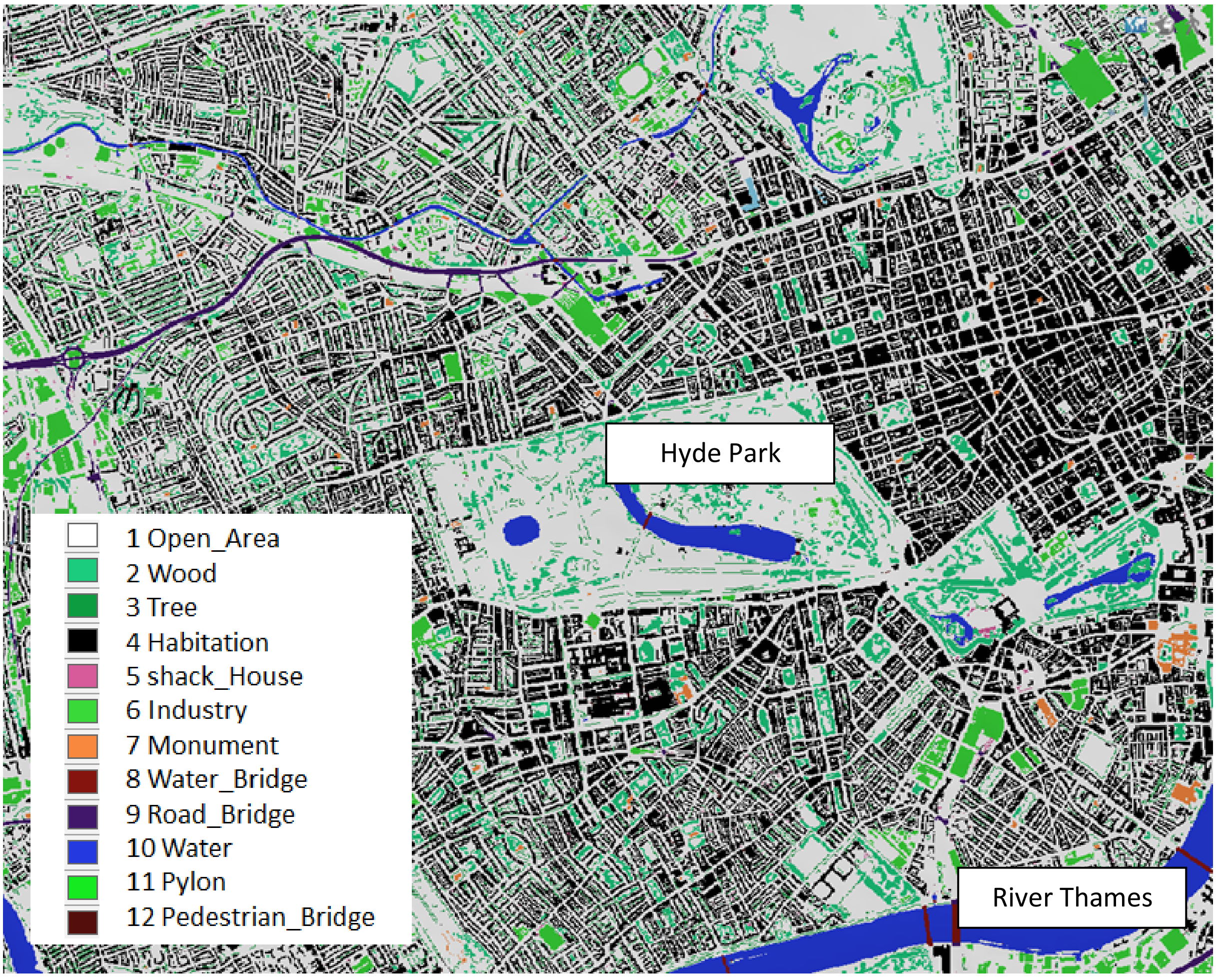


Figure 3: DLU (clutters) raster data in Smart City Explorer™ by SIRADEL

2.2.4. DHM Raster Data

DHM (clutter heights) describes for each pixel the relative height of the clutter above the ground in meters. DHM raster data used for this study is described as 5m resolution [x, y] raster data but accuracy in z is 1m.

Note that SIRADEL DHM layer does not include 3D information for buildings only but for vegetation and bridges as well. 3D vegetation has shown to be critical for accurate RF simulations in urban areas as well generating some obstacle effects such as vertical diffractions and shadowing.

2.2.5. 3D vector data

DLU (clutter types) and DHM (clutter height) data are also described as 3D polygon vectors. Note that 3D building vector polygon data is mandatory to carry out multi-path simulations through ray-tracing modelling techniques.

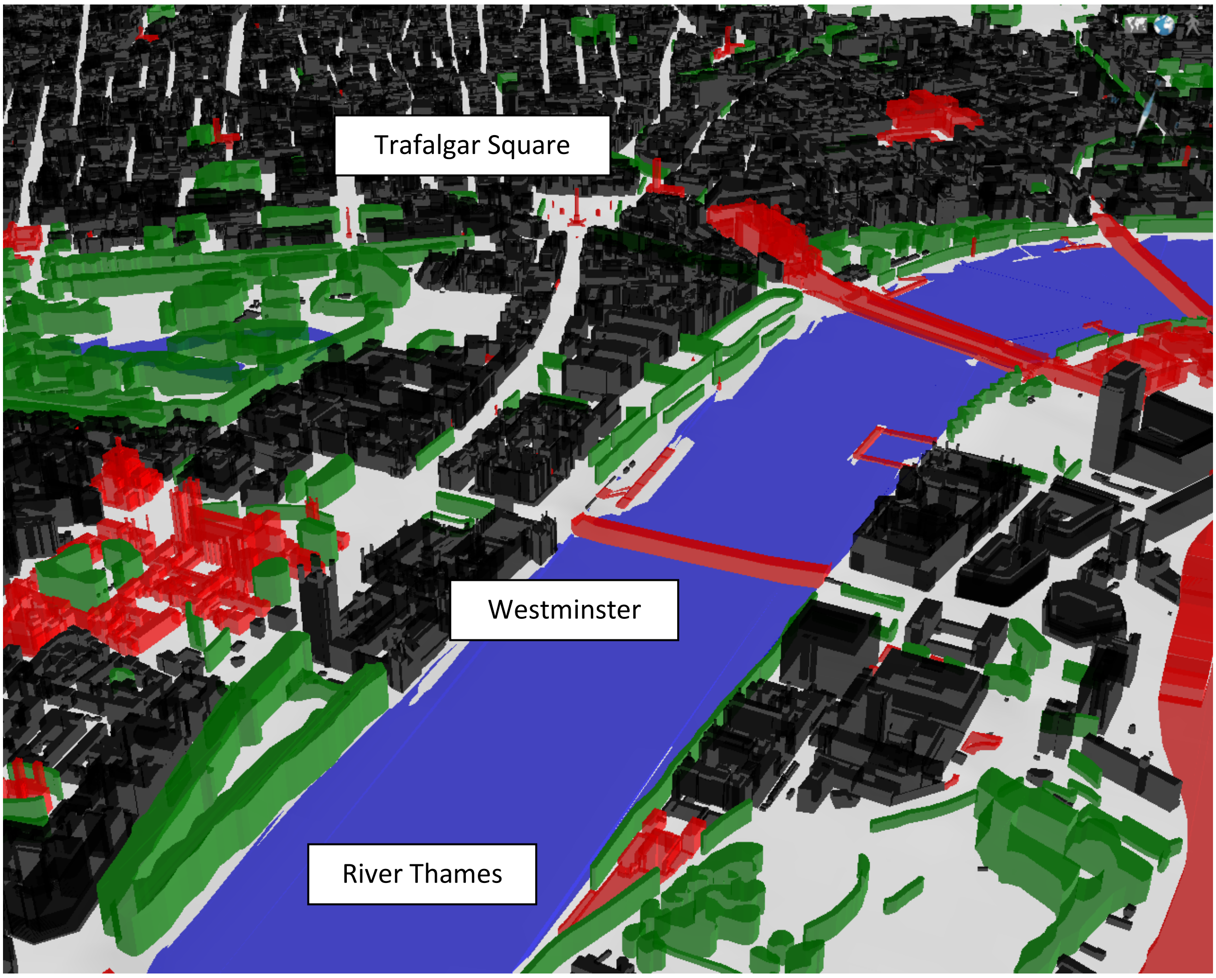


Figure 4: 3D vector data in Smart City Explorer™ by SIRADEL

3. RF Propagation Model

3.1. Introduction

SIRADEL develops since more than 15 years **Volcano** suite, its in-house technology for RF propagation simulations. It includes 3 types of models described hereafter:

- The **VOLCANO Rural Model** is suitable for transmitters located in rural or suburban environment. It is a deterministic propagation model based on multiple knife-edges diffraction, specifically adapted for macro-cellular sites, with antennas located above the surrounding building rooftops in rural environment.
- The **VOLCANO Urban Model** is suitable for any transmitters located in urban or suburban environment. It is a deterministic propagation model, based on the over Rooftop Diffraction and on multipath component modelling, i.e. 2D or 3D Ray-tracing. Depending on the site configuration (dominant or non-dominant), the ray tracing option can be activated.
- The **VOLCANO Indoor Model** is suitable for transmitters located in buildings based on the COST 231 multi wall.

It stands as a **wide-scale solution** that is compliant to **multi-RAT multi-frequency and heterogeneous networks** in all environments from rural areas to dense urban and indoor areas. It is an industry oriented solution with a first-class level of **efficiency**: accuracy/speed. Besides, it is notorious for offering **innovating features** to the market.

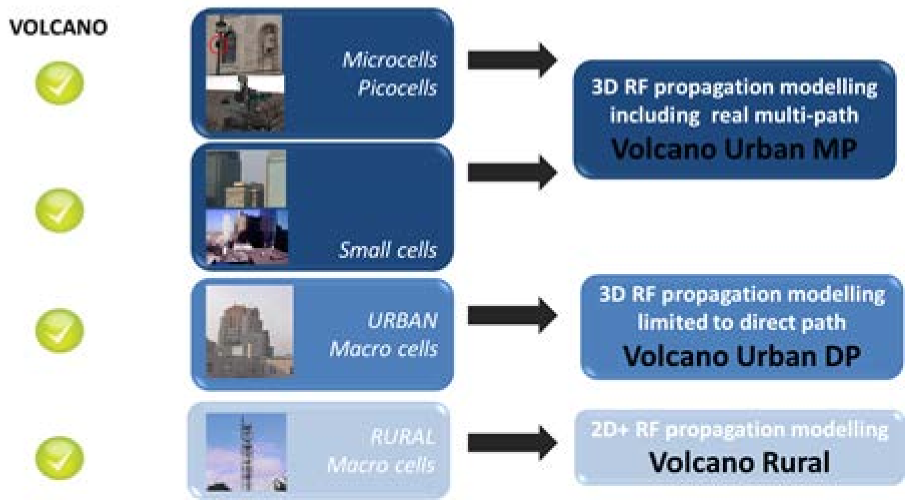


Figure 5: Volcano wide-scale application range

It is also very portable through the eco-system thanks to its software-component technology (it is currently available as a plugin module in the main RF planning tools of the market such as AIRCOM's Asset, FORSK's Atoll, INFOVISTA's Mentum Planet, HUAWEI's U-net, ZTE's CNP…). Interoperability of Volcano with other tools from the ecosystem (EMF exposure, ACP, Monitoring…) is also a key commitment of SIRADEL.

3.2. Volcano Urban Model

Volcano Urban model is dedicated to predictions in dense urban, urban and suburban environments based on 2D low-resolution (i.e. raster resolution greater or equal to 20m) or 3D high-resolution geographical map data (i.e. raster resolution less or equal to 10m and/or 3D vector representation). Volcano Urban model is able to carry out predictions with urban transmitters such as Macro-cells, Small-cells, Micro-cells and Pico-cells.

Depending on the transmitter configuration and user settings, Volcano Urban model takes advantage of direct path only or direct and multi-path contributions together.

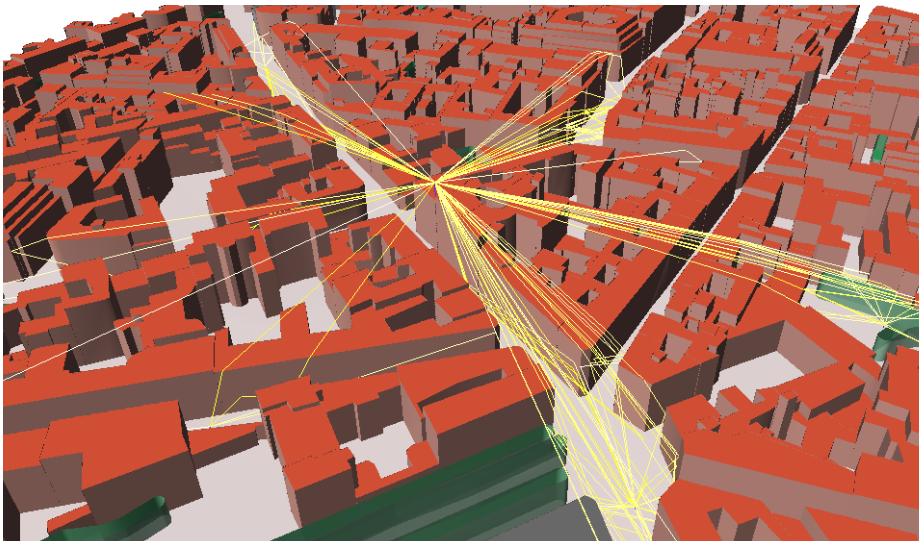


Figure 6: 3D View contributions from a rooftop transmitter to street-level receivers

The direct-path component is mandatory, resulting from the analysis of the vertical terrain profile along the straight path between both radio terminals, transmitter and receiver.

The multi-path component relies on ray-tracing and is optional. Its activation requires the presence of vector map data and permits to get accurate results in areas where signals are propagating along the streets (even after propagation above rooftops). This multi-path component is recommended in configurations where canyoning effect is significant: transmitter located in dense urban area, especially non-dominant transmitters, that is to say, located below the average surrounding environment. Note that it is also necessary to predict wideband channel properties (delay spread, departure angles, arrival angles, etc.).

For this study, URBAN model (called in this document URBAN MP model) was used with multipath contributions activated.

When multiple paths option is activated, Volcano Urban model combines the direct-path contribution as well as multi-paths that undergo reflections on the vertical building façades and diffraction on the vertical building edges.

The multi-path calculation is based on a ray launching technique that computes 3D contributions from interactions with the building facades, building rooftops, hills and vegetation. An optimised combination of **multiple knife-edge technique** and **UTD (Uniform Theory of Diffraction**) permits the construction of those 3D contributions and the calculation of the field strength. A specific 3D antenna gain is calculated for each contribution according to its emitting and arrival angles.

A list of 3D contributions is calculated at each receiver location. Wideband channel properties like the delay spread, departure and arrival angle spreads may be derived. And the propagation loss is obtained from the sum of field strength squares, assuming uncorrelated random field phases.

The user sets the maximum number of reflections (set by default to 2) and maximum number of diffractions (set by default to 1) allowed on vertical building façades along one single ray path.

3.3. Model Calibration

Although Volcano URBAN MP model is a deterministic model relying on accurate 3D description of the environment, that offers default settings based on SIRADEL's world wide experience, it is still recommended to carry out a calibration of the model parameters based on measurement data in order to better match with the application range of the model (environment, frequency band, type of cells, technology…).

Calibration of the model relies on outdoor Continuous Wave measurement data and/or SCAN drive test data and leads to a model which should be very accurate and in line with the field measurement data for outdoor to outdoor predictions.

3.3.1. Off-the-shelf CW measurement data

SIRADEL have a great experience collecting CW and SCAN measurement worldwide. In 2006, SIRADEL carried out a CW dual band (2.1 GHz and 3.5GHz) measurement campaign in London for one of its customers. CW data remains the property of SIRADEL since it does not rely on confidential data from the carrier and network whereas SCAN data property is limited to the measured network carrier only. Therefore, SIRADEL can reuse this 2117 MHz CW data for the calibration of Volcano model in the framework of that study for OFCOM, since it matches with the study application area and the application frequency difference is minor: 2117 MHz instead of 2300 MHz. Calibration of the model has been carried out with 2117MHz CW measurement data but predictions will be carried out at 2300MHz as specified in the scope of the study.

Figure 7: Dual band CW measurement campaign in London (2006)

3.3.2. CW Sites Locations and Measurement Footprints

CW measurement campaign was carried out by SIRADEL in London, for 10 CW site locations across the city, which antenna heights were from 18m up to 60m above the ground. Refer to the picture for site locations and measurement data footprint over the city map data.

3.3.3. CW Transmitter Antenna

CW transmitters were equipped with DORADUS 10dBi omnidirectional antenna which frequency application range is [2.15, 2.3 GHz] and horizontal and vertical patterns are illustrated below.

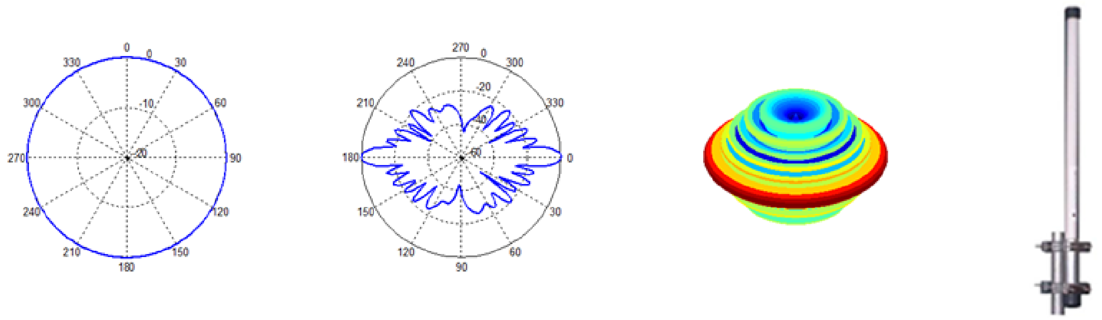


Figure 8: **CW transmitter antenna – H & V patterns – 3D pattern – Side view**

3.3.4. Calibration Outputs

Usually, **common key performance indicators (KPI)** include standard deviation error (SD) in dB, mean error (ME) in dB and Root Mean Square ($RMS^2 = ME^2 + SD^2$) in dB, which give a first level of information about the performance level of a propagation model but might not be sufficient to lead to a fair opinion about the model.

Two other KPIs – **correlation factor and mean error dispersion** – are complementary and must be analyzed in order to comfort the opinion about the given model or raise some unexpected limits and drawbacks (E.g. limited application range, unsteady behavior of the model, uncertain margins for operational use…). **Mean Error Dispersion (in dB)** illustrates the way the mean error between predictions and measurement data varies area by area (i.e. site by site).

Refer to Appendix 1 for detailed computation formulas of the KPIs.

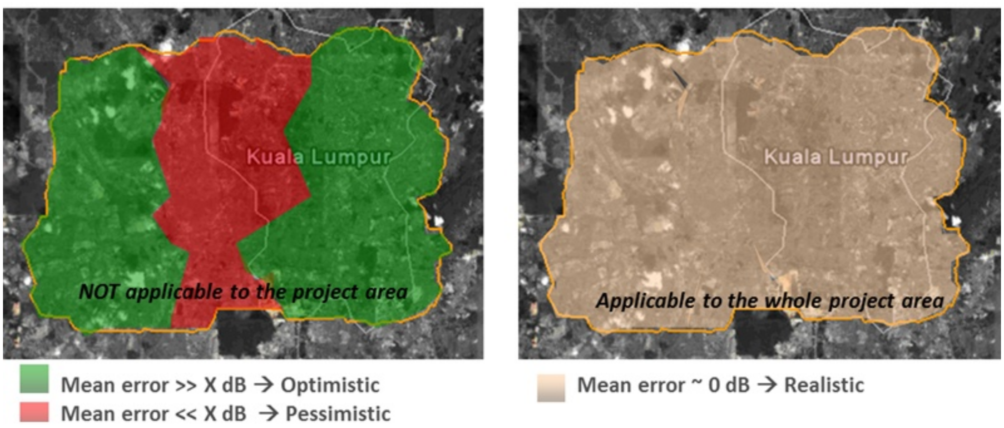


Figure 9: Mean error dispersion (bad on the left side, good on the right side)

For information, SIRADEL targets and commitments in term of KPIs after CW model calibration are as described in the table below.

Targets (Calibration KPI with CW data)	Commitments (Calibration KPI with CW data)
• Global mean error = 0dB • Global standard deviation error ~6dB • Global correlation >85% • Global Mean Error dispersion = 1.5dB	• Mean error = 0dB • Global standard deviation error <= 8dB • Global correlation >70% • Global Mean Error dispersion < 3dB

Table 1: Model KPI - Targets and Commitments

Volcano Urban MP model calibration carried out in the framework of that study provides following KPIs globally and per site.

CW site	Total number of pointsPoints	Number of predicted points	Mean Error (dB)	Std Error (dB)	RMS Error (dB)	Correlation Factor
Site1	8675	8413	-1.66	5.85	6.08	0.86
Site2	7559	7533	-0.04	5.11	5.11	0.91
Site3	7361	7143	1.23	5.82	5.95	0.9
Site4	7667	7403	-1.76	6.29	6.53	0.87
Site5	9726	9572	0.72	4.73	4.78	0.92
Site6	9562	9220	-1.89	5.72	6.02	0.85
Site7	7318	6773	0.01	6.12	6.12	0.78
Site8	7479	7258	-0.01	5.71	5.71	0.86
Site9	7024	6701	2.2	5.91	6.31	0.85
Site10	11230	11153	1.3	5.33	5.48	0.9
Total	**83601**	**81169**	**0**	**5.79**	**5.79**	**0.88**

Table 2: Calibrated model outputs – Key Performance Indicators

The model is centered (Global mean error is 0dB) with a very good standard deviation error (Global standard deviation error is lower than 6dB) and a very good correlation between measurement data and predictions (88%).

Note that the mean error dispersion is very low (about 1dB) which means that the model is quite stable across the whole calibration area.

Note that this CW model was not evaluated against real 2.1 GHz or 2.3 GHz SCAN drive test data and adapted accordingly, which usually consists in the second stage of the calibration process in order to slightly refine the calibration outputs.

3.4. Model Settings for Indoor Predictions

3.4.1. Introduction

Volcano URBAN model offers an indoor penetration method that predicts in-building received powers, adding **deterministic propagation losses in the outdoor environment** and **statistical propagation losses in the indoor environments**, simulating penetration through all building facades as well as through the building rooftop.

The indoor penetration is carried out in two different ways depending on the receiver location from the transmitter (Near area/Far area/Transition Area) and it relies on on 2 user-defined key parameters, which might be associated (with different values) to each building clutter.

- **Building loss (dB):** represents the attenuation when a ray penetrates inside the building (resulting from the exterior wall or rooftop)
- **Building linear loss (dB/m)**: represents the attenuation per meter when a ray propagates inside the building (resulting from internal partitions, furniture, etc.)

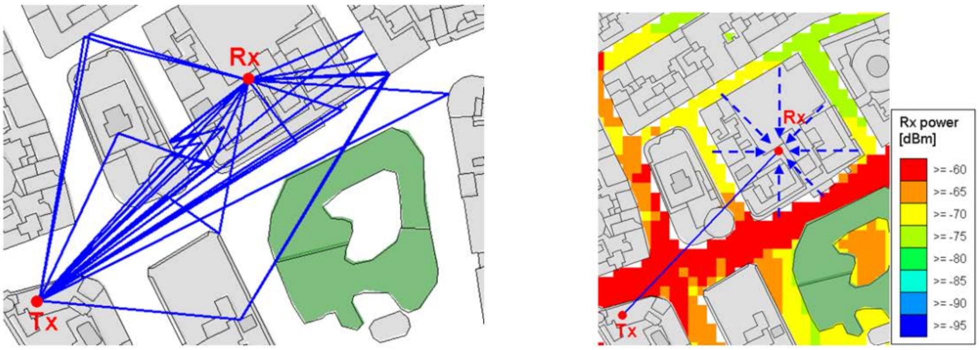


Figure 10: Outdoor to Indoor simulations(Near area from transmitters – left; far area from transmitters – right)

Note that Building losses and building linear losses are not set through an automatic calibration process based on measurement data. As mentioned in the previous section, model calibration considers outdoor measurement data and calibrates the RF propagation model parameters in order to get outdoor-outdoor predictions in line with measurement data. Building losses and building linear losses are usually user-set by experience, recommendations from the literature or specific measurement data that might have been handled to determine typical values.
Typically, Volcano URBAN model enables the user to simulate indoor in different manners as follows:

- **Outdoor-like levels**: Received powers predicted within buildings do not include any additional loss related to indoor penetration or in-building propagation
- **Indoor basic**: All received powers predicted within buildings include a regular additional loss (i.e. building loss) that can be either the same to all buildings or different according to the building type. It does not make the difference between light and deep indoor.
- **Indoor premium**: makes the difference between light and deep indoor.

Besides, note that Volcano enables to compute outdoor only, indoor only (as illustrated below for example) or outdoor + Indoor.

Figure 11: Indoor only prediction (only in-building areas are simulated)

3.4.2. Indoor Settings

As specified in the scope of work of the study, it is required to run simulations for 4 different scenarios mixing 2 different receiver heights – 1.5m and 5m – and two different types of simulations – outdoor everywhere and outdoor + indoor premium.

For indoor premium predictions, OFCOM fixed the values to be used for Building loss and building Linear loss as described below. Note that the values are the same for all building types in the geographical data.

Scenario	Receiver height (m)	Building Loss (dB)	Building Linear Loss (dB/m)
outdoor	1.5 / 5	0	0
indoor	1.5 / 5	6.9	0.6

Table 3: Volcano settings for indoor predictions

4. Simulations

4.1. Transmitters

Transmitter properties were provided by OFCOM in a excel file and included antenna location (Easting, Northing), antenna height above the ground, EIRP, Antenna type, azimuth and tilt. Original file counted about 300 cells but finally **260 cells were concerned** in the study since others were located outside the available 3D high resolution geo data.
Note that the small scale LTE network to be studied is based on the assumption of the most likely deployment of LTE base stations in London at 2.3 GHz.

4.2. Antennas

OFCOM provided SIRADEL with 5 horizontal patterns (33°, 45°, 62°, 65° and 70° beamwidth) and 2 vertical patterns (6° and 8° beamwidth). Antenna patterns were then created for the following configurations as mentioned in the base stations properties.

Antenna
H33V8
H45V8
H62V8
H65V6
H65V8
H70V6

Table 4: Antenna Configurations

Please refer to appendix for detailed illustrations of the corresponding patterns.

4.3. Outputs

4.3.1. Scenarios

8 scenarios of simulations were carried out as described in the table below.

Scenario	Coverage Array	Indoor \outdoor	Receiver height (m)
1	Downlink Received Power	Outdoor	1.5
2	Best Server Downlink Received Power	Outdoor	1.5
3	Downlink Received Power	Outdoor	5
4	Best Server Downlink Received Power	Outdoor	5
5	Downlink Received Power	Indoor	1.5
6	Best Server Downlink Received Power	Indoor	1.5
7	Downlink Received Power	Indoor	5
8	Best Server Downlink Received Power	Indoor	5

Table 5: Simulation scenarios

4.3.2. Arrays

For each scenario, Best server arrays are provided in mapinfo (*.TAB files) format and Received Power arrays are provided as ASCII grid (*.txt files) and Vertical Mapper (*.GRC and *.TAB files).

Note that Received power arrays are provided for two different RSRP ranges as follows:

- Range 1 = [-35dBm, -120dBm]
- Range 2 = [+20dBm, -120dBm]

In the next pages are shown the arrays corresponding to the range 1 which color legend is illustrated in Figure below.

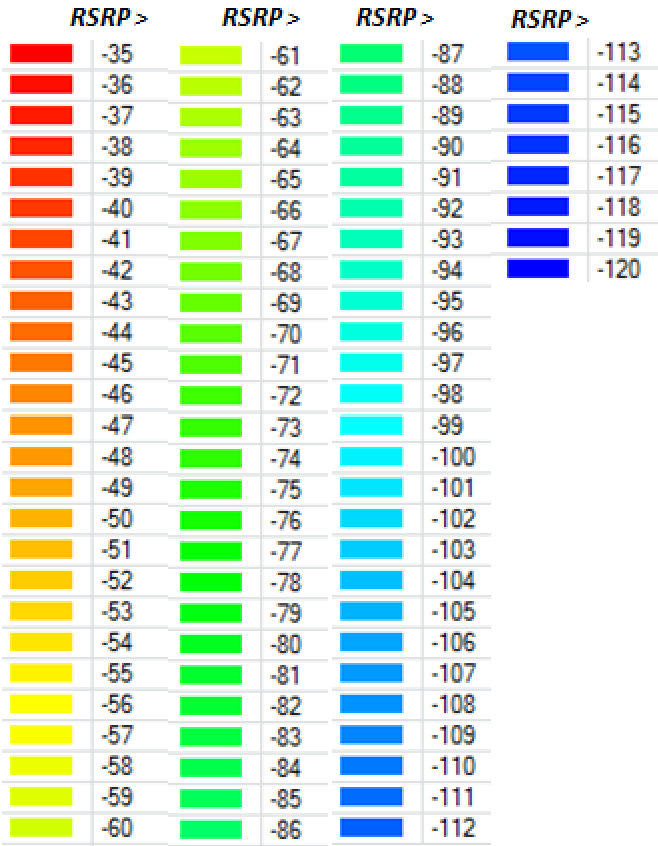


Figure 12: Received power legend (Range1)

4.3.2.1. Scenarios 1 & 2: Outdoor 1.5m

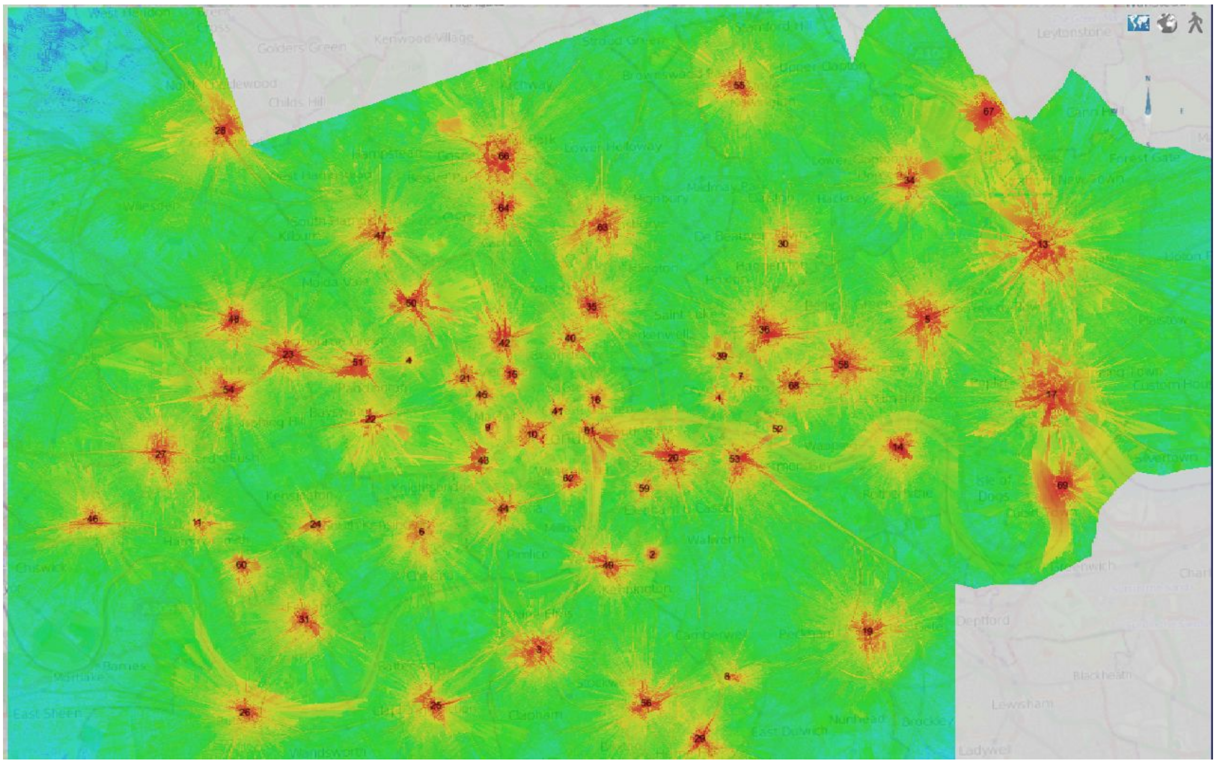


Figure 13: Received power array – outdoor 1.5m in Smart City Explorer™ by SIRADEL

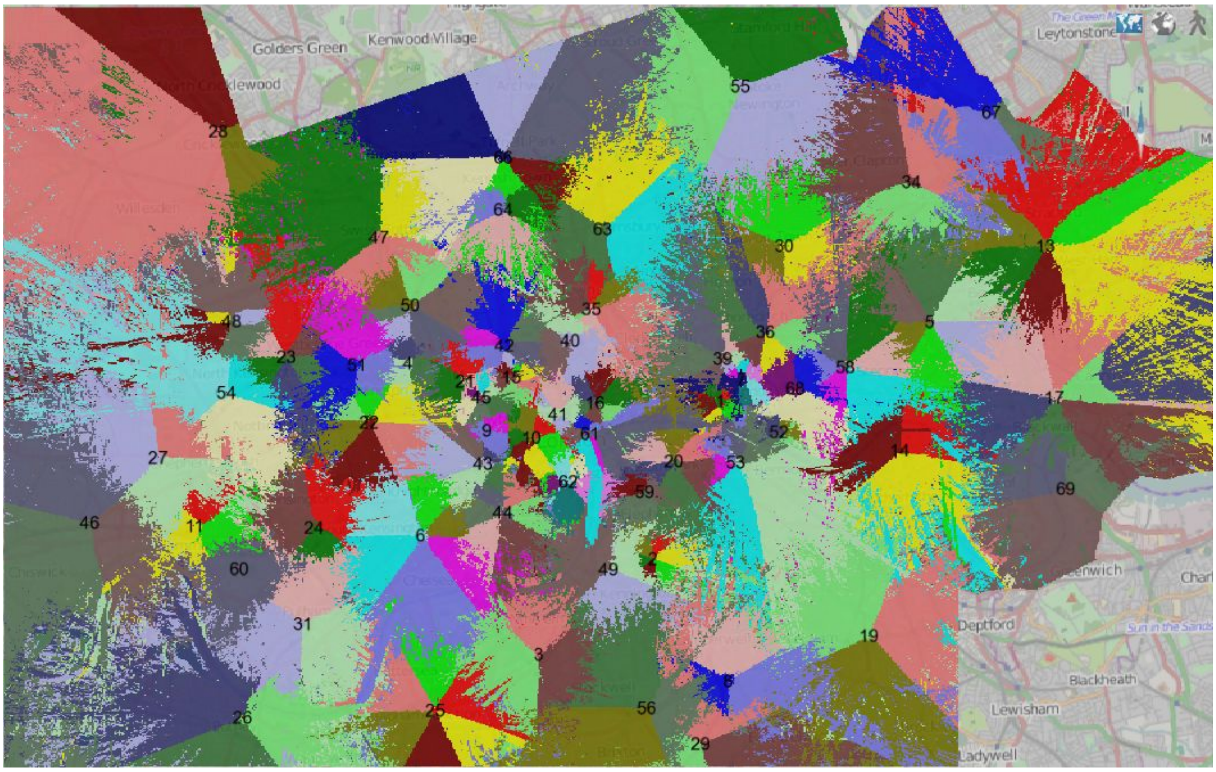


Figure 14: Best server array – outdoor 1.5m in Smart City Explorer™ by SIRADEL

4.3.2.2. Scenarios 3 & 4: Outdoor 5m

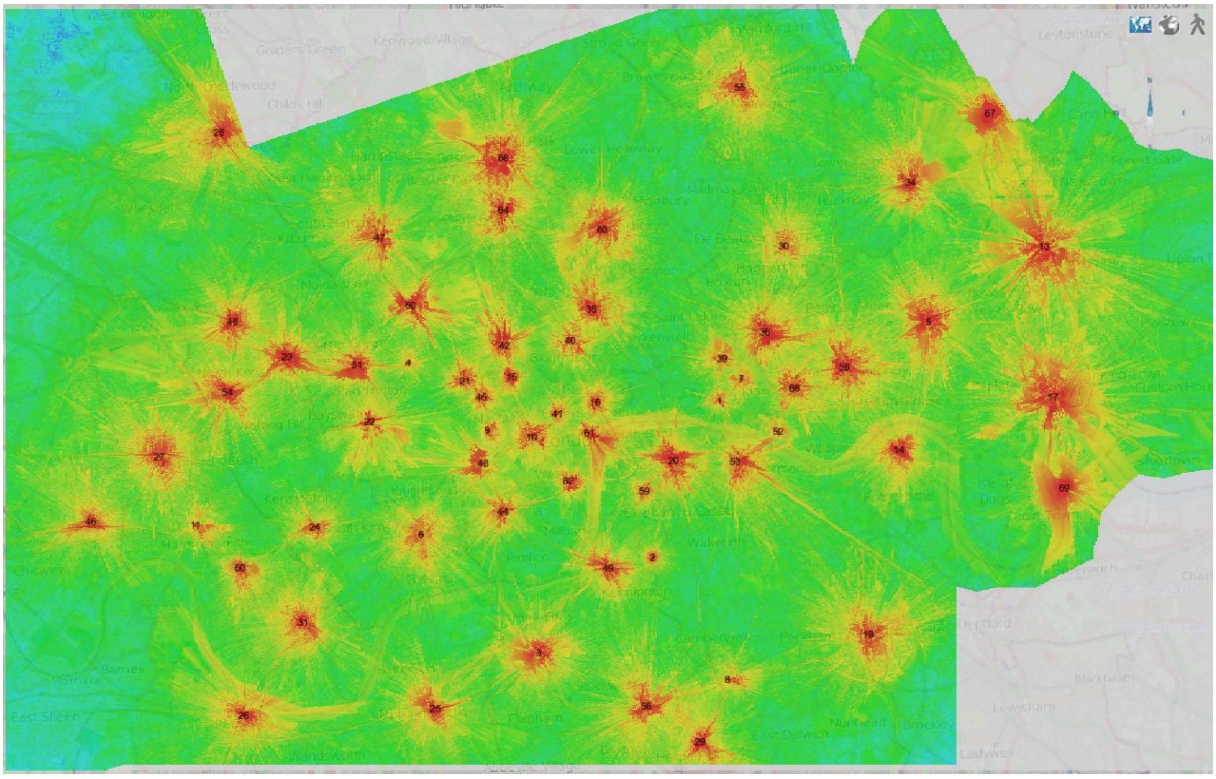


Figure 15: Received power array – outdoor 5m in Smart City Explorer™ by SIRADEL

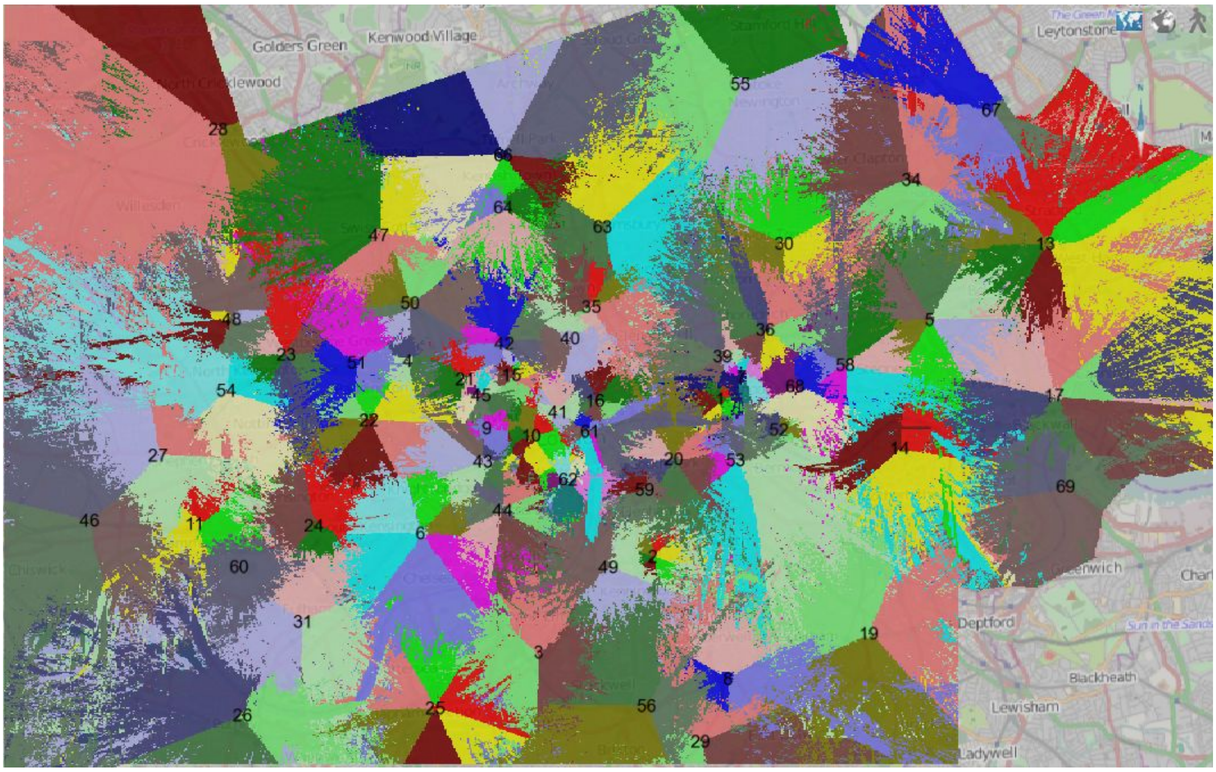


Figure 16: Best server array – outdoor 5m in Smart City Explorer™ by SIRADEL

4.3.2.3. Scenarios 3 & 4: Indoor 1.5m

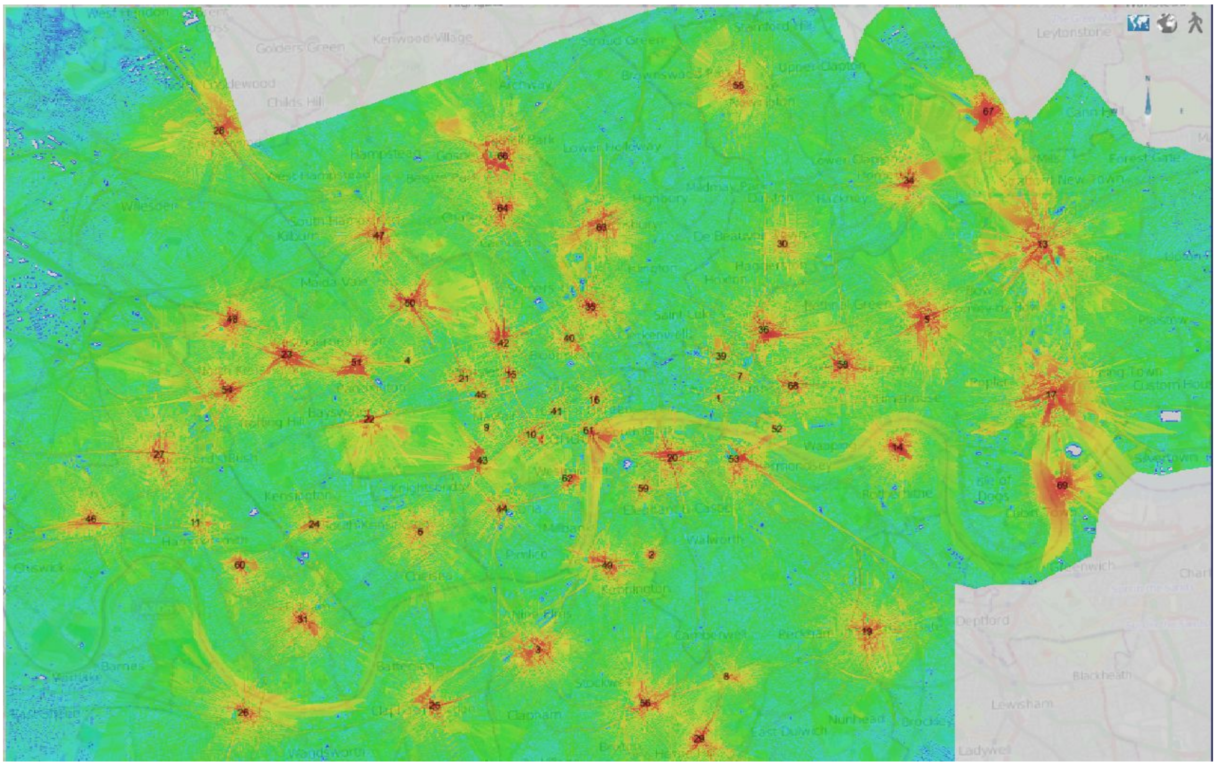


Figure 17: Received power array – Indoor 1.5m in Smart City Explorer™ by SIRADEL

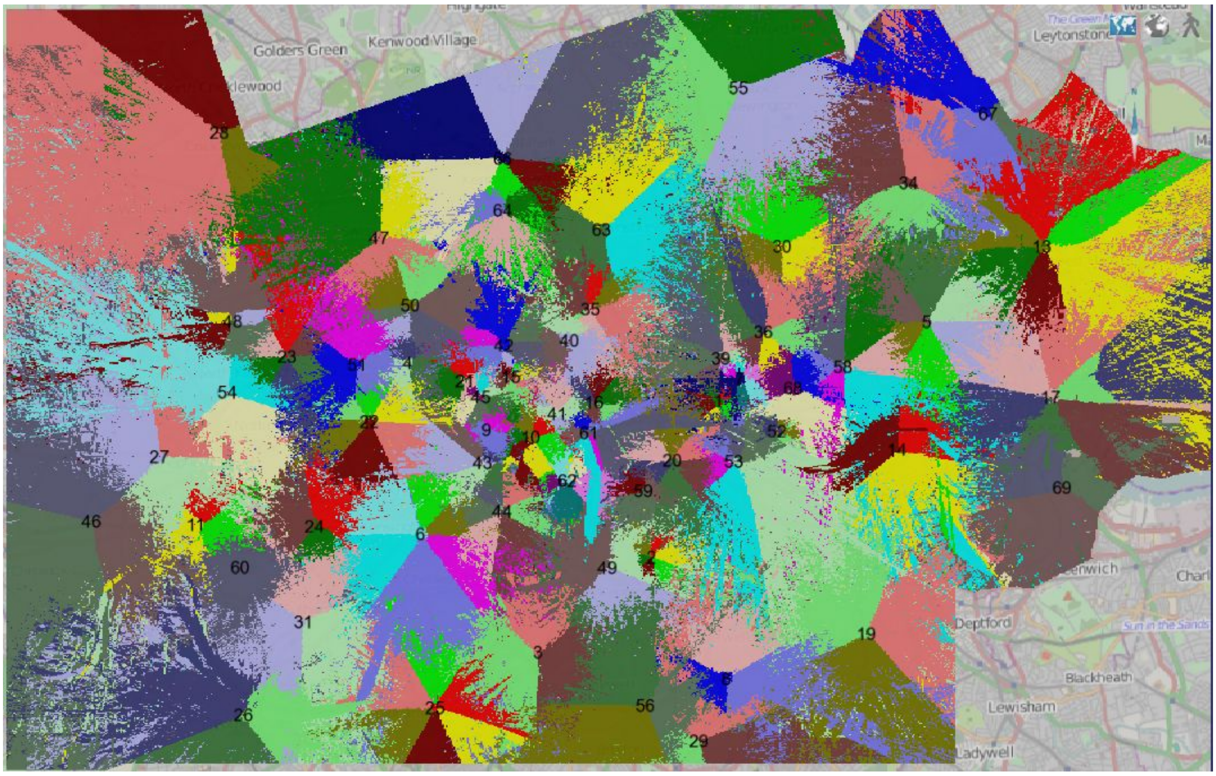


Figure 18: Best server array – Indoor 1.5m in Smart City Explorer™ by SIRADEL

4.3.2.4. Scenarios 3 & 4: Indoor 5m

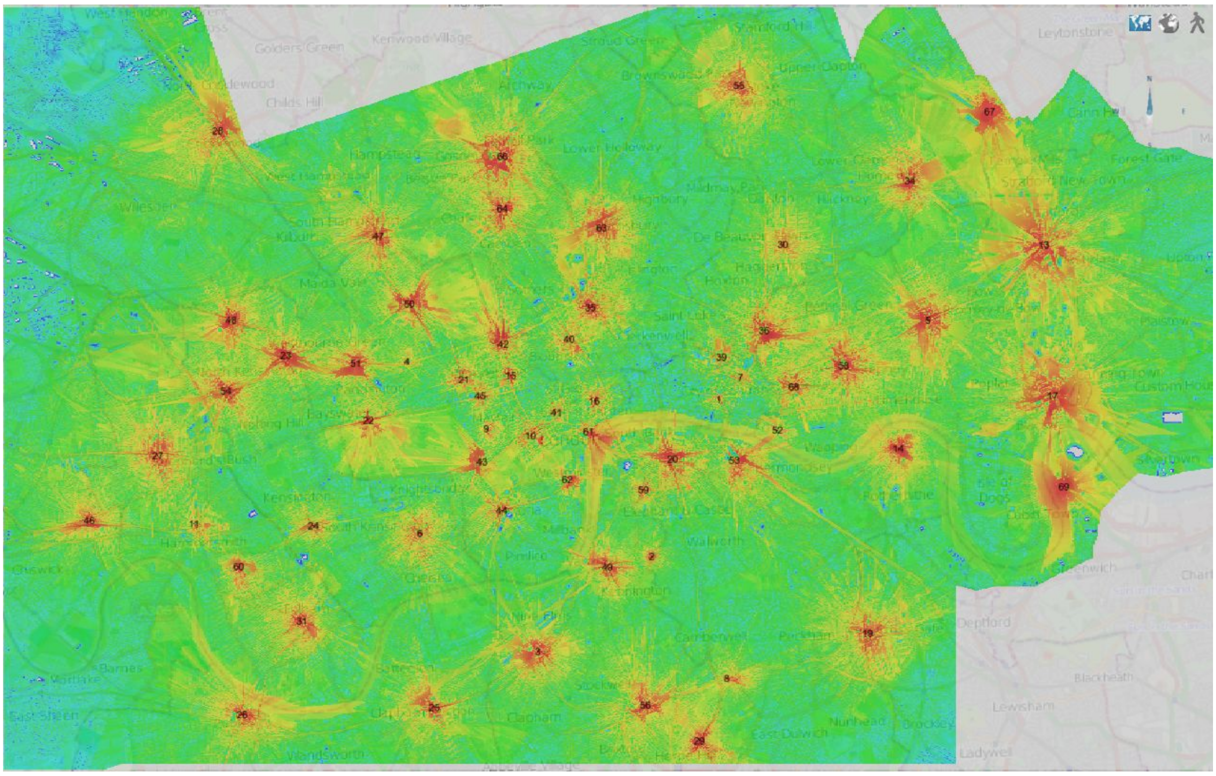


Figure 19: Received power array – in Smart City Explorer[TM] by SIRADEL

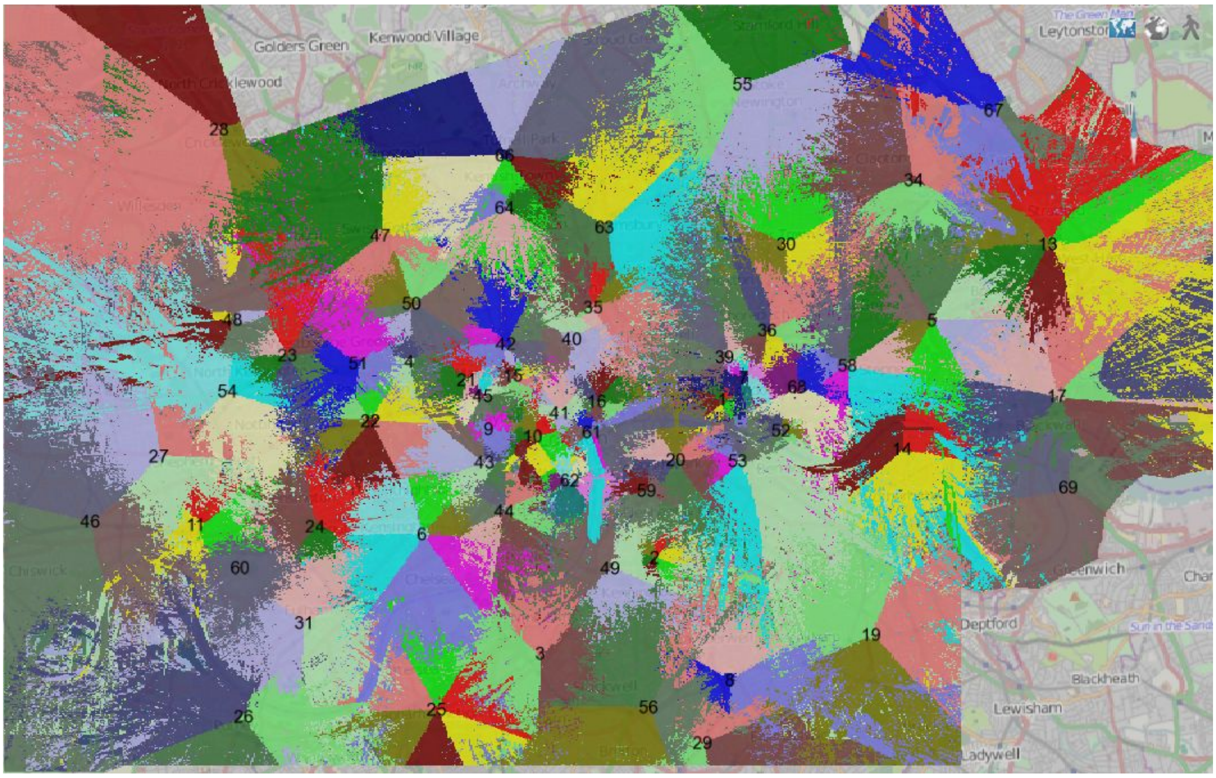


Figure 20: Best server array – in Smart City Explorer[TM] by SIRADEL

4.3.3. Signal Strength Statistics and CDF

For each scenario, coverage statistics for the “Best Server Downlink Received Power” arrays for both indoor and outdoor with receiver heights of 1.5 and 5 m have been provided in Excel files with respect of the categories (i.e. Best server Downlink Received Power ranges) and formats as per Table 7 and Table 8.

Category	Best Server Downlink Received Power (x dBm)
1	$-35 < x$
2	$-40 < x \leq -35$
3	$-45 < x \leq -40$
4	$-50 < x \leq -45$
5	$-50 < x$

Table 6: Signal strengths reporting ranges

Sector	Covered Area (sqkm)	Covered area per category (%)				
		1	2	3	4	5
A	4.1	20	30	10	5	35
B	...	...	...	...	...	...
C	...	...	...	...	...	...

Table 7: Distribution of signal strength per range and sector

As a complementary information, global indicators have been reported into Table 9. It includes for each scenario, the total best server areas in km² per category (i.e. per received power range) and the min, max and average best server area per cell within the whole study area.

Scenario	outdoor 1.5m	indoor 1.5m	outdoor 5m	indoor 5m
Total				
Total Best server Area (km²)	261,09101	260,68748	261,03589	260,74947
Total Best server Area - Cat 1 (km²)	1,13159	0,73857	1,49413	1,0653
Total Best server Area - Cat 2 (km²)	2,22215	1,62758	2,65694	2,01715
Total Best server Area - Cat 3 (km²)	3,26403	2,47520	4,13674	3,28977
Total Best server Area - Cat 4 (km²)	5,76059	4,50830	7,29558	6,00089
Total Best server Area - Cat 5 (km²)	248,71033	251,77097	245,4501	248,69011
per cell				
Max Best server Area (km²)	5,47277	5,42061	5,47198	5,43246
Min Best server Area (km²)	0,00676	0,00749	0,00644	0,00652
Mean Best server Area (km²)	0,38738	0,408017	0,40825	0,408001

Table 8: Global indicators per scenario

5. Conclusion & Perspectives

SIRADEL has been pleased to provide OFCOM for first time with services requiring the use of SIRADEL skills, data and tools combining GIS and RF expertise.

To meet with OFCOM requirements, SIRADEL proposed a comprehensive solution based on its off-the-shelf data and in-house simulation tools Volcano Lab and Smart City Explorer, leading not only to a study based on theoretical assumptions but on operational real-network use case.

SIRADEL used off-the-shelf CW measurement data collected in London in order to calibrate Volcano URBAN propagation model and better match with the project constraints (environment, transmitter topology, frequency…).

3D capabilities of the Volcano URBAN model combined with SIRADEL 3D high resolution London geographical data led to accurate and reliable simulations for the required scenarios, mixing outdoor-everywhere and outdoor-indoor distinction.

As an independent company in the telecommunication ecosystem, SIRADEL is being partnering more and more with regulators or administrations to act as RF expert in order to carry out evaluations, studies or audits.

SIRADEL expertise and solutions cover a wide range of applications and challenges such as Wireless HetNet multi-frequency multi-RAT simulations, EMF exposure, DVB-T/LTE interference, Wireless backhaul design, Small-cell design, Outdoor-indoor pilot pollution, In-building DAS design…

SIRADEL is very keen to collaborate with OFCOM on other studies or projects in the future.

Appendix 1 – Key Performance Indicators

Mean Error

For data samples, the mean is the sum of the data samples divided by the number of samples. The mean of a set of samples x_1, x_2, ..., x_n is typically denoted by $\bar{x}$. The mean is often quoted along with the standard deviation. The mean describes the central location of the data, and the standard deviation describes the spread.

The mean error $\bar{E}$ is therefore given by:

$$\bar{E} = \frac{\sum_{i=1}^{n} Ei}{n}$$

Where

Ei is the error for the i^{th} sample

n is the number of samples

Standard Deviation Error

The standard deviation shows how much variation there is from the average/mean. A low standard deviation indicates that the samples are close to the mean, whereas high standard deviation indicates that the samples are spread out over a large range of values.

The standard deviation of the error σ is given by:

$$\sigma = \frac{1}{n}\sqrt{\sum_{i=1}^{n}(Ei - \bar{E})^2}$$

Correlation

The correlation factor r_{PM} represents the correlation between both sets of samples, i.e. measurements and predictions.

$$r_{PM} = \frac{n\sum_{i=1}^{n} P_i M_i - \sum_{i=1}^{n} P_i \cdot \sum_{i=1}^{n} M_i}{\sqrt{n\sum_{i=1}^{n} {M_i}^2 - (\sum_{i=1}^{n} M_i)^2} \cdot \sqrt{n\sum_{i=1}^{n} {P_i}^2 - (\sum_{i=1}^{n} P_i)^2}}$$

Where
P_i is the i^{th} prediction sample
M_i is the i^{th} measurement sample

The correlation factor is +1 in the case of a perfect positive (increasing) linear relationship. The closer the coefficient is to +1, the stronger the correlation between both sets of samples (*P* and *M*). The correlation factor is 0 when there is no linear relationship between both sets of samples (*P* and *M*).

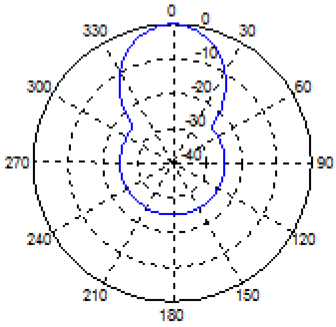
Mean Error Dispersion

The mean error dispersion ΔE is an additional statistical parameter used to evaluate the model accuracy. It is calculated as follows:

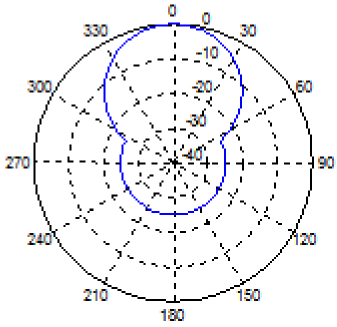
$$\Delta E = \frac{1}{\sum_K n_i} \sum_K n_i \times \left| E_i - E_{global} \right|$$

Where
K is the number of surveys,
n_i is the number of bins in the i^{th} survey,
E_i is the global mean error for the i^{th} survey,
E_{global} is the global mean error for all the surveys.

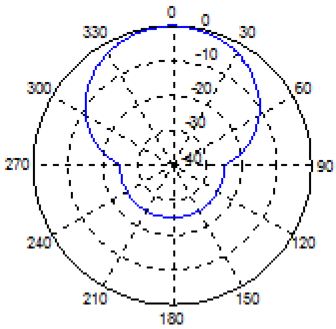
Appendix 2 – Antenna Patterns



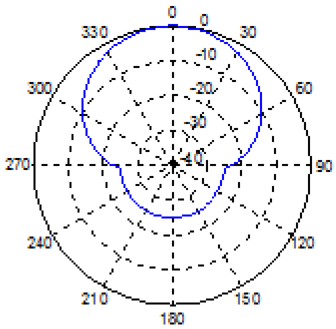
Horizontal pattern 33° BW



Horizontal pattern 45° BW

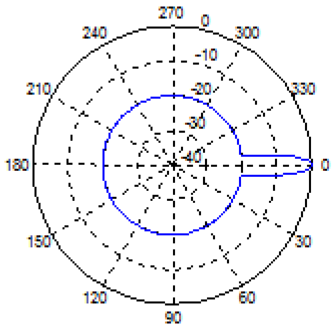


Horizontal pattern 62° BW

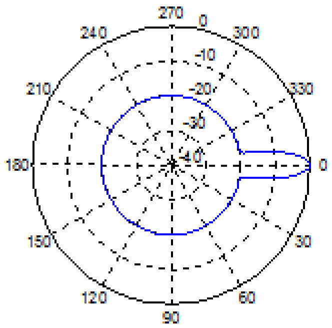


Horizontal pattern 65° BW

Figure 21: Horizontal antenna patterns



Vertical pattern 6° BW



Vertical pattern 8° BW

Figure 22: Vertical antenna patterns

Glossary

Downlink Received Power: Total received power at each pixel (*at underlying mapdata resolution*), contributed by all sources, including serving, non-serving sectors and thermal noise.

Best Server Downlink Received Power: Received power at each pixel (*at underlying mapdata resolution*) contributed by only the best serving cell and thermal noise. The Sector ID of the best server for each pixel should be recorded.