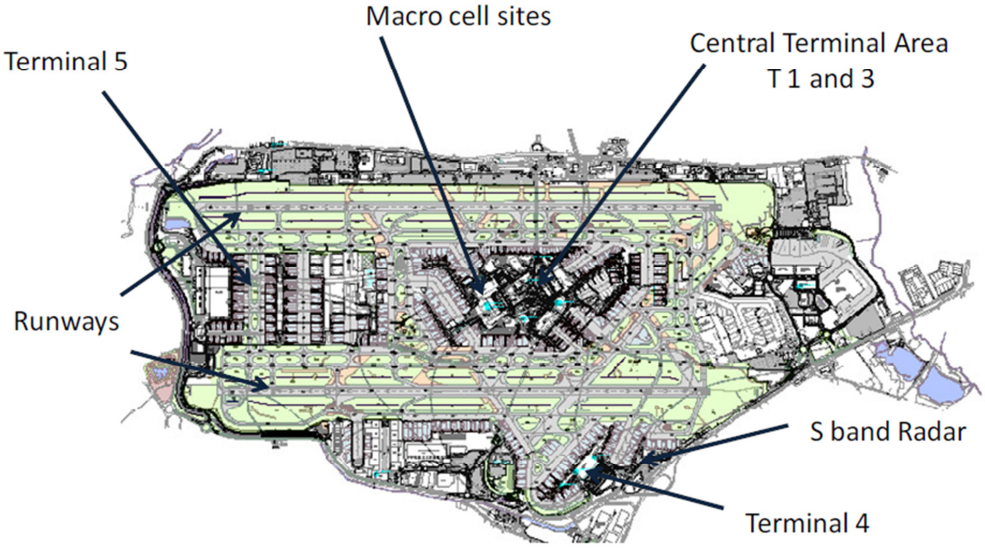
Final Report

Airport Deployment Study

Ref MC/045



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Contents

1 Executive Summary

This document represents the final report of Real Wireless' study of potential airport deployments of mobile broadband technology in the 2.6 GHz band and its potential interference impact on nearby radars operated in the 2.7 GHz band (also known as S-band). This is a deliverable on behalf of Ofcom within contract MC/045.

This document should be read in association with the Appendices document "Final Report Appendices - Airport Deployment Study" and the Addendum document to the final report "Phase 2 – Airport deployment study, impact to second modified radar design".

1.1 Study context

1.1.1 Ofcom has an on-going programme to minimise potential interference from 2.6GHz devices to S-band radar

Ofcom is intending to make a combined spectrum award, which includes the 2.6 GHz spectrum, to the market in Q1 of 2012 as announced in Ofcom's combined spectrum auction consultation of March 2011[1]. The 2.6 GHz spectrum is of importance to the development of next generation mobile services which can be used to offer, for example, mobile broadband via wireless technologies such as LTE and WiMAX. However, previous studies have shown that there is potential for devices deployed in the 2.6GHz band to cause interference to sensitive radar systems operated in the 2.7 GHz S-band radar band. This work forms part of Ofcom's wider radar upgrade program whose aim is to introduce modifications to the front end selectivity of S-band ATC radars deployed across the UK and thus help enable better co-existence between S-band ATC radars and 2.6 GHz systems.

1.1.2 This study focuses on the likelihood of interference to radar in a practical deployment based on London's Heathrow airport

This study into 2.6 GHz deployments at airports defines the interference environment that exists in the neighbourhood of an S-band (2.7 – 2.9 GHz) Air Traffic Control (ATC) radar to determine the impact of different 2.6 GHz deployment strategies. In contrast to previous work in this area, this study includes consideration of the practical deployment situation around airports, using London's Heathrow Airport as an exemplar, and includes the impact of both base stations and mobile stations operating in a mix of indoor and outdoor environments. Where there is scope for interference, potential mitigation techniques are examined for their efficacy and practicality. The study informs

[1] Ofcom Consultation on assessment of future mobile competition and proposals for the award of 800 MHz and 2.6 GHz spectrum and related issues, 22 March 2011

the Government's on-going radar remedial programme, which is modifying ATC radars to improve their selectivity. The analysis relates to the performance expected from radars after completion of this remedial programme.

Specifically it was important for this report to address and determine how practical 2.6 GHz deployments could co-exist with modified S-band radar receiver designs using the most relevant and current data available.

This final report captures the effects of blocking[2] and noise rise from both base stations and mobile stations into one particular radar design which is a generic modified radar[3] based on actual receiver design characteristics. Mobile emissions were characterised based on levels derived from 3GPP standards.

The behaviour of mobile emissions into the radar receiver was of particular interest due to the uncontrolled nature of mobile use and the potential close proximity that roaming mobiles can have to the radar. The addendum to this report (see document "Addendum to Final Report – Airport Deployment Study, impact second modified radar design") captures the effects of noise rise from the measured emissions of an LTE FDD mobile device into another radar design to provide a confidence check on more than one airport radar type. Measurements of a commercially available LTE FDD mobile device performed by RFI Global Service Ltd were used to characterise mobile emissions from a realistic 2.6 GHz device into the S-band. A representation of the emissions from this particular device was incorporated into the model and analysed to determine what level of interference it causes to both types of radar receiver.

1.2 Key findings and recommendations

1.2.1 Our results show that interference from 2.6GHz devices is unlikely to be an issue at airports under realistic deployment conditions

Heathrow Airport was used as a key case study of a challenging but real-world environment for the deployment of 2.6 GHz systems, such as LTE and WiMAX mobile broadband networks. Our study found that interference to S-band radar from both base stations and mobile equipment at 2.6GHz is manageable but will require mitigation action to cover worst case deployment scenarios. Base stations and mobile stations operating indoors produced less interference due to the attenuation

[2] Definition of blocking is the signal level that would cause the loss of radar performance due to a mechanism such as target compression, intermodulation and other effects
[3] In this study a generic modified radar represents a typical ATC radar receiver design that is modified to the new improved front end filter selectivity levels as specified by Ofcom

from building penetration losses and therefore caused a reduced impact to the radar by a margin of up to 14 dB.

The following key findings form the fundamental outcome of the study:

Key finding 1: A commercially available 2.6 GHz LTE FDD mobile device can co-exist with two types of S-band radars when deployed in an environment such as Heathrow airport without any additional emission restrictions

Key finding 2: 2.6 GHz base stations will need some level of coordination and practical site engineering applied when deployed at a principal airport such as Heathrow to ensure satisfactory co-existence with S-band radars

Key finding 3: Further synthesis of base stations, mobile stations and radar parameters were necessary to establish the corner cases that could impact upon normal operations of S-band radars in an airport environment

The analysis proceeded via simulations and assumed a generic radar, modified to provide improved selectivity. Two interference conditions were modelled in this environment a *challenging case* and a *typical case* (parameters detailed in section 10). The *challenging case* conditions include assumptions such as low radar towers and high base station transmit powers. The *typical case* is aimed at covering the majority of realistic deployments and what is more likely to occur in practice. In the *challenging case* this represents the more difficult deployment corner cases which are still feasible but less likely to occur in practice.

The study results indicate that when deploying 2.6 GHz **base stations** at airports exemplified by our case study:

- Under *typical case* conditions no blocking of the radar receiver occurs at any point in the receive chain. The radar noise rise is also kept below the maximum threshold I/N level of -5 dB except for 1% of time[4] when the radar antenna points in the direction of the highest interference. These short bursts of interference can be mitigated by careful planning of mast height and antenna orientation of base station deployments.
- Unde*r challenging case* conditions the radar may be affected by both blocking and a rise in noise. Under these conditions, the impact can be managed by careful planning of the 2.6 GHz equipment. In our analysis we found that a combination of careful planning of antenna orientation, power control the base station when in the radar main beam, improving spurious emissions and applying a coordination zone of 660m for outdoor deployments

[4] The 1% of time refers to point in time when the radar is directed towards the highest level of recorded interference over the horizontal beamwidth of the radar

(reduced to 120m for indoor deployments) was required to bring both blocking and the rise in noise floor to within acceptable levels.

We also examined the impact of **mobile equipment** on radar performance. The results in this case showed:

- In the *measured case* using emission levels based on a commercially available FDD LTE mobile device, mobile devices did not cause blocking or noise rise to occur at the radar receiver. There was 57 dB margin between the 3GPP emission limit and the measured spurious emission of the mobile device
- However, when we introduced an artificially generated spurious emission appearing on the centre frequency of the radar, the results showed that if the emission level exceeds -32 dBm/MHz (in the case of radar 1) and -39 dBm/MHz (in the case of radar 2) this will exceed the acceptable noise threshold limits in the radar receiver, but is 57 dB (max) higher than the measured level.
- Under *typical case* conditions no blocking of the radar receiver occurs. The radar noise rise is kept to an acceptable level except for 1% of time when the radar antenna points in the direction of the highest interference. These short bursts of interference generated by spurious emissions are close to the acceptable noise rise threshold limits and will depend on the quality of the mobile equipment being used.
- Under *challenging case* conditions the radar may be affected by both blocking and a rise in noise. In our analysis we found that a combination of applying a coordination zone and reducing the spurious emission levels relative to current specifications was required to bring both blocking and the noise rise due to mobile equipment to within acceptable levels.

The findings are summarised in the following table:

	Challenging Case	**Typical Case**
Base Station	*Impact:* • Blocking occurs and I/N threshold exceeded. *Mitigation:* • Careful planning of antenna orientation • Upgrade installation to power control the base station when in the radar main beam • Adhere to a significantly improved spurious emission mask (24dB improvement suggested over current limits) • Apply a coordination zone *Suggested coordination zones*: • Base stations may be deployed outdoors at distances greater than	*Impact:* • Blocking levels not exceeded. I/N threshold marginally exceeded but only for 1% of the time the radar points in the direction of the highest interference source. *Mitigation:* • Careful planning of mast height and antenna orientation at base station deployment

	660m from the radar if combined with the other suggested mitigation options listed above. This increases to 1km if no extra mitigation action is taken. • Indoor base stations may be deployed at distances greater than 120m from the radar if the suggested reduction in spurious emissions is also applied.	
Mobile Equipment	*Impact:* • Blocking occurs and I/N threshold exceeded. *Mitigation:* • Adhere to a significantly improved spurious emission mask (26dB improvement suggested over current limits). • Apply a coordination zone *Suggested coordination zones*: • Mobile stations may be deployed outdoors at distances greater than 300m from the radar if used in combination with suggested reductions in spurious emissions. • Mobile stations may be deployed indoors at distances greater than 70m from the radar if used in combination with suggested reductions in spurious emissions.	*Impact:* • Blocking levels not exceeded. I/N threshold just exceeded but only for 1% of the time the radar points in the direction of the highest interference source. *Mitigation:* • Ensure good quality handsets with low spurious emissions as interference is already close to an acceptable level

Table 1-1 – Summary of findings

1.2.2 There is a range of mitigation techniques that could be applied to 2.6GHz equipment which would make interference at airports manageable even in the most challenging deployments

In the absence of specific mitigations, there are circumstances in which interference due to blocking and noise rise can be significant. Although these circumstances are fairly unusual and may not represent typical deployments, there remains a risk that a particular deployment may exhibit behaviour closer to the *challenging case* than the *typical case*. For example, under different deployment conditions such as a lower radar height, or a radar channel much closer in frequency to the 2.6 GHz band compared to the generic modified radar, or mobile stations having higher spurious emissions than those assumed.

In order to ensure that any individual deployment has an acceptably low risk of causing interference over the whole range of its operating conditions, a number of mitigation techniques were proposed and investigated for their efficacy and practicality.

Base station interference mitigation techniques

Table 1-2below shows the outcome of applying various mitigation techniques to reduce the level of interference from base stations. The final column indicates how the mitigations impact on the performance of 2.6 GHz deployments. The mitigation techniques that demonstrated the best improvement for the base stations were the improved spectrum emission mask and the optimised antenna orientation. These two particular mitigations showed the greatest improvement by a margin and maintained a low impact to the performance of the 2.6 GHz networks.

Although most of the individual mitigations could still result in interference in some cases, mitigations 4, 5, 6 and 7 as shown in Table 1-2were combined to reduce the interference levels to negligible amounts.

No.	Mitigation technique	Parameter value without mitigation	Parameter value with mitigation	Improvement in I/N when the radar points at the angle of BS 8 (BS 8 is situated 1 km from the radar)	Improvement in I/N when the radar points at the angle of BS 1 (BS 1 is situated 50m from the radar[5])	Impact on 2.6 GHz deployments
1	Reduced EIRP	63 dBm/ 20MHz	57 dBm/20 MHz	6 dB	6 dB	6 dB in reduced EIRP is translated into 25% availability of resources
2	Antenna downtilt	6°	10°	9 dB	9 dB	The coverage area reduces to 16% of its original size
3	Antenna height	20 m	15m	3.2 dB	30.4 dB	The coverage area reduces to 53% of its original size
4	Antenna orientations	0, 120,240° 0 deg = East	12 dB max attenuation	8.4 dB	8.4 dB	100% availability of resources
5	Power control the BS transmitter as radar sweeps past BS	63 dBm/20 MHz	-107 dBm/5MHz	3.1 dB	30.5 dB	99% availability of resources
6	Improved OOB/Spurious	-13 dBm/MHz	-37 dBm/MHz	24dB	24 dB	100% availability of resources

[5] The improvement to mitigations were captured at two locations from the radar to determine the dominating effects (at BS 1) and comparison metric at a second fixed distance away (BS 8)

	emissions (EIRP)					
7	Coordination zone	N/A	600 - 700m	-2 dB	45.1 dB	The area covered reduces to 84% of its original size
8	Combined mitigations 4-7			41.6 dB	63.5 dB	The area covered reduces to 83% of its original size

Table 1-2 Results of mitigations applied to reduce interference from base stations

The efficacy of any given mitigation should be balanced against the cost and other impact on the relevant network deployment, as indicated in Table 1-3.

No	Mitigation	Impact to 2.6 GHz deployments	Estimated cost to 2.6 GHz deployment
1	Reduce EIRP levels of BS	May require up to four additional low power sites to maintain the same level coverage/capacity	Four times base station build at up to 100,000 GBP a site *if coverage limited*.
2	Improve unwanted spectrum emission mask	May require the addition of high specification cavity filter which would mean additional cost per site	Cost of cavity filter and installation up to £500 - £1000 per transmitter
3	Optimise antenna orientation to lowest gain facing radar	Adjustment to antenna orientation will not only impact coverage to the network but will affect the re-use pattern adopted to surrounding sites which could mean extensive on-going optimisation to an operators network	Cost neutral. Site specific engineering would be included at the point of installation
4	Increase downtilt of antenna	Adjustment to antenna downtilt will have an impact on the coverage of the network which may require the addition of fill in sites to cover the shortfall	Cost neutral. Site specific engineering would be included at the point of installation
5	Lower antenna height	Adjustment to antenna height will have an impact on coverage and require more power to compensate	Could require additional sites to maintain coverage.

6	Move base station further away from radar	Will impact on coverage and capacity to area being served and require additional sites	Cost of re-installation and commissioning plus cost adjustment relative to new site
7	Power control the BS transmitter as radar sweeps past base station	Estimated percentage of capacity reduction between 0.4% and 0.8%. This would be negligible to users of the network	Cost neutral (once developed) but currently only theoretically possible. Site specific engineering would be included at the point of installation. Requires an implementation of a method to detect when the radar is pointing at the BS.

Table 1-3: Summary of impact to 2.6 GHz base station deployments

The following deployment recommendations are proposed as a result of the conclusions found from this study.

1. Extending the -45 dBm/MHz EIRP limit of the Ofcom specified Block Edge Mask from 2720 MHz to 2750 MHz and above to protect radar frequencies beyond those specified by Ofcom
2. Coordination and collaboration with the airport authority. It is anticipated that as part of the planning of new mobile communications networks that coordination and collaboration between the airport operator and the mobile network operator will be necessary for the deployment of 2.6 GHz networks. Findings from this report can inform the approval procedures of 2.6 GHz networks at airports.
3. Airport operators to implement a coordination zone around their radar for the deployment of 2.6 GHz base stations dependent on the layout and specific deployments. It is recommended that operators seeking to deploy base stations within the coordination zone, which can start from 660m for outdoor base stations, would need to further reduce the values such as EIRP or use lower antenna heights and other mitigations as appropriate on a site-specific basis
4. Implementation of a high specification filter for the base stations located within the airport perimeter to meet the desired limits specified in section 11.2.1
5. Careful selection and design of base station locations taking into account the typical case conditions used for modelling as a benchmark for further study and analysis
6. Optimisation of the antenna pattern with the lowest gain of the pattern pointing towards the radar
7. Adoption of alternative deployment strategies, for example, operators limit 2.6 GHz deployments indoors and mobiles can roam to an alternative spectrum band when outdoors.

Mobile station mitigation techniques

Table 1-4 shows the outcome of applying various mitigation techniques at the mobile station to reduce the level of noise interference. The final column indicates how the mitigation would impact on the 2.6 GHz deployment.

No.	Mitigation technique	Parameter value without mitigation	Parameter value with mitigation	Improvement in I/N when the radar points at the worst interference	Impact on 2.6 GHz deployments
1	Cap maximum EIRP	23 dBm	20 dBm	~0 dB	83% of the users are unaffected
2	Coordination zone (outdoor /indoor users)	No coordination zone	70m I/D 300m O/D radius around radar	4.4 dB	The coverage area reduces to 97% of its original size
3	Improved OOB/Spurious emissions (EIRP)	-30 dBm/MHz	-56 dBm/MHz	26 dB	Dependent on quality of components used by vendors but could be additional cost if there is a need to satisfy any strict emissions mask 100% availability of resources
4	Additional low power BS located in highest interference area	12 BSs	13 BSs	~0 dB	Additional site cost no detrimental impact to service
5	Cap number of users on 2.6 GHz network around airports	53 simultaneous users (100%)	44 simultaneous users (83%)	1.2 dB	83% of the users are unaffected, the rest served by another band OR reduced throughput for 100% of the users

Table 1-4 Results of mitigations applied to reduce interference from mobile stations

The efficacy of any given mitigation should be balanced against the cost and other impact on the relevant network deployment, as indicated in Table 1-5.

No	Mitigation	Practical value range	Impact to radar	Impact to 2.6 GHz deployments
1	Cap maximum EIRP of mobiles	20 dBm	Reduces overall interference power from mobiles into radar	Will require intervention from operators but at a technical and operational level. Will limit availability of network resources such as capacity and throughput but only in certain areas, on certain sectors to a limited number of mobiles
2	Coordination zone around the radar	150m – 500m	Reduces overall interference power from mobiles in close proximity to radar	Requires restricted use of phones near to radar that may be costly and complex to implement. Could be a managed function by airport authority such as via BAA's electronics communications approval process.
3	Improve the OOB/Spurious emission mask	-56 dBm/MHz	Reduces interference noise power into receiver	May require regulatory intervention and development could be time consuming. Possibly difficult to implement due to mass production of handsets for global market and difficulty of controlling access to only compliant user devices
4	Introduce coupled antenna from a BS into area of worst mobile interference, direct sector towards mobiles and away from radar	Variable MS EIRP	Reduces power of mobiles connected to the base station due to reduced pathloss which will lower overall interference power to radar	Will require some additional engineering from the operators perspective and a risk the base station antenna will increase the interference to radar

Table 1-5 Summary of impact to 2.6 GHz mobile station deployments

The following deployment recommendations are proposed as a result of the findings from the investigation of interference generated by mobile stations within an airport environment.

1. The introduction of an outdoor and indoor coordination zone around the radar. The simulations found that a 300m outdoor coordination and a 70m indoor coordination zone are sufficient to reduce interference to below the threshold for each mechanism. For smaller coordination zones parameters such as EIRP and building penetration loss must be investigated in detail for the particular airport.

2. Appreciation of the typical case conditions used for modelling as a benchmark for further study and analysis of the interference within an airport environment. For example the activation of power control for the uplink with appropriate parameters was found to help reduce the interference levels into the radar.
3. Identify the range of out-of-band and spurious emissions produced by commercial mobiles and re-model using the measured data. This will establish more firmly the degree of additional mitigations which will be needed to ensure operation within the threshold limits of interference and can co-exist in an airport environment.

1.2.3 Further investigation into the viability of suggested mitigation techniques would confirm they are pragmatic, commercially viable and suitable for other airport deployments

Further investigation into the viability of some of the suggested mitigations would help confirm their suitability in a practical airport deployment. The following suggestions have been made on that basis:

- Understand the coordination procedures with the relevant airport authorities, as many different deployment parameters can materially affect the interference performance of 2.6 GHz base stations in and around airports[6].
- Analysis of the power control feature of a base station that could offer the potential reduction in interference power as the radar rotates passed the base station
- A catalogue of the radar heights at other UK airports would help ensure suitable coordination zones are established where necessary.
- Commercial and technical factors in site sharing should be reviewed as suggested mitigations applied by the airport owners could include the restriction on the number of base stations transmitting from a single site.
- Spurious emission measurements of a wider selection of mobile device types, such as smartphones, tablet PC’s and laptops to determine their behaviour in the S-band.

[6] These are specified in Section 8.

Ofcom's on-going work/studies

Ofcom has other scoping studies in progress that complement the work of this study including:

- Measurements campaign of the unwanted emissions of base stations and mobile devices to address the reality of LTE and WiMAX equipment performance of spurious and out-of-band emissions. Specifically, results from the measurements of an FDD LTE mobile device were used to inform part of the modelling of mobile emission behaviour
- Radar design and selectivity studies which quantify the improvement in front end filter selectivity for each of the airport radars. Each radar manufacturer will design its filter to maximise selectivity and minimise blocking. The addendum to this report includes analysis of a second modified hypothetical radar design which captures a second representative set of filters that could be deployed at an airport.

1.3 *Our approach and assumptions*

1.3.1 Our approach

The study used software modelling to assess the interference mechanisms caused by 2.6 GHz systems into a modified radar receiver operating in the S-band. The interfering effects analysed included:

- Blocking[2] to the front end of the radar receiver from high power in-band emissions, potentially causing false target identification and confusion with valid targets
- A rise in noise powers co-channel with the radar centre frequency from out-of-band and spurious emissions of 2.6 GHz systems, degrading the sensitivity of the radar receiver and thus its usable range.

The main steps of the study were as follows:

- Determining network deployment scenarios and associated technical parameters which are likely for 2.6 GHz operation around airport environments, taking particular account of inputs received from stakeholders such as mobile operators, equipment vendors and BAA.
- Creating and validating a simulation environment suitable for assessing the relevant interference mechanisms over the full set of scenarios, and accounting for interference from both multiple base stations, with some from shared sites and multiple active mobile stations.
- Conducting simulations for the different network deployment scenarios.
- Assessing the potential radar interference levels based on both extreme cases and overall statistical behaviour.
- Determining mitigation techniques which could reduce the impact of potential interference while being practical to apply without undue restriction on 2.6 GHz operation.
- Examining the efficacy of the most promising mitigation techniques via simulation and evaluating their potential impact on network services and costs of implementation.

1.3.2 Scenarios and assumptions analysed

There is a wide and varied range of parameters which impact on potential interference so the simulations included the study of three main cases for the various parameters modelled:

1. A *challenging case* where parameters are set to represent an extreme situation where interference to a radar might occur. Whilst such a case is, in principle, possible within the airport environment and consistent with a 2.6 GHz licensee's technical conditions, it is unlikely to occur in practice. This case consists of 13 base stations at distances ranging between 50m and 1674m and mobile stations at a density consistent with levels of usage which could occur in the airport environment. Spurious emissions are assumed to be at the relevant specification limits. Mobiles are assumed to be transmitting at full power.
2. A *typical case* where parameters are set to represent a plausible, though high-capacity, practical deployment. This case consists of 13 base stations at distances ranging between 50m and 1674m and mobile stations at the same density as in the challenging case. Spurious

emissions are assumed to be at levels significantly below the specification limits based on expectations from practical equipment and consultation with vendors. Mobiles are assumed to be power controlled by the serving base stations.

3. A *measured case* where measurements, conducted to determine the behaviour and performance of emissions in the S-band from an LTE FDD mobile device, were used for modelling the impact from the spurious emissions, co-channel with the radar receiver whilst all other parameters remained the same as the typical case.

The incidence of interference was judged based on the following conditions and metrics:

Conditions:

- When the power at particular points within the radar receiver exceeded thresholds specified by Ofcom as likely to cause 1 dB compression within the radar receiver sub-systems
- When the total power caused the radar receiver noise floor to increase, producing a carrier to noise ratio lower than a threshold between the example range-5 dB and -15 dB.

Metrics:

- The metric used for evaluating the results of the interference from base stations and mobile stations was the peak level which refers to 1% time the radar points at the worst interferer (i.e. ~0.01% of the time overall). This means the highest levels of interference are captured when the main beam of the radar antenna points at the highest interferer. This also suggests that lower (30 dB) levels of interference point towards the radar antenna sidelobes but at an attenuated level.
- Result metrics below 1% of time should be adjusted by adding maximum 5 dB for 0.1% and adding maximum 12 dB for< 0.01% time for systems with variability such as mobile. In contrast for base stations, due to little variability, only 1 dB is added for percentage time below 1%

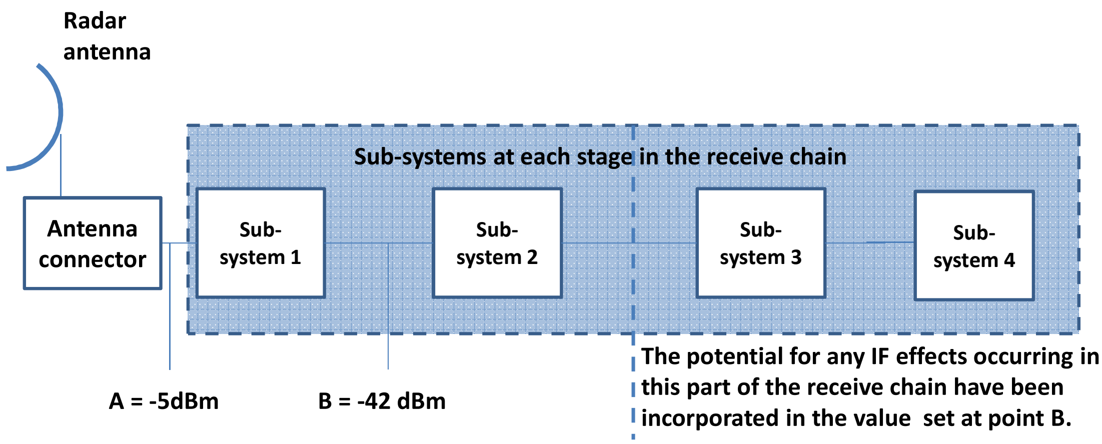


Figure 1-1 Example of modified radar receiver block diagram

The radar parameters are modelled as those applicable to a generic modified radar with an example shown in Figure 1-1at the same location as the current ATC radar at Heathrow and using a frequency of 2750 MHz. This is a hypothetical deployment but is based on composite design analysis and physical deployments and therefore constitutes a receiver that could potentially be deployed in practice. The analysis focused on 2.6 GHz mobile systems causing excessive blocking in the receiver at point A and point B and excessive I/N across the receiver bandwidth. The second hypothetical radar design that was used to model spurious emissions from mobile devices can be found in the addendum document ("Addendum to Final Report Phase 2 - Airport Deployment Study, impact to second modified radar design").

1.4 *Study results in detail*

1.4.1 Analysis of interference from base stations into radar

The analysis examined two types of layout environments for the base stations. 1) A layout representing the Heathrow airport environment, 2) a synthetic layout representing base stations at equidistant intervals from the generic modified radar. The two layouts were used to establish the extent of interference from base stations with the synthetic layout used to further analyse the required mitigations. The *challenging case* which could in principle occur in practice but is relatively extreme was used in both layouts, while the *typical case,* which is considered more realistic, was used in the Heathrow layout only. Both layouts consist of 13 base stations at distances ranging between 50m and 1674m from the radar.

The typical case results for the Heathrow layout showed no blocking occurs from base stations since the highest blocking level recorded did not exceed the – 5 dBm threshold level due to more realistic network deployment parameters being used. In addition, the signal level recorded at the input to the LNA (point B) was attenuated by 40 dB due to the modified front end radar RF filter. Some noise rise did occur and exceeded the minimum I/N threshold level (-15 dB) by 8 dB and the ITU I/N level (-10 dB) by 3 dB. The highest level of interference under typical case conditions came from the closest outdoor base station situated 660m from the radar.

The findings from the analysis of the base station to radar interference (see Table 1-6 and Table 1-7) showed the following results under the *challenging case* conditions without mitigations on the highest interferer:

Interference type	Heathrow layout	Synthetic layout (Outdoor)	Synthetic layout (Indoor)
Signal level at A 1% time (dBm) (Threshold -5 dBm)	4.9	16.9	0.3
Noise rise with respect to radar noise level 1 % time (dB)	37	47.8	32

Table 1-6 Summary of findings for blocking and noise rise of the radar by base stations without mitigations included

Challenging case conditions with combined mitigations on the highest interferer

Interference type	Heathrow layout	Synthetic layout (Outdoor)	Synthetic layout (Indoor)
Signal level at A (dBm) (Threshold -5 dBm)	-41.8	-39	-34.5
Noise rise with respect to radar noise level (dB)	-35.9 dB	-16.7 dB	-26.7 dB

Table 1-7 Summary of findings for blocking and noise rise at the radar by base stations with mitigations included

Comparing the two tables above shows the impact applying mitigations has to the highest interferer. In each case a significant reduction in the interference levels for both blocking and interference noise rise into the radar receiver is observed. This suggests under the *challenging case* conditions the radar would suffer from blocking effects from the first limiting point after the antenna connector if no mitigation action is taken.

Interference generated by the out-of-band and spurious emissions into the radar pass band causing a rise in noise across the receiver bandwidth exceeded the maximum threshold limits (I/N = -15 dB) under *challenging case* conditions. The levels recorded under *challenging case* conditions showed an interference noise rise of 37 dB into the receiver from the base stations which would significantly desensitise the receiver. However, if the mitigation options suggested in this report are applied this noise rise can be reduced to acceptable levels.

1.4.2 Analysis of interference from mobile station into radar

The findings from the analysis of the mobile station to radar showed that under the *challenging case* conditions blocking did not occur at any point in the radar receiver. The interference levels recorded at point A and point B did not exceed their respective threshold levels. Table 1-8 shows the blocking level at point B and noise rise for each of the scenario cases.

Interference type	Challenging case	Typical case	Measured case (flat response)
Signal level at B (Threshold -42 dBm)	-64 dBm	-93.5 dBm	N/A
Noise rise with respect to radar noise level (dB)	24.2 dB	-9.3 dB	-58.6 dB

Table 1-8 Summary results for mobile station blocking and noise rise of the radar receiver without mitigations included

It is interesting to note that blocking of the receiver did not occur at point A of the receiver as was found in the case of the base stations which suggests the aggregate power from multiple mobiles do not cause blocking at the front end of the receiver under the challenging case conditions. This is likely due to the frequency separation between the 2.6 GHz highest frequency uplink channel (2610 MHz) and the centre frequency of the generic modified radar (2750 MHz) being 140 MHz and the lower EIRP of the mobiles compared to base stations.

Using the measured spurious emission levels from the LTE FDD device in the model showed a flat response across the S-band at a peak spurious level of -87 dBm/MHz, which resulted in no effective increase in noise to the radar receiver. However, our initial investigation of interference into the radar pass band using emission levels at the 3GPP specification limit caused an unacceptable rise in noise across the receiver bandwidth which was exemplified under challenging case conditions.

In contrast, using our assumed emission level of -50 dBm/MHz, the interference was reduced by 33.5 dB which exceeded the ITU interference threshold (-10 dB) by less than 1 dB, this was exemplified under typical case conditions.

Clearly therefore, the results which produced the most positive (and potentially most important) outcome were those that were based on the practical measured emission values. In this case, the interference probability was significantly reduced compared to the typical and challenging cases for both blocking and noise rise in the radar receiver from 2.6 GHz mobile devices. This suggests that one particular commercially available 2.6 GHz LTE mobile device can co-exist with S-band radars when deployed within an airport environment without restrictions.

We highlight the following factors (apart from the modification to the radar receiver) that contribute to the reduction in interfering signal arriving at the receiver in the typical case compared to the challenging case:

1. **Activation of power control from the mobile** – If base station parameters are appropriately set, then mobile stations having a low path loss to their serving base station will be reduced in power significantly. This will also be impacted by the location of the base stations relative to the radar.
2. **Use of realistic noise estimated spectrum emission mask** – 2.6 GHz equipment, in the case of mobile devices have shown reduced spurious emissions of around 50 dB below the standard specification limits within the radar band**.** Therefore the assumed margin used for the typical case which was 20 dB below the specification limit into the radar band was conservative in comparison to the realistic value.
3. **Increased radar height –** Increasing the radar height has the effect of limiting the opportunity of interference to be captured in the main beam of the radar. As the height increases, so does the horizontal distance beyond the radar at which the main beam intersects the ground, thereby increasing the path loss to mobiles most likely to affect the radar.

Overall results with combined mitigations for 1% of the time that the radar points at the highest interferer were as follows.

Interference type	Mitigated case
Signal level at B (Threshold -42 dBm)	-98.8 dBm
Noise rise with respect to radar noise level (dB)	-17.7 dB

Table 1-9 Summary results for mobile station blocking and noise rise of the radar receiver with mitigations included

The results shown in the table above give the interference levels generated after applying the combined mitigations of a coordination zone and improved spurious emission levels in the challenging case.

In the case where interference was marginal and close to the threshold such as noise rise from mobiles in the typical case. We illustrated the impact percentages of time below 1% would have on the radar, which showed an additional 6 dB of extra interference at 0.01% and below. Under typical case conditions this means the noise rise with respect to the radar noise level is within the ITU (-10 dB) threshold level thus still enabling the unrestricted use of mobiles at airports.

1.5 Acknowledgements

The authors would like to thank the stakeholders who provided input to this study, particularly BAA, who provided details of the physical layout of Heathrow airport and the associated mobile infrastructure.

2 Introduction

Ofcom, CAA, MOD, MCA and other interested parties have been investigating the compatibility issues of emissions from mobile communications systems operating in the 2.6 GHz band into radar receivers operating in the upper adjacent 2.7 GHz band. Results that have been produced from a previous study[1] have identified the specific mechanisms that could cause critical degradation to the performance of Air Traffic Control radars and derived the associated protection criteria. In addition, field and laboratory trials have been conducted on behalf of Ofcom, to demonstrate the different effects on the different categories of radar. The results have shown that for a number of different scenarios the required protection distances estimated range from 1km within an urban environment up to more than 40km for a rural environment. These estimations were conducted for a range of different transmit and receive heights depending on those found within each environment.[2]

The compatibility work that has been conducted contributes to the overall radar remedial work programme which supports wider Ofcom policy. Ofcom under its statutory obligations and EC mandate under EC Decision 2008/477/EC (the "2.6 GHz RSC Decision") must make the 2.6 GHz spectrum available via award to the market in a timely manner. In advance of the spectrum award the technical licence conditions must be produced and regulations made which can be included in the new licences that will be awarded. The outcome of the airport deployment study will inform the development of technical conditions for 2.6 GHz deployments in and around airports potentially resulting in restrictions such as reduced EIRP, coordination zones and modified antenna patterns. These conditions could be applied in the licenses, or else in the form of agreement and approval process between stakeholders.

The extensive work already undertaken by Ofcom and other stakeholders has resulted in the generation of radar protection criteria as part of the technical conditions for the proposed spectrum licence award[3] and overall safety case. These have been incorporated in the analysis presented here.

This study focuses on interference from both base station and mobile station emissions into the adjacent radar band and investigates the various deployment scenarios and practical network configurations of technologies such as LTE and WiMAX which are likely to be operated in the 2.6 GHz band.

Specifically the modelling includes:

- detailed analysis of multiple base station deployments in and around airports
- different scenarios representing mobile usage and densities

- interference environment including propagation characteristics and clutter
- practical mitigation strategies from both a mobile operator, airport operator and radar operator perspective

The focus of this study is on the performance after application of the remedial work, rather than unmodified radars.

2.1 Airport deployment study

Ofcom initiated the radar remedial programme to address the modification of the radar receiver front end for those operating in the S-band and deployed at airports throughout the UK. This extensive programme includes a number of scoping studies each investigating the different areas of concern, one of which is the airport deployment study.

The intention of the airport deployment study was to focus on the mobile network deployments for LTE and WiMAX at airports, understand the authorisation processes of deployment of electronic communications equipment at airports and the types of mitigation strategies that can be practically and cost effectively applied to both the base stations and mobile stations to reduce interference to an acceptable level.

The basic scope of the study was to develop a fully modelled mobile communications network that could take into consideration all the necessary parameters of a 2.6 GHz mobile network which could simulate interference in a practical scenario in close proximity to a radar. Following the initial analysis suitable mitigation techniques could be applied to demonstrate any improvement to the interference situation.

2.2 Structure of report

This report is structured to address the findings of the study in a clear and logical way and describe how the main tasks have been tackled and analyse the effects of interference from base stations and mobile stations into radar receivers. The main chapters include:

Chapter 2, this **Introduction**, presents the main concepts of the airport deployment study and highlights the work which has previously taken place

Chapter 3, **Background and scope** describes the background of the study in more detail including a description of the interference mechanisms that are to be investigated, the focus on analysis of the modified radar receivers and importance of emissions from multiple interferers.

Chapter 4, **Characteristics of 2.6 GHz equipment** describes the findings from desk research of commercially available 2.6 GHz equipment from both LTE and WiMAX vendors.

Chapter 5, **Stakeholder engagement** describes the findings from stakeholder engagement including the views from operators and vendors with an interest in 2.6 GHz spectrum and also from BAA the airport authority for six UK airports including Heathrow Airport.

Chapter 6, **Interference analysis modelling** describes the methods for analysing the interference and the choice of modelling approach taken for the study.

Chapter 7, **Parameters** introduce the key input technical parameters used by the software model and describe the simulation assumptions made in order to develop the modelling environment.

Chapter 8, **Model overview** presents an overview of the software model and describes how the model works at a simplistic level.

Chapter 9, **Model outputs** describes how the modelling outputs such as graphs and plots are presented and explains what the outputs mean to the overall study.

Chapter 10, **Interference results without additional mitigation** presents results from simulations of base station and mobile station emission interference to radar with no mitigation techniques added.

Chapter 11, **Interference results with mitigation** presents results from simulations of base station and mobile station emission interference to radar with mitigation techniques added.

Chapter 12, **Conclusions and summary recommendations** describes the conclusions from the findings and provides a summary of recommendations.

Chapter 13 and 14 provide a glossary and full references respectively. A separate set of appendices[7] provides further technical details of the parameters used in the study.

[7] "Final Report Appendices Airport Deployment Study"

Figure 2-1 outlines the logical structure of the report.

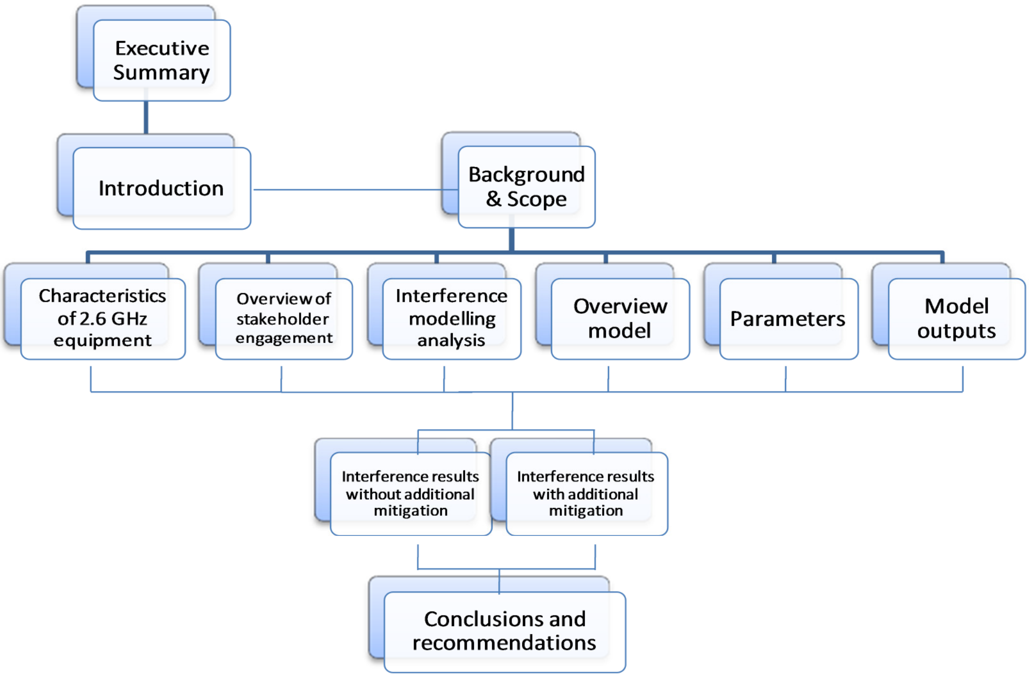


Figure 2-1 Structure of final report

3 Background and scope

3.1 Background

Ofcom would like to determine the potential impact of LTE and WiMAX emissions on radar receivers operating in airport environments. Specifically, the investigation is into interference:

- from LTE and WiMAX base stations, handsets and other user devices transmitting in the 2.5-2.69 GHz band
- to radar receivers operating in the 2.7-3.1 GHz band.

Previous work conducted by Ofcom[4] has been extensive including a study to assess the impact of 2.6 GHz transmissions on ATC radars. The modelling assumptions used to estimate the interference power levels input to the radar receiver are representative of a generic modified ATC radar created for the purposes of modelling, which whilst being representative in a generic sense does not represent any specific radar.

The aggregate impacts on ATC radars estimated by Ofcom focused on the potential for macrocell base station transmitters having a transmit EIRP 61 dBm and a 30m antenna height to determine the extent of the coordination area around the radars. The estimations were based on the impact to the Watchman ATC radar which is the predominant ATC radar used in the UK.

This investigative work has led to the development of modified filtering applied to the radar receiver chain. For example, to improve the selectivity of the front end of a generic modified radar there is a requirement for an additional RF filter in front of the LNA. This would improve the selectivity and thus reduce the level of received interference from in band 2.6 GHz emissions.

The aim of this study is to investigate the performance of only the modified radar which at this stage is based on a generic modified design prior to the development of any commercially available ATC radars. Therefore this study addresses the impact of interference to the upgraded radars and focuses on the mitigations from 2.6 GHz equipment that reduce the interference levels.

This study extends the previous work in the following ways:

- Incorporating the actual physical and operational characteristics of key airport environments.

- Accounting for the interference potential arising from user devices (handsets, 'dongles', mobile internet devices etc.)
- Incorporating the impact of base stations deployed in indoor and other environments as well as macrocells.
- Examining the impact of the detailed specifications and likely operating parameters of practical equipment including measured spurious emissions of a commercially available mobile device.
- Examining the reduction of interference potential arising from the installation of the proposed filters.
- Assisting Ofcom to develop the technical licence conditions for awarding the 2.6 GHz spectrum and stakeholder to develop arrangements for mutual coordination where necessary.

The mechanisms that have been identified to cause interference to radar receivers by transmitters in the 2.6 GHz band are:

1. Blocking of radar receivers from in-band base station emissions
2. In-band interference from base station out-of-band and spurious emissions
3. Blocking of radar receivers from in-band mobile station emissions
4. In-band interference from mobile station out-of-band and spurious emissions

These mechanisms are illustrated in Figure 3-1.

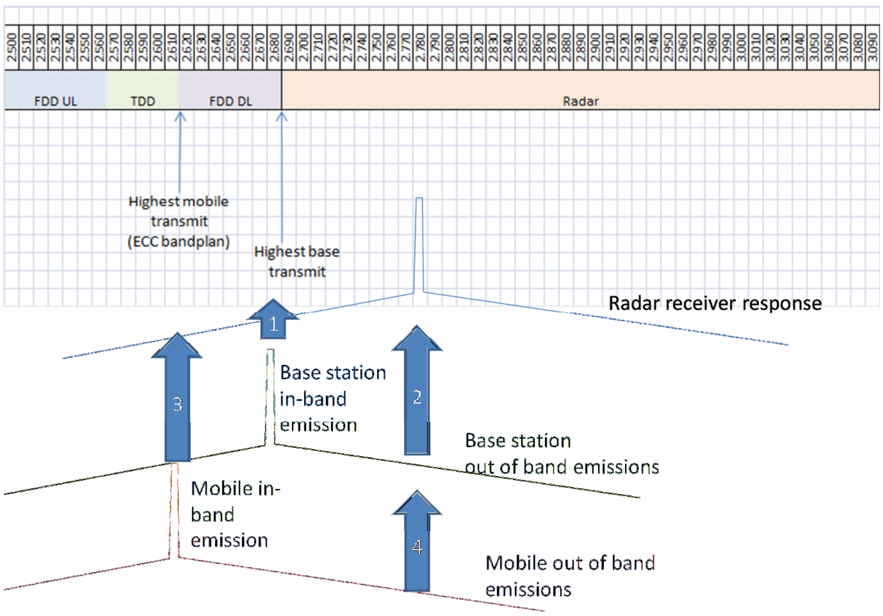


Figure 3-1: Main interference mechanisms

Mechanisms 1 and 3 can be mitigated by improved filtering of radar receivers, but this will not help with mechanisms 2 or 4. This study has investigated all 4 mechanisms and determined the efficacy of the filtering mitigation in realistic airport scenarios and evaluated additional mitigations to assist with challenging conditions for all 4 mechanisms.

It should be noted that the limiting case of interference from individual mobile transmissions will occur for mobile use at the top end of the unpaired 2.6 GHz spectrum (i.e. at 2.62 GHz assuming the ECC bandplan), which may be used by either WiMAX or TD-LTE mobiles. However, FDD LTE mobiles transmitting up to 2.57 GHz may be more numerous and contribute a larger aggregate interference level.

3.2 Scope of study

The scope of the study was to create a software model that could perform simulations of the different interference scenarios applicable in an airport environment. They type of simulation required the development and creation of the transmission characteristics of the base stations and mobile stations for both in band and out of band emissions, the inclusion of the OFDMA specific peak to average power ratio for the simulated signals and the antenna geometry for both the base stations and the radar.

In addition the software included the creation of the airport environment to be modelled based on a particularly busy London airport layout which required the construction of specific features in and around the airport such as all the buildings and roads in the Central Terminal Area, plus the buildings and roads around the terminal which is in close proximity to the radar.

The model structure was created based on a collection of parameter assumptions gathered through desk research and engagement with stakeholders and the use of appropriate interference calculations capturing all relevant effects at each point in the environment. The simulations were carried out by applying different deployment scenarios that would either trigger interference in the radar receiver or not. An assessment could then be made of the impact from a 2.6 GHz deployment before commencement of the mitigation strategies.

The simulations took into account the main technical parameters which are significant in setting the interference levels. Firstly the emissions from both the base stations and mobile stations required the model to enable the adjustment of certain parameters, including:

- EIRP
- Antenna height of the radar and base stations
- Antenna tilt
- Power control
- Propagation model
- Spectrum emission mask

Secondly, the rotation of the radar and the radar antenna pattern were modelled to ensure all possible interfering effects were captured. Developing the modified radar receiver characteristics required a number of different generic representative filters in the receiver chain to establish the entire receiver selectivity from the front end to the limiting amplifiers. In addition, assumptions were made regarding the radar antenna patterns, for example a synthetic antenna pattern was derived for the side lobes of the horizontal pattern, to ensure a smooth roll off of attenuation occurred rather than a sharp cut-off.

The parameter information gathered was from a variety of sources but mainly from the specifications of commercially available equipment, technical parameters from mobile field trials, real-world mobile device emission measurements, specification limits from equipment standards and the regulatory conditions as specified in various Ofcom published material.

Specific attention was paid to the out of band and spurious emissions which can cause co-channel interference on the radar centre frequency occurring as a rise in noise over the receiver bandwidth. In particular the production of the spectrum emission masks which were used for the different scenario cases and the real world emission measurements from a single FDD LTE mobile device as an exemplar.

The information relating to the radar technical parameters was mainly developed and obtained from Ofcom, with the specific parameter values being based on material provided by Ofcom for a generic modified radar. This information was used to determine the receiver characteristics of the modified radar with the newly designed front end filters applied. Other information regarding the radar receiver includes:

- Receiver bandwidth
- Radar antenna pattern
- Radar antenna gain
- Radar noise floor

Once all the input parameters, assumptions and calculation functions were defined the model was constructed. The software model was designed to incorporate the necessary calculations to evaluate the interference and enable different deployment scenarios to be simulated and introduce the different mitigation techniques. Furthermore, Monte Carlo analysis was built into the software model to account for the random nature of the deployment of mobile stations within the airport area and enable the production of cumulative distribution functions for the results as a form of output.

The deployment scenarios contribute to the evaluation of the impact from each of the potential situations that could occur for a practical network deployment in the 2.6 GHz spectrum band and within an airport environment. The main assessments that have been considered for this study include:

- Multiple base stations in proximity to the radar both indoor and outdoor
- Multiple active mobiles in use in proximity to the radar both indoor and outdoor

For each of the scenarios a more detailed analysis was conducted that examined a *challenging case* scenario followed by a more *typical case* deployment scenario that is likely to occur in an airport environment. Once an assessment for each of these scenarios was complete, a set of mitigation techniques was identified and applied to the model to determine the improvement to the overall interference generated from both base stations and mobile stations. Establishing the mitigation techniques assisted with understanding further the improvements required to reduce interference and what specific actions need to be taken in relation to base station and mobile station characteristics. The mitigation techniques were then compared to determine their efficacy and impact on the mobile network cost and performance.

The outputs of the study present the results from the interference modelling of the base station and the mobile station in terms of percentage time of interference occurring against a threshold level for either blocking the different parts of the radar receiver or exceeding the specified threshold I/N levels. The assessment was conducted for both in band blocking and co-channel interference from out-of-band and spurious emissions and for simulations without mitigation and simulations with mitigation. The results show a comparison of the extent to which both the base station and mobile station produce interference into the radar receiver and how this relates to the overall increase in allowable interference and ultimately demonstrates the overall impact of introducing 2.6 GHz networks in an airport environment.

4 Characteristics of 2.6 GHz equipment

Advances in wireless technology have seen impressive developments in the production of mobile communications equipment. Most recently the developments in wireless standards such as WiMAX and LTE which have chosen to adopt novel spectrum access techniques such as OFDMA for improved spectrum efficiency and flexible allocation of network resources. This airport deployment study has focused on these next generation or (loosely, '4G') technologies which will likely be deployed in the 2.6 GHz spectrum. Although 2.6 GHz was originally intended as a capacity enhancing expansion band for 3G technology, there is little commercial support for this so will not be investigated in this study. The study has investigated the emissions performance of the equipment so that an in depth analysis of the realistic scenarios can be evaluated. Sources of information have included desk research of the relevant base station and mobile station specifications and also direct engagement with stakeholders.

The following section addresses the technologies that will be deployed in 2.6 GHz band, the performance of transmission equipment and their practical constraints.

4.1 LTE and WiMAX equipment

The candidate radio technologies that are most likely to be deployed in awarded spectrum at 2.6 GHz are going to be LTE or WiMAX technology or some mixture of the two. Already WiMAX deployments are being rolled out in markets across the world at 2.6 GHz with a maturing equipment portfolio. In addition LTE pre-commercial deployments at 2.6 GHz have been launched which provides supporting evidence of these technologies to be deployed in the UK.

The 2.6 GHz band was designated an IMT band at WRC 2000 for mobile terrestrial services at which point regulators, operators and vendors started referring to it as the 3G expansion band and expected 3G services to be deployed. In more recent years LTE and WiMAX have been identified as candidates for deployment in the 2.6 GHz band. Both technologies include the band as one of those supported by the relevant standards bodies (3GPP for LTE and IEEE/WiMAX Forum for WiMAX).

WiMAX technology has seen an increasing number of deployments appear around the world in recent years due to an early to market strategy and technology choice in OFDM in TDD mode. WiMAX has taken advantage of the flattened network topology, which means fewer nodes in the overall network architecture, and IP based infrastructure as a competing technology in the mobile broadband market. However, the technology has had some issues to overcome specifically in the areas of hard handover and high speed mobility due to the legacy of WiMAX, which was originally intended for wireless DSL or last mile replacement and not intended for mobile broadband.

In terms of numbers of deployments and time to market WiMAX is clearly ahead of LTE. The WiMAX Forum states that WiMAX has over 560 network deployments worldwide out of which 112 deployments use 2.6 GHz spectrum[5]. A significant proportion of the deployments are in the Asia Pacific region however, more deployments are emerging in developed markets such as the US, Korea and Italy.

Although LTE has been at an earlier stage of development than WiMAX, it is gaining momentum and already there are showpiece deployments of LTE in the 2.6 GHz band. For example, TeliaSonera deployed the first commercial LTE network in Stockholm, Sweden in December 2009[8] which demonstrates the pace at which LTE standards development has been set. Also Verizon[9] and AT&T [10]in the US have chosen to deploy LTE using their 700 MHz spectrum across their network to compete with Clearwire[11] which is rolling out WiMAX across the US in the 2.6 GHz band. It is possible that in the future Clearwire will also deploy TD-LTE technology[12], and they have proposed that the 3GPP LTE specification supports TDD across the whole 2.6GHz band rather than purely the central unpaired 50 MHz sub-band as is presently the case.

Furthermore, LTE is based on the 3GPP family of standards which has significant support from an operators' upgrade path perspective. It is very likely those operators that have adopted the use of 3GPP systems such as UMTS/HSPA will naturally upgrade their network to LTE which also supports backwards compatibility[6] from LTE to HSPA. The benefits to operators are likely to outweigh any decision to adopt a non-3GPP technology and therefore likely to be the dominant technology deployment within the FDD portion of the 2.6 GHz band.

The table shown in appendix F in the Appendices document provides a non-exhaustive list of vendor equipment for both WiMAX and LTE equipment available on the market. The table includes best product information available based on the manufacturers' technical specification such as maximum output power, modulation and coding scheme and bandwidth. The first commercial products to

[8]http://www.teliasonera.com/News-and-Archive/Press-releases/2009/TeliaSonera-first-in-the-world-with-4G-services/
[9]https://www.lte.vzw.com/AboutLTE/VerizonWirelessLTENetwork/tabid/6003/Default.aspx
[10]http://gigaom.com/2008/04/03/open-access-restrictions-may-have-undervalued-spectrum/
[11]http://www.clearwire.com/
[12]http://www.clearwire.com/

market typically include limited features and can perform closer to the specifications, with features[13] added and performance improving over time as newer generations of each model is introduced. The information in this table has been used to inform the modelling parameters to ensure the typical scenarios take account of the practical limitations of current equipment types.

4.2 Equipment performance statistics

This study has researched the performance of the emissions from mobile communications equipment designed to operate in the 2.6 GHz band. The two key parameters investigated in this research were the out-of- band emissions and spurious emissions of the equipment. It is these emissions that can cause interference as a rise in the noise floor of the radar receiver which is fundamental to the interference analysis.

In general poor emissions performance can be related to equipment who's OOB and spurious emissions operate close to the specification limits in terms of causing co-channel interference into the radar receiver pass band.

Typically manufacturers design their equipment to meet the minimum requirements of the standard in order for safe and compliant use of the equipment and so their equipment can be placed on the market.

The standard specification limits of interest for this study are found in the standards listed below:

- IEEE 802.16e[7] standard for the case of mobile WiMAX equipment for both base stations and mobile stations emissions
- 3GPP standards TS 36.104[8] for base stations and TS 36.101[9] for mobile stations for the case of LTE equipment

In the case of 2.6 GHz equipment the 3GPP and IEEE standard specification limits for spurious emissions are as follows:

Band	Measurement bandwidth	Allowed emission Level
30 MHz ≤ f< 1000 MHz	**100** kHz	-36 dBm
1 GHz ≤ f < 13.45 GHz	30 kHz If 2.5 x BW <= $\|f_c-f\|$<10 xBW 300 kHz If 10 x BW <= $\|f_c-f\|$<12 x BW 1 MHz If 12 x BW <= $\|f_c-f\|$	-30 dBm

[13] GSA Status of the LTE ecosystem report June 2011 http://www.gsacom.com/gsm_3g/info_papers.php4shows evolutions of mobile devices with enhanced features

Table 4-1 IEEE base station spurious emission limits

Frequency range	Maximum Level	Measurement Bandwidth
9 kHz ↔ 150 kHz	-36 dBm	1 kHz
150 kHz ↔ 30 MHz	-36 dBm	10 kHz
30 MHz ↔ 1 GHz	-36 dBm	100 kHz
1 GHz ↔ 12.75 GHz	-30 dBm	1 MHz

Table 4-2 3GPP base station spurious emission limits

As can be seen in Table 4-1 and Table 4-2 the maximum level is -30 dBm/MHz which is applied to the frequency range 1 GHz to 13.45 GHz and thus includes the 2.6 – 2.7 GHz band of interest. All specification limits are quoted at the antenna port of the base station and therefore when undertaking the modelling analysis the antenna gain of the base station (assumed to be 17 dBi) will be applied and thus produce a level of -13 dBm/MHz radiated out of the base station for the spurious emissions.

It should be noted that the radar frequency investigated for this study falls in the spurious domain of the base station and the mobile station. However, the S-band starts at 2700 MHz while the 2.6 GHz band stops at 2690 MHz leaving a 10 MHz wide gap which is allocated to passive space services. The out of band emissions from the base stations do fall into the 10 MHz gap and beyond into the radar band if the highest 2.6 GHz channel is transmitting in a 20 MHz bandwidth. Therefore the out-of-band limits are important to this study and are captured by the following tables:

Frequency offset of measurement filter -3dB point, Δf	Frequency offset of measurement filter centre frequency, f_offset	Minimum requirement	Measurement bandwidth
0 MHz ≤Δf < 5 MHz	0.05 MHz ≤ f_offset < 5.05 MHz	$-7dBm-\frac{7}{5}\cdot\left(\frac{f\_offset}{MHz}-0.05\right)dB$	100 kHz
5 MHz ≤Δf < min(10 MHz, Δf_{max})	5.05 MHz ≤ f_offset < min(10.05 MHz, f_offset_{max})	-14 dBm	100 kHz
10 MHz ≤Δf ≤Δf_{max}	10.5 MHz ≤ f_offset < f_offset_{max}	-15 dBm	1MHz

Table 4-3 3GPP Out of band emission limits for 5 MHz, 10 MHz, 15 MHz and 20 MHz bandwidths

Frequency offset from centre	*Allowed emission level*	*Measurement bandwidth*
5 ≤ f < 6 MHz	*-13 dBm*	*50 kHz*
6 ≤ f < 25 MHz	*-13 dBm*	*1 MHz*

Table 4-4 IEEE Out of band emission limits for 10 MHz bandwidths

In contrast the Block Edge Mask proposed by Ofcom[3] for inclusion in future 2.6 GHz licences specifies a limit of -45dBm/MHz EIRP. Assuming a 17 dBi antenna gain this results in a -62dBm/MHz level at the antenna connector. It should be noted that as part of Ofcom's spectrum award program for 2.6 GHz this limit is specified beyond the end of the band (2690 MHz) up to 2720 MHz. The centre frequency modelled as part the study is 2750 MHz which is not covered by the Ofcom BEM which means emissions beyond 2720 MHz are less restrictive compared the block edge mask. The limits that apply at frequencies above 2720 MHz must adopt the spurious emission limits specified in ITU-R SM 329[20] which is the same as those specified by the 3GPP and IEEE standard for the spurious emission limits and are applied in the model for the *challenging case* conditions.

There are a growing number of 2.6 GHz deployments emerging around the world, however all are relatively new, with the first network (Teliasonera in Sweden) being deployed in 2009. So there is only limited experience of the emissions from 2.6 GHz causing interference in the out-of-band/spurious domain into the upper adjacent band.

Therefore in terms of parameters used in the study, a set of assumptions were made based on the available product data of 2.6 GHz equipment performance of the filters normally found in base stations and also for mobile station equipment. The modelled emissions were set either at or some margin below the standard specification limit depending on whether it was the challenging or typical case being analysed. However, in the latter stages of the study measurements of a mass produced LTE FDD mobile device were made available for additional analysis (See addendum report).

This study has used the discussions held with stakeholders who have reported that equipment performs within a certain, variable margin below the emission specifications of the base station equipment. For example, the following table shows the vendor estimates for the emission margin that could be seen in practice.

	Specification limit	Vendor estimate
Spurious emission	-30 dBm/MHz	-35 to -50 dBm/MHz

Table 4-5 Spurious emission specification levels vs vendor estimates

It can be seen in Table 4-5 that a 5-15 dB range for the improvement in the out-of-band and spurious emission domain below the mobile equipment specifications has been quoted by manufacturers [10].

Equipment vendors such as Alvarion, Airspan, Nokia Siemens, Samsung, Huawei and Motorola are key players in the development of both WiMAX and LTE standards and manufacture both base station equipment and user equipment within their product portfolios. However, there is limited availability of emissions performance statistics from these vendors and therefore specific assumptions have been made which can be found in appendix B of the Appendices document with regards to the margin of improvement for the out-of-band and spurious emissions actually transmitted by the equipment.

RFI Global has conducted some spectrum emission measurements to demonstrate the general performance of a commercially available FDD LTE device operating in the 2.6 GHz band. The device under test was a 2.6 GHz FDD USB mobile broadband modem, which is a very common device (see Figure 4-1 as an example), and used by many mobile operators around the world on, HSPA, WiMAX and LTE networks.

Figure 4-1 Mobile broadband USB dongle modem

The results from the measurements were used in the latter stages of the study which captured the behaviour of spurious emissions in the S-band. The measurement results produced by RFI Global Services Ltd provides detailed test set up and measurement results which includes the in-band power, measured Adjacent Channel Leakage Ratio (ACLR), CCDF of the peak to mean ratio and the spurious domain emissions.

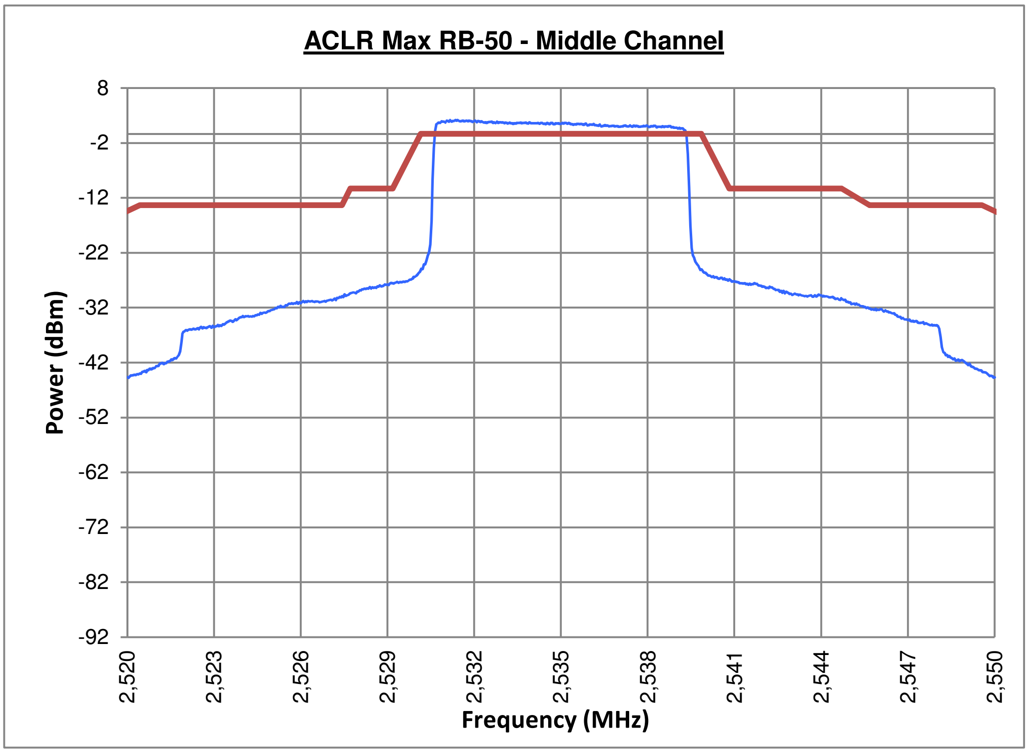


Figure 4-2 ACLR emission plot from RFI Global Services Ltd measurement of Samsung LTE UE – 1 at maximum transmitted power 21 dBm

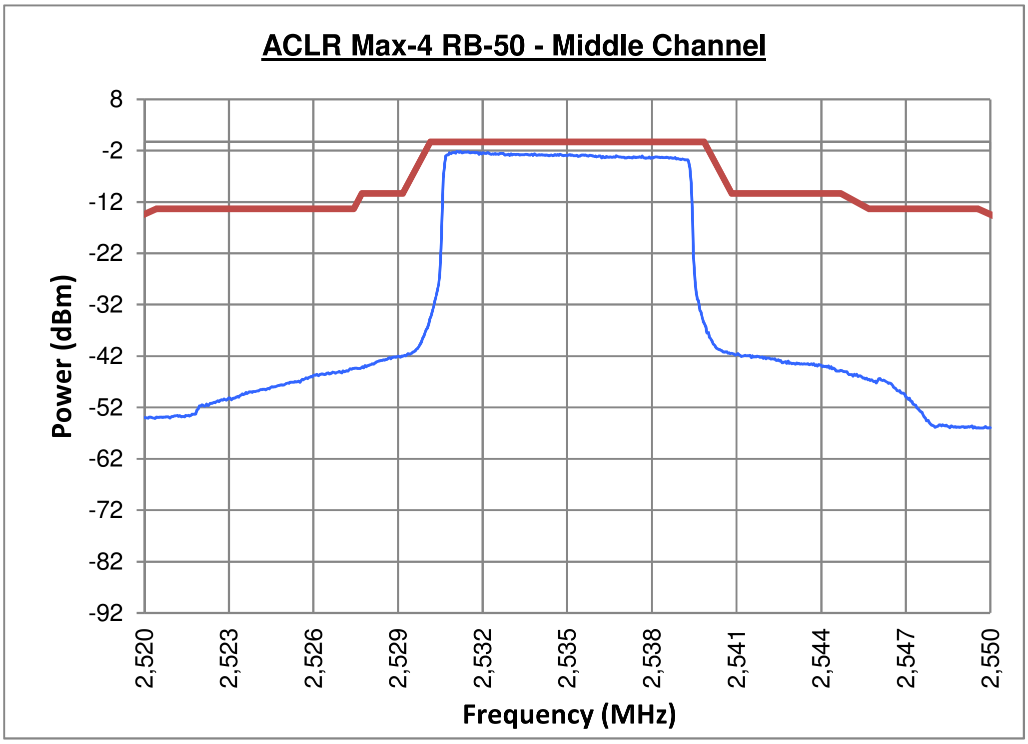


Figure 4-3 ACLR emission plots from RFI Global Services Ltd measurement of Samsung LTE UE – 2 at reduced power -4 dB

Figure 4-2 and Figure 4-3 show the ACLR measurement plots of the signal transmissions from the Samsung UE. The output produced shows the spectral emissions that have been specifically set up to measure the in band and ACLR emissions. The red line is the 3GPP UE spectrum mask to show how the emissions fit within the mask at 0dBm reference level.

These plots are used to illustrate the actual emissions performance that can be achieved by commercial devices. The measurements show how the unwanted emission levels change with a change to the output power. The measurements are of the adjacent channel power and do not explicitly show the specific emission levels in the radar band. Therefore these plots are used to demonstrate how the adjacent channel power changes with reduced in-band power.

In Figure 4-2 the total carrier power shown on the analyser was set to 21 dBm in a 10 MHz bandwidth the measurements were taken using some attenuation which has been applied to the input and therefore the output power recorded across the bandwidth is around 2 dBm. The unwanted emissions are those found either side of the channel edge of the main carrier centred on 2535 MHz. At 15 MHz offset from the right of the channel edge shows peak levels reaching -44 dBm/100 kHz. This is compared to Figure 4-3which used a reduced total carrier power of 17 dBm. The unwanted emission at 15 MHz offset from the right of the channel edge shows peak levels reaching approximately -55dBm/100kHz.

The two sets of measurements show how a reduction in carrier power of 4 dB impacts the unwanted emissions in the adjacent channels. In Figure 4-2 at maximum output power there is around 20 – 30 dB margin between the 3GPP mask and the measured emissions, this, compared to the plot in Figure 4-3, shows a 30 – 40 dB margin between the 3GPP mask and the measured emissions. This non-linear reduction effect in unwanted emissions in the adjacent channel demonstrates, in part the type of behaviour exhibited by commercially available mobile devices. It should be noted, however, that measurements in the S-band showed no change of power in the spurious domain of the mobile device with a change in in-band power. This is discussed further in section 10.9.

4.3 Practical considerations for mobile communications equipment operation

Macrocell outdoor base station equipment is of key interest to this study due to the potential for high power transmissions located relatively close to the radar without site shielding. However, in recent years the form factor of the base station equipment has reduced in size and can now be mounted in small cabinets. This reduction in size has also reduced the cost of producing the equipment due to reduced component size with improved baseband component quality and improved internal cooling. The impact of this development would limit the use of large internal cavity filtering and thus harder to achieve the high performance emissions that were evident in previous technology deployments such as GSM. The following images illustrate an example of how form factors of equipment have changed and therefore how site specific engineering may play a part in improving emissions performance from base stations.

GSM 900 base station rack	2.6 GHz WiMAX base station
	

Figure 4-4 Base station form factor comparison GSM v WiMAX[14]

It is expected base station equipment used in 2.6 GHz deployments will be of a reduced size form factor compared to previous mobile technologies. 3G equipment, for example, has evolved over time from large cabinet sizes into smaller cabinets compared to GSM technology by as much as half the original size. Smaller cabinet size can have an effect the quality of key components such as filters, isolators, and combiners. It may transpire therefore that base stations cause interference from the poor performance from its internal filters and thus out of band and spurious emissions. A requirement for improved additional filtering external to the base stations to further reduce the unwanted emission levels could be necessary. This study captures the effects of reduced size equipment form factors by modelling the spurious emission limits at the minimum specification levels (-30 dBm/MHz) to represent the lower performing filter equipment under the challenging case conditions and the use of improved filtering with more realistic limits as described in the next section for noise estimates at the base station for the typical case conditions.

[14] Images from www.usedtelecoms.com/siemens_bs.asp and www.quantumwimax.com

The mobile station equipment form factors include handsets such as smartphones, mobile phones, USB dongles, integrated laptops such as netbooks and in some cases portable modems. These mobile devices are currently used in 2.6 GHz deployments around the world and therefore considered as an assumption of the likely emissions performance of equipment to be deployed in the UK. Below are some example images of the form factors of the smartphones, dongles and other devices that could be used by operators in the 2.6 GHz band.

In modelling interference the study has assumed a mobile station which under the typical case will have a 5 dB body loss. This assumption is based on the use of a handset being used close to the body which is likely as users tend to operate handsets closer to the body compared to laptops and dongles which can be placed on a table at a distance where body loss will not be an issue.

USB Dongle	Smartphone	Netbook
		

Figure 4-5 UE equipment likely to deployed in 2.6 GHz[15]

Assumptions of emission performance have been based on the use of miniaturised components and commercial designs of the power amplifiers and ceramic resonator filters to achieve a low price point which is considered a trade-off in achieving high quality emission performance. This is discussed in more detail in the next section.

However, in the absence of measured data the noise estimates of equipment have been made based on the stakeholder discussions and information relating to filter performance of 2.6 GHz equipment which is presented in the next section.

[15] Images from experts.thelink.co.uk/.../12/3-e160g-modem.jpg, www.wimaxian.com and www.maximumpc.com/article/news/dells_mini_10_gets_wimax_treatment

4.3.1 Unwanted emission performance of 2.6 GHz equipment

In relation to unwanted emission performance of equipment and with only limited measured data available, this study has addressed the performance of equipment by way of estimated noise calculations at the BS and MS antenna connector of the *typical* out-of-band and wideband noise levels, and contrasted these with the 3GPP specification limits.

In this study we have considered three methods of estimating the noise floor in the radar bands – the area of interest in this study: (a) by calculation using a typical transmitter cumulative levels and noise figure plans, (b) by using the 3GPP noise limit as defined by the standard, and (c) by using a noise level of 10dB below the specification limit in the standard. The noise floor in the radar bands are shown below for these three methods:

(a) The noise estimates were calculated for typical base stations and mobile stations using the best available information of cavity filters and ceramic filters[11], transmitter gain between the DAC and antenna connector, frequency synthesis phase noise and transmitter noise figure. A transmitter levels plan was used to carry out the estimation, and the results are shown below and depicted in Figure 4-6.

FDD Macro base station noise estimate:

With an output power of 44dBm/10MHz, the noise floor in the radar bands 30MHz away between the power amplifier and cavity filter can be estimated at -11dBm/10MHz. We then add atypical cavity filter rejection of 80dBc, giving a noise floor in the radar bands of -161dBm/Hz.

TDD Macro base station noise estimate:

With an output power of 44dBm/20MHz, the noise floor in the radar bands 100MHz away between the power amplifier and cavity filter can be estimated at -43dBm/20MHz. We then add atypical cavity filter rejection of 70dBc, giving a noise floor in the radar bands of -186dBm/Hz.

FDD mobile station noise estimate:

With an output power of 23dBm/10MHz, the noise floor in the radar bands 150MHz away between the power amplifier and output filter can be estimated at -40dBm/10MHz. We then add atypical output filter rejection of 75dBc, giving a noise floor in the radar bands of -185dBm/Hz.

TDD mobile station noise estimate:

With an output power of 23dBm/10MHz, the noise floor in the radar bands 110MHz away between the power amplifier and output filter can be estimated at -40dBm/10MHz. We then add a typical output filter rejection of 50dBc, giving a noise floor in the radar bands of -160dBm/Hz.

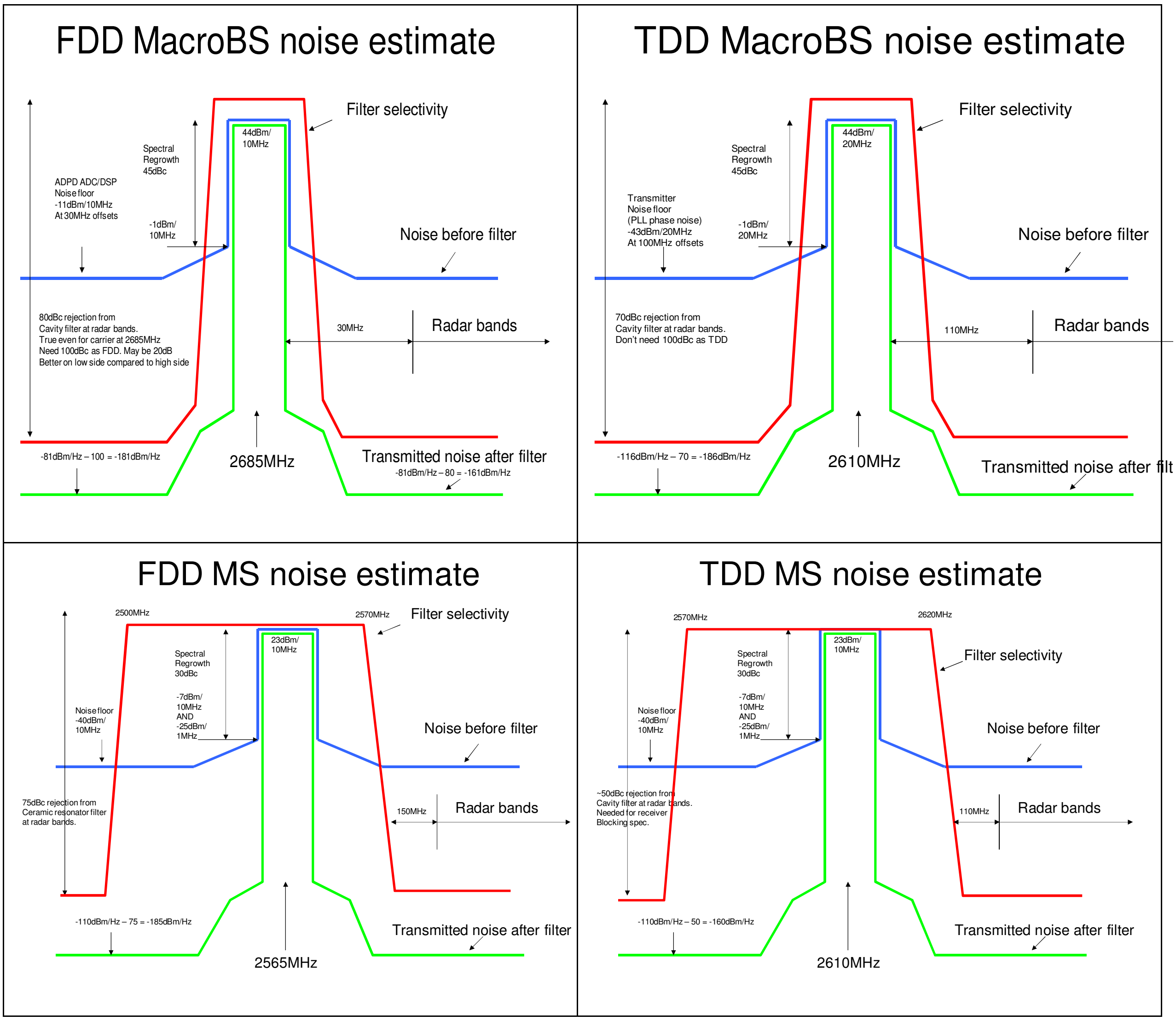


Figure 4-6 Noise floor estimates for BS and MS (FDD/TDD) referred to the antenna connector

(b) The noise specification limits given in 3GPP standard are shown above in section 4.2.

(c) The noise limits which are 10dB below the 3GPP specification are shown below:

Frequency range	Maximum level	Measurement bandwidth
1-12.75 GHz	-40 dBm	1 MHz

Noise specification choice discussion

It is necessary to make a choice between these three noise estimations above for the radar interference analysis and simulations. Although it might be expected that the equipment in use around Heathrow airport might typically produce a noise floor in the radar bands as estimated in (a) above, it may not be safe to assume such favourable equipment characteristics are and will be present without specific steps being taken to ensure this. Manufacturers are always trying to cost reduce their designs whilst remaining specification compliant. In this study we have therefore decided to use the 3GPP specification limits (b) as the worst case levels, and 10dB inside this (c) for the typical case levels.

4.3.2 Uplink Power control for LTE

LTE uses uplink power control to set the power levels of the user equipment within specific channel conditions. This feature is used so that powers from multiple mobile stations do not saturate the base station receiver. Additionally, power control acts as an efficiency mechanism as the power is nominally reduced from maximum down to a given lower level depending on the path loss from the base station receiver thus preserving battery life of the mobile station and reducing interference levels to other cells.

In LTE the power control parameter is important for optimising system capacity. The mobile stations calculate the path loss to determine the transmit power necessary to maintain the link budget. Furthermore power control can be combined with frequency-domain resource allocation strategies which allow interference coordination to further enhance cell edge performance and allow higher overall spectral efficiency[16]. However, interference coordination of the UEs is the responsibility of the scheduler and is dependent on the vendor's scheduling algorithms and the associated parameters set by the operator. Thus, operators can adjust the maximum transmit power of UEs on any given cell and also the range and rate of power control applied.

Power control in LTE can improve the potential interference situation within an airport environment in a number of ways:

- A reduction in transmit power from the UE based on its path loss from the base station within a cell reduces overall interference and thus would be of benefit to radar receivers
- The functionality is implementation dependent and could be designed by the operator to operate at an overall lower power level within close proximity to a radar.

The software model uses the total path loss between the mobile and each base station to determine the power control operation using the following calculation:

Total pathloss = free space loss + log-normally distributed shadowing

[16] LTE- The UMTS Long Term Evolution from theory to practice by Baker, Sesia Toufik

The transmit power of each mobile station is then calculated from the following equation:

$$P_t = P_{\max} \times \min\left\{1, \max\left[R_{\min}, \left(\frac{\mathrm{PL}}{\mathrm{PL}_{x\mathrm{ile}}}\right)^{\gamma}\right]\right\}$$

where $P_{\max}$ is the maximum transmit power, $R_{\min}$ is the minimum power reduction ratio to prevent mobile users with good channels from transmitting at a very low power level, PL is the total path loss and $\mathrm{PL}_{x\mathrm{ile}}$ is the 95th percentile of the path loss (plus shadowing) value. With this power control equation, the x percent of mobile users that have the highest path loss will transmit at $P_{\max}$.Finally, $0 < \gamma \leq 1$ is the balancing factor for terminals with bad channel and terminals with good channels[12]. The values of these parameters are defined in Appendix B of the Appendices document.

The serving site is chosen from the base stations which provide the minimum total pathloss. The following example graph illustrates the UE transmit power that results from employing the power control algorithm. The plot is based on the statistics of a large number of UE locations within the simulation polygons and with the presented network deployment. The transmit power is 23 dBm for 5% of the locations, whereas the power level falls to less than 15 dBm for 90% of the time. There is an almost linear decline in the transmit power from 90% to 20% where the transmit power falls from 15 dBm to 5 dBm. For 50% of the time the transmit power of the mobile is below 10dBm. Furthermore for small percentages of time (about 5%) it can be seen that the power falls below 0 dBm.

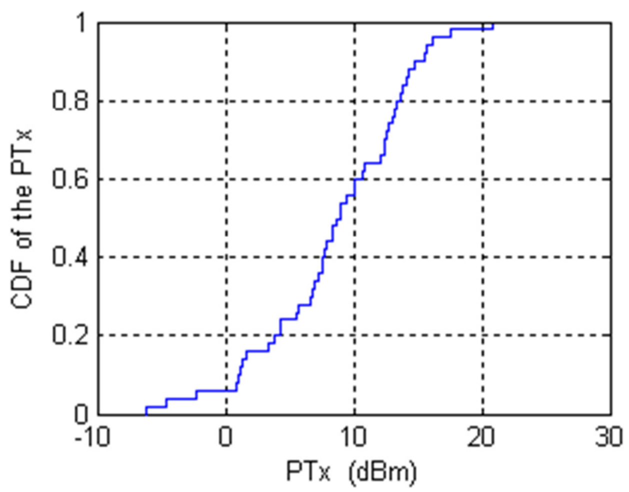


Figure 4-7 CDF of power control of the mobile

The power control functionality of the mobile network operating at 2.6 GHz introduces a powerful interference reduction mechanism. In this example the base stations were positioned at their real locations, see Figure 7-8. Given that the transmit power levels increase with an increasing BS-UE pathloss, one particularly useful mitigation would be to locate the base stations within as close a distance as possible to the location of high mobile user density areas.

In contrast to the base station for which the transmit power density is constant, the maximum power of the mobile is independent of the transmission bandwidth. Thus a mobile which is occupying all the resource blocks in a 20 MHz bandwidth will have its maximum power of 23dBm divided equally amongst all resource blocks, while the whole of the power will be radiated in a single 180 kHz bandwidth if a single resource block is transmitted by the mobile, see Figure 4-8.

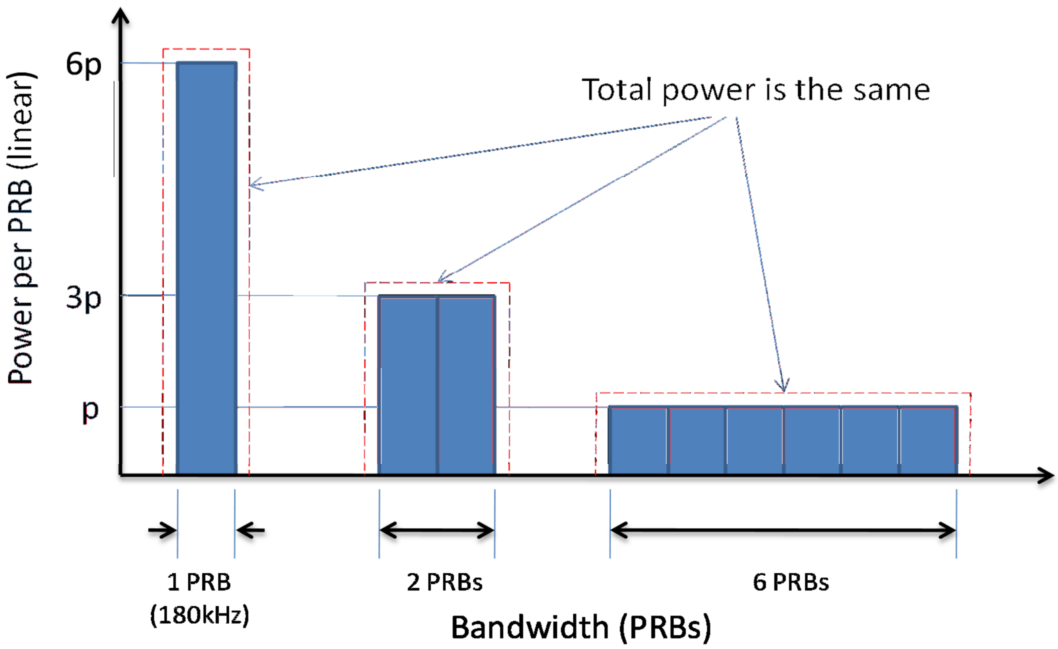


Figure 4-8 Physical Resource Block configurations

It is useful to note that the power control algorithm, as specified in the 3GPP standard (see Ref 3), regulates the power in discrete steps. This function limits the possible transmit power values that the mobile station can assume so as to mitigate the usage of the control channel. However, in the software model the power control is assumed to be perfect, i.e. the step size is not discrete and the transmit power values is equal to that required, regardless of consequences at the control channel. This is a common assumption in such simulations and is not expected to significantly affect the results.

4.3.3 Allocation of uplink resources for LTE

The use of resource blocks provides a method for allocating resources efficiently. In LTE there are a number of different strategies for allocating resources. Allocations of resources are made based on a set of conditions within the scheduling process at a high level, these are the channel state and traffic measurement.

Based on the available channel measurements the scheduling algorithm implemented in the eNodeB manages all the UE requirements within the cells under its control. This is to ensure that sufficient radio transmission resources are allocated to each UE within acceptable latencies to meet their QoS requirements in a spectrally efficient way. The impact of resource allocation relies on being able to adapt the power dynamically according to the channel state. This level of system dynamism is not typical of other cellular technologies and therefore may play a role in system deployments in and around airports.

Ultimately the scheduling algorithms are the responsibility of the vendor/operator wishing to produce optimum performance with minimum cost. However, there could be an opportunity for operators/vendors to use the algorithms in way that minimises interference from the UE into a radar and maintains a certain level of performance.

Resource allocation is used in the software model to represent a fair allocation of network resources to the mobile stations and ensure equal spread of the power.

5 Overview of stakeholder engagement

The stakeholder engagement element of the study included a mixture of discussions, interviews and correspondence with a select number of organisations. The stakeholders were chosen from a list of organisations known to be interested or involved in work and development of 2.6 GHz equipment and networks. The objective of the stakeholder engagement was to gather the vital information which could inform the technical aspects of the study in relation to the technical parameters and simulation assumptions for input to the interference model.

Real Wireless developed a stakeholder questionnaire which can be found in appendix G of the Appendices report, with the aim of obtaining specific information in relation to:

- Performance of base station and mobile station equipment
- Mobile network deployment strategies in the 2.6 GHz band around airports

Views were gathered from respondents represented from both the mobile equipment vendor industry and the mobile network operator industry in order to seek the required information. In total five stakeholders responded to the questionnaire, two mobile operators and three equipment vendors including one chipset manufacturer, handset manufacturer and base station vendor.

In general stakeholders expressed an interest in the 2.6 GHz spectrum band and provided views of likely technical characteristics of network deployments and equipment performance. In the sections below a summary of the information gathered from the perspective of both equipment vendors and network operators is discussed.

5.1 *Mobile Network Operator view*

In summary, the views from the mobile operators based on issues concerning 2.6 GHz deployments at airports include the following:

- The operators would use existing sites for 2.6 GHz deployments and load the macrocell network to capacity deploying a carrier at each site where possible.
- The operator would need to upgrade their distributed antenna systems (DAS) to accommodate 2.6 GHz frequencies as they currently only operate up to 2.1 GHz.
- Upgrades to the existing antennas would be needed to accommodate 2.6 GHz combined with the other cellular bands
- 2 x 20 MHz channels are the only bandwidths being considered for high capacity networks. Some thought has been given to 2 x 10 MHz for more rural deployments to improve coverage but this is an unlikely configuration for a high capacity location such as an airport

- It is expected existing arrangements and processes exist between existing operators as to the RF parameters used for shared sites and it is expected that these will be extended to include the specific characteristics of 2.6 GHz equipment. It is therefore plausible that a single site could support multiple 2.6 GHz operators.
- It is not foreseen that UMTS would be used at 2.6 GHz the band has clearly been earmarked for 4G technologies
- Although 100% resource occupancy is possible, 70% occupancy of resource blocks were used for trial simulations and seen as a good benchmark, although 100% would have to be treated as the worst case for interference analysis.

5.2 Equipment vendor view

In summary, the views from mobile station equipment manufacturers based on issues concerning equipment performance and 2.6 GHz deployments at airports include the following:

View on network deployments:

- Mostly deployments will be indoor microcells to deliver high capacity using one carrier per site. It is not anticipated that macrocells will be heavily used if at all for 2.6 GHz. Assuming operators have access to lower frequency bands such as 800 MHz.
- Operators are likely to acquire either 1 FDD channel 2 x 20 MHz or 2 x 10 MHz or 1 TDD channel 1 x 20 MHz or 1 x 10 MHz. This could mean 3 operators obtaining 2 x 20 MHz each and one operator obtaining the final 2 x 10 MHz.
- It is likely a frequency reuse of 1 will have to be used due to the restricted number of 2 x 20 MHz channels available in the band and the competition for it
- There could be a mix of FDD and TDD used by operators. For example if some operators also obtained TDD this could be used for extra capacity in the downlink.
- UMTS 2.6 GHz is supported by some chipsets but there is little demand for it. Most demand is for LTE or WiMAX at 2.6 GHz.
- Use of maximum output power is likely since if WiMAX operators obtain spectrum they will be seeking blanket coverage and have no alternative spectrum to make up any shortfall in coverage
- It is likely that 2.6 GHz deployments would use distributed antenna systems and femtocells although more likely to use picocells for an airport deployment
- Peak to mean power ratios being observed for UEs are in the range 4:1 with maximum power for UEs at 23 dBm

View on UE equipment emissions

- Vendors apply the ACLR as the critical limit to be met, therefore if equipment meets the ACLR limit the out of band limits are easily met
- Spurious emissions from equipment is always much better than the specification. For example -50dBm/MHz is a typical level. However spikes can occur on the intermodulation frequencies that reach the spurious limit of -30 dBm/MHz
- There is little difference in the performance between handsets and USB dongles due to the limited range of RF filtering components available on the market
- Power control performance is measured from the point the UE is transmitting at full power. As long as the UE respects the ACLR emission mask at full power then vendors are generally satisfied. There is little concern over performance at lower powers as long as the minimum requirement is met at full power, so it should be met easily at lower powers

- Maximum power of the UEs is 23 dBm and is going to remain so for the future. There are no plans to increase this due to the need to preserve battery life and Specific Absorption Rate limits under the Health and Safety guidelines

5.3 Airport operator support

The main focus of this study was to determine interference from 2.6 GHz emissions within an airport environment and thus close proximity to the radar. This has required essential input and support from BAA the airport operator at Heathrow particularly, the information relating to the positions of electronic communications equipment.

BAA provided data that supported the placement of base stations at the specific airport locations so that a meaningful interference analysis could be conducted. The information related to confirmation of cellular site locations and the geographical layout of the airport. It is worth noting that BAA uses a formal process to facilitate the use and operation of electronic communications equipment within the airport perimeter. This process ensures the necessary policies and compliances are met in accordance with Health and Safety, spectrum usage and managed infrastructure.

In addition BAA supplied the layout plans of Heathrow airport for use to derive the locations of base stations in line with the actual deployment that exists at the airport. The layout plans used for the study can be seen in the three figures below which show:

- A high level layout plan of Heathrow Airport
- A detailed layout plan of the Central Terminal Area
- A detailed layout plan of the area around Terminal 4

The model used the following specific layout areas and locations:

- Central Terminal Area (consisting of Terminals 1 and 3 and surrounding area) and position of base stations 1, 2, 3,4 and 5 including antenna heights and number of carriers per site
- Terminal 4 and surrounding area (including outside airport perimeter) and position of base stations, 6 – 13 including antenna heights and number of carriers per site

The airport is currently undergoing re-development within the Central Terminal Area with construction of new Terminal 2 buildings which may impact upon the present location of the base stations. This is due to BAA adopting a common approach for the deployment of electronic communications equipment as seen at Terminal 5 which uses common infrastructure for both indoor and outdoor sites.

The conclusion of this study could be that BAA will liaise with NATS with regards to the outcome of base station site locations and proximity to the S-band radar which could build in the necessary procedures for the deployment of 2.6 GHz base stations. In addition the study outcomes will be useful to the operation of 2.6 GHz mobile stations in proximity to the S-band radar which may propose the use of an interference coordination zone if necessary.

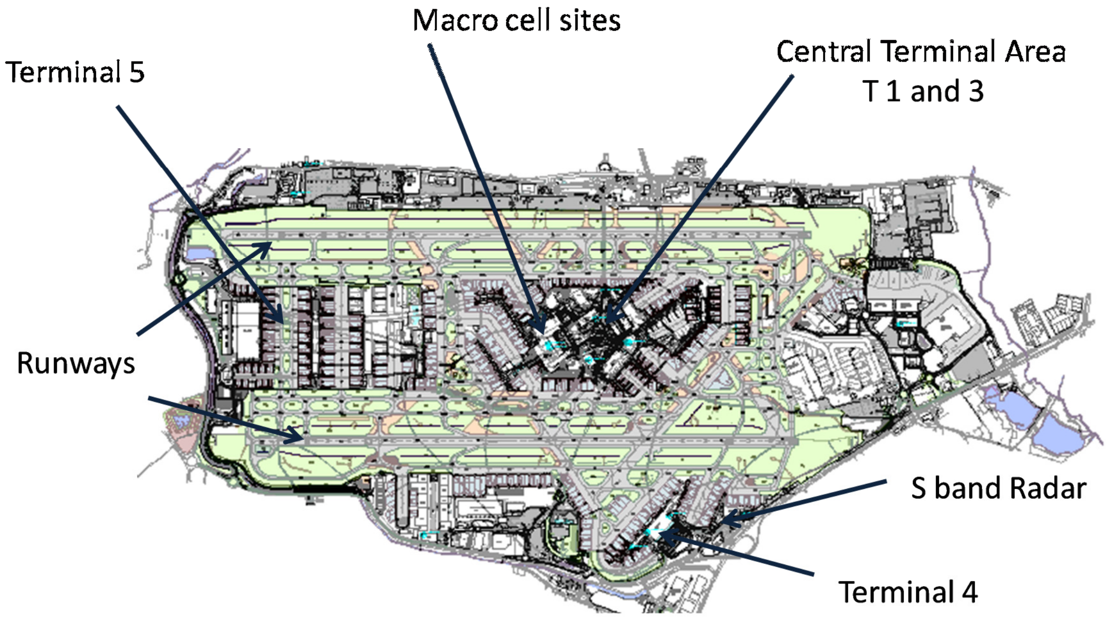


Figure 5-1 High level layout plan of Heathrow Airport

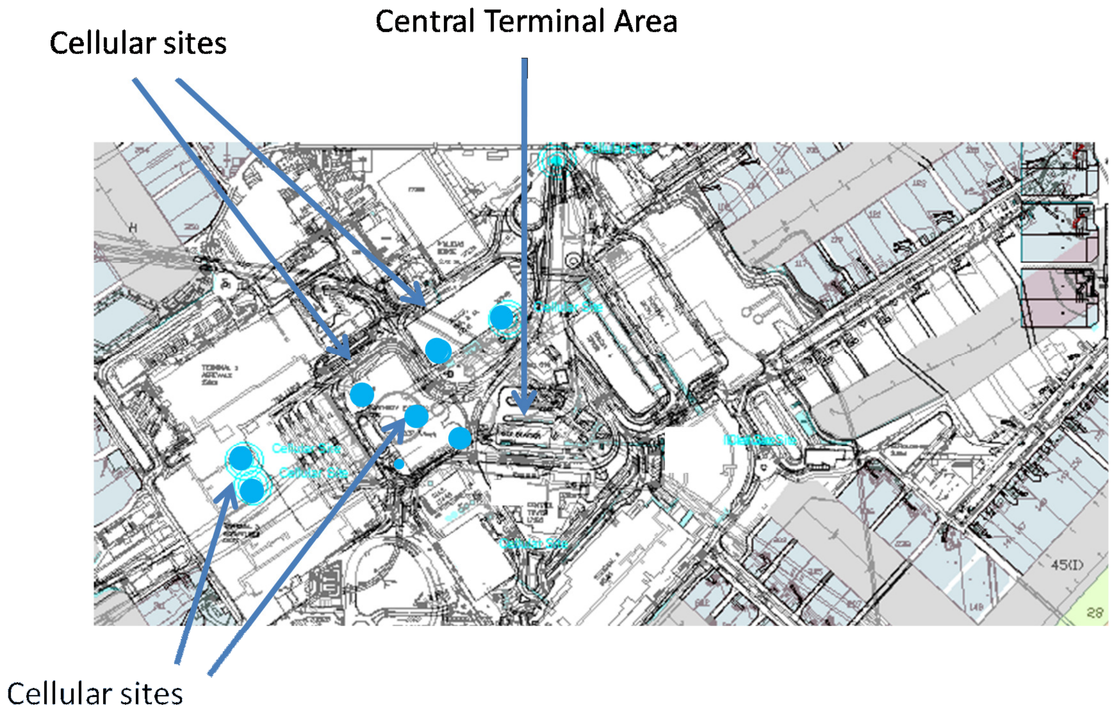


Figure 5-2 High level layout of Central Terminal Area with cellular sites locations

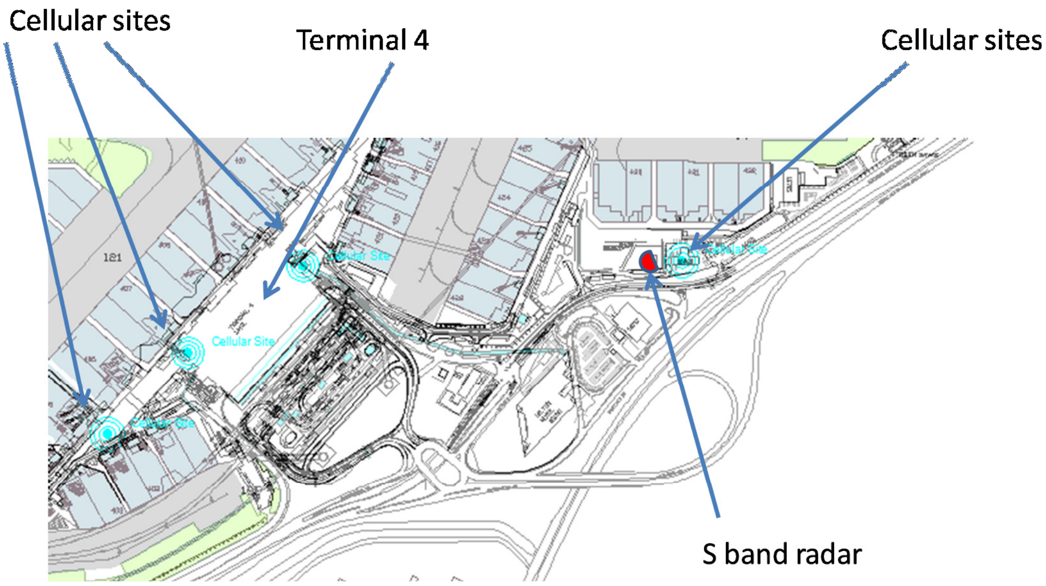


Figure 5-3 High level layout of the area surrounding Terminal 4 and the S-band radar at Heathrow airport

The contribution from BAA has enabled the practical and realistic parameters to be implemented into the model Data such as the airport layout diagram including building positions, cellular site locations, roads etc (as seen in Figure 5-1,Figure 5-2 and Figure 5-3) and passenger figures which were used to determine the relative density of mobile users for each of the modelled areas was vital to analysis for this study.

5.4 Summary of RF site survey at Heathrow Airport

Real Wireless conducted a cellular RF site survey of Heathrow Airport central terminal area (CTA) as part of the information gathering exercise. The aim of the RF site survey was to collect evidence of:

- The actual mobile operator base station and mast installation locations and antenna heights
- The number of operators radiating from each of those sites
- The number of carriers radiating from the site
- The proximity of both the base stations and mobile equipment to the radar
- The feasibility of additional antennas/masts being installed for services operating in 2.6 GHz.

The details of the survey findings can be found in appendix D of the Appendices document which provides results of the carrier emission measurements from the different base station locations. The results were useful to the study to understand how many carriers were transmitted from a single site and the number of operators located at each site.

The information gathered from the site survey was used as input to the modelling parameters and assumptions which can be found in appendix B of the Appendices document.

Heathrow Airport CTA is not typical of most UK airport environments this is based on a number of factors that differentiate it from other airports such as:

- The ATC radar at Heathrow is one of the tallest out of all licensed S-band ATC radars in the UK at 40m above local terrain (Note our modelled assumptions are based on generic radar parameters)
- Heathrow has the most number of terminal buildings of any airport and can accommodate several million passengers per month
- According to the Ofcom Sitefinder the extent of mobile phone operator outdoor deployments for the Heathrow CTA exceeds the next largest airport, Gatwick, by more than 2:1.

The findings from the RF survey showed that up to three operators were co-located at some of the rooftop sites transmitting a combination of both GSM and UMTS carriers which demonstrates the need for site sharing at the airport. In addition, it was noted that there was clear line of sight path from the rooftop to the radar that contributes to the decision to use a propagation model that takes account of free space at distances greater than 1km. In relation to the present study macro sites for 2.6 GHz deployments would need the highest rooftop sites to maximise coverage which may come at a premium based on the number of existing services and operators already established at the airport.

However, it was found that it may be possible for additional outdoor masts and antennas to be built at the current sites with the current CTA layout to accommodate upgrades or new installations at 2.6 GHz. As discussed in the previous section the CTA at Heathrow is undergoing renovation and any new layout is likely to be very different to the present layout. It is not known at this stage in detail what the new CTA layout will look like and therefore understanding the coordination zones for the radar may help inform the planning stages of CTA development.

5.5 *Summary of stakeholder engagement*

The stakeholder engagement provided the essential information relevant to the study. In particular each stakeholder offered its view on the 2.6 GHz landscape and provided specific technical information that was used to derive the input parameters and building blocks for the software model.

Specifically, stakeholders provided information relating to 2.6 GHz channel configurations such as the use of 2 x 20 MHz carriers and that it is likely multiple carriers can co-exist on a single site. This information has been used to inform the parameters for modelling the interference scenarios within an airport environment. The importance of the stakeholder engagement provides the credibility and a sound source of reference for the model parameters and therefore adds a layer of confidence to the software model and the outputs. Overall the stakeholder engagement was useful to provide the parameters used for setting up the simulations from the network deployment perspective which focused on maximising coverage, capacity and Quality of Service for the 2.6 GHz deployments. Therefore, the values of each of these parameters were important when addressing the mitigation techniques and by what margin these values could be altered before impacting upon the performance of the networks.

6 Interference Analysis Modelling

This section describes the options for addressing the interference analysis approach and discusses the different elements required to undertake the analysis. This section also addresses the choice of modelling option used for evaluating the interference at an airport between both base stations and mobile stations operating in the 2.6 GHz band and an air surveillance radar operating in the upper adjacent S-band.

6.1 Objectives

The objectives of the interference modelling were to:

- Use practical technical parameters likely to be employed at 2.6 GHz
- Produce modelling results which clearly show the most challenging case and typical case impact of emissions from the 2.6 GHz band into the 2.7 GHz S-band.
- Provide robust rationale for the choice of modelling criteria and supply evidence that can be used as an input contribution for radar interference levels and protection criteria.
- Replicate real world network performance parameters such as power control, cell edge performance and high quality of service for users as far as practicable while still producing a tractable simulation approach.
- Understand the interference implications for deployments at airports
- Include the flexibility to model mitigation techniques to the deployment scenarios

6.2 Interference assessment methods

The assessment of interference and co-existence is addressed by many publications from the ITU or CEPT with specific studies conducted depending on the particular type of services to co-exist. For example ECC report 148[13] which addresses the performance of DVB-T receiver in the presence of LTE transmitters and ECC report 140[14] which addresses the compatibility between RLAN on board aircraft and radars in the bands 5250-5350 MHz/5470-5725 MHz are studies that include specific assessment methods that address the nature of the interference mechanism.

However, the interference mechanisms investigated in this study are commonly found in many co-existence/compatibility studies in European Communications Office Spectrum Engineering Working Group. For example SE42 (now closed) was studying flexible bands, WAPECS and new sharing approaches which included the 2.6 GHz band. Therefore an acknowledged and well-established approach has been adopted for this study.

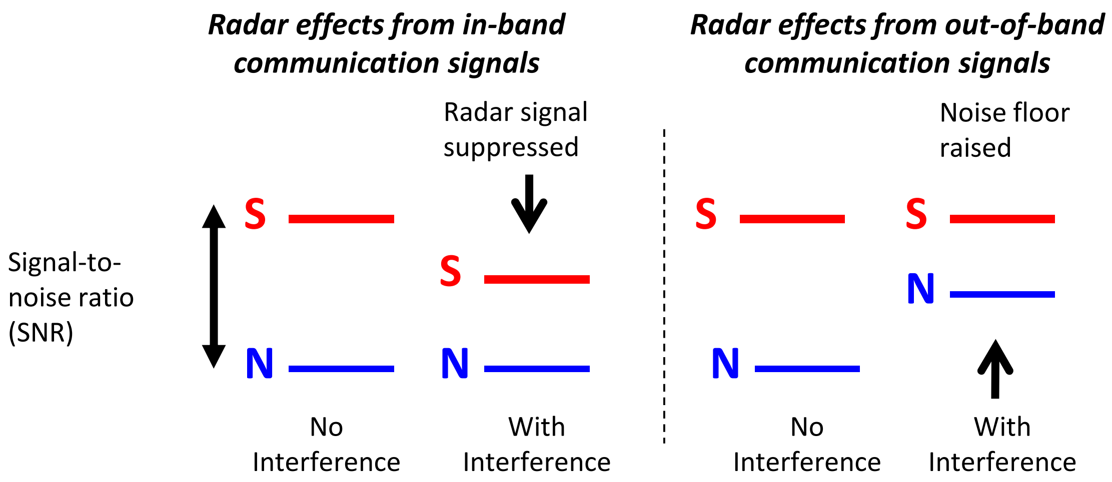


Figure 6-1 Out-of-band and in-band 2.6 GHz interference mechanisms into radar receiver[17] NOTE: There are complex intermodulation and radar receiver mixing effects which can cause a result similar to the sum of both effects

Blocking the radar receiver front end from base stations and mobile stations:

In-band interference manifests itself as the integrated power into the front end of the receiver when emissions of a certain magnitude cause saturation of the sensitive components in the receiver. The mechanism can be seen at a basic level on the left hand side of Figure 6-1 showing how the signal-to-noise ratio is reduced, producing an equivalent effect to reducing the wanted signal relative to the noise. The LNA and other components in a radar receiver are highly sensitive to allow detection of low level signal reflections from moving targets. Each component in the receiver chain exhibits a different threshold level for the 1 dB compression point and if the total integrated power from in band 2.6 GHz systems exceeds the threshold level that particular component goes into compression and thus degrades the performance of the radar. In the case of base stations the interference is more significant due to the close separation in frequency between the top of the 2.6 GHz band and the bottom of the adjacent 2.7 GHz band. The large in band emissions from base stations could cause compression of the active components of the radar receiver if close enough to the radar and in certain circumstances can cause a noise floor rise.

The potential for interference from mobiles is much lower for several reasons:

[17] Diagram sourced from Cobham Technical Services report

- A wider frequency separation of the mobile portion of the 2.6 GHz band and the reduced power output. There is a 98 MHz minimum frequency separation from the highest uplink channel 2610 MHz and the lowest radar channel 2708 MHz.
- In addition the mobile station transmit power is also much lower than the base stations which will also minimise the interference levels into the front end of the radar.
- Power control will typically be used, so that mobiles rarely transmit at their maximum rated power.

However, these reductions are offset somewhat by the reduced potential to suppress spurious emissions in mass-market devices, and this will remain a source of significant uncertainty for this investigation until the performance of practical devices becomes more clear.

Noise rise co-channel with radar centre frequency from base stations and mobile stations:

Systems operating in the 2.6 GHz band are very likely going to use 20 MHz bandwidths and can generate a noise rise in the radar receiver. The right hand side of Figure 6-1 shows how the mechanism affects the radar when an increase in noise impacts on the SNR and thus degrades performance.

Any rise in noise can affect the performance of the radar and therefore a protection ratio is applied to the radar noise floor to provide sufficient protection from interference. The interference threshold level is the allowed interference which if exceeded by the interference noise power from 2.6 GHz emissions will de-sensitise the receiver and degrade performance of the radar.

The interference noise power is calculated by integrating the spurious and out of band emissions from 2.6 GHz system applied across the radar band. The rise in noise is calculated in the following way:

$$\text{Allowed interference (I)} = \text{Radar}_{\text{Noise floor}} + \text{Protection ratio (I/N)}$$

These methods for analysing interference are generally used for the assessment between two different systems but can be used for the assessment between two types of the same system such as co-existence between FDD and TDD systems in the same band. The analysis is also dependent on a number of factors such as the frequency band of operation, the location of the transmitters, terrestrial or space, propagation model and so on.

In the case of co-existence between mobile communications systems and other services, CEPT published report ECC report 045[15] which addresses the interference between UMTS/IMT 2000 systems operating in the 2500-2690 MHz band and other services. It describes the methods for interference analysis using Minimum Coupling Loss calculations and Monte Carlo and the benefits of adopting each approach. This is relevant to the present study based on a similar set of parameter requirements for the mobile communications system in addition to the victim parameters which in this case is the radar receiver.

These two approaches are addressed in more detail in the following sections.

6.2.1 Initial blocking interference analysis

Ofcom has conducted a number of previous studies[4] to establish the impact of 2.6 GHz systems causing interference to radar in the adjacent 2.7 GHz band and identified there is a significant problem from base station emissions causing interference to current ATC radars. Each of the studies performed the basic calculations to establish the out-of-band emissions, path loss, protection distance and interference power for either blocking the radar or increase in interference noise power. The results from the calculations were used to validate the findings from practical trials or the laboratory tests and thus inform the necessary regulatory decisions for spectrum award.

It is useful to develop a full appreciation of the impact which 2.6 GHz emissions have on radars in the 2.7 GHz band and making some high level calculations provides the baseline outputs. Prior to this study Ofcom made some initial calculations[16] to understand the impact of interference using minimum coupling loss calculations. The minimum coupling loss is often used for an initial assessment of the interference scenarios and generates values in the order of magnitude expected of a static scenario. This occurs for example, when a single transmitter causes interference into a single receiver and not intended to represent a realistic scenario.

For the present study an initial assessment was made using the same method to establish a basic understanding of how each interference mechanism is treated which showed good correlation between the two sets of results.

Using the minimum coupling loss equation below and the main parameters from the parameters assumption booklet (found in appendix B of the Appendices report) the following minimum coupling loss and thus protection distance can be calculated for blocking:

MCL = Transmit power (dBm) + Transmit antenna gain (dBi) + Receive antenna gain (dBi) – Receive interference threshold (dBm)

Where:

MCL is the minimum coupling loss in dB

Transmit power is the transmitter power in a given bandwidth = 50 dBm/(20) MHz

Transmit antenna gain is the gain of the transmit antenna = 17 dBi

Radar antenna gain is the gain of the receive antenna (horizontal direction) = 28 dBi

Equivalent pre LNA power level required for no radar performance degradation = -42dBm (pre modified radar filter)

MCL = 50 + 17 +28 – (-42)

MCL = 137 dB

The minimum coupling loss of 137 dB is the minimum amount of loss necessary to not cause interference to the front end of the radar LNA. This equation and calculation is useful to calculate the protection distance using basic free space path loss equation to establish a high level protection distance. Using free space path loss the following protection distance applies:

$$FSPL = 32.45 + 20 \log(f)\ \text{MHz} + 20 \log(d)\ \text{km}$$

$$137 = 32.45 + 20 \log(2685) + 20 \log(d)$$

$$d = 10^{(137 - 32.45 - 68.5)/20}$$

$$d = 63\ \text{km}$$

This distance d of 63 km is the result of realistic input parameters used in this basic calculation function. This distance suggests that base stations transmitting at full power should be 63 km away or more from the radar under free space conditions to not exceed the blocking level at the input to the LNA. A result of this nature is useful to establish the extent of a problem and in this case suggests a more detailed further examination is necessary. The minimum coupling loss equations only allow a limited static case to be examined for the interference without the considerations of dynamic changes in the mobile environment such as movement of mobiles, power control and rotation of the radar antenna. The aim of this study is to obtain the realistic mobile environment within an airport and the output from the minimum coupling loss does not provide the sufficient information to conduct the full analysis.

Therefore, the minimum coupling loss calculations are useful for establishing indicative values to provide the order of magnitude of results and have not been taken any further for this study. The requirement for this study was to consider a more detailed analysis of the interference situation, provide the ability to use actual, realistic system parameters and take account of the antenna patterns for example and the actual pathloss between the interferer and the victim. A more appropriate method for this type of interference assessment is Monte Carlo analysis which is discussed in more detail in the next section.

6.2.2 Monte Carlo simulation

An alternative and more detailed method for interference analysis is the use of Monte Carlo simulations. Monte Carlo simulations add a layer of complexity to the scenarios by introducing a probability of interference for a given set of parameters and deployments. In addition Monte Carlo simulations offer more realistic results, offers a dynamic and variable modelling environment but are highly dependent on the accuracy and knowledge of the input parameters.

In the case of the present study the Monte Carlo method enables the ability to randomly distribute the mobiles within the defined modelling areas of the airport and repeat the generation of interference to the radar multiple times and at different locations. This method has the benefit of fine tuning the statistical outputs that produce confident and robust results.

The placement of active mobiles in random locations is representative of mobiles moving around a densely populated area such as an airport terminal to represent a realistic scenario as much as possible. Another important factor is the use of accurate input data such as the technical parameters. The more accurate and precise the input technical parameters the more accurate and precise the outcomes will be.

Furthermore, Monte Carlo analysis is used extensively by regulators across the European Community as an established approach to evaluate co-existence between different radio services and determine various modelled outcomes. For example the Seamcat (Spectrum Engineering Advanced Monte Carlo Analysis Tool) has been used in the spectrum engineering community of CEPT to analyse many different co-existence studies and scenarios such as co-existence between FDD and TDD systems in the 2.6 GHz band[17]. Therefore Monte Carlo analysis has been deemed as an appropriate analysis approach for this study.

There are some downsides of using Monte Carlo analysis, specifically the level of complexity in modelling the dynamic mobile environment and the difficulty of determining reliable values for parameters such as the density and duty cycle of mobiles. In order to capture the interfering effects from the mobiles the software model makes calculations for the mobiles in each position, this requires a significant level of computer processing and calculation complexity since the pathloss between each mobile and the base station is taken into account in addition to the pathloss between the mobile and the radar for each mobile position. Nevertheless, the resulting model is tractable for realistic environments and provides insight into the interference situation which more simplistic approaches could not replicate.

6.2.3 Choice of modelling approach

There is a clear choice for the modelling approach to use for an investigation such as the airport deployment study and Monte Carlo analysis was considered to be the simplest credible technique for each of the given scenarios.

The decision to use Monte Carlo analysis with the inclusion of specific propagation models for the study was made based on a trade-off for modelling complexity against the use of a commercial propagation modelling tool which may offer a more generic static path model. In comparison the accuracy that can be realised from adopting a Monte Carlo analysis with specific propagation models provides a unique blend of interference analysis from the dynamic perspective to model the movement of mobiles and inclusion of functions such as power control in addition to analysing the specific paths that exist within an airport environment. These functions combined provide a powerful tool for modelling a full 2.6 GHz deployment for a specific simulation area.

A generic model would have been a suitable alternative for modelling the airport environment but with generic models the user is restricted to the input variables offered by the particular model which may remove the ability to perform certain functions for the simulations. The particular function which is not usually available within generic models is the power control mechanism from mobiles. The choice of method adopted enabled the activation of power control which is deemed to be a fundamental feature in minimising interference into radar from mobiles.

Furthermore, Monte Carlo analysis provides the flexibility to build up statistics of results to a very detailed level which means extensive sensitivity analysis can be carried to refine and tune the results.

7 Overview of software model

This section describes how the software model works, the assumptions made in relation to the airport deployments, high level representation of the calculation functions and the types of output that can be generated.

7.1 Model flowcharts

The model was built using the Matlab programming language following the basic structure shown in Figure 7-1. This includes defining the input parameters associated with the overall system, the simulation process which carries out the functions, reads the main program and generates the resulting outputs. The results themselves are derived from post processing the output files from the simulation process to derive blocking and noise rise interference levels relative to the defined thresholds.

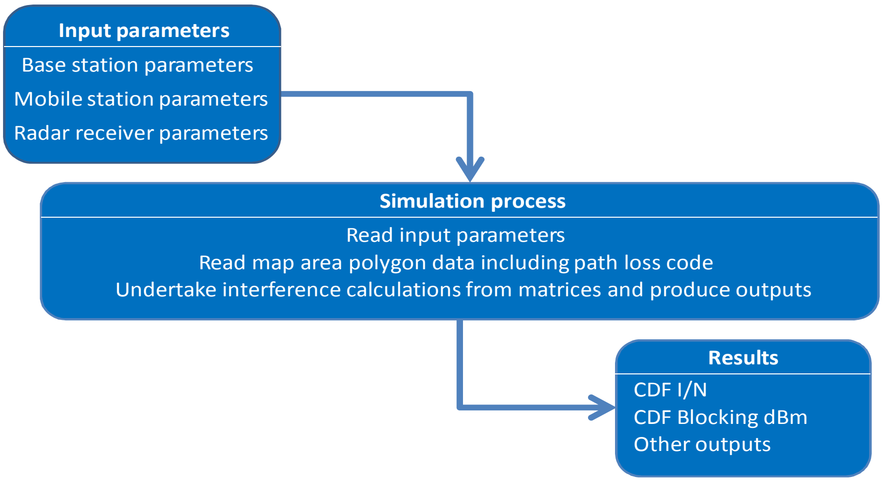


Figure 7-1 MATLAB software model flowchart

7.1.1 Input parameters

A complete list of the input parameters is provided in appendix B of the Appendices document. Also refer to Chapter 8 for a detailed discussion on the simulation parameters.

7.1.2 Simulation process – High level

Flowcharts for the interference calculation process are shown in Figure 7-2 (uplink) and Figure 7-3 (downlink).

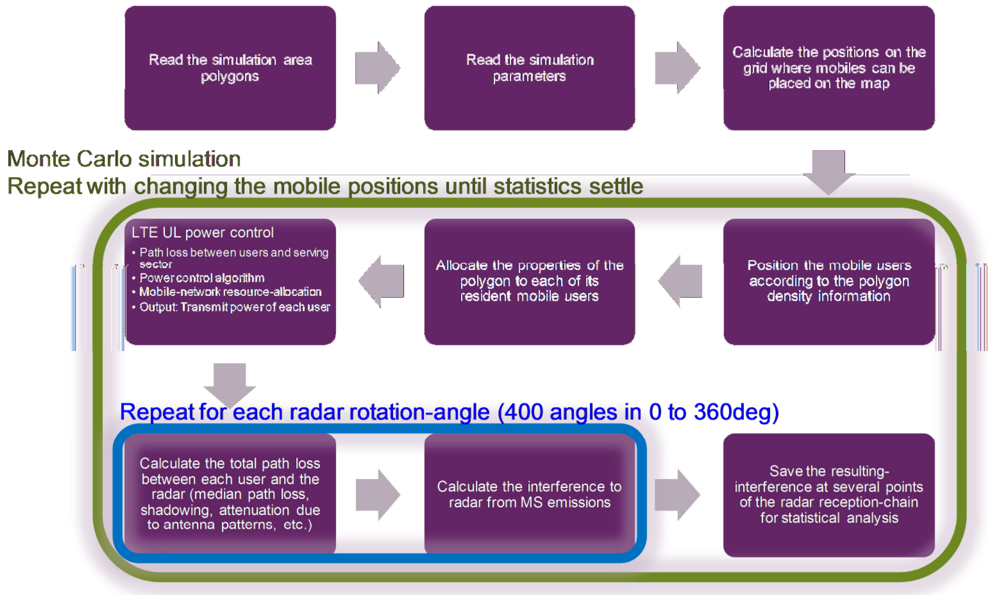


Figure 7-2 High level model flowchart of simulation process for the uplink

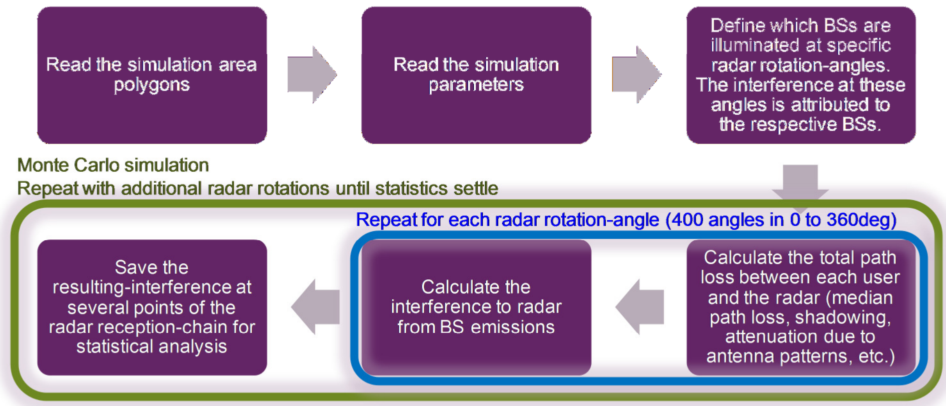


Figure 7-3 High level model flowchart of simulation process for the downlink

The uplink calculation consists of the following steps:

1. Firstly the simulation area polygons are read, these are the map areas defined to represent specific areas within the airport such as terminal buildings, car parks, pick up/drop off areas etc.
2. Secondly all the simulation parameters are read: the base station and mobile station emissions, antenna heights, antenna gain etc and the radar receiver parameters such as the antenna height, receiver filter responses and antenna patterns.
3. The system calculates the positions on a grid where mobiles can be placed on the map and thus included in the interference analysis. The grid consists of a large number of unique pixels within the simulation polygons where mobiles may be present. They may be modified to remove mobiles according to a coordination-zone.

4. The mobile users are randomly positioned on the map according to the corresponding polygon density information, with a uniform distribution within each polygon.
5. The properties of the polygon (polygon height, median path loss model to radar, indoor/outdoor location, etc.) are assigned to its resident mobile users.
6. The transmit power of each user is calculated by using the power control algorithm. In order to achieve that, the total path loss between the users and their serving sector is calculated (refer to section 4.3.2 for details on power control). The mobile-network resource-allocation algorithm is also employed (refer to section 4.3.3 for a high level description).
7. The total path loss between each user and the radar is calculated, including the median path loss from the relevant path loss model, a random shadowing component draw from a lognormal distribution, and the attenuation due to antenna patterns and indoor penetration where applicable.
8. The interference to the radar from MS emissions is calculated, taking into account the relevant filter responses within the radar receiver.
9. The resulting-interference at several points of the radar reception-chain is saved for statistical analysis.

A similar sequence of logical steps is followed in the mobile network downlink operation, see Figure 7-3.

7.1.3 Simulation process – Medium level

Figure 7-4 and Figure 7-5 show at a more detailed level the flowchart in the actual process that takes place at each step in the program for calculating the interference between mobiles and the radar which is discussed further below.

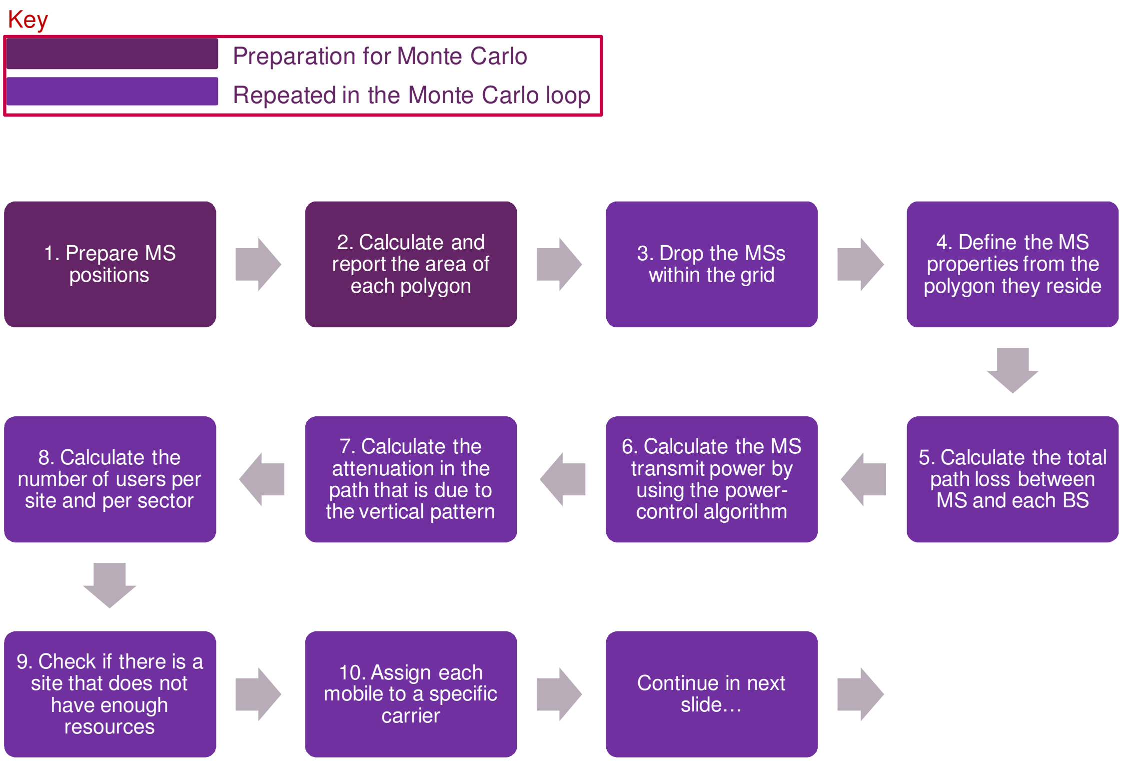


Figure 7-4 Medium level model flowchart of simulation process for the uplink (Part 1)

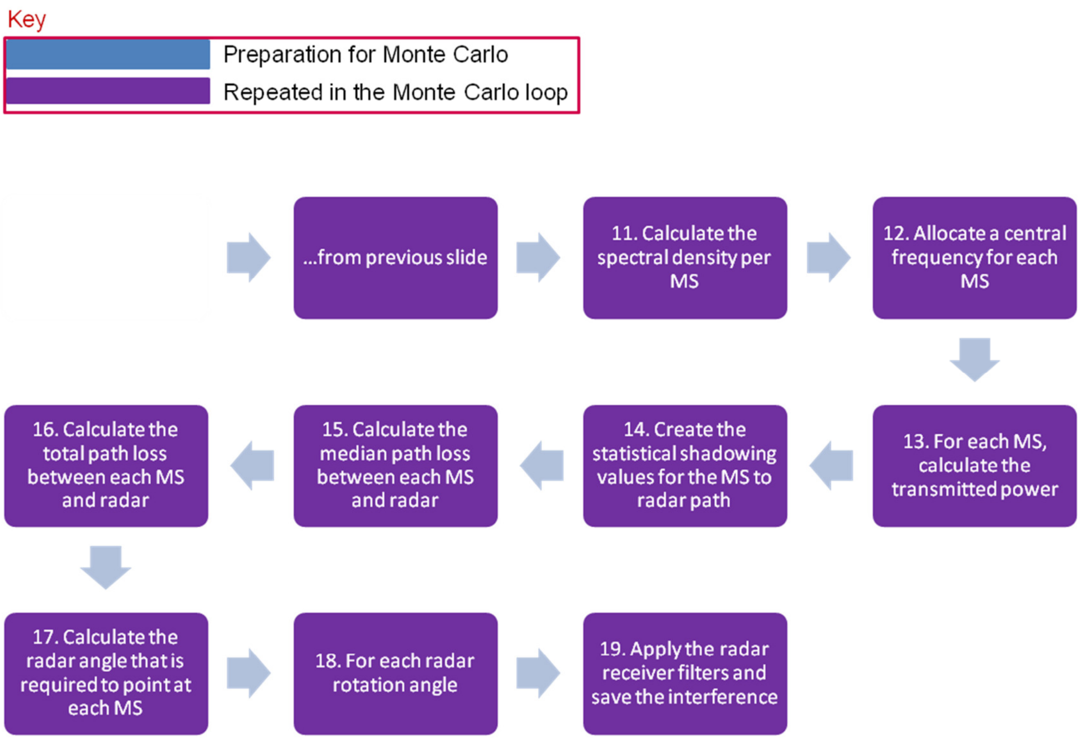


Figure 7-5 Medium level model flowchart of simulation process for the uplink (Part 2)

In a more detail, the following steps are conducted:

1. A grid of potential MS position is constructed. In order to do so, the limits of the simulation area are first calculated from the simulated polygons. Then a fixed grid for placing the mobile users within the polygons is defined. This grid excludes any pixels that do not respect the potential coordination zone The limits of the simulation area for Heathrow are:
   a. Easting: from 506706 to 510014
   b. Northing: from 173432 to 176298
2. The area of each polygon is calculated from the number of available mobile user pixels of the grid. The area is reported and is used for identifying the total simulation area. Table 6 provides the polygon areas and the distance from the radar location.

Polygon	Minimum distance (km)	Median distance (km)	Mean distance (km)	Maximum distance (km)
1	0.05	0.44	0.43	0.77
2	0.02	0.58	0.74	1.71
3	0.22	0.28	0.28	0.35
4	0.17	0.69	0.71	1.38
5	0.13	0.23	0.25	0.38
6	0.23	0.34	0.33	0.44
7	0.25	0.28	0.28	0.32
8	0.36	0.39	0.39	0.43
9	0.39	0.86	0.87	1.65
10	0.72	0.83	0.83	0.95
11	0.73	0.97	0.96	1.15

12	0.55	0.95	0.96	1.43
13	1.05	1.08	1.08	1.12
14	0.45	0.72	0.71	0.95
15	1.70	1.87	1.86	1.99
16	0.99	1.21	1.19	1.35
17	1.34	1.49	1.51	1.69
18	1.36	1.74	1.73	2.09
19	1.32	1.39	1.39	1.45
20	1.51	1.56	1.56	1.61
21	1.56	1.60	1.60	1.63
22	1.37	1.45	1.45	1.54
23	0.97	1.26	1.31	1.73
24	1.27	1.40	1.41	1.56
25	1.36	1.60	1.59	1.72

Table 6 Polygon properties

3. The mobile users are dropped within the grid. The pixels are selected randomly and according to the defined per-polygon user-density. The number of unique grid positions, where a user terminal can be placed during the simulation, is 21,567.
4. The mobile user properties are copied across from the polygon within which they reside (indoor/outdoor, height, path loss between mobile user and radar, etc.), according to Table 8-6.
5. The total path loss between each mobile user and each base station is calculated. The following equation is used: Total path loss = free space loss + log-normally distributed shadowing. The serving site is chosen as that base station which provides the minimum total path loss to the mobile.
6. Each mobile station's transmit power is calculated by using the uplink power-control algorithm, as described in Section 4.3.2.
7. The attenuation in the path that is due to the vertical pattern of the mobile station and radar antennas is calculated.
8. The number of users per site and per sector is calculated.
9. A logical enquiry is performed to check if there is a site that does not have enough resources to accommodate its users. This could occur if there are not enough resource blocks to be allocated to the users, so that the users should be sharing the resources in time.
10. Each mobile is assigned to a specific carrier.
11. The spectral density per mobile user is calculated by taking into account the power control and the available resources per connection. The power is spread across the number of resource blocks that each mobile user is assigned. The load adjusts the power level, and the load does not affect the number of available LTE resource blocks for the uplink transmission.
12. A central frequency is allocated for each mobile user.
13. For each mobile user, the transmitted power spectral density is calculated. Variations due to the crest factor are included. The output at this step is the user density noise emissions at the mobile antenna connector.
14. The statistical shadowing values are constructed for the mobile user to radar path.
15. The median path loss between each mobile user and the radar is calculated.
16. The total path loss between each mobile user and the radar is calculated. The equation is: total path loss = median path loss + shadowing + body loss + polarisation discrimination + attenuation due to vertical angles (mobile user and radar) + antenna gains (mobile user and radar) + median building penetration loss + statistical value of the building penetration loss.
17. The radar rotation angle that is required so as to point at each mobile user is calculated.

18. For each radar rotation angle, the angle between the radar boresight and the direct path radar-mobile is calculated. Then, the attenuation that is due to the horizontal pattern of the radar antenna is calculated. The output at this step is the interference power at the radar antenna connector.
19. The radar receiver filters are applied and the interference power is saved at each point of the radar receiver chain. The model calculates the power at each point of the receiver filter chain and presents the result as blocking level prior to the next stage in the receiver.

The simulation steps 2 to 19 (Monte Carlo iteration) are repeated, with a new set of different randomly chosen mobile user positions within the polygon areas and with different signal envelope that is due to the OFDMA signal (time) variability. The model calculates the interference for each mobile station at each radar rotation-angle and for a large number of Monte Carlo iterations (typically 200) so as to allow the recorded statistics to settle.

Figure 7-6 and Figure 7-7 show the detailed simulation process for downlink interference calculations.

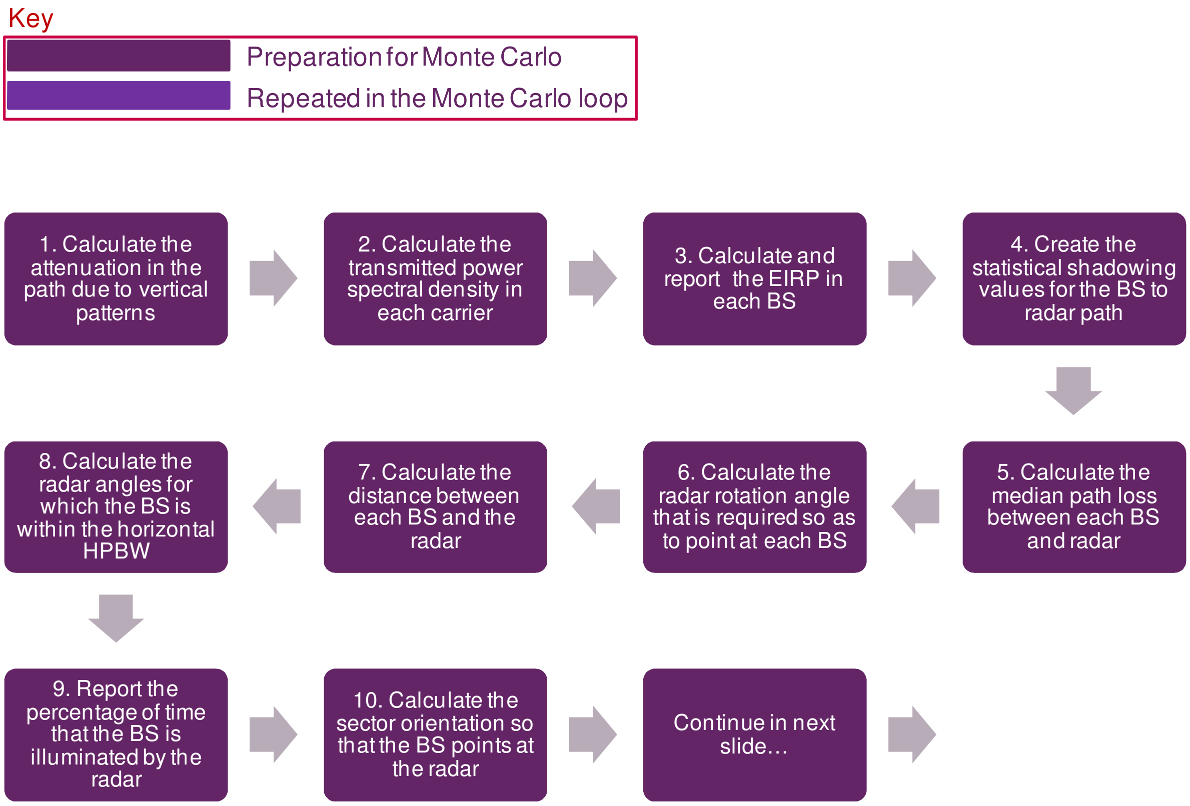


Figure 7-6 Medium level model flowchart of simulation process for the downlink (Part 1)

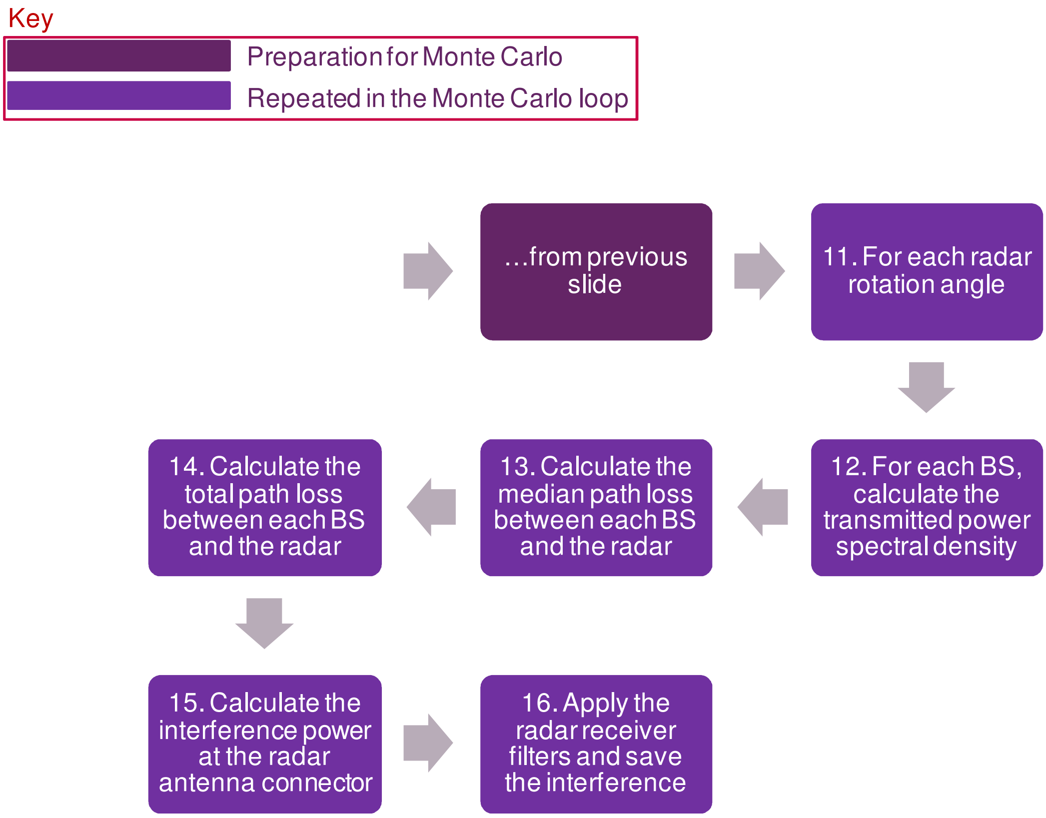


Figure 7-7 Medium level model flowchart of simulation process for the downlink (Part 2)

The following steps are followed for the downlink:

1. The attenuation in the path that is due to the vertical pattern of the base station and radar antennas is first calculated.
2. For each site, the transmitted power spectral density is calculated for each of the active carriers. The output after this step, which includes the effect of signal envelope variability, is the base station noise emissions at the antenna connector.
3. The EIRP of each base station is calculated. The EIRP is reported for a checkpoint against the simulation desired inputs.
4. The statistical shadowing values for the base station to radar path are created.
5. The median path loss between each base station and the radar is calculated.
6. The radar rotation-angle that is required so as to point at each base station is calculated.
7. The distance between each base station and the radar is calculated.
8. For each base station, the radar rotation-angles for which the base station is within the horizontal Half-Power Beam-Width (HPBW) of the radar are calculated. More details about the radar antenna pattern and the HPBW are provided in the appendix B of the Appendices document.
9. The percentage of time that the base station is illuminated by the radar is calculated. This percentage is reported and is equal to the percentage of time that the base station is required to be inactive to mitigate interference to the radar receiver.
10. The orientation of each sector is calculated, for the sectors whose orientation is not explicitly defined by the user. At this step, the sector's boresight is set to point at the radar (worst-case orientation), or the sector's HPBW is set to point towards the radar (best-case orientation).

11. For each radar rotation angle, the angle between the radar boresight and the direct path radar-site is calculated. The attenuation that is due to the horizontal pattern of the radar antenna is calculated.
12. For each base station, the transmitted power spectral-density is calculated. The output at the end of this step is the base station emissions at the antenna connector. In the calculation of the base station emissions the variability due to the signal envelope and the reduced EIRP in the restricted spectrum-block are taken into account. More information on the restricted block is provided in section 8.2.
13. The median path loss between each base station and the radar is calculated.
14. The total path loss between each base station and the radar is calculated. The equation is: total path loss = median path loss + shadowing + body loss + polarisation discrimination + attenuation due to vertical angles (base station and radar) + antenna gains (base station and radar) + median building penetration loss + statistical value of the building penetration loss.
15. For each radar rotation-angle, the interference power at the radar antenna connector is calculated.
16. The radar receiver filters are applied. The interference power at each point of the radar receiver chain is saved for statistical analysis.

The simulation steps 11 to 16 (Monte Carlo iteration) are repeated, with the same base station positions, however with a varying signal envelope due to the OFDMA signal variability. The model calculates the interference for each mobile station at each radar rotation-angle, and for [25] Monte Carlo iterations so as to allow the recorded statistics to settle.

7.1.4 Form of output

Figure 7-8 shows the simulation area, and plots the base stations and mobile stations on to the polygon areas. The pink triangles represent the base station locations, the blue dots represent randomly distributed mobile stations and the red star is the radar location. The polygon areas are represented by different coloured shapes that are based on the different areas of the airport such as a terminal building or car park. The mobiles can be placed in each polygon which has its own specific properties in relation to the simulation parameters. The properties for each polygon include the mobile height, mobile user density and median path loss model for the link polygon-radar.

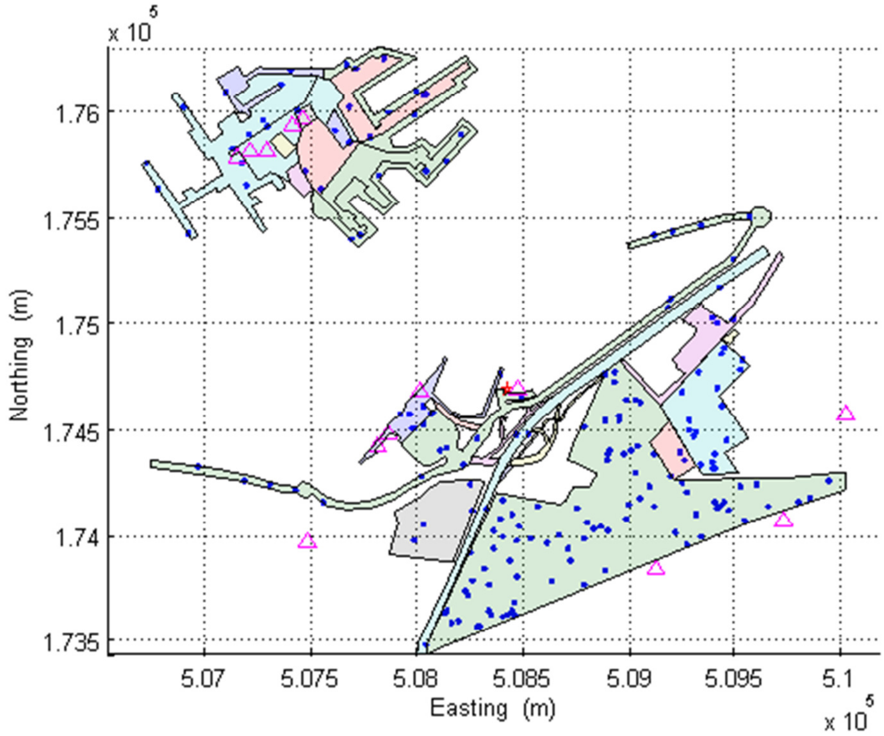


Figure 7-8 Mobile station and base station position plotted on map area

The calculations made between the base stations and the mobile stations are generally similar apart from the following differences:

- Power control is applied in the uplink (mobile to radar interference)
- A total of 7 carriers can be transmitted from one base station, resulting in stronger and more wide-band interference
- Base stations are static, as opposed to the dynamic mobile locations
- The variability due to shadowing and building penetration losses is set to 0dB for the base stations. This is because the base stations have fixed positions and their shadowing and penetration losses are invariable with time. The median interference is approached with the values set to 0dB. The variability is then statistically added to the results (in the integrated power at the various points of the receiver chain and in the I/N calculation).
- The outdoor base stations cause interference that attenuates with the vertical and horizontal angles due to the antenna pattern. The indoor base station antennas and the mobile antennas are treated as omni-directional in both vertical and horizontal cuts.

Figure 7-9 shows an output plot from the software model of the in band power of all 7 carriers from all base stations received at the radar antenna connector (PRx). The plot is an illustration of how each of the carriers are assembled and shows how the impact of the integrated power can be measured at the radar receiver. The dark red horizontal blocks show each of the 2.6 GHz carriers with the power reducing at the band edges.

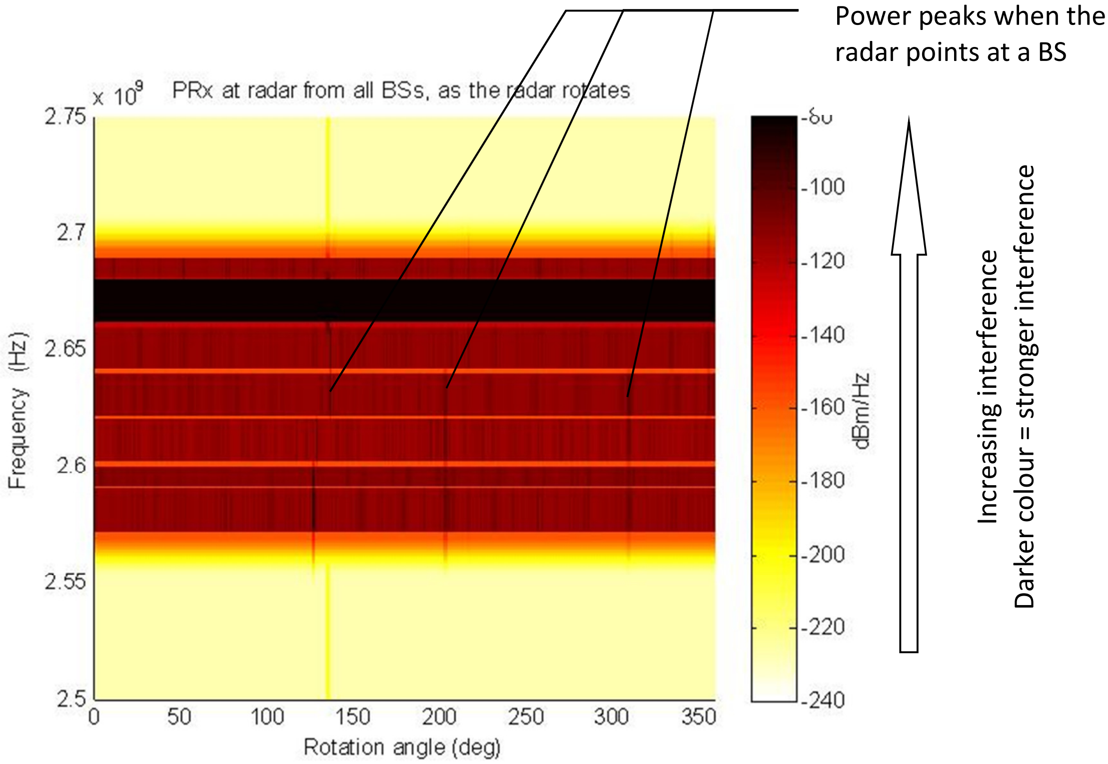


Figure 7-9 Blocking power from all base stations at radar antenna connector

This example graph shows only limited directionality due to the large dynamic range plotted on the graph. However very narrow peaks (vertical dark lines) can be observed where the radar points towards the interfering base stations. The rotation angle/direction when not pointing at a base station is in the radar antenna sidelobes (i.e. 30 dB below the main beam gain).

7.2 Program structure

The software program has been written in a modular format which calls each of the key functions from the main program. For example, there are separate functions for generating the base station and mobile station emissions whose outputs are read by another calculation for the next step in the process. Other functions include calculation of the pathloss using a set of different propagation models, calculation of attenuation due to the antenna patterns of the base station and the radar. The main function performs the core process bringing all the constituent parts together to run through and produce the outputs.

There are several core technical functions that have been written to perform the key calculations on the main technical parameters which include:

- base station and mobile station noise emissions
- Interference power received through the radar filters

- Attenuation due to antenna pattern
- Read map (plot base stations and polygon areas for mobile stations)
- Pathloss (call different pathloss codes corresponding to each given path)

These functions contain invariable parameters that are not expected to change when running through the various scenarios. The model also includes a function which contains the variable parameters and provides the capability to adjust the input parameters to reflect the different scenario criteria. The input parameters function allows the user to set the values of each of the main input and simulation parameters.

A list of the variable type of parameter values that can be modified are given below:

- Base station and mobile station EIRP
- Base station and mobile station spectrum emission mask
- Base station and mobile station antenna height
- Base station and mobile station antenna gain
- Base station antenna tilt
- Base station carrier loading
- Mobile station body loss
- Building penetration loss
- Shadowing variability
- Radar antenna height
- Radar uptilt
- Radar filter responses
- Radar antenna gain
- Radar half power beamwidth
- Radar vertical pattern
- Radar frequency

A change to the input parameters function will reflect a change to the outputs that are produced. For example, when simulating the challenging case scenario the maximum base station EIRP was used. This value was then reduced from the input parameters function to a lower EIPR to reflect the typical case scenario to a more realistic EIRP value.

The final step in the modelling process is the production of the outputs. The outputs are established as MATLAB (.mat) files output to a user defined folder directory. A MATLAB results output file is created for every Monte Carlo iteration and contains the resulting power and time percentage spread for each snapshot. The actual results are pasted into a pre-prepared MS Excel spread sheet where the resulting CDF curves are created.

8 Parameters

The following section addresses the input technical parameters used in the software model and includes a description of the key parameters that are critical to the credible, accurate and successful generation of sensible results. Also addressed are the simulation assumptions which have been made in order to establish a synthetic mobile communication network deployment within the proximity of a radar receiver in an airport environment.

8.1 Main input parameters

The aim of achieving accurate outputs from the software model is highly dependent on the quality and accuracy of the input technical parameters. The technical parameters were discussed and agreed with Ofcom and presented in the appendix B of the Appendices document. This Appendix lists in detail the parameters, the associated values and assumptions including reference sources required for generating the defined outputs and interference environment which are addressed in more detail in section 9.

Appendix B also captures the parameters in a way that represents both the challenging and typical case values. In both cases, 13 base stations were simulated at distances ranging between 50m and 1674m and 53 mobile stations assuming high levels of usage in the airport environment. In more detail:

1. *Challenging case*- The parameters are set to represent an extreme situation. Whilst such a case is, in principle, possible within the airport environment and consistent with a 2.6 GHz licensee's technical conditions, it is unlikely to occur in practice. Spurious emissions are assumed to be at the relevant specification limits. Mobiles are transmitting at full power (no power control is assumed).
2. T*ypical case*- The parameters are set to represent a plausible, practical deployment and a busy day with respect to airport passengers and mobile network demand. Spurious emissions are assumed to be at levels significantly below the specification limits based on expectations from practical equipment and consultation with vendors. Mobiles are assumed to be power controlled by the serving base stations.

8.2 *Base station and mobile station parameters*

8.2.1 Base station signal characteristics

The base station signal characteristics used in the model are shown in the figures below and a description of the assumptions used to generate these signals is given.

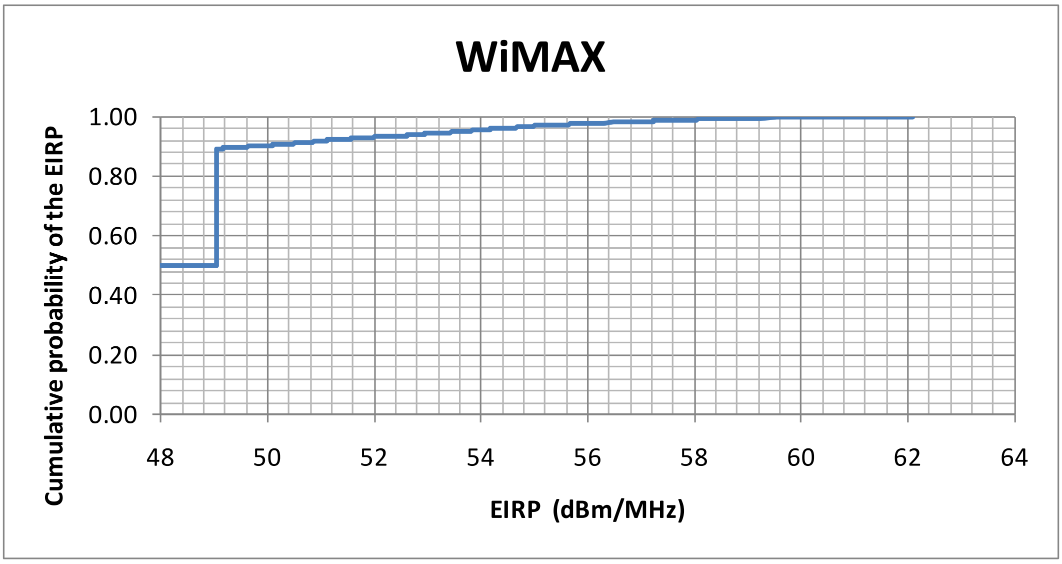


Figure 8-1 WiMAX BS CDF of the EIRP used in the model

The CDF curves of the outdoor BS EIRP, expressed in dBm/MHz, are plotted in Figure 8-1 (WiMAX channel) and Figure 8-2(LTE channel), under the typical case EIRP assumption. It is reminded that under the typical case assumptions:

a) The mean EIRP is 50dBm/MHz, when the channel is active

b) The carrier loading is 80%, so that the power over time is 1dB less than that of 100% loading

The power that is transmitted at each channel is circa 49dBm/MHz. This explains the high probability of the signal being circa 49dBm/MHz in the plots. Also note that the active WiMAX channel power is <48dBm/MHz for 50% of the time, which corresponds to the uplink time of the TDD operation, as opposed to the power >48dBm/MHz for 100% of the time for the active LTE channel in FDD operation.

Due to variations of the signal envelope the instantaneous power is variable with time. The CDF curves show that for 1% of the time the power is >58dBm/MHz (WiMAX) and >56dBm/MHz (LTE).

The OOB emissions follow these statistics, but offset in the x-axis due to the assumed spectrum emission mask. Therefore further in the text of this report, the reference to '1% of the time that the radar points at the worst interferer' coincides with the 99% level of these CDF plots. This is because, in the BS simulations there is no further variability assumed other than the signal envelope, as opposed to the shadowing and building penetration loss variability of the mobiles.

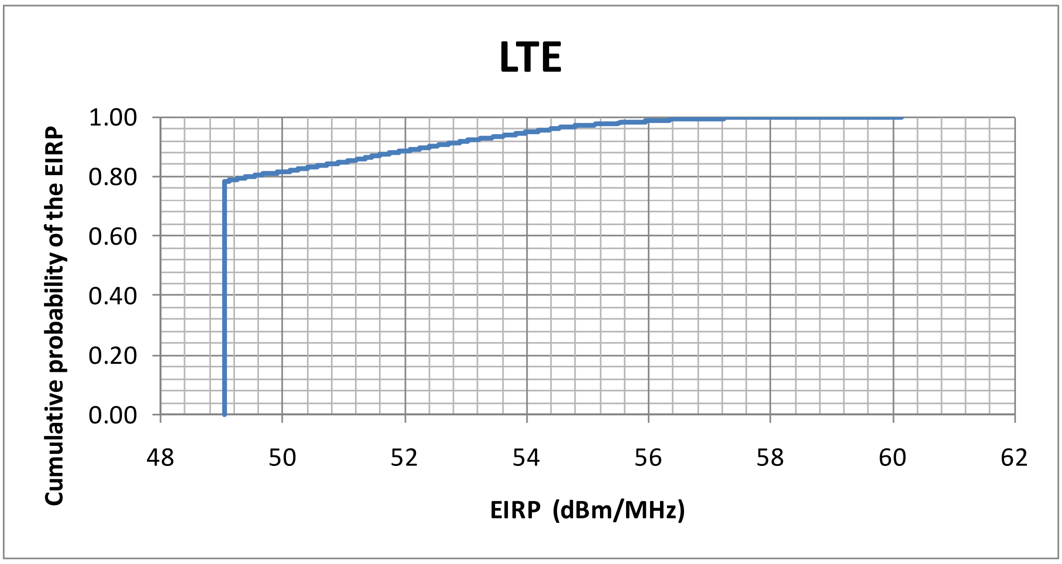


Figure 8-2 LTE BS CDF of the EIRP used in the model

The PDF curves are an alternative view to the CDF curves, however they do not reveal any further information on the EIRP statistics as seen in Figure 8-3 and Figure 8-4. Indoor BSs will have the same CDF as the curves plotted, but offset in the x-axis due to greater restriction on EIRP for indoor deployments.

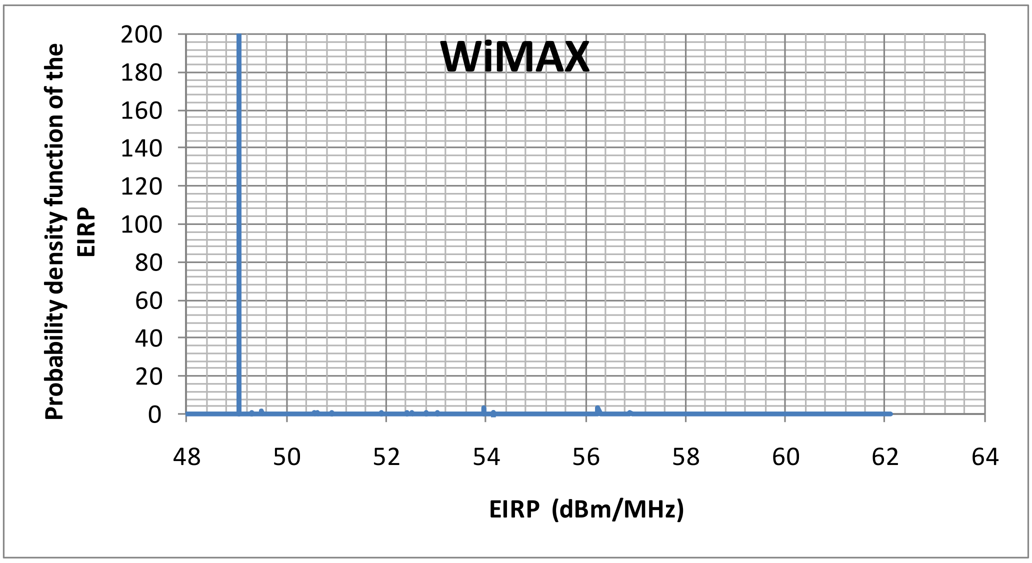


Figure 8-3 WiMAX BS PDF of the EIRP used in the model

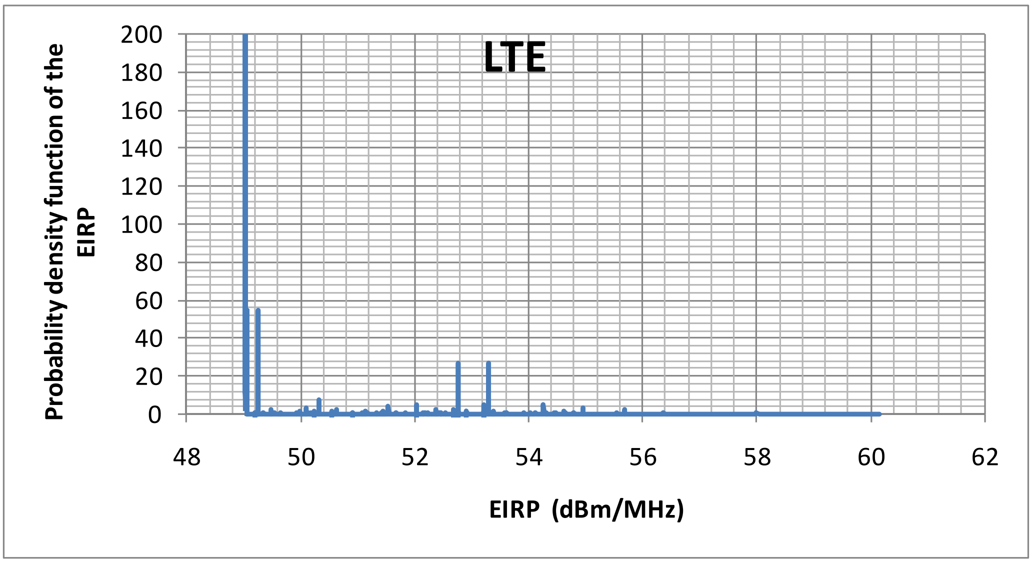


Figure 8-4 LTE BS PDF of the EIRP used in the model

8.2.2 Peak to average power ratio (PAPR)

The variations in the signal envelope are due to the peak to average power ratio found in OFDMA systems such as LTE and WiMAX, to help keep the limiting aspects of the base station power amplifier within a sensible range, for example the BS power amplifier can support up to 10 dB of signal variability.

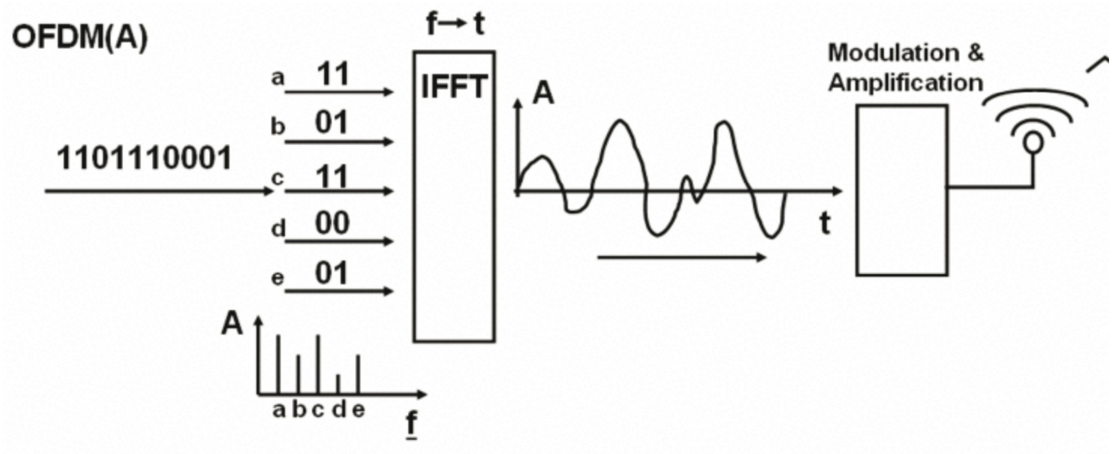


Figure 8-5 Creating an OFDM signal[18]

Figure 8-5 shows the creation of an OFDM signal from the serial data input which is passed through a serial to parallel converter. The spectral components of each symbol are identified and input to an Inverse Fast Fourier Transform (IFFT) process. The IFFT process converts the frequency domain signals into time domain signals. Each resulting time domain FFT symbols is now mapped onto its sub-carrier, and the final time domain signal is a composite of all sub-carriers.

The technical challenges presented by OFDM are the resulting composite waveforms which display large variations in amplitude caused by the combination of a number of individual signals. The resultant effect displays the signal fluctuating in amplitude as a result of the combining of many signals with discrete phase and amplitude differences. See Figure 8-6 as an example the OFDM waveform.

The signal used in the model for the study used 20 individual sine waves combined to form a near-Rayleigh distribution which is truncated to the average level. The mean value of the resulting distribution is slightly higher than the input-average value and the specific peak to mean values used in the code are shown in the table below.

2.6 GHz Equipment type	Modelled PAPR values
WiMAX BS PAPR	11 dB (64 QAM)
LTE BS PAPR	8 dB (64 QAM)
WiMAX MS PAPR	8.3 dB
LTE MS PAPR	7.8 dB (16 QAM)

Table 8-1 PAPR values for LTE/WiMAX both base stations and mobile stations source can found in Appendix B of Appendices document

[18] Source Informa Telecoms & Media course notes – LTE Air Interface course

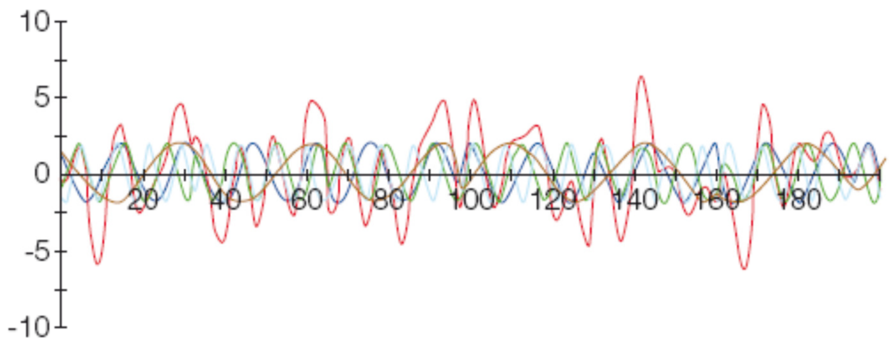


Figure 8-6 Example combination of multiple sine waves to obtain PAPR[18]

The peak-instantaneous I/N values for the mobile stations are considered as average I/N values for the purposes of the study. This is because the variability that the peak-to-average provides is small compared to the combined variability of shadowing and BPL. This should be taken into account when analysing the I/N results of the mobile stations.

8.2.3 In-band and out-of band emission levels

The maximum EIRP for the base station and mobile station used for the model have been extracted from the Ofcom auction statement [3]in line with technical licence conditions that are likely to be imposed on licensees operating in the 2.6 GHz band and are modelled as the interfering signals.

61 dBm/5 MHz is the value used in the Ofcom auction statement[18] as the maximum EIRP for a base station which has assumed a maximum output power of 44 dBm with a 17 dBi antenna gain. The maximum EIRP value used for the present study was 67 dBm in a 20 MHz bandwidth and 64 dBm in a 10 MHz bandwidth for the challenging case.

The typical case values have been derived from analysis of the Ofcom Sitefinder database and the RF site survey conducted at Heathrow Airport (see appendix D) to establish the type of actual powers used by cellular operators compared to their licence permitted powers. In general it was found that on average 4 dB below the maximum permitted power levels were used for actual transmission EIRP, therefore 63 dBm/20 MHz and 61 dBm/10 MHz were used for the typical case values.

A restricted block has been implemented in the model between the FDD uplink portion and TDD portion of the 2.6 GHz band to limit mobile station to mobile station blocking. The restricted block is implemented as reduced EIRP (25 dBm/5MHz) to conform with Ofcom’s latest technical limits[3].

Base station and mobile station out of band and spurious emission levels

The out of band and spurious emissions from base stations and mobile stations are used to calculate the increase in noise to the radar receiver landing co-channel on the radar centre frequency. The key to values that are likely to cause interference that exceed the I/N threshold levels of the receiver are the minimum limits specified in the LTE and WiMAX standards[7,8,9] which assumes a constant emission level into the radar band. The assumptions made on the typical case values regarding the out-of-band spectrum emission mask and the spurious emissions falling inside the radar band assume a roll off of 1-2 dB/decade into the radar band which formed the basis of the typical case emissions.

The challenging case uses the 3GPP and IEEE specification mask to simulate the possibility of equipment performing up to the specification limits. This means, in the case of emissions in the downlink portion of the band with the carrier centre frequency 2680 MHz and 20 MHz bandwidth, the out-of band emissions extend into the radar band by up to 40 MHz, this is clarified based on the following criteria:

Out-of-band domain extends ±250% outside of the necessary bandwidth therefore 2.5 x 20 MHz = 50 MHz after which point the spurious domain predominates[19]. Therefore at the channel edge 2690 MHz + 50 MHz (out-of-band) equates to 2740 MHz and the limit can reach up to -15 dBm/MHz in this out of band domain. However, outside of these limits within the spurious domain the level is specified from ITU-R SM 329[20] as:

Frequency band	Maximum level	Measurement bandwidth
1 GHz – 12.75 GHz	-30 dBm	1 MHz

Table 8-2 3GPP and IEEE spurious emission limits

At the maximum level a number of assumptions can be made. For example, setting a constant level for the spurious emissions captures the possibility of a discrete spurious emission falling co-channel with the radar centre frequency, which emulates a challenging case scenario. Each of the spectrum emission masks shows the EIRP in dBm/MHz.

All of the unwanted emission masks incorporate the Ofcom Block Edge Mask (BEM). In the case of base stations the -45 dBm/MHz BEM extends 30 MHz from upper most block edge in the downlink portion of 2.6 GHz band from 2690 MHz to 2720 MHz in the upper adjacent S-band. In the case of the mobile stations the -19 dBm/MHz BEM extends from top block edge of uplink portion the 2.6 GHz band to 2720 MHz in the upper adjacent S-band. The emissions limits from ITU-R SM 329[20] were used at frequencies beyond the BEM. The figures below show simplified overview of the spectrum emission masks for the base stations and mobile stations used in the model.

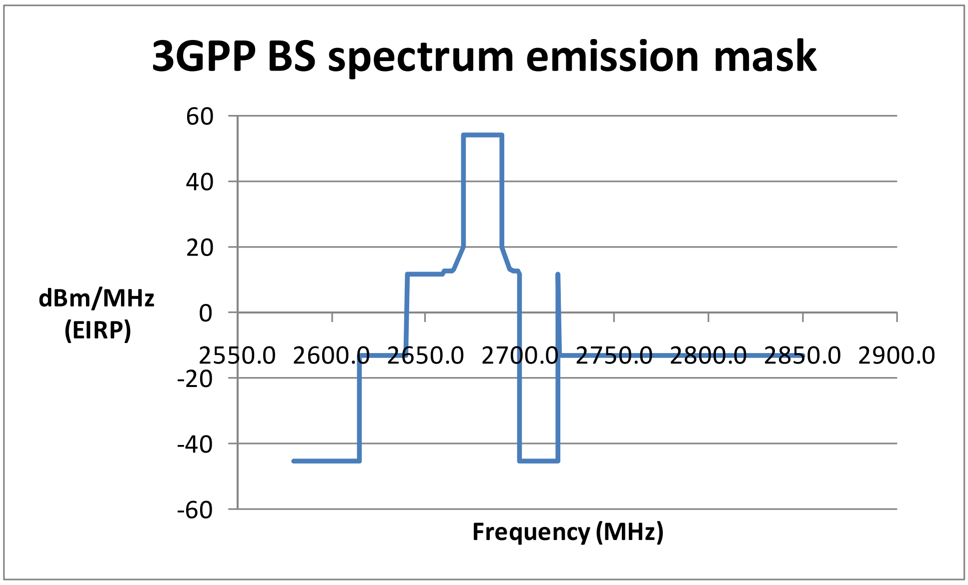


Figure 8-7 3GPP BS spectrum emission mask including Ofcom BEM

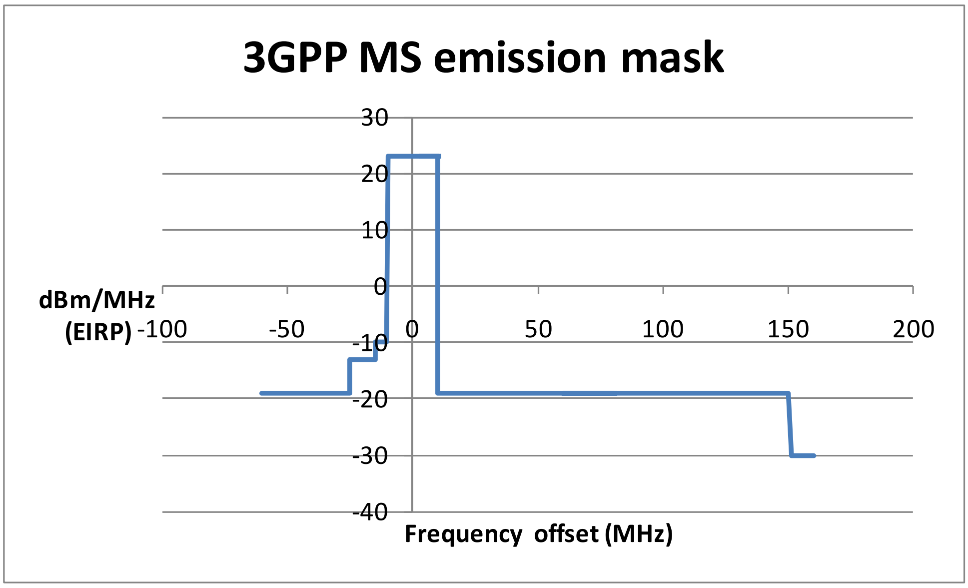


Figure 8-8 3GPP UE spectrum emissions mask including Ofcom BEM

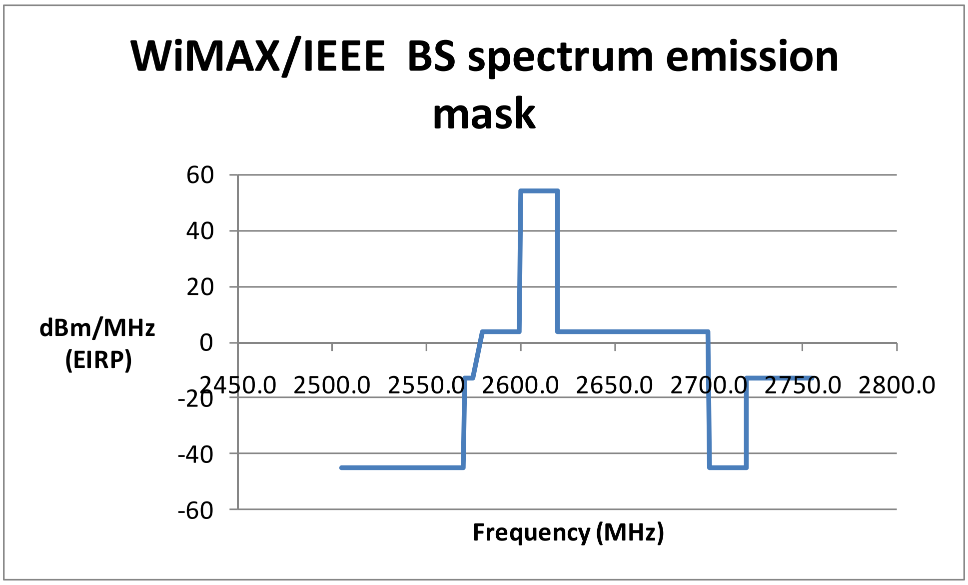


Figure 8-9 WiMAX BS IEEE specification spectrum emission mask including Ofcom BEM

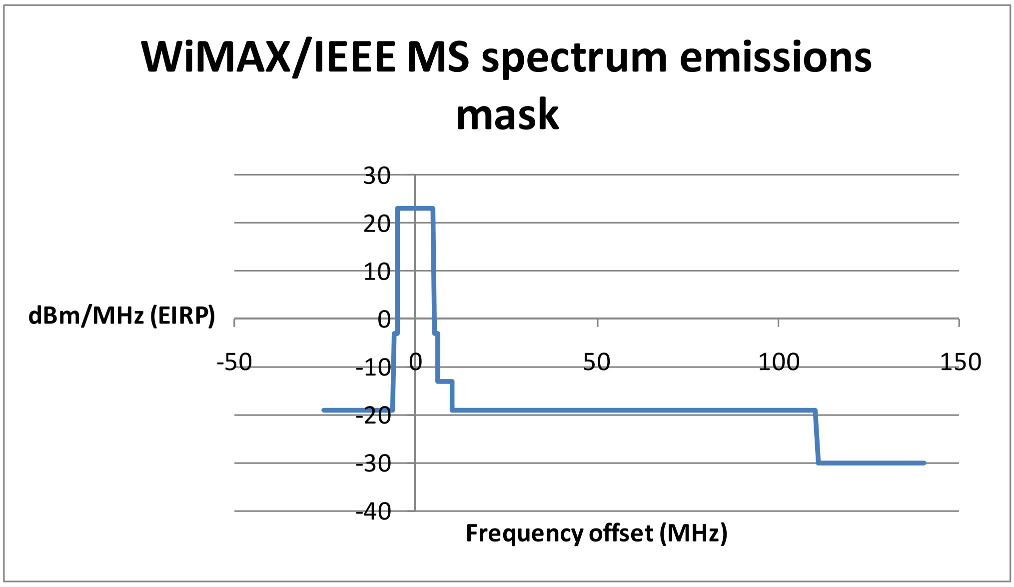


Figure 8-10 WiMAX MS IEEE specification spectrum emission mask including Ofcom BEM

The spectrum emission masks used for the typical case can be seen in Figure 8-11 and Figure 8-12 that have been derived from the noise estimates in section 4.3.1. It can be seen that there is likely to be an improvement in the out-of-band and spurious emission levels below the specification limits due to the filters used within both the base station and mobile station. It has been assumed that the types of filters used in practice will be dominated by the requirement to protect the adjacent channel with a 45 dBc rejection of the spectral regrowth sidebands for the base station and a 30 dBc rejection of the spectral growth sideband for the mobile station.

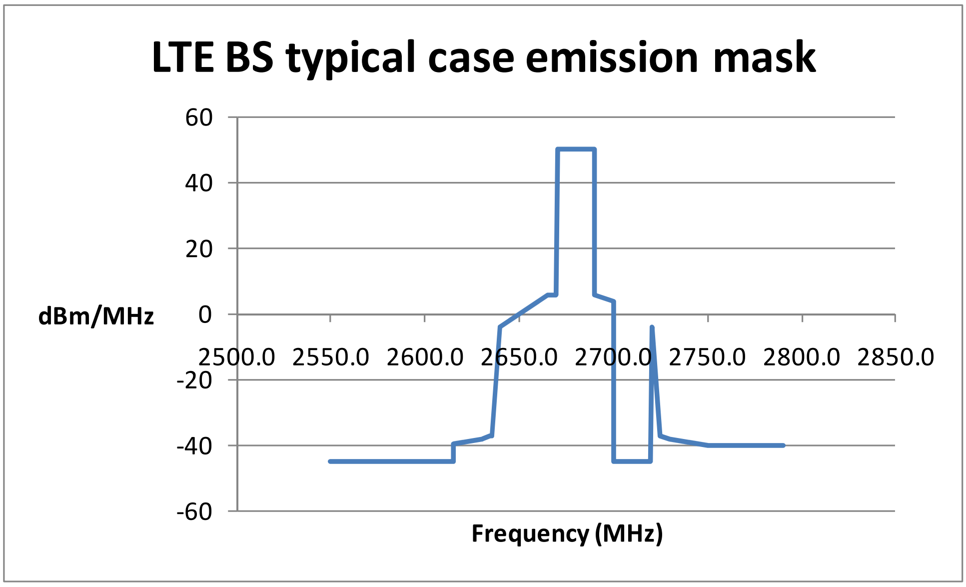


Figure 8-11 LTE BS typical case spectrum emission mask including Ofcom BEM

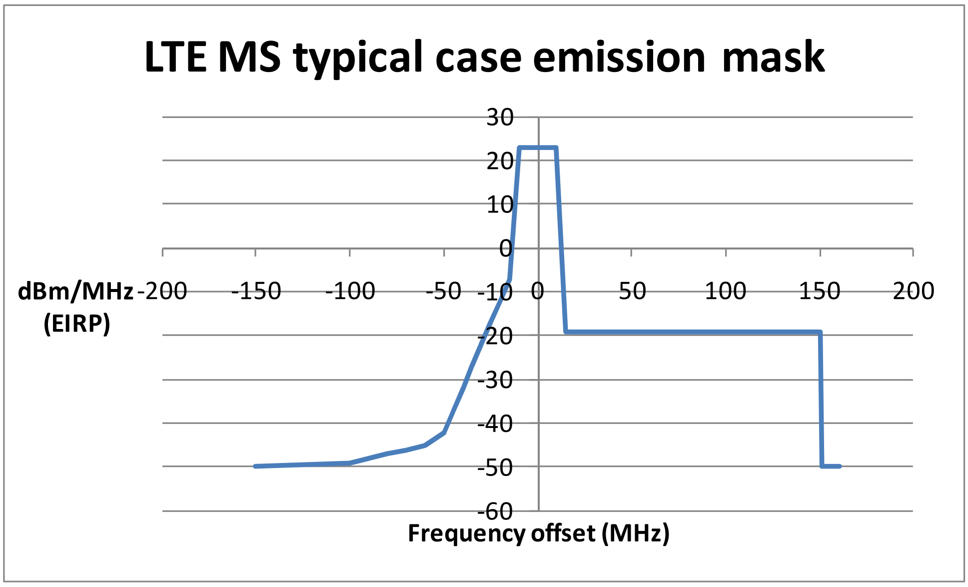


Figure 8-12 LTE UE typical case spectrum emission mask including Ofcom BEM

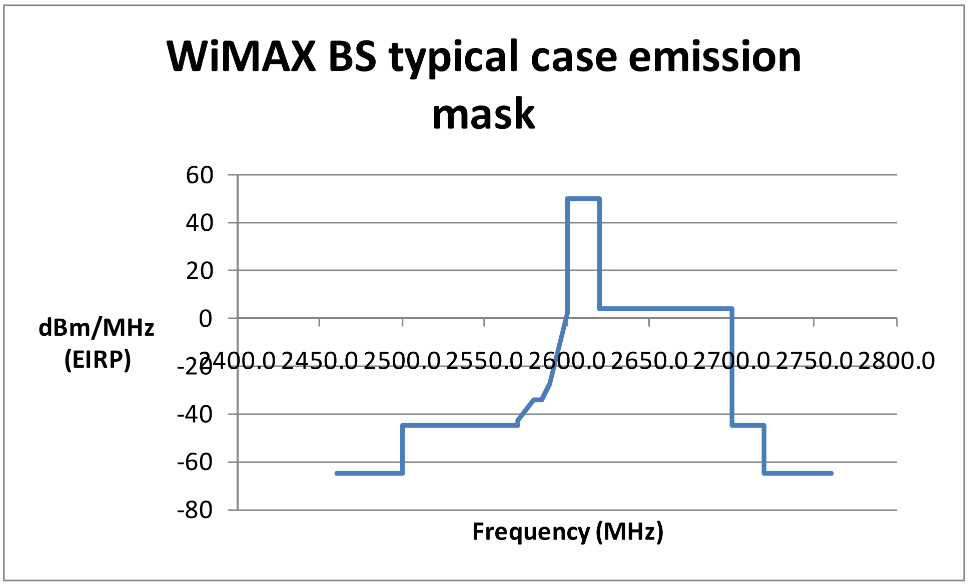


Figure 8-13 WiMAX BS typical case spectrum emission mask including Ofcom BEM

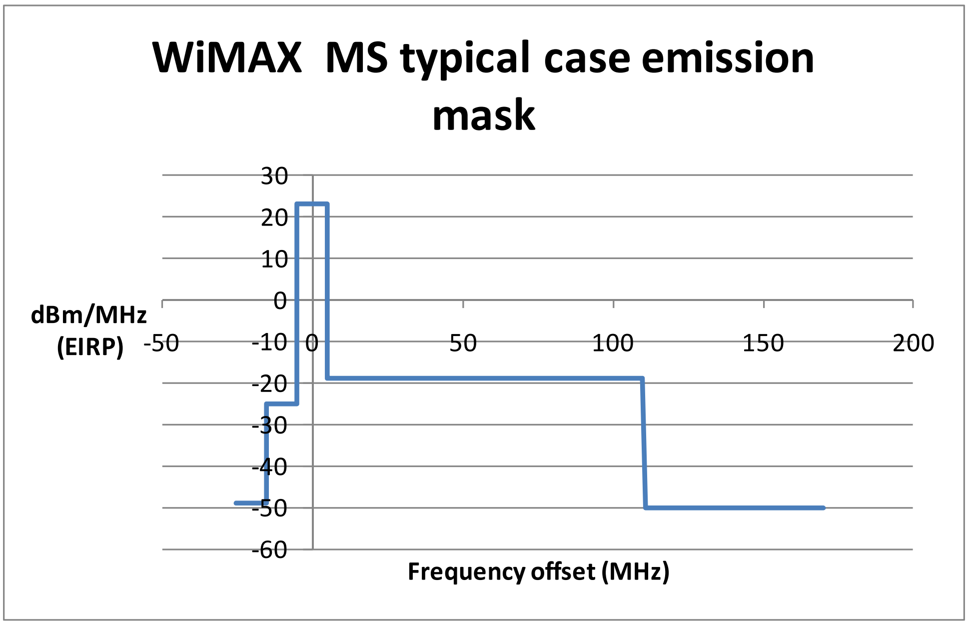


Figure 8-14 WiMAX MS typical case spectrum emission mask including Ofcom BEM

It should be noted that the OOB and spurious emissions vary with the same statistics as the in-band power. Therefore, the distribution of the signals in the out-of-band and spurious domain will be Rayleigh-like and not Gaussian.

8.2.4 Antenna heights (BS and MS) and antenna tilt

The assumed antenna heights of the base station and the mobile station are expressed in Table 8-3. The maximum base station antenna heights used in the software were the maximum antenna heights found during the RF site survey conducted at Heathrow Airport which can be found in appendix D. The base station heights for the typical case use the actual heights found from the RF survey with further supporting evidence provided by BAA and Ofcom Sitefinder.

The base station antenna downtilt, used by mobile operators to control coverage and interference levels over a given area, was set to 0° for the challenging case as the most practical setting to represent the full main beam of the signal directed towards the radar main beam. In the typical case a 6° downtilt has been used based on 3GPP Technical Report 36.814 v.9.0.0[21] which includes a number of different simulation parameters for modelling 3G cellular systems that are intended to be representative of different scenarios. In practice downtilts will be optimised per site but typically bounded by this range (4 - 6°).

The mobile station heights are defined by their particular position within their respective polygon area. For example, if the polygon area is a road then the mobile station height is set to 1.5m to simulate the typical mobile receiver height which is generally used for modelling mobiles in urban/suburban environments. However, if the polygon area is a car park then the mobile station heights is set to 15m which simulates the mobile on the top floor of a multi-storey car park. This was implemented to capture the likelihood of mobile station emissions occurring at a height within the vertical pattern of the radar main beam.

Parameter	Challenging case	Typical case	Unit
BS antenna height	25	Variable according to scenario	M
MS antenna height	1.5	1.5	M
BS antenna downtilt	0	6	Degrees

Table 8-3 BS and MS antenna height and BS antenna tilt assumptions

8.3 Radar parameters

The radar remedial programme that is currently underway within Ofcom is seeking to establish modified radar receivers which can improve the selectivity and ultimately improve the overall radar receiver. The following radar parameters take account of the modified radar parameters expected to be deployed at airports in future.

The radar parameters that have been used in the model have been derived from generic modified radar receiver design characteristics. This is due to the commercial sensitivity of bespoke radar designs and the limited availability of information for specific receivers.

The study has focused on the radar filter responses used to protect the different amplifiers in the receive chain and the noise floor of the receiver since it is this part of the radar that is sensitive to incoming interference. However, in order to generate an accurate deployment scenario the other parameters such as radar antenna height, radar uptilt, half power beamwidth etc. have all been established based on previous studies or trials reports[2], and are shown in Table 8-4.

The block diagram shown in Figure 8-15 is a high level representation of the radar receiver chain which was incorporated into the software model. The diagram shows the two critical points in the receiver chain that can either cause complete shutdown of the radar it the interference threshold is exceeded (point A) or significant performance degradation if the interference threshold is exceeded (point B). It should be noted that the levels expressed at these points are the interference (blocking)threshold levels referred to the antenna connector which takes into account all the losses and gains of the whole receiver. The values have been estimated based on a representative set of radar receiver assumptions which comprise a sub system level filter and amplifier at each stage in the receiver. The aim of the upgrade is to improve the selectivity of the front end which would include improved filtering. It has been assumed that the front-end filtering and the protection threshold (-42 dBm) at point B is low enough to remove any IF mixing effects that could cause problems further down the receive chain. Therefore, sub-system 3 and sub-system 4 are not included in the analysis but required for calculation purposes.

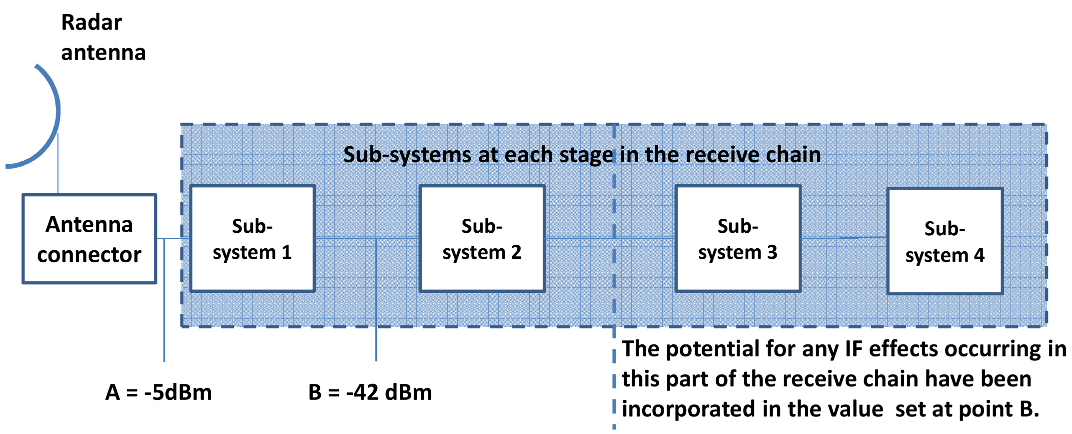


Figure 8-15 Block diagram of modified generic radar receive chain

The interference noise threshold levels have been derived from an example range of -5 dB to -15 dB. This range establishes the upper and lower bounds of the interference spread of interest. ITU-R report M 1464[31] shows that a threshold level of -10 dB is a particular level of interest which falls in the middle of the example range.

Parameter	Challenging case	Typical case	Unit
Radar receiver IF BW (-3dB)	1.7	1.7	MHz
Radar system noise temperature	379	379	K
Thermal noise for radar	-110.5 (1.7 MHz)	-110.5(1.7MHz)	dBm
Radar antenna gain (horizontal)	28	28	dBi
Feeder loss	2	2	dB
Radar antenna HPBW hor	1.4	1.4	degrees
Radar antenna HPBW ver	5.2	5.2	degrees
Radar uptilt	2	2	degrees
Polarisation discrimination	0	3	dB
Position of radar on map area	TQ08427468		
Radar antenna height	5	20	M

Table 8-4 Radar parameters

The assumed filter responses of each stage in the generic modified radar receiver have been incorporated into the software model. Figure 8-16 shows the first RF filter response as developed by Isotek[22] which is one example filter that could be used in the generic modified radar design. This RF filter was placed in sub-system 1 to improve selectivity to the front end of the receiver and help attenuate the powerful transmissions from the 2.6 GHz band.

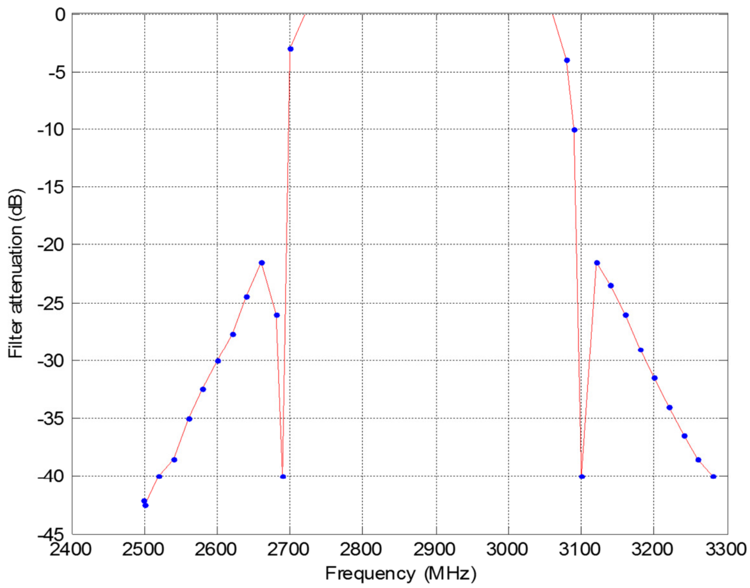


Figure 8-16 1st RF filter response (isotek)

Previous studies[23] have shown an improvement in selectivity in the order of 20-30 dB is needed to reduce blocking to acceptable levels. The filter responses for sub-systems 2 to 4 are assumed to provide further attenuation at each stage but are not included in the analysis at those stages.

The attenuation of the RF filter is taken into account when calculating the blocking level at point B. It is assumed the filter response continues linearly towards the edge of the 2.6 GHz band.

8.4 Modelling assumptions and simulation parameters

This section discusses the simulation parameters that have not been addressed in the above sections i.e. not directly related to base station and mobile station emissions or the radar receiver parameters. The following parameters are discussed in more detail in this section:

- Pathloss
- Shadowing
- Penetration loss from indoor BS/MS
- Sector orientation of the base station antenna
- Attenuation due to antenna patterns
- Channel raster and frequency assignment
- Density of mobile deployment

These parameters are associated with functions related to the communications channel such as the pathloss or a more specific feature with the base station or mobile station. For example, there is a function to calculate the pathloss which takes into consideration all the possible path types that will be simulated and included as options for selection by the program depending on the properties of the path. The path types and propagation models are discussed in more detail in the following sections. The other simulation parameters are discussed in more detail below.

1) Shadowing occurs due to the obstructions in the path and will impact the signals between the base station and the radar and the mobile station and the radar. The shadowing used for simulating interference from base stations has been set to 0 dB due to the static nature of the interference from base stations with no variability in the path and the relatively high heights of both the BSs and the radar. An assumption of 0 dB has been made on the basis the radio path will remain constant.

2) Penetration loss due to indoor base stations and mobile stations has been included in the model to take account of these types of deployments. Confirmation from BAA and Ofcom Sitefinder indicates a number of indoor base stations are deployed across the airport and therefore considered in the model. A value for the typical case of 13.5 dB for indoor penetration loss has been used for the model based on derived values from previous case studies and simulation parameters used for example in Ofcom report "Application of spectrum liberalisation and trading for the mobile sector"[24]. The value for indoor penetration loss for the challenging case is 3.5 dB based on a value for a windowed wall[25].

3) Sector orientation of the base station antenna takes into account the direction of maximum gain of the three sector antenna. The software model is able to rotate the base station to direct the antenna pattern towards the radar. This has the added benefit of directing the null sections of the antenna pattern towards the radar and thus reducing the interference power levels. The antenna orientation directed the maximum gain towards the radar antenna to simulate the challenging case and directed the null of the base station antenna towards the radar antenna to simulate the mitigation technique.

4) Attenuation due to antenna patterns for both the base station and radar antenna has been implemented into the software model. The effect of using the attenuation of the antenna patterns represents the practical deployment environment for both the mobile communications installation and the radar installation. The base station antenna pattern has been sourced from theoretical horizontal and vertical patterns developed in 3GPP technical report TR 36.814 v9.0.0[26] which has been modified according to Kathrein "2-Multi-band Panel, Dual Polarization, 1710-2200 and 2300-2690" base station antenna. The following values have been used for the challenging case scenario:

   - Half power beamwidth (Vertical) = 6.5°
   - Half power beamwidth (Horizontal) = 60°

The base station horizontal antenna pattern can be seen in Figure 8-17

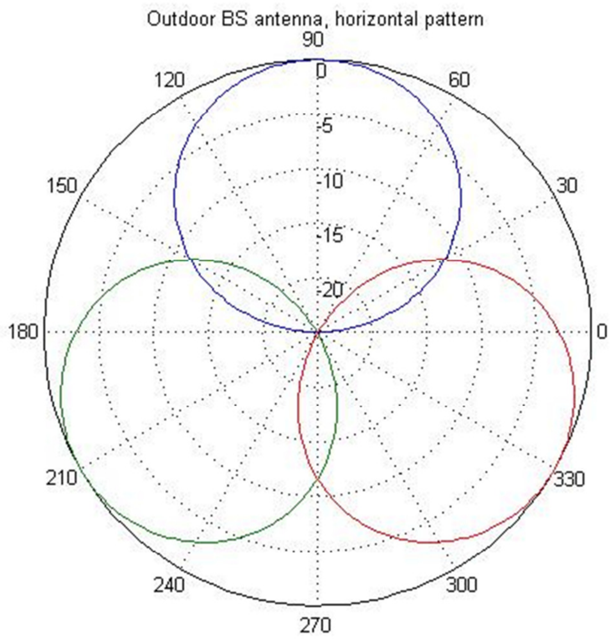


Figure 8-17 Three sector base station horizontal antenna pattern

5) The channel plan assumed for the software model can be seen in Table 8-5 which has been based on one possible outcome of the spectrum award of 2.6 GHz band. Although the outcome of the auction is unknown including likely number of bidders an assumption can be made on a particular outcome that could be considered possible from the auction. The channel configuration was also derived to maximise the potential for interference into the radar. For example, using 20 MHz bandwidth for the highest FDD channel aims to ensure the out-of-band emissions from the FDD fall within the radar band and thus represent the worst case. Information that contributed to the channel configuration was gathered from the stakeholder engagement and knowledge of the use of 2.6 GHz frequencies and from the equipment characteristics being developed for the market, it should be noted no competitive analysis or considerations have been given to the share of spectrum amongst operators and was purely based on deriving the optimum interference characteristics for modelling.

The following assumptions have been made for the parameter inputs to the modelling:

It is unlikely 5 MHz LTE channels will be deployed by operators, since operators will wish to make the most of the additional bit rate and capacity capabilities of LTE, particularly in the 2.6 GHz band relative to lower frequency bands such as 800 MHz. Therefore 20 MHz channels are the most likely option with the remaining 10 MHz picked up for additional capacity. An example channel configuration which can be seen in Table 8-5 could result in a total of seven potential carriers being awarded and thus potentially transmitted from a single shared site. The assumed downlink configuration includes:

- 3 x 20 MHz Downlink FDD

- 2 x 20 MHz Downlink TDD
- 1 x 10 MHz Downlink FDD
- 1 x 10 MHz Downlink TDD

The assumed uplink configuration includes:

- 3 x 20 MHz Uplink FDD
- 2 x 20 MHz Uplink TDD
- 1 x 10 MHz Uplink FDD
- 1 x 10 MHz Uplink TDD

Channel raster for 2.6 GHz				
Channel Number	**Centre Frequency (MHz)**	**BW (MHz)**	**FDD/TDD**	**DL/UL**
Ch 1	2510	20	FDD	UL
Ch 2	2525	10	FDD	UL
Ch 3	2540	20	FDD	UL
Ch 4	2560	20	FDD	UL
Ch 5	2580	20	TDD	DL/UL
Ch 6	2595	10	TDD	DL/UL
Ch 7	2610	20	TDD	DL/UL
Ch 8	2625	10	FDD	DL
Ch 9	2640	20	FDD	DL
Ch 10	2660	20	FDD	DL
Ch 11	2680	20	FDD	DL

Table 8-5 Assumed 2.6 GHz channel plan

Table 8-5 also shows the centre frequencies implemented into the software model and the bandwidths for each channel assignment. Furthermore it was assumed a single operator obtained the central 50 MHz TDD portion which, will use WiMAX technology, so that analysis of the whole spectrum portion could be made without the inclusion of 5 MHz guard blocks separating each channel to protect different operators.
Channel 5 includes a 5 MHz restricted block as specified in the Ofcom auction statement [3] which restricts the in-block EIRP to 25 dBm/MHz to reduce adjacent block interference between neighbouring base stations.

As part of the interference analysis and in particular the challenging case conditions each base station transmitted all seven carriers. Transmitting all seven carriers at full power gives a total EIRP of 74.6 dBm. In contrast under typical case conditions the maximum number of carriers per base station was four. This was to represent a situation more likely to be found within an airport environment. The total EIRP for four carriers transmitting 4 dB below full power gives a total EIRP of 65.4 dBm

6) The density of mobile deployments represents the maximum number of active mobiles within the simulation area. The simulation area is broken up into 25 distinct polygons which represent different areas inside and outside the airport perimeter. For example, the model includes polygons that represent the terminal buildings, car parks and roads where mobiles

can be used. The density of mobile users is divided amongst each of the polygon areas relative to the lowest density area. The following table shows how the distribution of active mobiles was made for the simulations.

Figure 8-18 shows the simulation area polygons in which mobiles are distributed. The relative density is derived for users per polygon based on an assumption that the largest density of users will be in the terminal area compared to the lowest number of users on the service roads. The relative user density relates to users in the busy hour and therefore represents the worst case. It should also be noted that the highest density of users are located indoors within the terminal buildings and therefore interference will be subject to building penetration losses. The next highest density of users is at the bus terminal (polygon 24) and located outdoors but the location is over 1.5 km from the radar (represented by the star shape) and is unlikely to cause interference from blocking or a noise rise based on static case estimations.

Figure 8-18 Simulation area polygons: the star represents the radar location

Polygon number	Name	Indoor/ outdoor	Height wrt ground	Relative user density	Propagation path/model	LOS/ NLOS	PL Code
24	Bus Terminal	Outdoor	1.5m	15	COST 231	NLOS	7
20, 21, 22	Car Park	Outdoor	15m	9	ITU-R P 1546	LOS	8
18	Terminal 3	Indoor	1.5m	60	COST 231	Pen Loss/ NLOS	7
19	Car Park	Outdoor	15m	9	ITU-R P 1546	LOS	8
15, 16, 17, 23	Pier	Indoor	4.5m	30	COST 231	Pen Loss/ NLOS	7
15	Service Roads	Outdoor	1.5m	3	COST 231	NLOS	7
25	Drop off area	Outdoor	1.5m	6	COST 231	NLOS	7
1	Terminal 4	Indoor	1.5m	60	FSPL	Pen Loss/ LOS	1
2	Pier	Indoor	4.5m	30	FSPL	Pen Loss/ LOS	1
3,4,5,6,7,8	Road	Outdoor	1.5m	9	FSPL	LOS	1
9,10,11,12,13	Low rise residential area	Outdoor	1.5m	45	FSPL	Pen Loss/LOS	1
14	Industrial site	Outdoor	1.5m	5	FSPL	LOS	1

Table 8-6 Polygon area properties

The maximum number of active mobiles has been derived from a variety of assumptions which are given in appendix B of the Appendices document. BAA data on the number of passengers flowing through the airport and associated assumptions on the potential penetration of LTE lead to an assumption that the number of active users distributed across the simulation area polygons is 53.

The study has focused on 2.6 GHz cellular deployments within an airport environment. Specifically the airport environment chosen for the study was Heathrow Airport which can be considered atypical due to the extensive geographical area covered and very large passenger densities. However, the airport layout offers an interesting interference model environment providing different scenarios for analysis, such as interferers transmitting close in to the radar or interferers transmitting far away from the radar yet still within the airport demise.

Airports tend to have common layouts which include similar common terrain and clutter features, such as flat terrain, low rise buildings, densely populated areas such as terminal buildings and moving vehicles (including aircraft). These features all contribute to the type of propagation model used for each path between the base/mobile station and the radar.

Some of these features can be seen in Figure 8-19, including terminal buildings, car parks, drop off areas, piers and other related structures. The passenger areas are usually located close to each other for convenient access between car parks, terminals and collection/drop off areas. The structures and layout determine the type of path that exists between the base stations / mobile stations and the radar.

The software model is based on the features of Heathrow Airport and it can be seen that in the Central Terminal Area the passenger buildings are located close to each where the majority of the mobile emissions will be transmitted from and the greatest sources of interference to the radar.

The aim of the study was to determine the interference into a single radar receiver at one airport to establish the interference environment that could exist at all airports using Heathrow Airport as a reference. It is then possible to apply the principles used in the present study to other types of deployments and airport environments. The general processes will remain the same only the parameters will require change depending on the type of environment to be modelled.

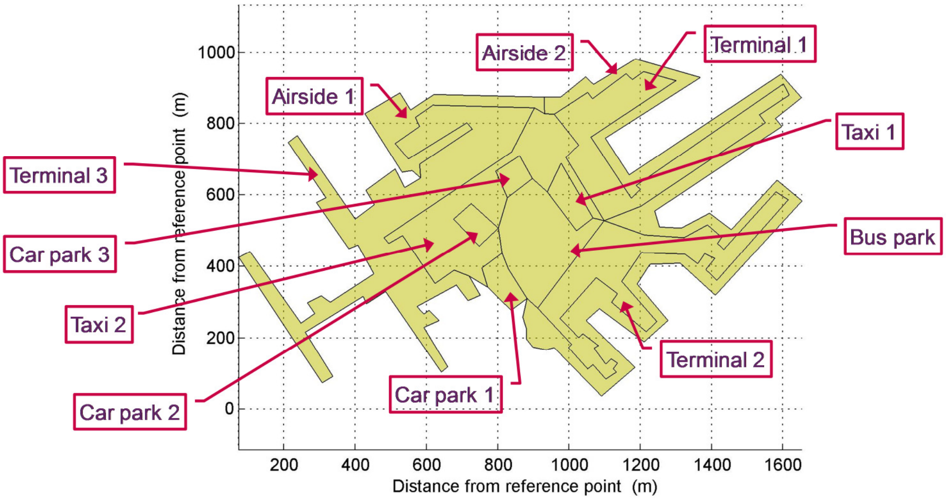


Figure 8-19 Heathrow Airport Central Terminal Area clutter layers

Figure 8-20 Heathrow Airport Central Terminal Area landscape[19]

Figure 8-20 shows a landscape view of the Central Terminal Area at Heathrow airport to demonstrate the types of structures that feature between the interferers and the radar. Generally the structure heights are low apart from those structures necessary for air traffic control. Typically heights do not exceed 25-30m in the Central Terminal area and predominantly are the multi-storey car parks (where the photo was taken from) and the terminal buildings. It can be seen that mobile use outdoors will be at ground level or from the roof of the multi-storey car parks, otherwise it is indoors. Additionally, base stations on the roof of the car parks and terminal buildings will have unobstructed paths to the radar location.

[19] Image sourced from Google images

8.4.1 Propagation models

The software model includes a list of relevant propagation models that are used by the program depending on the path type, described in the section above, that exists between the victim receiver and interfering transmitter. Each propagation or loss model was selected based on the relevant propagation criteria found within the specific airport environment. The following types of propagation/loss models were considered relevant for inclusion in the software model were:

Free space path loss models used for distances greater than 1km become meaningless due to the impact of terrain and obstacles that must be taken into account. Therefore FSPL are useful for the airport deployment study due to the short coordination distances of interest.

Empirical models such as COST 231[27] or ITU-R Rec P.1238[28] are used for indoor and short distances which are appropriate for an airport environment and will be used for this study.

The benefits to this study from the use of the more complex models due to the short distances include:

- Consideration given for high clutter environments (representative of airport environment)
- Provides accuracy of results
- Robust and confident set of results

The study did not consider the use of detailed site specific models such as ray tracing due to the complexity involved in modelling the path from each base stations site and each mobile. There would be intensive computer processing required for the analysis from each interferer which would be time consuming and considered unnecessary due to the suitability and appropriateness of standard propagation models within an airport environment.

In previous related studies one particular propagation model that has been used for interference assessment was ITU-R Rec P.452-12[29]. This propagation model is used for the interference assessment of stations on the surface of the Earth above 0.7 GHz and was independently verified for Ofcom. A previous study [30] concluded the propagation model ITU-R Rec P.452-12 is an appropriate model for calculating co-ordination areas around radars by calculating the minimum safe distance an interference source transmitting in the 2.5 to 2.69 GHz could be from a radar without exceeding a defined signal level at the radar receiver.

On the basis of the above layout the following paths were used to derive the propagation models:

1. Base station transmitting into radar close in or far away either outdoors or indoors
2. Mobile transmitting into radar either close in or far away either outdoors or indoors
3. Base station to mobile station path indoor and outdoor

Figure 8-21 and Figure 8-22 illustrate the paths of relevance to the interference assessment.

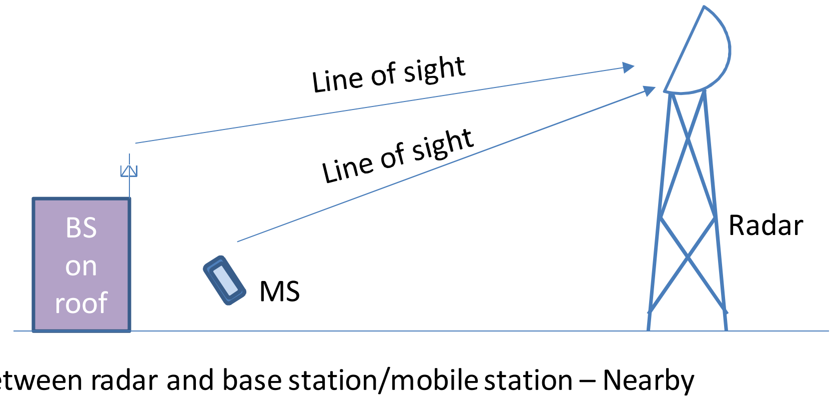


Figure 8-21 Path distance with line of sight – Radar and MS nearby

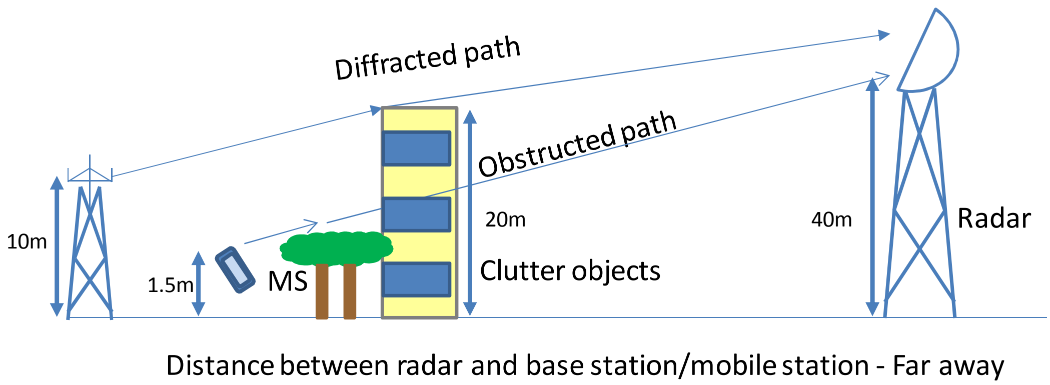


Figure 8-22 Far away path distance taking clutter into account

The three main paths contain six potential path lengths which are discussed in more detail below:

Scenario 1a – The base station to radar is a nearby (<500m) line of sight path and the following models apply i) FSPL ii) FSPL – 6dB which takes account of multipath effects around the radar in cases where possible reflections may contribute to the addition of signals appearing at the radar receiver. Scenario 1b - The base station to radar is a far away (>500m) line of sight path with clutter obstacles and ducting occurring for small percentages of time. There is the possibility of a mix of the paths due to the part line of sight and reflections. The percentage time variability used in this scenario was 99.9% as specified from previous Ofcom studies[30]. The propagation model used in the software was ITU-R P 452 with options 8a (LOS) and 8b (LOS with sub path diffraction).

Scenario 1c - The base station indoor path to radar, used very low power and penetration loss through walls and windows using FSPL

Scenario 2a - The mobile station to nearby radar. The path is line of sight using time variability of 99.9% for Monte Carlo at 1.5m above ground level. There is a fixed path loss around the base station so FSPL will be the worst case scenario surrounded by scatterers. Therefore the Rayleigh fading case was applied with a range of 3-5 dB i.e. an 'inverted' Rayleigh distribution coming from the mobile due to the application of power control.

Scenario 2b - The mobile station to radar for far out distances. The propagation model used for this instance is COST 231 Hata[27] modified for 2.6 GHz at ground level. This was due to the path being LOS with some clutter likely causing obstruction. As the mobiles increase in height above local ground another option is ITU-R Rec P. 452 or ITU R Rec P 1546[20]. ITU-R Rec P. 1546 includes a correction factor for varying the height of the mobile.

As discussed above in the case of an airport deployment, considerations of interfering signals within, a 5km radius have been analysed. Therefore a propagation model must take into account the specific loss effects of the signal within the defined environment. In the case of ITU-R Rec P.452-12[29], considerations for line of sight, clutter losses and diffraction are given whose effects would all be appropriate for an airport deployment specific scenario.

The other models of interest to the study are considered due to the mix of paths for example, multiray losses, short-range and indoor propagation which have been taken into consideration. The propagation models that have been used are specific to the paths between each of the base station locations and the radar with the same principle applied to the mobile stations using the properties of the polygon area as method to assign the specific propagation model. In addition for an airport deployment environment there is a mixture of indoor sites using a distributed antenna system and outdoor sites using a mixture of shared infrastructure and individual sites. This mix of propagation paths means that considerations for the various losses are accounted for by different models.

[20] ITU-R P. 1546 Method for point-to-area for terrestrial services in the frequency range 30 MHz to 3000 MHz

This is implemented in the software using different pathloss codes for each path type that can be assigned to each base station and each polygon area to ensure the appropriate propagation model is applied for each specific path.

The paths that are found between the base station sites and the radar site include a mix of free space at short distances within hundreds of metres and obscured paths from concrete and glass buildings, moving vehicles and moving aircraft. Table 8-7 shows the base station location properties used within the software model which includes the location using National Grid Reference coordinates, the antenna height with respect to ground, the propagation model, whether the path is line of sight or not and whether the site is indoor or outdoor. Most of the outdoor base stations modelled within the airport perimeter are located within 2000m separation distance of the radar and some outdoor base stations located outside the airport perimeter are within 500m of the radar which validates the use of the particular models implemented in the software model.

Name	In/Out-door	Easting	Northing	Height above ground	Propagation model/Path	LOS/NLOS	PL CODE
BS 1	Outdoor	507465	175955	25	ITU-R P 452	LOS	2
BS 2	Outdoor	507415	175925	25	ITU-R P 452	LOS	2
BS 3	Outdoor	507215	175805	25	ITU-R P 452	LOS	2
BS 4	Outdoor	507295	175805	25	ITU-R P 452	LOS	2
BS 5	Outdoor	507155	175775	25	ITU-R P 452	LOS	2
BS 6	Outdoor	507815	174415	24	FSPL	LOS	2
BS 7	Indoor	507865	174475	6 (Omni)	FSPL	Pen Loss/LOS	2
BS 8	Indoor	508015	174675	4 (Omni)	FSPL	Pen Loss/LOS	2
BS 9	Indoor	508475	174685	3 (Omni)	FSPL	Pen Loss/LOS	2
BS 10	Outdoor	510018	174566	16	FSPL	LOS	3

BS 11	Outdoor	509725	174065	11	ITU-R P 452	LOS	3
BS 12	Outdoor	509125	173835	11	ITU-R P 452	LOS	3
BS 13	Outdoor	507485	173965	14	ITU-R P 452-12	LOS	4

Table 8-7 Base station location simulation properties

9 Explanation of modelling outputs

Ofcom's requirements were to understand the interference situation from 2.6 GHz systems into radars within an airport environment. Therefore, the forms of output must represent the most appropriate means of expressing the situation. The following section describes the form of output and what it signifies in relation to the interference scenarios that have been generated.

9.1 Statistical analysis

Statistical analysis for the present study enables the variation in the likelihood of a particular result occurring. In the case of an interference threshold being exceeded, deriving the probability of occurrence is a useful analysis tool that helps establish the overall interference situation and thus determine the severity of the problem.

The interference assessment has addressed blocking at two main stages in the radar receiver chain and also analysed an increase to the interference noise power into the radar receiver. For each mechanism there is an interference threshold that, if exceeded, degrades the performance of the radar.

The statistical analysis is useful for generating results for a particular dynamic situation which has a degree of variability. It has been established that due to the variability in the mobile environment the statistical output will provide the spread of results necessary to capture the varying interfering effects. In contrast a statistical output for the base station interference does not provide interesting results due to the static nature of the environment with variability limited to the fluctuations in signal envelope.

The results for the mobile stations therefore will be of a statistical nature and include output plots of Cumulative Distribution Function (CDF) curves for each modelled mobile station position within each polygon area for a full radar rotation. This output presents the probability of interference occurring at a certain level and calculates the interference for each mobile position. The statistical analysis determines the interference for the worst angle after 200 Monte Carlo iterations which is then produced as the output. An example plot of the CDF curves for each point in the receiver chain can be seen in Figure 9-1 below, which shows all the CDF curves for the particular simulation for each angle around the radar.

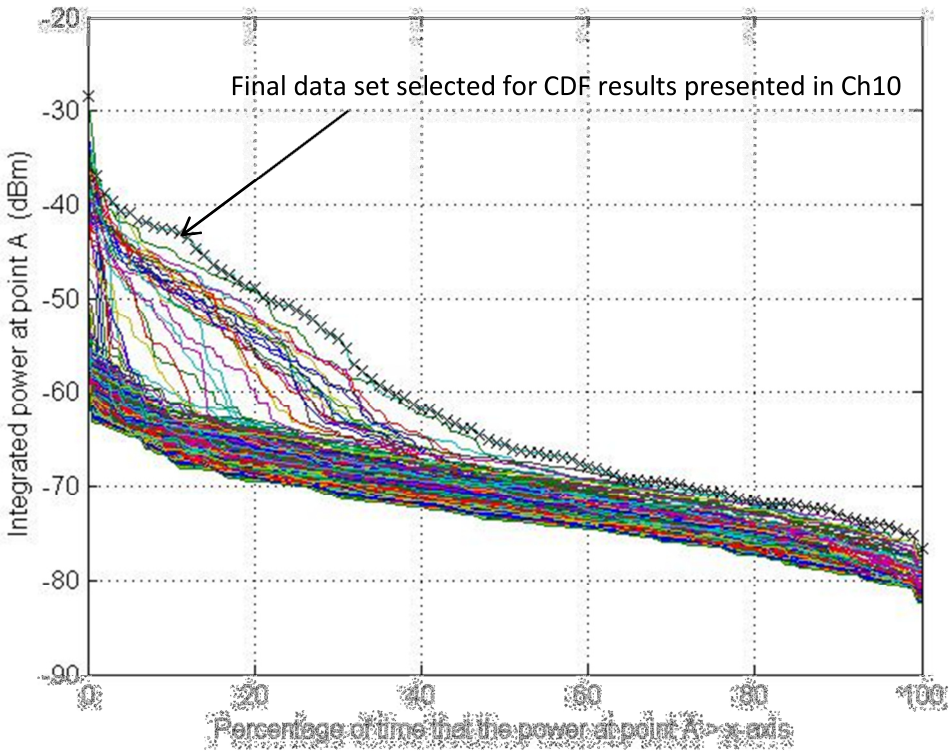


Figure 9-1 Example cumulative distribution functions (CDF) of power received at the radar antenna connector. Each line represents the distribution for a given radar orientation angle. The line with crosses represents the composite worst-case CDF across all angles.

For each output CDF curve individual CDF curves are produced which represent different radar rotation angles. Each CDF represents variation due to mobile locations, shadowing, power control and signal envelope fluctuations. The worst-case CDF is derived from the set of angles that are characterised by the greatest interference power as shown in Figure 9-1.

Across the statistical range the interference or blocking levels are output and the interference level at a particular percentage of time can be determined. The worst angle is a result of all the calculations which provides the information to be used for each interference scenario. For example, if the output shows significant levels of interference identified from a particular angle from the radar then the next stage of analysis can investigate the mitigation techniques required to combat the sources of interference in that specific area.

As the radar rotates the main beam of its antenna creates a rotating sector which sweeps across the simulation area and illuminates several mobile- and base-stations. For a given illuminated sector the mobile stations have a variable position and transmit power, due to user mobility, shadowing and building penetration loss variability, mobile-network power-control, signal envelope variability and resource allocation. Therefore, for a particular radar rotation-angle the received interference power at the radar is a variable. Each rotation-angle thus corresponds to a CDF, as plotted in Figure 9-1

Note that each CDF curve corresponds to a specific illuminated simulation area sector. Therefore, the percentage of time (probability in a CDF plot) in the x-axis refers to the percentage of time instances that the power is less than that of the x-axis, given that the radar illuminates that particular sector. This conditional-probability should not be confused with the probability of occurrence that is irrespective of the radar-angle. The conditional-probability is of interest in this study, because as the radar rotates it periodically sweeps across the worst-case polygons (or base stations). Therefore, overall the blocking probability of the radar is very small, partially because the radar-antenna horizontal-pattern attenuates the interference by several decibels (see Figure 8-16), even though the blocking probability may be systematically high at the particular worst-case angle. The CDF plots given later in this report correspond to the worst-case conditional probability of interference.

Also note that, the CDF curves in Figure 9-1 are an example of received interference from mobile stations. The interference from base stations is expected to have less variability when compared to Figure 9-1, due to the base stations' fixed locations, and therefore the CDF curves are anticipated to be flatter.

Due to the mobile stations' mobility within the simulated polygon areas the worst-case CDF is built across a range of rotation-angles, for which the worst-case polygon is illuminated. In order to pick-out the worst-case CDF we choose the greatest interference-power across the rotation-angles. This is shown by example in Figure 9-1 with the x-markers.

To give an example of how the angles of interference are represented against a large interferer can be seen in Figure 9-2. The plot shows a spike on the diagram with a blocking level of -25 dBm at an angle of 135°. All other angles show lower levels of interference below -50 dBm. It is also noted that the polar plot designates 0° angle towards the East from the radar and the angles increase in an anticlockwise direction from 0°. Therefore 90° lies to the North of the radar and so on and all angles expressed in the results are based on the polar plots shown in Figure 9-2.

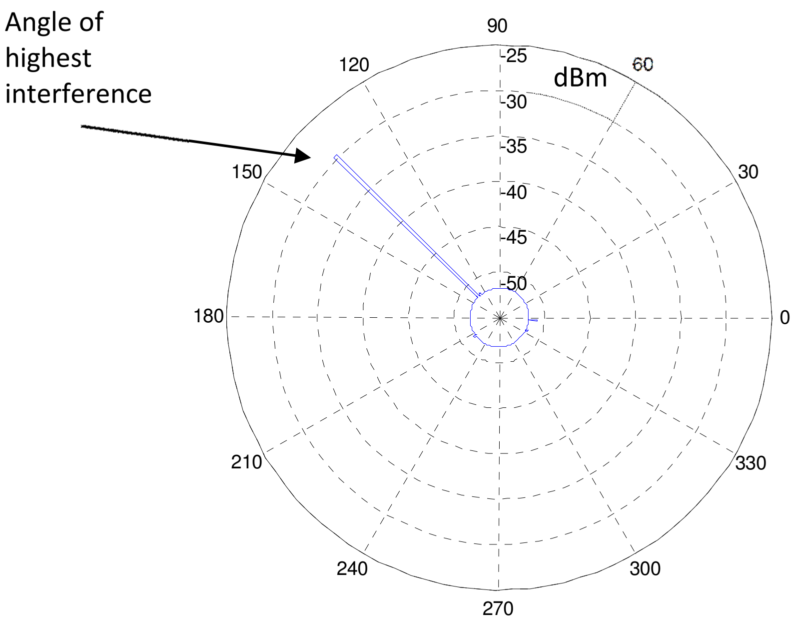


Figure 9-2 Polar plot of angle of highest interference showing blocking level from direction of the base stations

9.2 Example result output plots

9.2.1 Blocking of the radar receiver from base stations

The form of output produced arising from base station interference can be seen in Figure 9-3. The plot shows the overall blocking level at each stage in the receiver chain against its corresponding threshold level at the worst orientation angle for the radar. For example, in Figure 9-3 it can be seen the blocking level at Point A (red line) exceeds the threshold (dotted red line) for 100% of the time the radar was pointing at the base station and the radar is considered to be in compression at this point in the receiver. This output plot was considered under challenging case conditions.

The blocking levels start to increase for smaller percentages of time the radar is pointing at the base stations which captures the effects of the peaks in the signal envelope. The output levels have been produced in the same manner as the mobile stations but with fewer Monte Carlo iterations due to the limited variability and consequent reduced requirement for the statistics to settle.

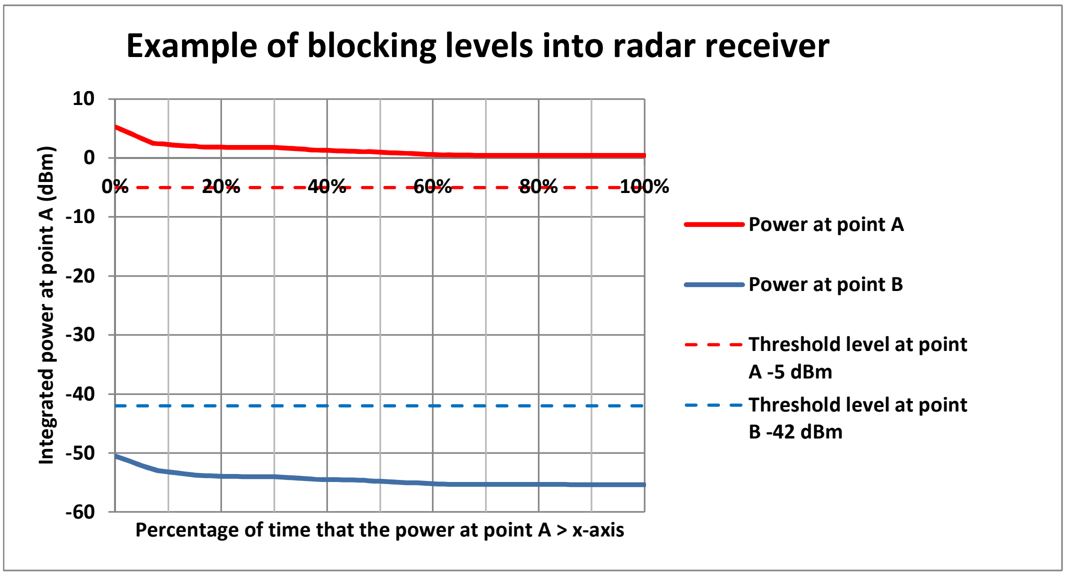


Figure 9-3 Example CDF of blocking levels from base stations at point A and point B in the receiver showing its corresponding threshold limit

Further analysis of the blocking levels can be undertaken to identify which base stations cause the highest level of interference. The plot in Figure 9-4 shows a bar chart of the peak blocking level, which is instantaneous peak blocking level at 1% of the time the radar points at the angle of the base station. Therefore blocking levels occurring above the threshold line generate interference at point A. For example, it can be seen from Figure 9-4base station 9 has a peak blocking level recorded at 4.9 dBm, which is 9.9 dB above the threshold. Just two of the thirteen base stations do not exceed the threshold, however, suggesting that appropriate siting of base stations relative to the radar can substantially mitigate interference.

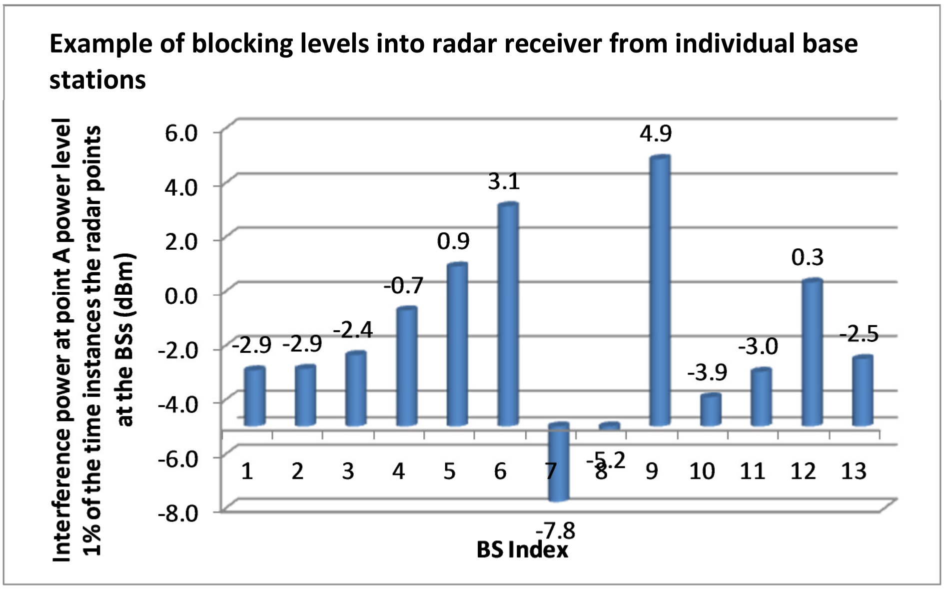


Figure 9-4 Example graph of each base station peak blocking level at Point A in radar receiver Noise rise at the radar receiver co-channel with the radar centre frequency from base stations

The software model calculates the interference noise power that is co-channel within the overall radar receiver bandwidth. These calculations are made for both the base stations and mobile stations and generate the total interference noise power from the out-of-band and spurious emissions. The I/N is calculated from the baseband interference noise emissions and the output is produced as an interference level that either exceeds the threshold level or not and plotted onto the graph for the CDF.

It can be seen in Figure 9-5 that the limits of interest are bound between -15 dB and -5 dB which is the range of interference noise rise is at which radar performance is acceptable, as specified by Ofcom. This range also includes the median level of -10 dB which is a protection level as specified in ITU-R M.1464[31].

The output shows the variability of interference exceeding the limits of interest for 100% of the time.

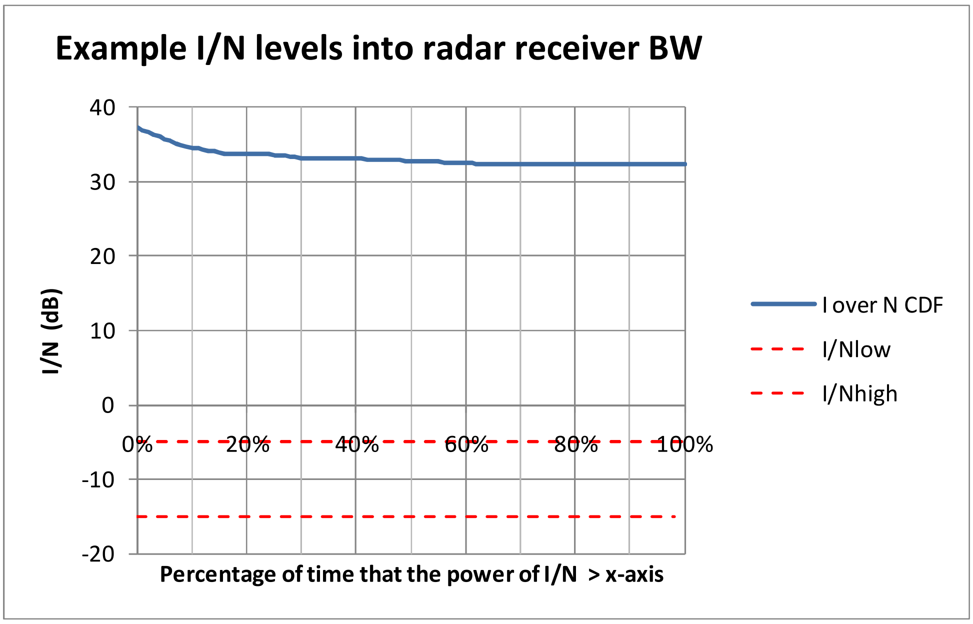


Figure 9-5 I/N level from base station into radar

Further post processing of the base station results can be seen in Figure 9-6. The bar chart shows the peak I/N level which is recorded for 1% time instances the radar points at each base station. This output representation enables the analysis of each base station and its contribution to the overall interference and establish which base station(s) contribute to the rise in noise above the levels of interest. Further analysis such as that shown below helps to identify the specific base stations contributing the highest levels of interference and address the types of mitigation that could be implemented. The results below show that a 42 dB reduction is necessary to bring the peak noise power within the minimum (-15 dB) threshold level.

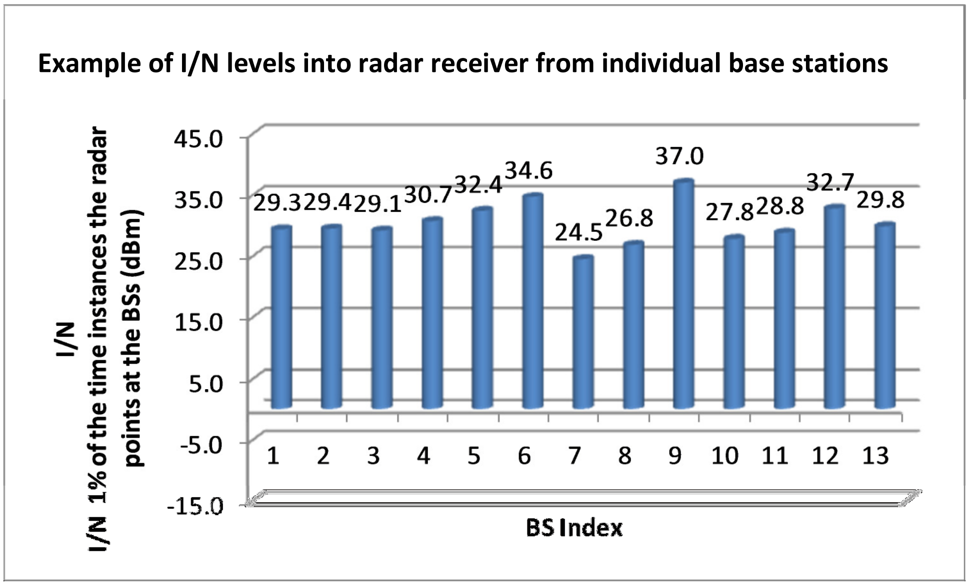


Figure 9-6 Bar graph of each base station I/N level into the radar receiver

9.2.2 Blocking of the radar receiver from mobile stations

The form of output produced from the mobile station interference can be seen in Figure 9-7. The plot shows how the overall blocking levels vary with the x-axis. This is due to the variable nature of the mobile station environment as discussed in the previous section.

The larger changes in blocking level occur at each end of the curve with a gentle sloping middle section. The particular output occurs due to the cases where high levels of blocking have been recorded infrequently across the spread of results.

Similar to the base stations the plot shows the highest overall blocking level recorded from each iteration and calculated for each stage in the receiver against its corresponding threshold level. In Figure 9-7 it can be seen the blocking level at Point A does not exceed the threshold level. The blocking level begins to increase for percentages of time of 10% and lower as the statistics capture the high levels of interference for the smaller percentages of time. This output plot was considered under challenging case conditions.

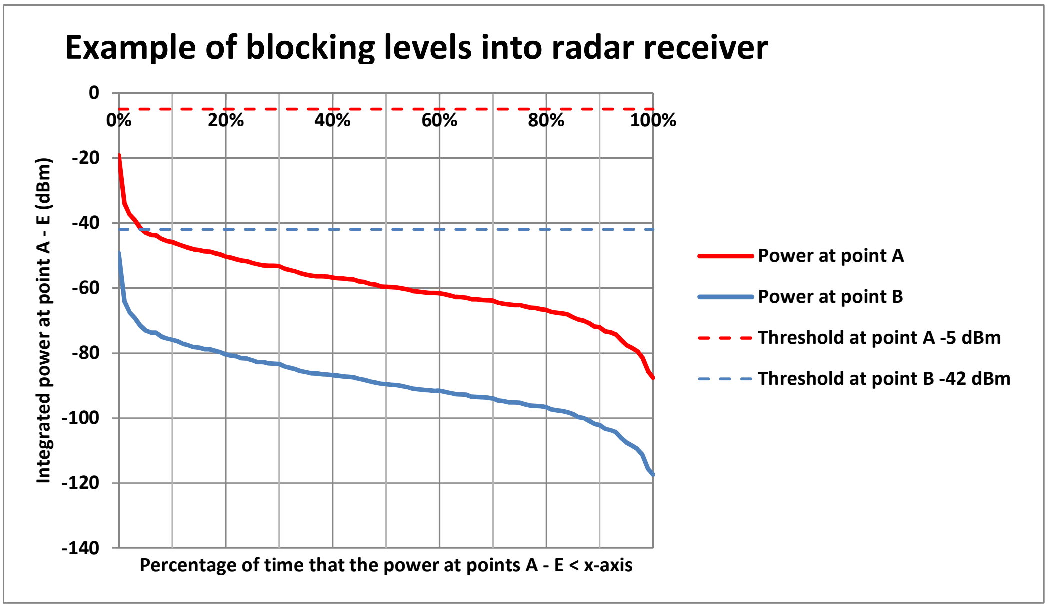


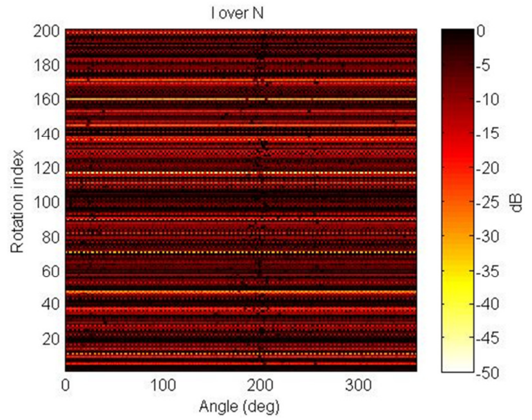
Figure 9-7 Example CDF results of blocking levels from mobile stations showing blocking at point A and point B in radar receiver with its corresponding threshold.

The example polar plots below show how the areas of highest interference are captured using 2D and 3D polar plot diagrams which give the levels of interference against the direction the interference is coming from towards the radar and described in more detail in Figure 9-8 below.

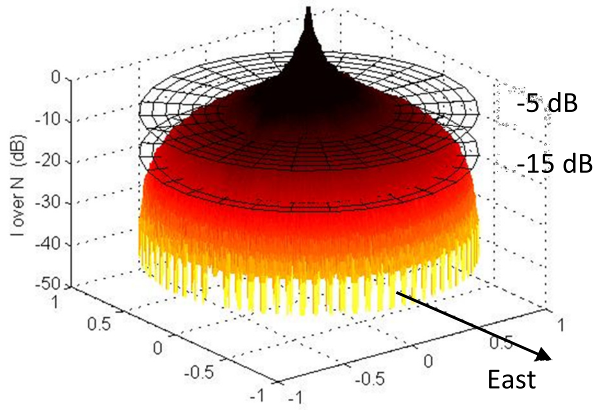
Plot (a) shows an example of the I/N noise rise distribution for a different rotation index which translates as the unit metric for the radar rotation for capturing all possible interference effects. This is particularly important for TDD systems where the transmissions are either uplink or downlink and may not be transmitting whilst the radar is pointing in the direction towards interference.

Plot (b) is a 3D polar plot of the I/N noise rise depicting the level of interference incoming from each angle which helps demonstrate the direction of maximum interference.

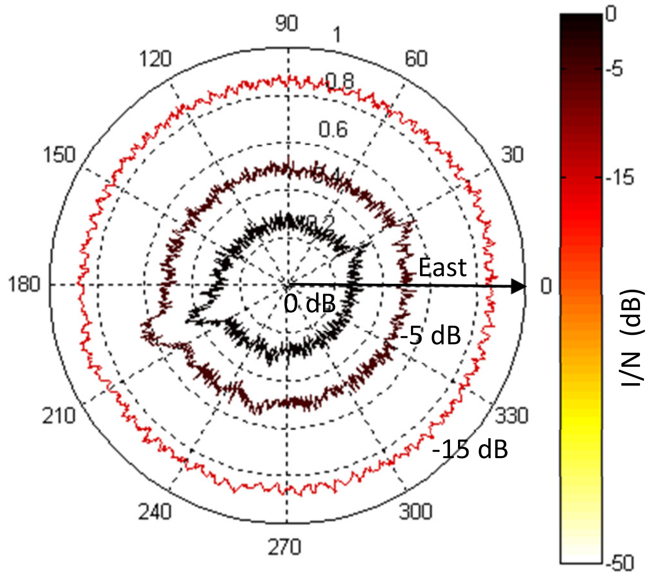
Plot (c) is a plan view polar plot of (b) which provides a more distinguishable view of the direction of maximum interference from the different intensity levels of the contours plotted. Contours closer to the centre of the plot have increasing interference level.



(a) Noise rise level at the radar receiver as the radar rotates. Colour intensity is used as scale of the noise rise value. The starting rotation angle is when the radar points east. The radar rotates counter-clockwise. Different rows depict the noise rise for varying mobile locations. For each angle (column of values) the CDF of the noise rise can be assessed, see subplot (b).



(b) CDF of the noise rise level at the radar receiver as the radar rotates (3D view). The noise rise values are positioned on the longitudinal-axis. The percentage of time that the noise rise exceeds the level of the longitudinal-axis is given by the polar-axis. The further the horizontal cut, at a given threshold value in the longitudinal-axis, is from the longitudinal-axis, the higher the probability of the noise rise exceeding this threshold value. Two horizontal cuts are plotted at the maximum and minimum I/N thresholds. Each radar rotation-angle corresponds to a column of values from subplot (a). Colour intensity is used as scale of the noise rise value.



(c) CDF of the noise rise level at the radar receiver as the radar rotates (contour view). This is a top-down view of subplot (b), and it plots the horizontal cuts at different contour levels. The percentage of time that the noise rise exceeds the contour-level is given by the polar-axis. The further the cut is from the pole, the higher the probability of the noise rise exceeding this contour level value. Colour intensity is used as scale of the noise rise value in the plotted contours.

Figure 9-8 2D and 3D polar plots for detailed analysis of angle of worst interference

9.2.3 Example noise rise at the radar receiver co-channel with the radar centre frequency from mobile stations

The software model calculates the interference noise power that is co-channel within the overall radar receiver bandwidth. These calculations generate the total interference noise power from the out-of-band and spurious emissions for each mobile. The output produced is the overall interference level from the worst angle plotted onto the graph for the CDF of I/N against percentage of time that the I/N exceeds the x-axis.

It can be seen in Figure 9-9 that the I/N levels of interest liebetween-15 dB to -5 dB. The maximum acceptable interference increase above the noise level as specified by the ITU is -10 dB. The output shows the interference exceeding the ITU threshold for less than7% of the time the radar points towards the angle from where the highest interference is generated from the mobile stations.

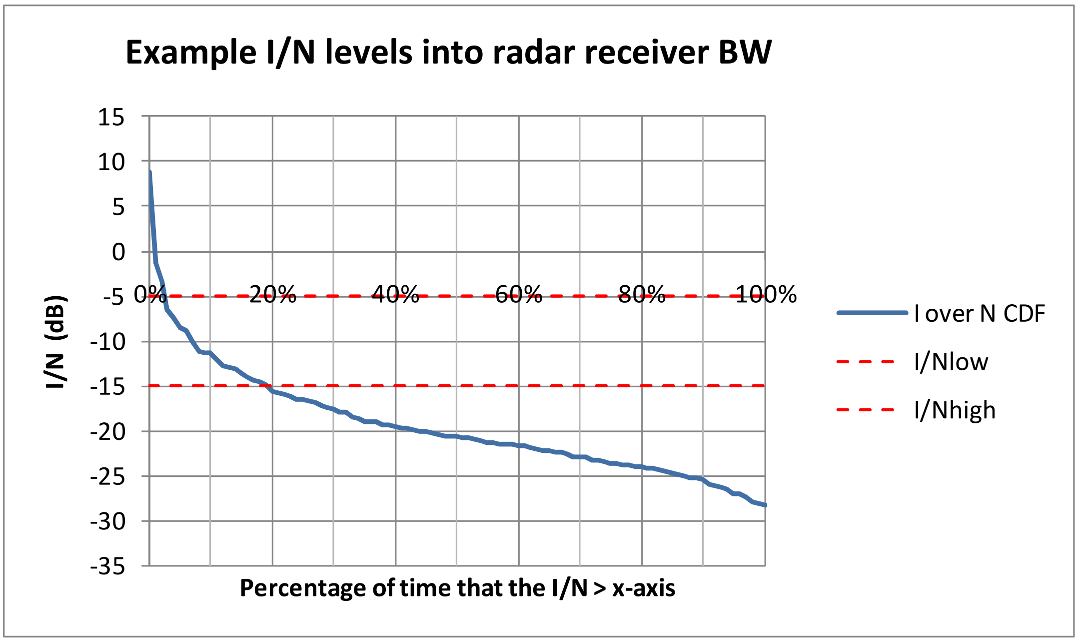


Figure 9-9 Example CDF results of interference noise rise for MS into radar

The outputs from the results have been derived to establish all the possible interference mechanisms into the radar, capture the variability from base stations and mobile stations within the interference environment and provide sufficient evidence to draw conclusions on the basis excessive interference causes degradation to radar performance.

The interference blocking levels which show the plots for each point in the receiver are useful to understand quickly the impact of the particular scenario has on the radar. The in-depth analysis for the base stations showing the contributing interference level from each base station provides the necessary detail to identify the mitigation required to bring the interference within acceptable limits.

9.3 *Interference over all angles*

This study considers the interference at the worst angle to determine the maximum tolerance of the performance the radar can withstand from 2.6 GHz deployments at airports. An alternative metric that can be considered is described in this section which refers to the interference over all angles.

The interference over all angles is an average of the calculated CDF's at each angle which can be interpreted as the absolute percentage time results for a given scenario. Below is an example comparison of interference at 1% time at the worst angle compared to interference at 1% time over all angles.

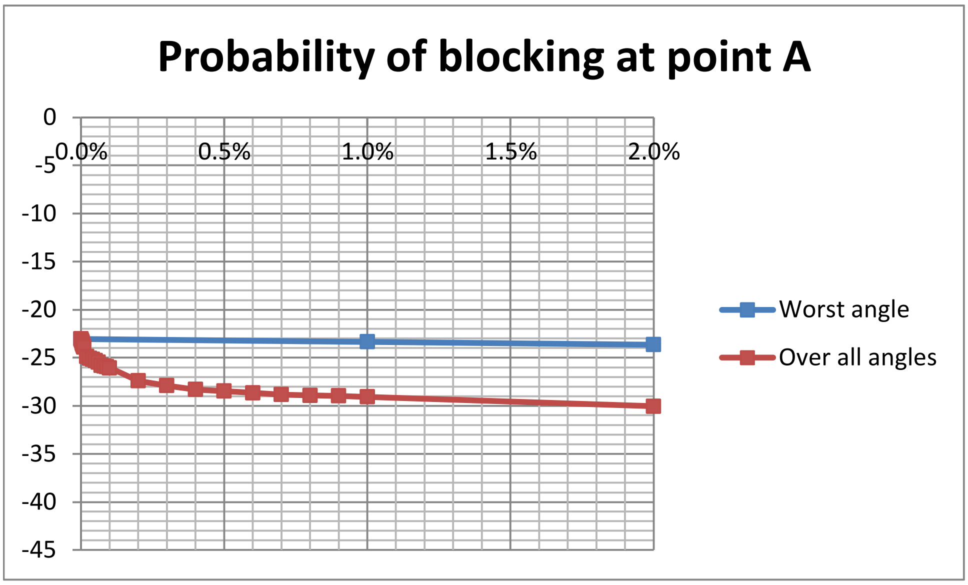


Figure 9-10 Comparison of CFD curve at 1% time between the worst angle and over all angles

Figure 9-10 shows an enhanced example plot of the results from modelling the blocking at point A in the radar receiver from a base station. At the 1% time point on the graph (x-axis) there is a 6 dB difference between the interference from the worst angle and over all angles indicating the absolute time probability of interference. A rule of thumb can be used when examining the results to translate them from 1% time at the worst angle into 1% time over all angles is as follows:

Base station (Blocking):

$$1\%\ time\ over\ all\ angles = Blocking(1\%\ time\ worst\ angle) - 6\ dB$$

Base station (Noise rise):

$$1\%\ time\ over\ all\ angles = \frac{I}{N}(1\%\ time\ worst\ angle) - 12\ dB$$

Mobile station (Blocking):

$$1\%\ time\ over\ all\ angles = Blocking(1\%\ time\ worst\ angle) - 6\ dB$$

Mobile station (Noise rise):

$$1\%\ time\ over\ all\ angles = \frac{I}{N}(1\%\ time\ worst\ angle) - 5.5\ dB$$

The decrease in the level of interference in the order of 6-12 dB arises due to the mix of variables contributing to the interference levels. These include different antenna heights, mix of distances of the base stations from the radar and reduced level of interference from indoor sites.

10 Interference modelling results from base stations and mobile station scenarios without additional mitigations

The following chapter presents the modelling results from the simulations of interference from both base stations and mobile stations into radar without additional mitigations beyond the improved radar filtering specified by Ofcom. The results are presented to demonstrate the impact of interference under various scenario conditions that builds up the picture of interference that occurs from 2.6 GHz deployments into a nearby S-band radar receiver.

The interference scenarios are broadly categorised into two main cases for the analysis:

- Challenging case – Parameters chosen are set to the maximum levels possible but unlikely (or rarely) to be used in practice and the values are given in Table 10-1 and Table 10-5
- Typical case – Parameters chosen are set to the more realistic practical level and more likely to be used in practice and the values are given in Table 10-4

An additional measured case was conducted to determine the impact from spurious emissions of a commercially available FDD LTE mobile device into a radar receiver and the analysis is discussed further in section 10.9.

The interference environment is presented in a way that initially validates the results from the model by moving a single interferer closer to the radar which can be seen in sections 10.1 for the base station and section 10.6 for the mobile station. The next analysis investigates the base station interference mechanisms which simulated the challenging and typical cases for a fully deployed 2.6 GHz network using the synthetic network at Heathrow Airport which can be seen in sections 10.2 and 10.3. Section 10.4 presents the results from a challenging synthetic layout case placing all the base stations in a spiral formation at different distances away from the radar.

The final analysis investigated the mobile station interference mechanisms which simulated the challenging, typical and measured cases for a sample 2.6 GHz network using the actual base station locations at Heathrow Airport.

The output results are presented in the following way showing Cumulative Distribution Function (CDF) curves of interference to the radar from the overall worst angle at 1% of the time for:

a. The interference blocking level at the different points in the radar receiver chain to determine if the blocking threshold level was exceeded and thus cause degradation to the radar performance.

b. The interference noise power rise at the final stage of the radar receiver to determine if the I/N threshold was exceeded and thus cause degradation to the radar performance.

In addition, where results are marginal the interference levels for less than 1% time are identified this illustrates the impact to radar services where greater percentages of time availability may be applicable. This effect predominantly applies to interference from mobiles since the variability is greater compared to that of the base stations however both are taken into consideration where appropriate.

10.1 Base station to radar – Single base station transmitter at variable distance from the radar with challenging case conditions

The initial analysis investigated the impact of a single base station operating with all carriers active at full power into the radar receiver. The analysis determined the impact of decreasing the distance between the base station and radar to ensure sensible results were being generated by the model and explain the behaviour of the antenna patterns and the pathloss. Table 10-1 and Table 10-2 summarise the main input parameters used for this investigation. Figure 10-1 plots the simulation area and the BS positions.

Parameter	Value
BS EIRP	67 dBm/20 MHz
BS channels	All seven (FDD/TDD) channels active at 100% loading
BS location	Outdoor
BS antenna height	25 m
BS spurious emissions	See Figure 8-7 section 8.2
BS Ofcom Block Edge Mask	Modelled
BS tilt	0 deg
BS sector orientation	1 sector pointing towards the radar, the other 2 sectors at 120 deg increments
Propagation model	Free space loss + 6 dB, see Section 8.4.1
Shadowing standard deviation	0 dB
Radar height	5 m

Table 10-1 Challenging case parameter values for base station

Base station Position	Distance from radar (m)	Free Space Path Loss (dB) (fc = 2600 MHz)
1	1592	104.79
2	982	100.59
3	601	96.33
4	346	91.53
5	92	80.03

Table 10-2 Distances between the base station positions and the radar

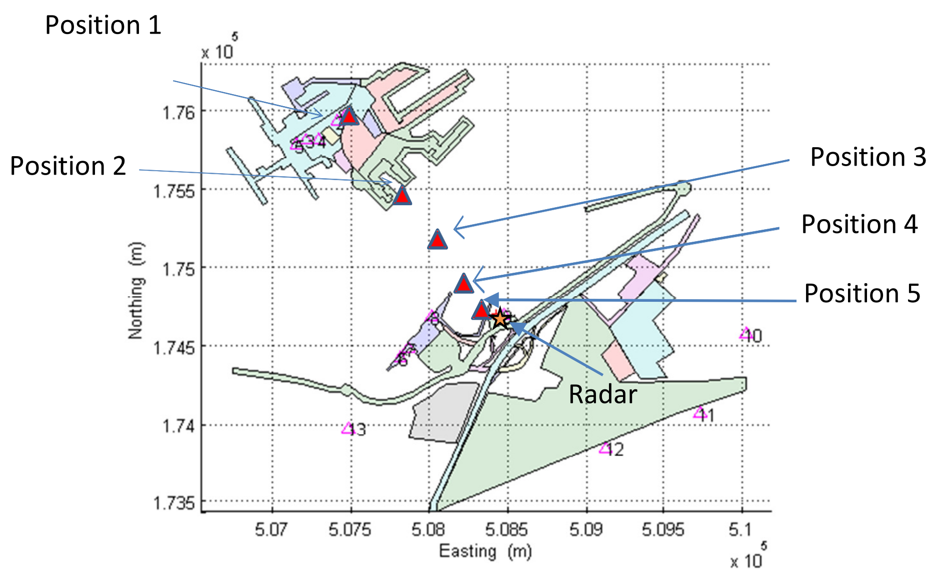


Figure 10-1 Base station locations under investigation

Figure 10-2 and Figure 10-3 show the CDF plots of the results from interference calculations for each base station position at point A and point B in the receiver chain (refer to Figure 8-15). Within each plot the result shows the blocking levels for the different base station positions as the distance was reduced towards the radar. It can be seen from the results that blocking levels from positions 1, 2, and 3 exceed the -5 dBm threshold level at point A in the radar receiver for 100% of the time the radar is pointing at the base station. Blocking level from Position 4 exceeds the threshold level at point A for 23% of the time and below the radar is pointing at the base station. The interference from the base station at position 5 does not exceed the threshold at point A in the receiver. The plots show a steady increase in blocking level against the percentage time the radar is pointing at the base station which begins to decrease from 20% and below. At percentages of time less than 10% the blocking level rises more sharply compared to the rest of the plot demonstrating the instances in the variability of the signal envelope power at its maximum level. Blocking at point B does not occur for all five positions of the base station with 11 dB of margin between the threshold level and the highest recorded interference level.

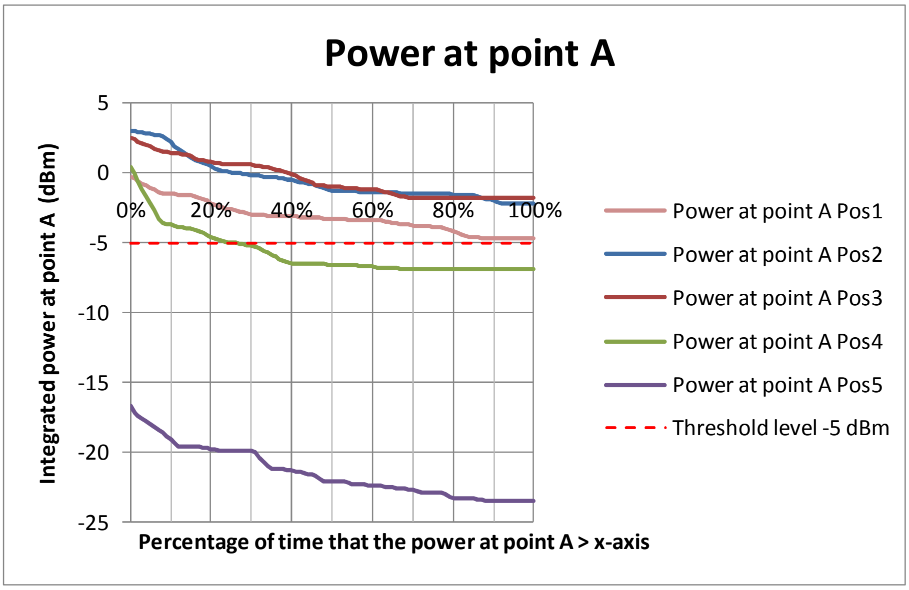


Figure 10-2 Blocking at point A for base station positions 1 to 5 using challenging case parameters (Before filtering)

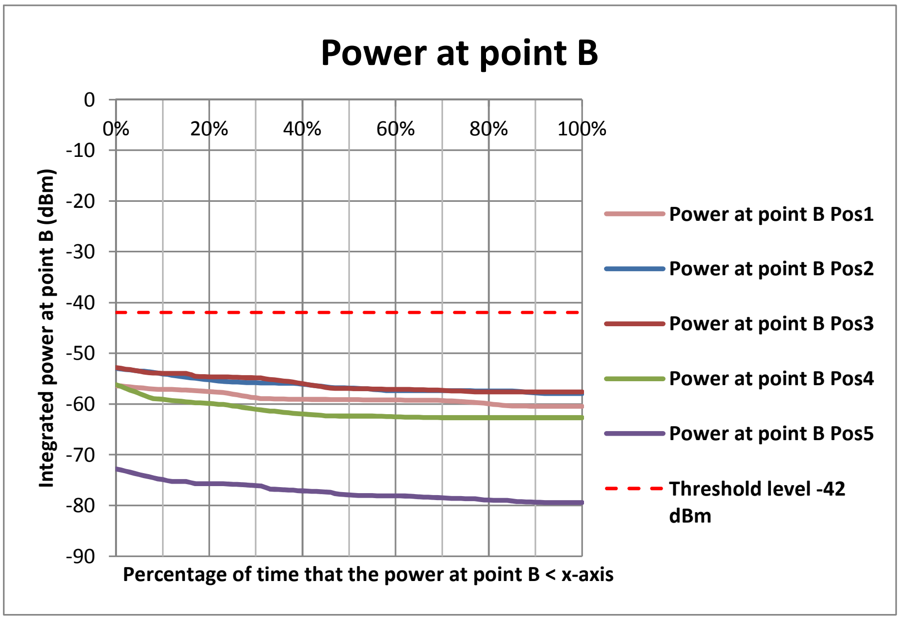


Figure 10-3 Blocking at point B for base station positions 1 to 5 using challenging case parameters (after filtering)

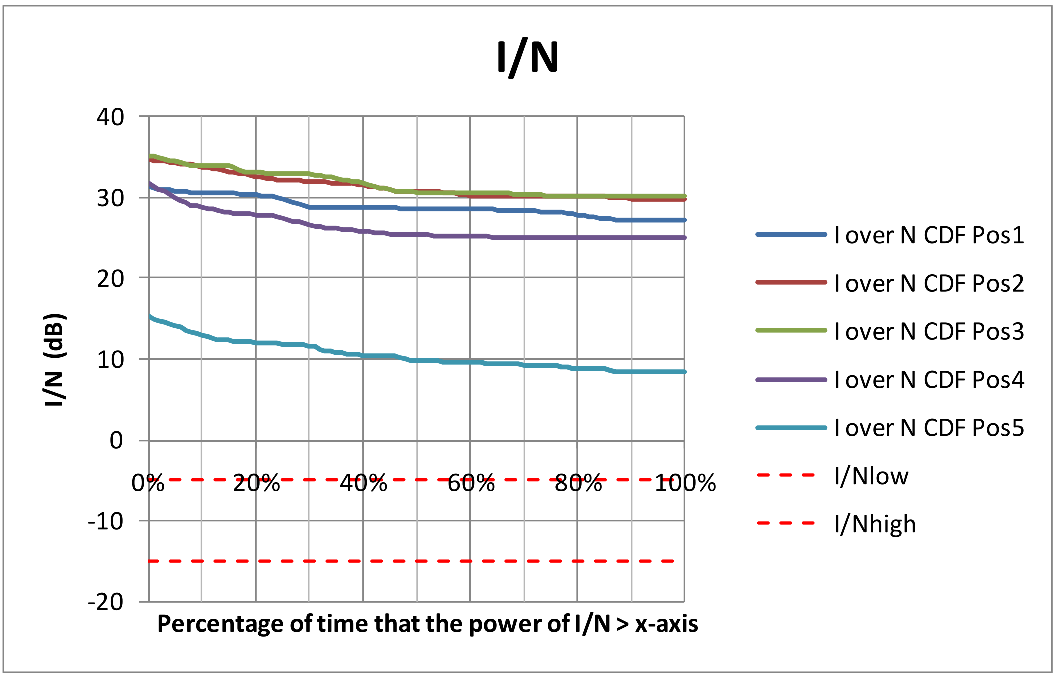


Figure 10-4 I/N levels for base station positions 1 to 5 using challenging case parameters

The results from the I/N calculation show that the peak levels at 1% of the time the radar points at the worst interferer are the cause the highest levels of noise rise. The I/N levels taken at 50% of the time the radar points at the worst interferer shows a 5.2 dB difference between the peak and the mean. Positions 2 and 3 have the highest peak interference noise power levels at 35 dB and 34.6 dB respectively which are 40 dB and 39.4 dB above the maximum threshold. The interference peak noise power from positions 1 and 4 for 1% of the time the radar is pointing at the base stations are 31.2 dB and 31.4 dB respectively which occur 36 dB above the minimum threshold limit. Position 5 has the lowest interference noise power at 15 dB which is 20 dB above the maximum threshold limit. The interference noise rise is caused by the out-of-band and spurious emissions from the base stations and the pattern produced for each position correlates with that found for blocking at point A. These findings suggest the model is producing consistent results for both blocking and interference noise power.

The results in Figure 10-5 show how the impact of the combined BS and radar antenna patterns and pathloss vary with distance. The top subplot shows the attenuation of the path BS-radar due to the vertical pattern of the BS and the radar antenna, separately. For a variable distance BS-radar, the attenuation due to the vertical patterns changes for close distance to the radar. The attenuation is at maximum when the direct path crosses the vertical patterns from the sidelobe region. For far distances the attenuation is smaller because the BS gets closer to the radar main beam.

The bottom subplot shows the attenuation of the path BS-radar due to the median path loss model + attenuation due to the vertical patterns. The path loss is greater with an increasing distance.

The combined effect of path loss plus pattern is that, very close to the radar the high attenuation due to the vertical patterns means that emissions in that zone do not cause interference.

Bear in mind that the above apply for uneven height between radar and BS. In the case that the heights are equal, the attenuation due to the vertical patterns is constant with the distance, and therefore emissions from close to the radar cause greater interference than further away.

Using the plot in Figure 10-5 the results can be interpreted based on the attenuation for a variable BS distance from the radar location. The attenuation in the y-axis of the bottom subplot is the combination from the BS and radar antenna vertical-patterns, and from the median path loss model. It can be seen from the top subplot that the attenuation of Position 1 due to the vertical patterns is 0.1 dB (due to the BS antenna) plus 4.6 dB (due to the radar antenna). Position 1 has the furthest distance from the radar and therefore the greater median pathloss. As the position of the BS is moved closer to the radar (Position 2 and 3) the attenuation due to the vertical patterns becomes greater, however the attenuation due to the path loss becomes smaller. The effect of the path loss is greater than the vertical patterns for Position 2 and 3, so that the interference increases with a decreasing distance.

The antenna patterns begin to make a greater impact with respect to the path loss for distances closer than Position 3 (Positions 4 to 5). This explains the lower interference level of Position 4 against Position 1, 2 and 3. Note that in Position 5, which is the closest position considered in this investigation, the emissions are attenuated by 50 dB due to the antenna patterns.

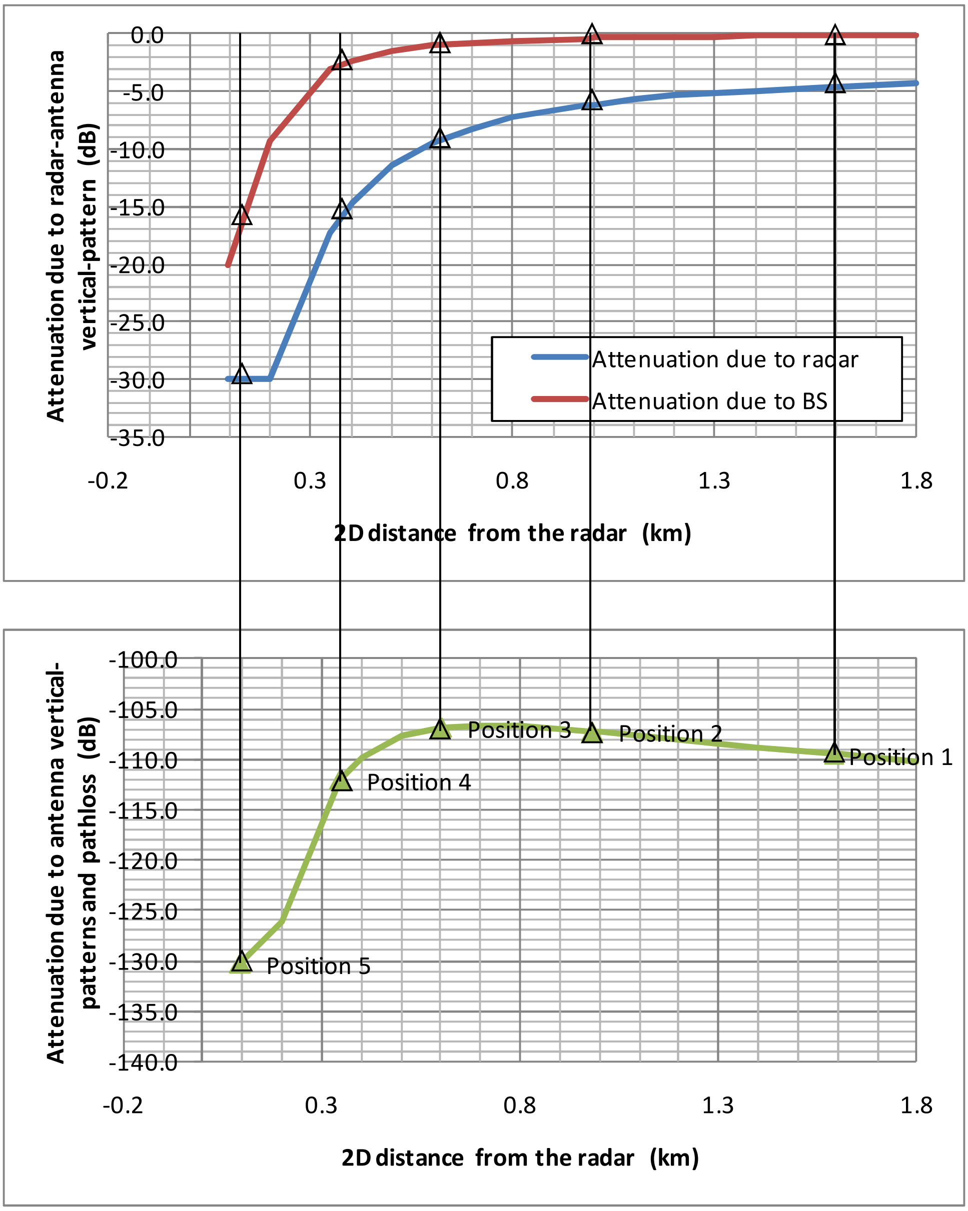


Figure 10-5 Combined pathloss and vertical-pattern attenuation vs distance from the radar. Radar effective vertical HPBW= 4.4deg, radar height= 5m, radar uptilt = 2deg, BS height = 25m, BS downtilt = 0deg, BS vertical HPBW = 6.5deg.

Once the signal arrives at the input to the radar antenna connector the RF filter attenuates the received 2.6 GHz signals by 40 dB, see Figure 8-16 in section 8.3. A further 10 dB of attenuation is achieved due to the modified sub-systems assumed in the receive chain.

10.2 Base station to radar – Challenging Heathrow layout

This section presents the results for interference caused by all the modelled base stations in the simulation area as shown in Figure 10-6 using the challenging case input parameters. The results show that the radar is blocked from 2.6 GHz transmissions based on the assumptions and conditions used in this case.

The challenging case input parameters represent the scenario that creates severe interference conditions using the most extreme practical values possible for the base station, the main values can be seen in Table 10-3.

The modelled base station deployments can be seen in Figure 10-6 which are drawn from the actual base station locations found at Heathrow Airport. The base station locations are therefore representative of actual mobile network operator deployments.

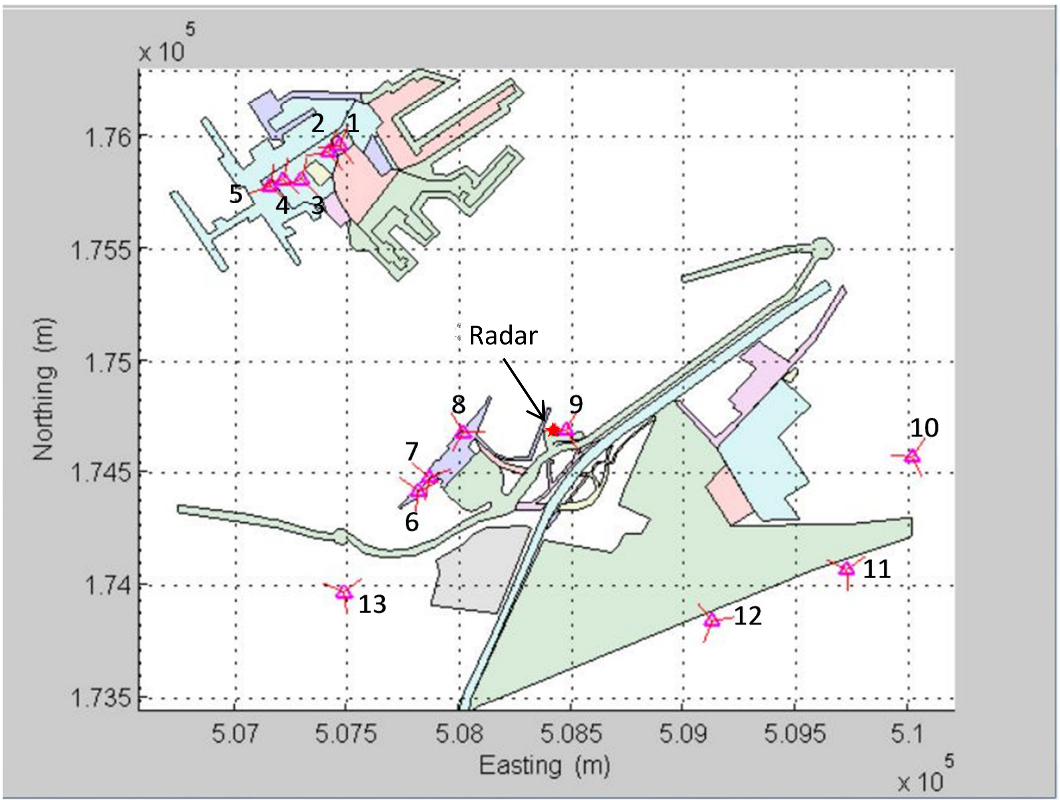


Figure 10-6 Base stations modelled for BS to radar scenarios

Parameter	Value
BS EIRP	67 dBm/20 MHz (outdoor) 52 dBm/20 MHz (indoor)
BS channels	All seven channels active at 100% loading[21]
BS location	Indoor and outdoor
BS antenna height	3 to 25 m, see Appendix B
Spurious emissions (EIRP)	See Figure 8-7 in section 8.2
BS Ofcom Block Edge Mask	Modelled
BS tilt (outdoor)	0 deg
BS sector orientation (outdoor)	1 sector pointing towards the radar, the other 2 sectors at 120 deg increments
Propagation model	Free space path loss+ 6 dB, ITU-R P 452-12
Building penetration losses	0 dB (outdoor), 3.5 dB (indoor)
Shadowing standard deviation	0 dB
Radar height	5 m

Table 10-3 Main parameters used for the challenging Heathrow layout scenario

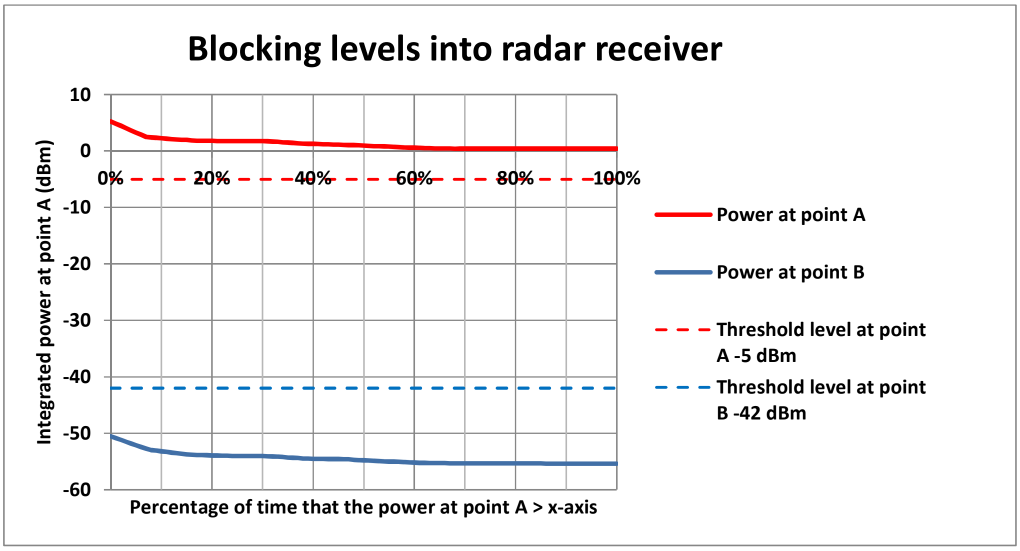


Figure 10-7 Blocking levels from BS into radar receiver - Challenging Heathrow layout scenario

[21] The site locations 1 and 2 are sufficiently close together to justify the assumption that different mobile network operators are operating in each site. Therefore sites 1 and 2 are partially loaded. The same was assumed for sites 3 and 4.

Figure 10-7 shows the overall blocking levels calculated by the software model at each point in the receiver chain from the worst angle of interference. It can be seen from the plot that the blocking level at point A exceeds the first threshold level into the receiver for 100% of the time the radar points at the worst interferer. This would cause total saturation at the front end of sub-system 1 and cause complete shutdown of the radar under the challenging conditions before reaching the first filter. In summary the plot shows that for 100% of the time the radar points at the base station it is being blocked due to the significant levels of interference from the largest interferer.

Analysis of the blocking level at point B in the receiver does not exceed the -42dBm threshold level which means the modified filter attenuation is large enough to protect the amplifier components further down the receive chain. This case, however becomes irrelevant since the interference at point A exceeds the -5 dBm threshold level.

Figure 10-8 shows the interference noise rise that occurs into the radar receiver from the out-of-band and spurious emissions under the challenging case conditions. The simulated peak interference noise level exceeds the minimum I/N threshold by 52 dB for 1% of the time the radar is pointing at the highest interferer. Furthermore all base stations in the modelling area contribute to the excessive interference noise power which suggests that the spectrum emission mask used for this scenario causes severe degradation to the radar performance.

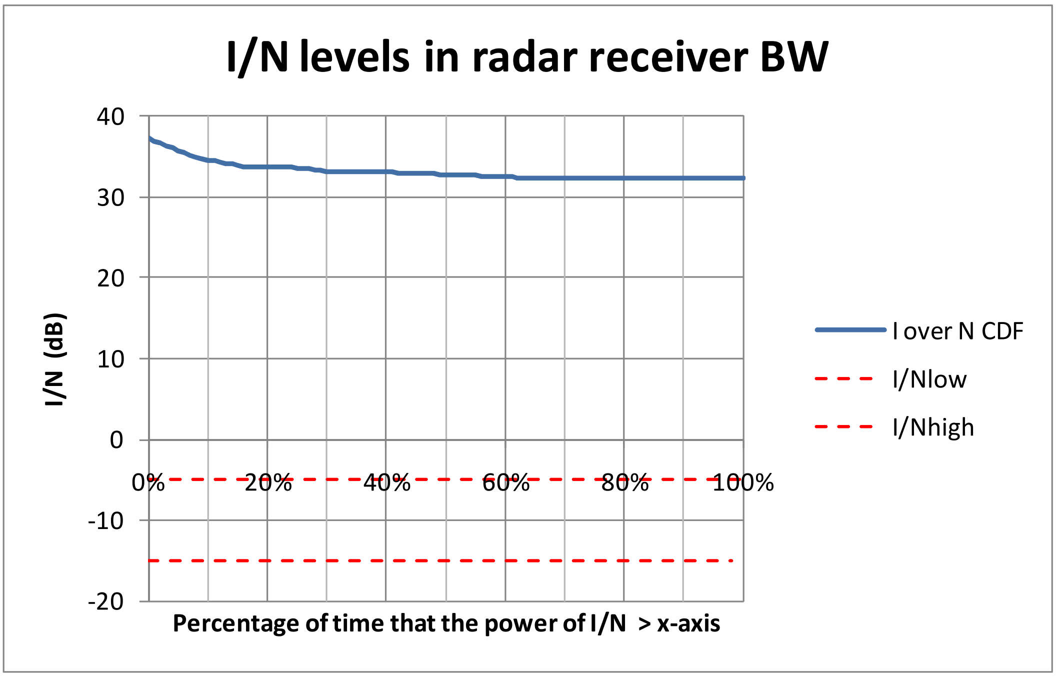


Figure 10-8 Peak I/N level from BS into radar receiver – Challenging case Heathrow layout scenario

Figure 10-9 plots the interference level at point A, when the radar points to each base station. This bar plot aids to identify the specific contribution of each BS to the radar blocking and thus the most severe ones can be picked out. In the case of Figure 10-9, all BS's besides 7 and 8 (which are both indoor) exceed the -5 dBm threshold level at point A. This means all outdoor BS's and one very close indoor BS (BS9) causes blocking in this scenario.

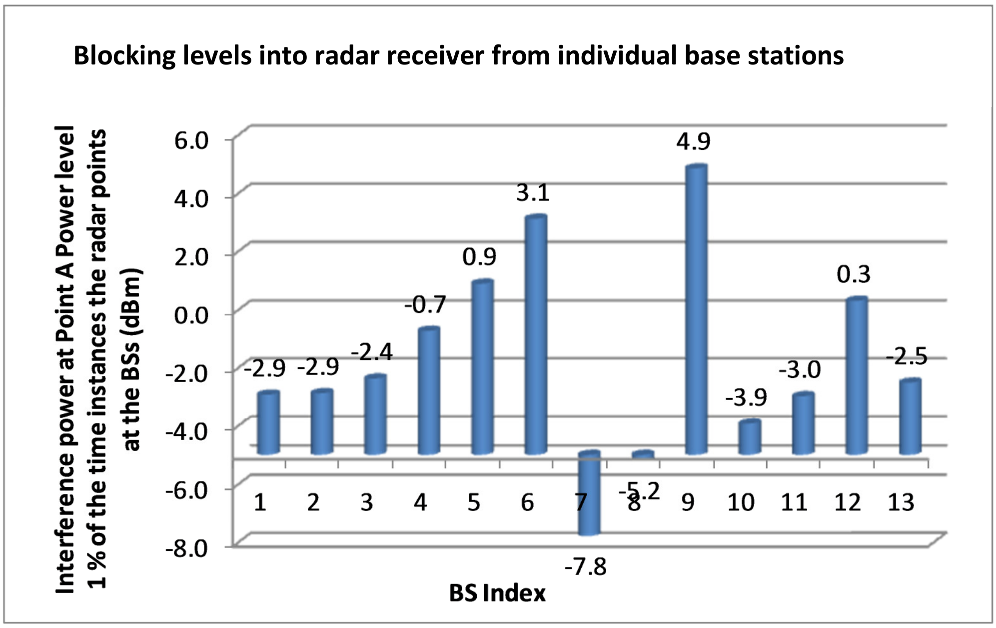


Figure 10-9 Received peak interference power at Point A of the receiver chain, when the rotation angle of the radar points at each BS

BS9 generates the largest interference level with a margin of 9.9 dB above the threshold level and is also located indoors (with 3.5 dB penetration loss) 50m from the radar which is the closest base station. It is also noted that all outdoor BS's are located between 0.67km and 1.67km from the radar. BS's 1, 2, 3, 4 and 5 for example are located in the Central Terminal Area at approximately 1.6 km away from the radar and exceed the threshold ranging from 2.1 dB up to 5.9 dB. BSs 10, 11, 12 and 13 are located outside the airport perimeter at distances varying from 1.1 km to 1.6 km from the radar and exceed the threshold by a maximum margin of 5.3 dB. The interference level increases with a decreasing distance between the base station and the radar, as expected, because in the particular deployment of outdoor base stations in Heathrow all BSs are located further than 600m from the radar.

Figure 10-10 shows the peak I/N levels recorded under challenging case conditions for each of the base stations. It can be seen that all the base stations exceed the maximum threshold level. The highest interferer is BS9 which is located closest to the radar and exceeds the threshold by 52 dB.

The lowest of all interferers is BS7 (indoor) with a level of 24.5 dB and exceeds the maximum threshold by 39.5 dB.

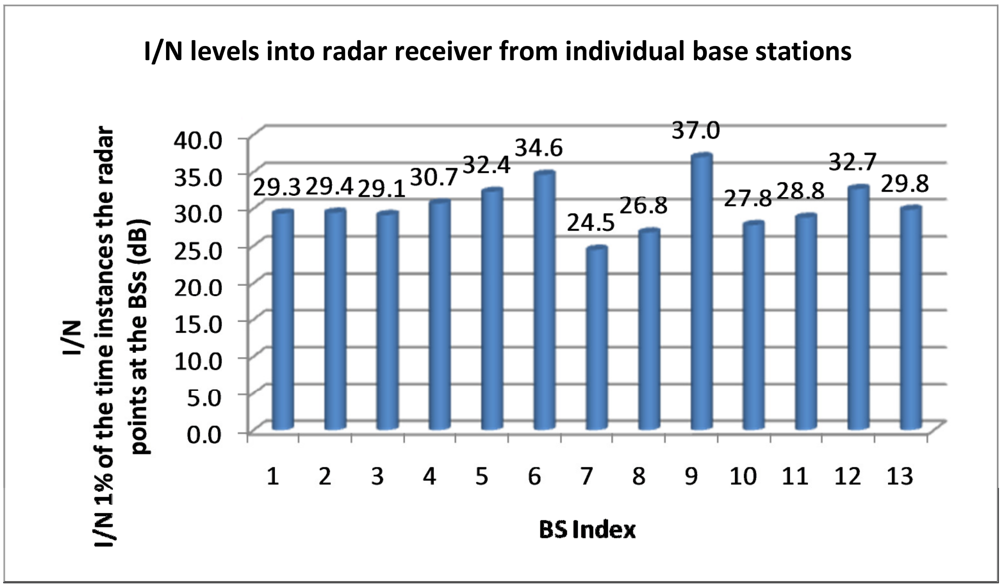


Figure 10-10 Peak interference noise rise, when the rotation angle of the radar points at each BS

The results from the simulation with the worst-case parameters support the finding that the increase in noise is the dominant interfering effect due to the extensive margin by which all the base stations exceed the acceptable I/N limits of the radar. Note that in the case of blocking the maximum margin exceeded is 9.9 dB which is less than that of the I/N. Therefore mitigations should focus on reducing the peak I/N level to within the acceptable limits and doing so will have addressed the blocking at point A in the receiver chain.

10.3 Base station to radar – Typical Heathrow layout

The base station to radar under typical case conditions was conducted to determine the impact of interference into the radar at the Heathrow Airport. Figure 10-6 plots the simulation area and Table 10-4 summarises the values used for the typical case. The complete set of chosen parameters for the typical case is provided in appendix B.

Parameter	Value
BS EIRP	63 dBm/20 MHz (outdoor) 48 dBm/20 MHz (indoor)
BS channels	Max four channels active at 80% loading[22]
BS location	Indoor and outdoor
BS antenna height	3 to 25 m, see Appendix B
Spurious emissions (EIRP)	See Figure 8-11 in section 8.2
BS Ofcom Block Edge Mask	Modelled
BS tilt (outdoor)	6 deg
BS sector orientation (outdoor)	1 sector pointing east, the other 2 sectors at 120 deg increments
Propagation model	Free space path loss+ 6 dB, ITU-R P 452-12
Building penetration losses	0 dB (outdoor), 14dB (indoor)
Shadowing standard deviation	0 dB
Radar height	20 m[23]

Table 10-4 Typical case parameters

Figure 10-11 shows the blocking levels calculated by the software model at each point in the receiver chain for the typical-case parameters. It can be seen from the plot that the overall blocking level at point A does not exceed the threshold level into the receiver and would not cause blocking at the input of sub-system 1. The highest overall blocking level recorded for the worst angle was -16 dBm which is 11 dB below the threshold level at Point A of the receiver chain.

The blocking level recorded at point B further down the receiver chain is around 40 dB below its respective threshold level. The improved selectivity of the modified radar filters attenuate the already low blocking levels from the 2.6 GHz band frequencies compared to the challenging case.

It can be seen from Figure 10-11 that blocking does not exceed the interference threshold limit at point A or point B across the statistical range and therefore considered to not cause blocking in the radar receiver under typical scenario conditions.

[22] The site locations 1 and 2 are sufficiently close together to justify the assumption that different mobile network operators are operating in each site. Therefore sites 1 and 2 are partially loaded. The same was assumed for sites 3 and 4.

[23] 20m antenna height was used for the model as the radar antenna height at Heathrow Airport is 40m which was not considered to be typical of radar heights found in general.

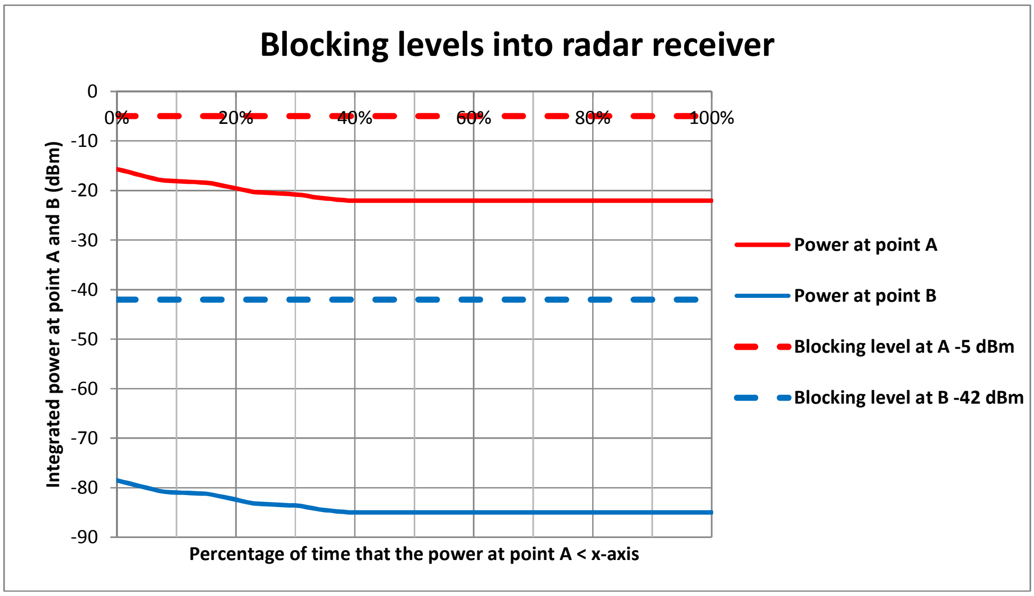


Figure 10-11 Blocking level from BS into radar – Typical Heathrow layout

In this typical case scenario it was expected that the resulting I/N level would be much reduced compared to the challenging case I/N levels due to the use of the noise estimates for the out-of-band and spurious emission mask, instead of the 3GPP/IEEE masks. The noise estimates used in the model assumed a 27 dB margin below the specification limits in the spurious domain for LTE and a 47 dB margin below the specification limits into the radar band for WiMAX. As can be seen in Figure 10-12, the highest peak I/N level for this scenario was recorded at -7 dB which is 8 dB above the minimum threshold level and 3 dB above the ITU -10 dB limit. The results show an improvement of 42 dB on a like for like basis on the challenging case conditions.

The interference generated from the typical case conditions greatly improve the interference situation from the base station deployments compared to the challenging case scenario. This is mainly due to adjusting parameters such as the EIRP and unwanted emission levels to values deemed more practical and realistic. However, adjustment to other parameters such as the antenna downtilt has also had an effect to the reduction of interference. For example, up to 11dB less power is pointed towards the radar from the attenuation of the base station antenna due to having a 6° antenna downtilt. The application of more realistic parameters not only generates a more accurate deployment environment but also inherently adds some mitigating factors that reduce the interference levels appearing at the front end of the radar.

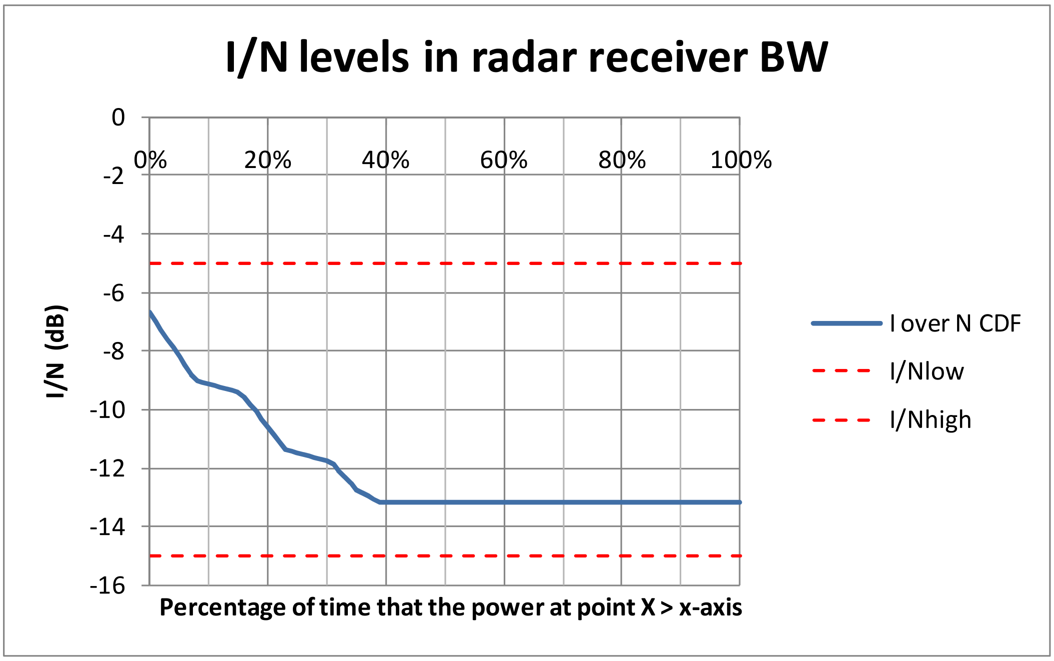


Figure 10-12 I/N level from BS into radar – Typical Heathrow layout

Figure 10-13 and Figure 10-14 plot provide more detail of the interference level at point A and the noise rise I/N respectively, when the radar points to each base station. Both plots identify the individual base stations and their respective blocking levels and in the case of blocking no single base station exceeds the threshold limit. However, in the case of noise rise BS7, 10 and 12 each exceed the I/N threshold limit by a small margin.

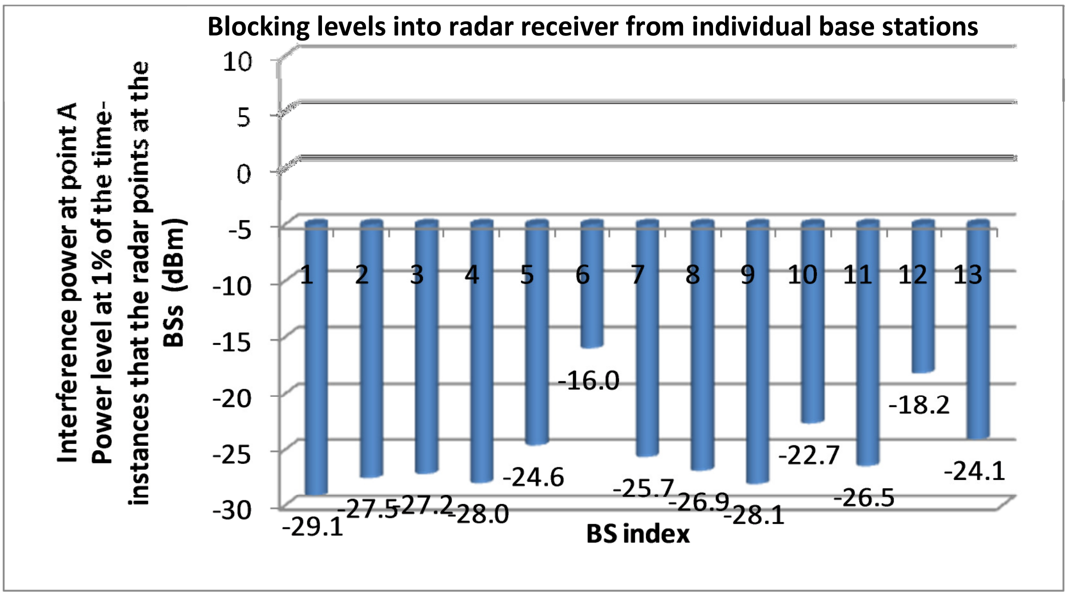


Figure 10-13 Blocking levels from BS into radar - Typical Heathrow layout

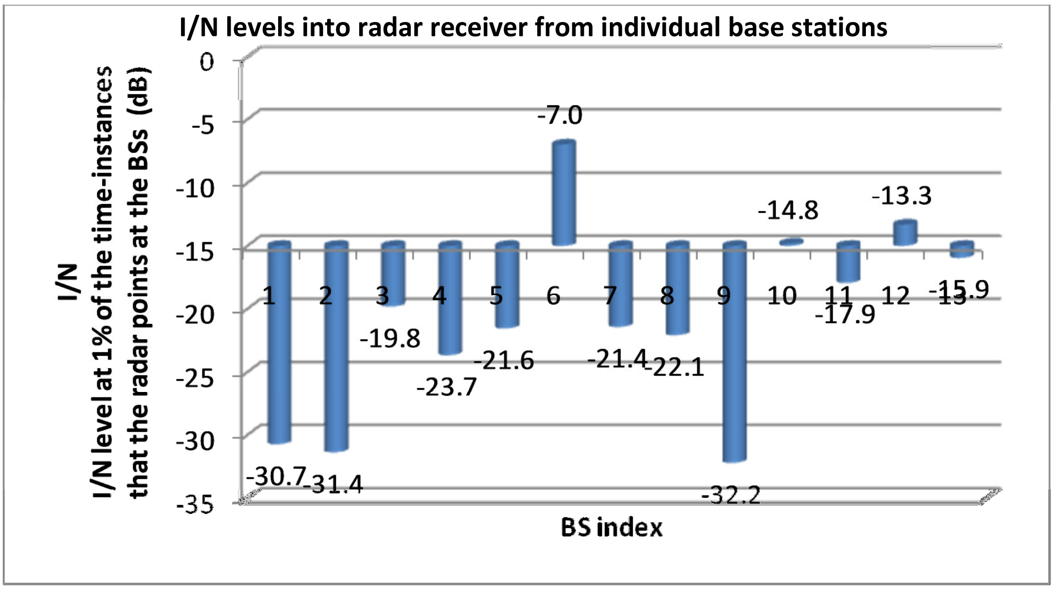


Figure 10-14 Peak I/N levels from BS to radar - Typical Heathrow layout

The results of the simulation for Heathrow Airport layout under typical case conditions show that blocking is no longer a problem and that interference noise rise occurs within the acceptable limits of the radar receiver from all base stations. Although the findings show a significant reduction to the interference situation for the Heathrow layout under typical case conditions, there is still a requirement to understand the impact under different deployment scenarios. The next section uses a synthetic layout of the base stations to support the establishment of a coordination zone for the base stations to aid development of the mitigation techniques.

10.4 Base station to radar – Challenging synthetic layout

The simulations conducted for this scenario considered the spread of an indoor case and an outdoor case for the base stations in a spiral formation from the radar. The aim of this scenario was to capture the effects of the base stations from distances that are very close starting at 50m up to 1.6km away from the radar. The formation aims to help define a coordination zone for the base station locations around the radar.

The diagram in Figure 10-15 shows how the base station positions were configured to capture the effects of interference. The simulation assessment was undertaken under a mix of challenging and realistic case conditions to establish which distances exceed the interference thresholds. Table 10-5 summarises the main parameters. Table 10-6 summarises the 2D distance of each BS from the radar location.

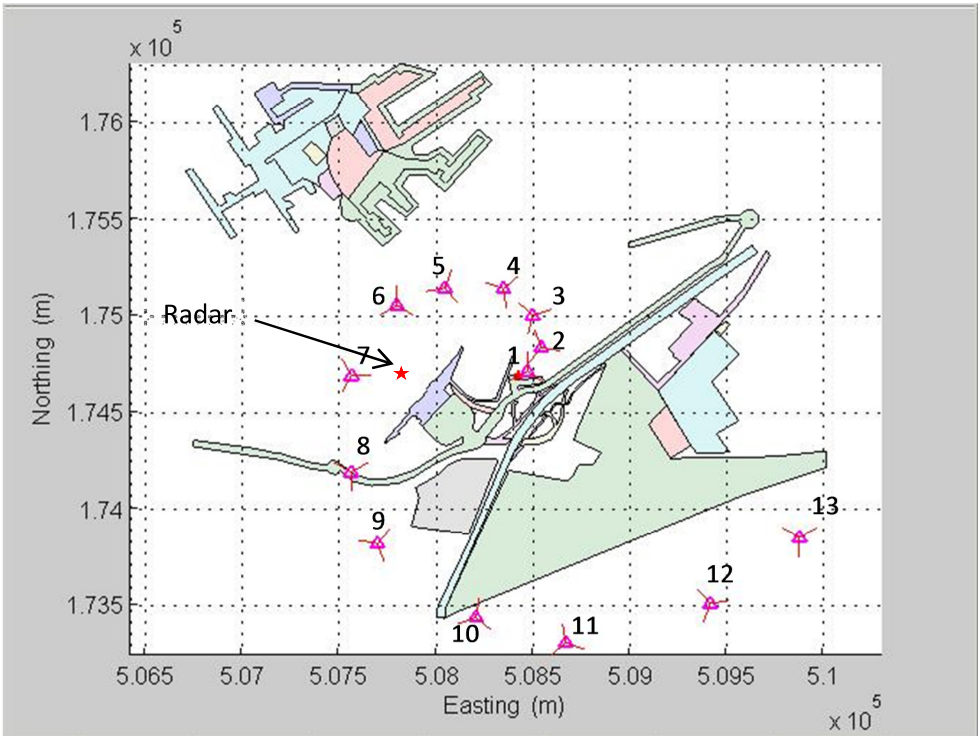


Figure 10-15 Base stations at incremental distances from the radar – Challenging synthetic layout

Parameter	Value
BS EIRP	63 dBm/20 MHz (outdoor), 52 dBm/20 MHz (indoor)
BS channels	All seven channels active at 80% loading
BS location	Outdoor and indoor
BS antenna height	20m
Spurious emissions (EIRP)	See Figure 8-7 in section 8.2
BS Ofcom Block Edge Mask	Modelled

BS tilt (outdoor)	6 deg
BS sector orientation (outdoor)	1 sector pointing away from the radar, the other 2 sectors at 120 deg increments
Propagation model	Free space path loss+ 6 dB
Building penetration losses	0 dB (outdoor), 14 dB (indoor)
Shadowing standard deviation	0 dB
Radar height	20m

Table 10-5 Incremental distances from radar – Challenging synthetic layout

BS Index	1	2	3	4	5	6	7	8	9	10	11	12	13
Distance (m)	50	185	321	456	591	727	862	997	1133	1268	1403	1539	1674
Intermediate distances between…		1 and 2	2 and 3	3 and 4	4 and 5	5 and 6	6 and 7	7 and 8	8 and 9	9 and 10	10 and 11	11 and 12	12 and 13
Distance (m)		118	253	389	524	659	795	930	1065	1201	1336	1471	1607

Table 10-6 Incremental distances from radar

10.4.1 Challenging synthetic layout - Outdoor case

The outdoor case was treated first and the results are shown below. The overall blocking level from the worst angle shows that blocking occurs at point A in the receiver. The peak blocking level, which is recorded at 1% of the time the radar points at the worst interferer, at point B is 2.1 dB above the threshold limit. This is caused by the very close proximity base station and the excessive power levels that would cause blocking at this very close range. The modified RF filter is not able to attenuate the signal below the threshold level for 1% of the time. Peak blocking at point A exceeds its threshold by 20.1 dB for 1% of the time the radar points at the base station and would therefore cause the radar to cease operating.

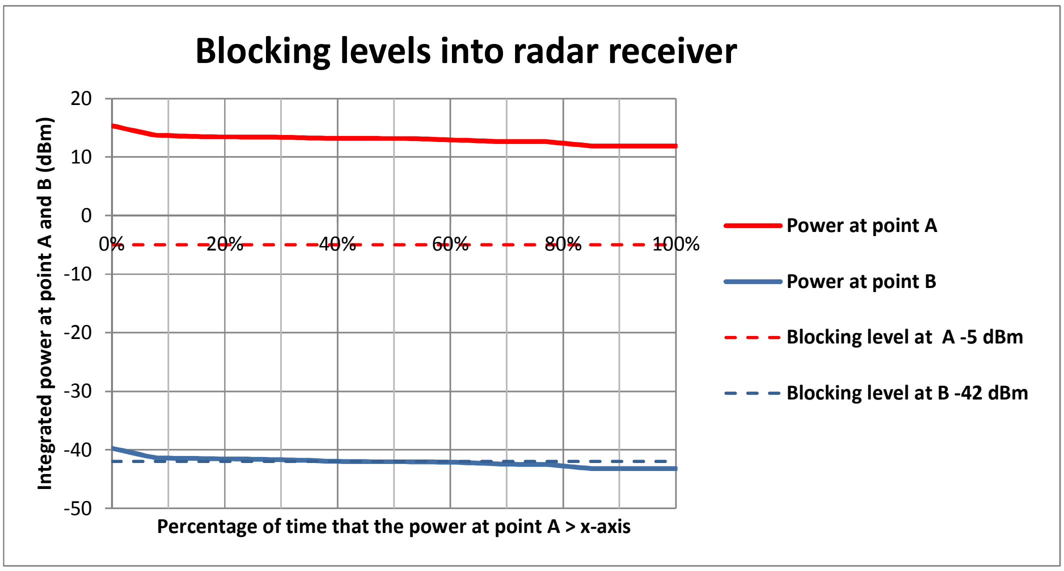


Figure 10-16 Overall blocking levels at worst angle of BS into radar – Challenging synthetic layout (outdoor)

Figure 10-17 plots the CDF of the I/N levels at the worst angle. It is noted that the BSs' noise emissions are at the levels specified from 3GPP/IEEE specs (See section 8.2.3). The minimum threshold level (-15dB) is exceeded by 62.8 dB for 1% of the time the radar points at the worst angle. This margin is used to set the target for reduction of the overall interference levels. Focusing on reducing the noise rise will also resolve the situation for blocking into the receiver.

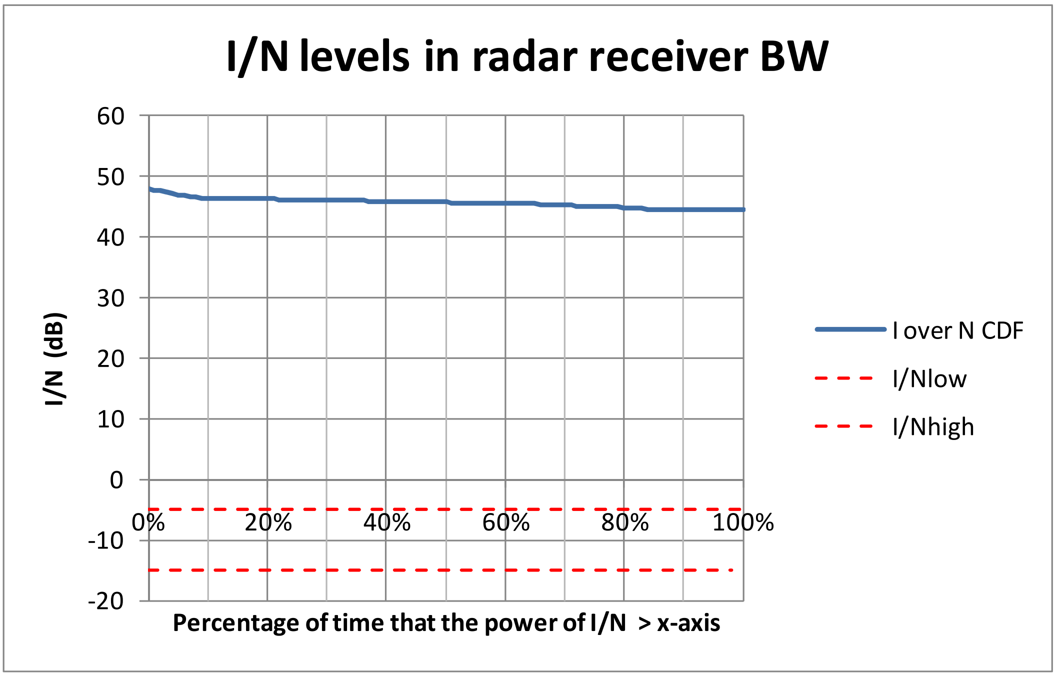


Figure 10-17 I/N levels at worst angle of BS into radar – Challenging synthetic layout (outdoor)

The investigation can be analysed further using the detailed results shown below which identifies the specific base stations and distances at which the interference starts to become a problem. The received power when the radar points at BS1 to BS4 exceed the -5 dBm threshold at point A for 1% of the time the radar is pointing at each BS. The blocking threshold at point A in the receiver is exceeded by 20.1 dB from BS1, 8.6 dB by BS2, 8.2 dB by BS3 and 1.9 dB by BS4. BS5 to BS13 do not exceed the threshold level at point A. The pattern shows a steady decrease of the peak blocking level starting from the closest base station with the highest blocking level of 15.1 dB and quickly reducing in magnitude for each base station at distances further away from the radar. In general at distances beyond base station 4 (456m) the received interference levels at Point A of the receiver chain drop below the -5 dBm limit.

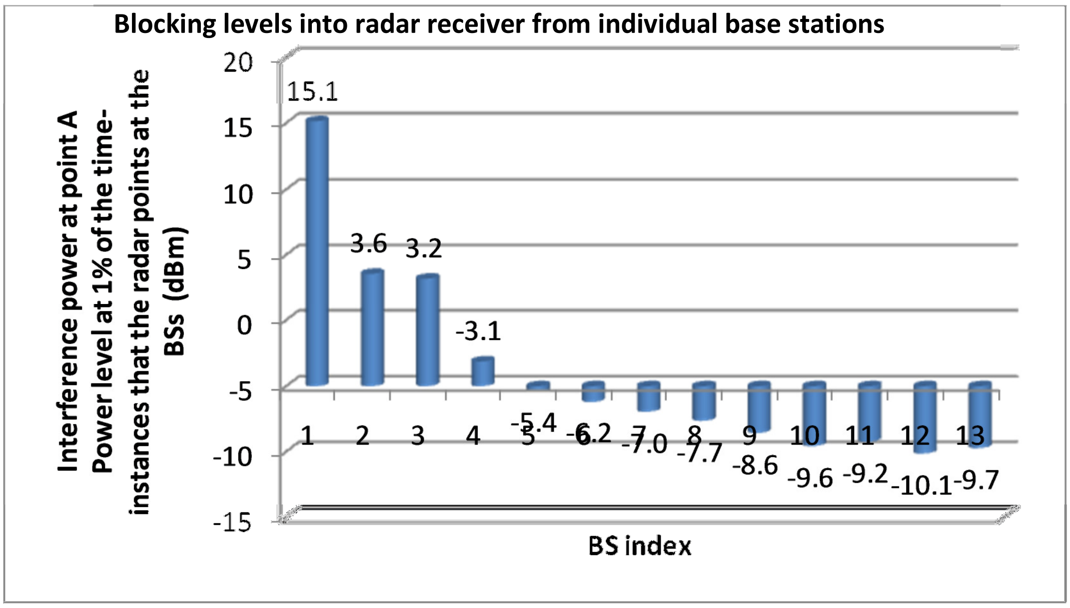


Figure 10-18 Results of peak blocking level at point A – Challenging synthetic layout (outdoor)

As already discussed the peak noise rise exceeds the threshold by a margin that is greater than the interference power exceeding the thresholds at the various points of the receiver chain. Figure 10-19 shows that all base stations exceed the minimum threshold for I/N. Therefore any exclusion zone would commence at a distance much beyond the furthest base station modelled. For example using free space path loss the coordination zone would need to be 140km under the conditions used for this scenario.

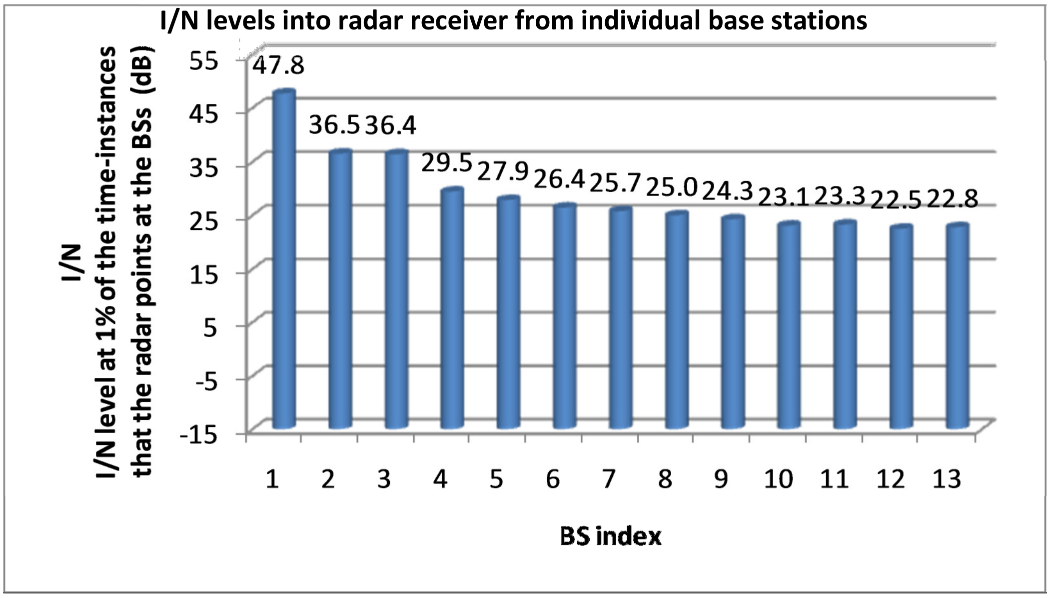


Figure 10-19 Results from peak interference noise power – Challenging synthetic layout (outdoor)

10.4.2 Challenging synthetic layout - Indoor case

The results from the indoor case can be seen below which uses the same process and layout as the challenging synthetic layout outdoor case. The figure below plots the CDF curves of the received powers at the various points of the receiver chain and their respective threshold blocking-levels. The peak interference level at point B is 12.4 dB below its threshold limit. Blocking occurs at Point A (exceeds its threshold by 5.3 dB for 1% time) which means the closely located base stations, even when indoors, will cause blocking to the radar in this layout.

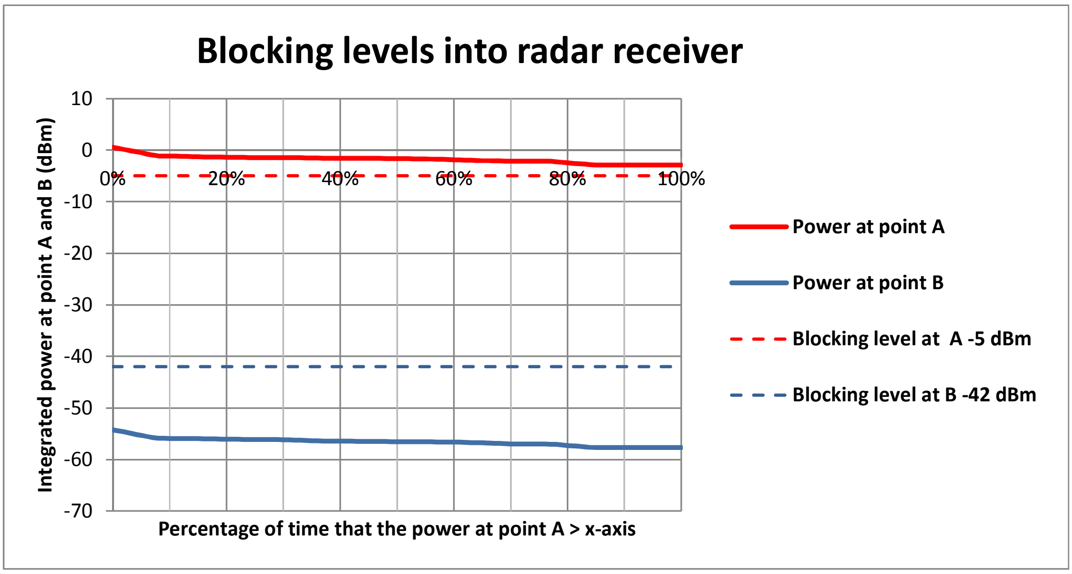


Figure 10-20 Overall blocking levels at worst angle of BS into radar – Challenging synthetic layout (indoor)

Figure 10-21 plots the noise rise CDF when the radar points at the worst-interference angle. The minimum threshold level (-15dB) is exceeded by 47 dB for 1% time. This margin (47 dB) is the target for interference reduction that is required so that blocking does not occur and the peak I/N is below the acceptable threshold level (-10 dB). Note that the BS emissions mask in this scenario is as defined in the 3GPP/IEEE specifications (See section 8.2.3).

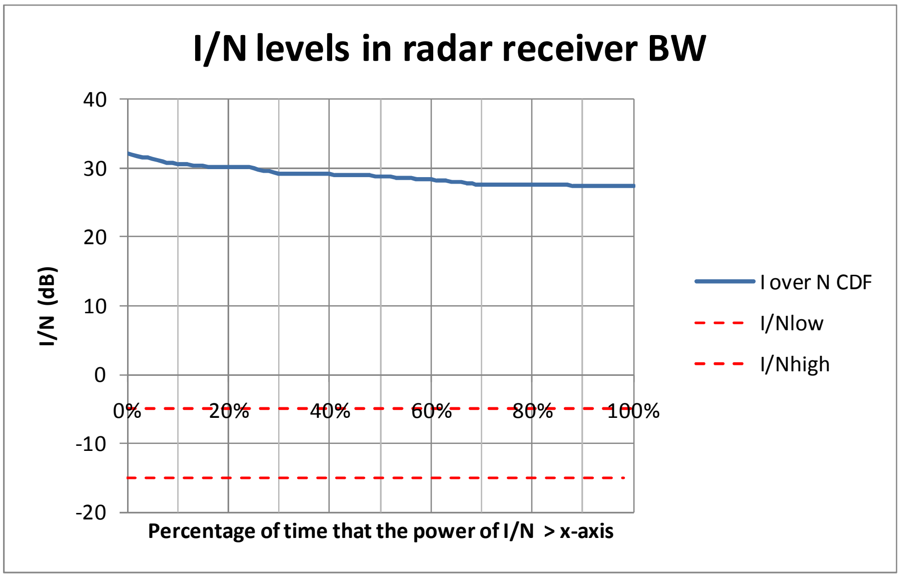


Figure 10-21 I/N levels at worst angle – Challenging synthetic layout (indoor)

The investigation is analysed further using the detailed results shown below which identifies the specific base stations where the interference is excessive. It can be seen in Figure 10-22 that blocking at point A is caused when the radar points at BS 1 which is the closest base station to the radar. All other base stations do not cause blocking, e.g. the Point A threshold (-5 dBm) is not exceeded by BS 2 and further. It should be noted that once the signal has passed through the RF filter and on to point B the interference is below the -42 dBm threshold level and would not degrade radar performance.

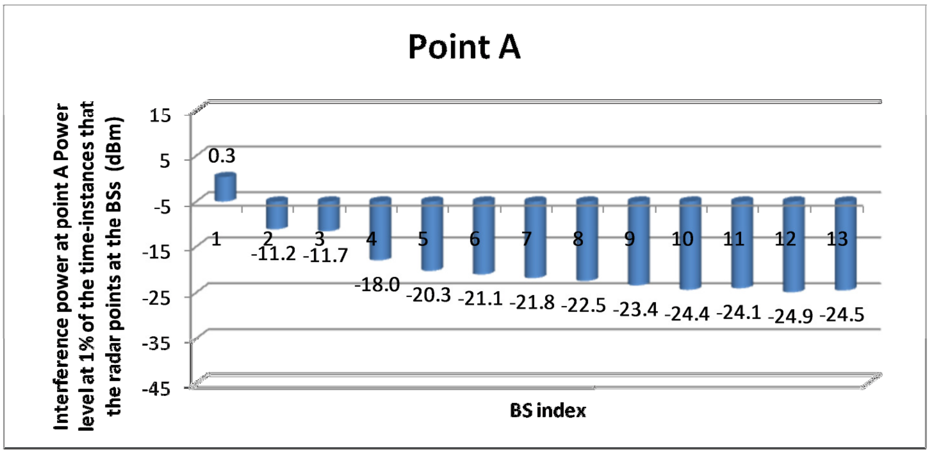


Figure 10-22 Blocking from each base station at Point A

It can be seen in Figure 10-23 all base stations exceed the minimum threshold by a margin of 47 dB, from base station 1, and 10.9 dB, from base station 13. Similar to the outdoor case if a coordination zone were to be required it would need to commence at a distance much beyond the furthest base station modelled.

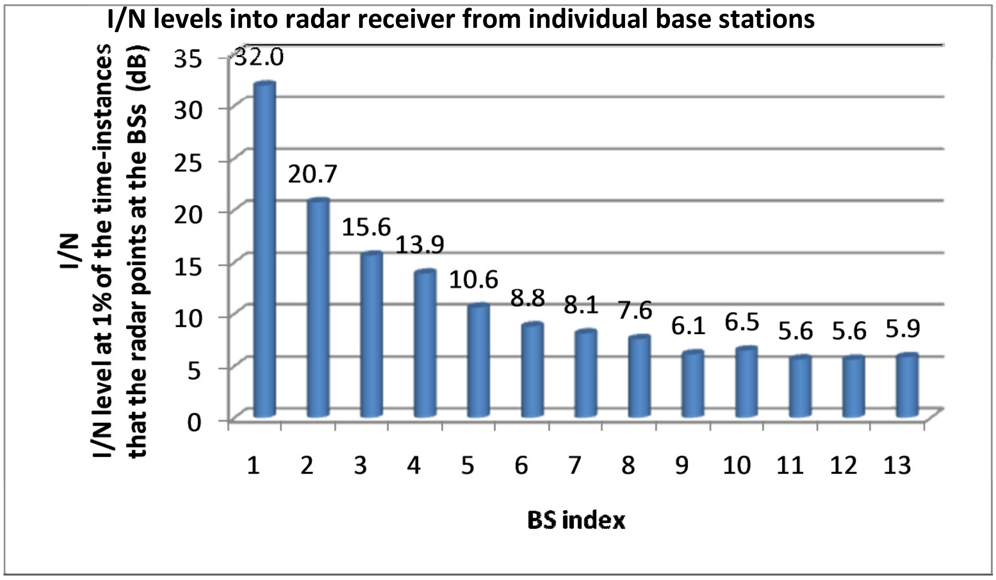


Figure 10-23 Results from peak interference noise power – Challenging synthetic layout (indoor)

Therefore, using the incremental distance layout scenario the maximum interference levels have been established based on the different distances the base stations are located from the radar. The next step is to apply the mitigations to determine whether the reduction in decibels can achieve acceptable margins that fall below the threshold limits.

10.5 Summary findings of base station to radar

This summary of base station to radar first addresses the findings from the simulations with a single transmitter at variable distances towards radar under challenging case conditions. Then the findings of the Challenging Heathrow layout, the Typical Heathrow layout, and the Challenging Synthetic layout are discussed.

10.5.1 Base station to radar – Single transmitter at variable distances towards radar with challenging case conditions

This section summarises the findings from the scenario of a single transmitter causing interference to the radar with challenging case conditions, positioned in 5 discrete locations, see Section 10.1. It is assumed that the transmitter fully utilises all seven carriers at full power. We found that at distances close to the radar this base station will cause blocking to the radar receiver. The blocking power arriving at the radar antenna connector/front-end exceeded the receiver-chain Point A threshold-level (- 5dBm) for BS-radar separation-distance greater than 300 m (Position 1, 2, 3 and 4), across the statistical range when pointed at the worst angle. The interference blocking level at point B does not exceed its respective threshold level with 11 dB of margin. This is because the assumed RF filter used at the front-end of the receiver attenuates the signal by 40 dB which reduces the peak blocking levels below the limit at point B. The values of the input parameters used for the evaluation were the challenging case parameters and therefore it was expected that under these conditions high interference levels would be generated. This has been confirmed from previous static case calculations (addressed in section 6.2.1) that resulted in blocking at the sub-system 1 occurring from a single base station. It was also found that for all 5 distances from the radar the peak interference noise power (I/N) levels exceeded the acceptable limits.

This result confirms the need for further investigation to improve the interference noise power from the base stations. This could include a number of adjustments to the input parameters to improve the situation for this interference mechanism. Similarly for the blocking under the challenging case conditions adjustment of the parameters to improve the blocking situation can be made by adopting more realistic parameter values.

However, one of the main objectives of the study was to identify which parameters can be adjusted and introduced as the mitigation techniques to further improve the situation and take into consideration the following criteria:

a) Limit the adjustment of parameters to ensure minimal loss in performance of the 2.6 GHz network
b) Limit the cost of introducing new parameters or additional costly adjustments to the base stations as much as possible
c) Maximum value is maintained of the 2.6 GHz spectrum in the vicinity of airports

Table 10-7 summarises the blocking power levels at Point A of the receiver chain. Some observations about the received interference are:

i. As the position of the BS moves closer to the radar the attenuation due to the vertical patterns (BS and radar) becomes greater. In the closest BS position to the radar the attenuation due to patterns is greatest.
ii. As the position of the BS moves closer to the radar the attenuation due to the path loss becomes smaller. This is because the separation distance between the radar and the BS becomes smaller.
iii. The combined effect of the vertical-patterns and pathloss is that the interference is worst for distances greater than about 400m from the radar, see Figure 10-5.

Position	Distance from radar (m)	Peak blocking power at Point A, 1% of the time the radar points at the worst-angle (dBm)	Blocking threshold at point A (dBm)
1	1592	-0.5	-5
2	982	2.9	-5
3	601	2.4	-5
4	346	-0.1	-5
5	92	-17.1	-5

Table 10-7 Base station to radar initial investigation results summary

The table above can be compared to the basic link level analysis (See section 6.2.1) when the base stations appear in the half power beamwidth of the radar antenna. Blocking arises at distances of 300m to 400m and beyond and is maximum at a point between 300m and 1500m. After 1500m the blocking levels begin to decrease as the pathloss starts to take effect.

10.5.2 Base station to radar – Challenging Heathrow, Typical Heathrow, and Challenging synthetic layouts

This section summarises the findings from the scenarios Challenging Heathrow layout, Typical Heathrow layout, and Challenging Synthetic layout. In the first two scenarios the transmitters were located at real sites on the Heathrow Airport map. Within the Heathrow layout, this summary demonstrates that the interference problem under typical-case parameters is improved compared to the challenging-case parameters.

The results from the analysis in this section informed the next stage of the study by identifying the mitigation techniques that could be implemented to resolve the interference to a more acceptable level that aims to satisfy the safety case criteria of the regulatory authorities. The findings from the main investigation show the impact of interference to the radar under the different scenario conditions. The scenario conditions analysed included:

- **Challenging Heathrow layout.** Heathrow layout with the most challenging parameters. This scenario is investigated so as to reveal the maximum potential of the blocking problem.
- **Typical Heathrow layout.** Heathrow layout with typical parameters. This scenario approaches the Heathrow-specific deployment and a busy 2.6 GHz mobile network.
- **Challenging synthetic layout.** Synthetic layout with a mix of challenging and realistic parameters. The base stations are positioned at incremental distances from the radar.

The findings from the Challenging Heathrow layout, which used the most extreme settings to produce severe interference conditions into the radar, showed significant blocking levels appearing at point A of the radar receiver. The blocking was predominantly caused by the indoor base station located 50m away from the radar, regardless of its low EIRP, most probably due to the low building penetration losses assumption (3.5 dB). The outdoor base stations in the Central Terminal Area on the roof of the car parks and the roof of Terminal 4 contributed the next highest levels of blocking (e.g. the outdoor base station 6 is located 660m away from the radar, at height 24m with a line of sight to the radar).

The findings from the Typical Heathrow layout, in which the parameters were adjusted to the Heathrow-specific typical values (e.g. tilt at 6°, EIRP 4 dB lower than the challenging value, OOB/spurious emission masks reflecting a typical high-end commercial transmitter), showed reduction of the blocking level, when compared against the Challenging Heathrow layout. The results suggested that base stations do not cause blocking of the radar, but exceed the minimum threshold I/N level by 8 dB.

The findings from the Challenging synthetic layout, assisted in the investigation of potential mitigations, due to the incremental distance of the base stations from the radar and because of the different angle each base station is illuminated as the radar rotates. The findings from this layout showed that blocking occurred up to at a distance of 659m from the radar. After this distance the interference from all other base stations did not exceed the threshold at point A. Although blocking occurs under these conditions the dominating interference mechanism was the interference noise rise, whose maximum threshold was exceeded by each base station modelled and therefore more challenging to resolve using mitigations. In all instances the maximum threshold was exceeded with the furthest base station exceeding the maximum threshold by 37.5 dB. The focus of the investigation in the next chapter seeks to reduce the peak interference noise power by introducing the mitigation techniques and reduce the I/N levels within the acceptable limits.

To summarise, some observations about the received interference are:

- **Different antenna heights of the base station and the radar**. The maximum interference is received at the radar when the BS and the radar antennas are at the same height
- **Radar antenna height**. The radar antenna height in the Typical Heathrow layout is 20m which is considered to be a typical height for the radar. However, the actual antenna height at Heathrow is 40m which means the results obtained will be more conservative compared to reality.
- **Separation distance between the base station and the radar**. Increasing the separation distance between the base station and the radar increases the path loss and therefore reduces the amount of interference into the radar, see Figure 10-5
- **Combined pathloss and vertical –pattern attenuation vs. distance from the radar.** At BS within close proximity to the radar the attenuation from the radar antenna pattern is capped at the maximum attenuation (30 dB). The attenuation due to path loss is small. For greater distances the attenuation from the radar and BS antenna patterns is smaller, because the BS gets closer to the main radar beam, see Figure 10-5.
- **The base station antenna downtilt**. It was found that by increasing the downtilt of the base station antenna from 0° (Challenging Heathrow layout scenario) case to 6° (Typical Heathrow layout scenario) reduces the interference. This is because the downtilt increases the attenuation due to the antenna pattern from the base station.
- **The mobile network carriers.** A reduction in the loading level of the carriers causes a moderate drop of interfering levels
- **Spectrum emissions mask.** Typical high-end transmitters have spurious emissions below the 3GPP/IEEE specification limits at the radar band. The suggested margin is 24 dB below the specification limit at the radar band frequency.
- **Radar frequency.** The generic modified radar frequency modelled was 2750 MHz. Licensed frequencies assigned to radars found at other airports may be closer in frequency to the 2.6 GHz band and the impact from adjacent 2.6 GHz emissions at these frequencies may generate higher interference levels compared to the generic modified radar frequency.

The following tables below summarise the findings from the Challenging synthetic layout scenario to show the highest blocking (Table 10-8) and interference noise rise levels (Table 10-9) that will help determine the distance from which the mitigations will apply. It can be seen that at very close distances the threshold I/N limits are exceeded by a maximum margin of 62.8 dB for outdoor base stations. It is possible to establish a coordination zone which is introduced by eliminating the interferers closest to the radar. The effect of eliminating the first base station, for example, closest to the radar would start the coordination zone at about 120m radius from the radar, see Table 10-6.

Scenario	Peak blocking level (dBm) exceeding threshold (1% of time given that the radar points at the worst angle)	Threshold at point A (dBm)	Base station	Distance from radar
Outdoor	15.1	-5 dBm	1	50m
Indoor	0.3	-5 dBm	1	50m

Table 10-8 Summary of highest Base station blocking level exceeding threshold

Scenario	Peak I/N level (dB)exceeding threshold(1% time given that the radar points at the worst angle)	Threshold level (dB)	Margin to max threshold level (dB)	Base station	Distance to radar
Outdoor	47.8	-5 to -15	62.8	1	50m
Indoor	32	-5 to -15	47	1	50m

Table 10-9 Summary of I/N level for BS into radar

The next step for the analysis is to identify which mitigations can be applied to reduce the margin of interference from the interference noise rise and then establish the set of mitigations that are required to bring the interference within the acceptable threshold limits. The mitigation techniques for base stations are addressed in section 10.11.1.

10.6 Mobile station to radar – Single mobile station transmitter at variable distance from the radar with challenging case conditions

The analysis of interference from a single mobile station into the radar was modelled by deploying a single mobile station at 200 random locations (200 Monte Carlo iterations) for 5 different polygon areas. The simulation calculates the interference as the radar antenna main beam sweeps past the polygon area and is illuminated by the mobile at a particular angle from the radar in each location per rotation.

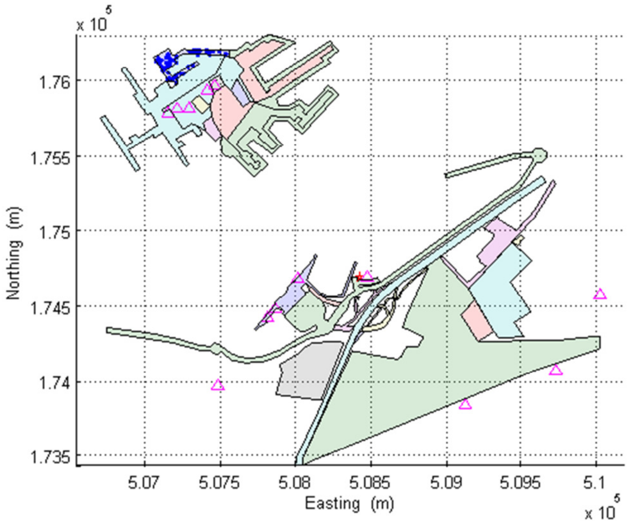
The mobile station was assigned a single FDD uplink channel at 2560 MHz with a 20 MHz bandwidth. The analysis determined the impact of decreasing the distance between the mobile station and the radar to discuss the model results.

The main input parameters used for this investigation were challenging case conditions which can be seen in the table below.

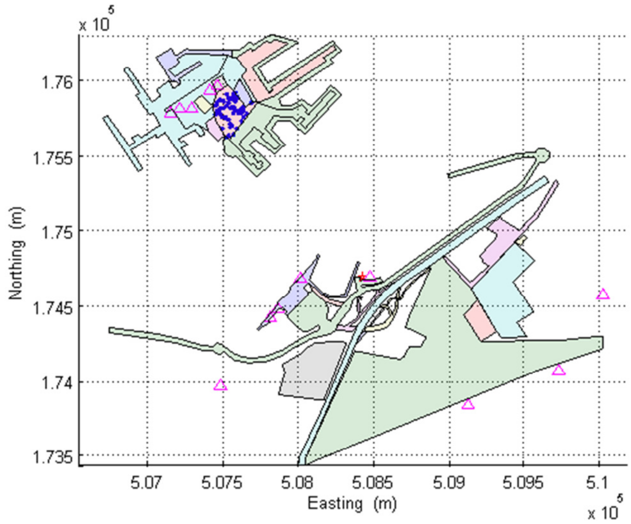
Parameter	Value
MS EIRP	23dBm/20 MHz
MS Power control	Not active
MS antenna height	1.5 m
MS body loss	0 dB
MS spurious emissions	-30 dBm/MHz (3GPP/IEEE)
Propagation model	Free space loss + 6 dB, see Section 8.4.1
Radar height	5 m

Table 10-10 Challenging case parameter values for the mobile station

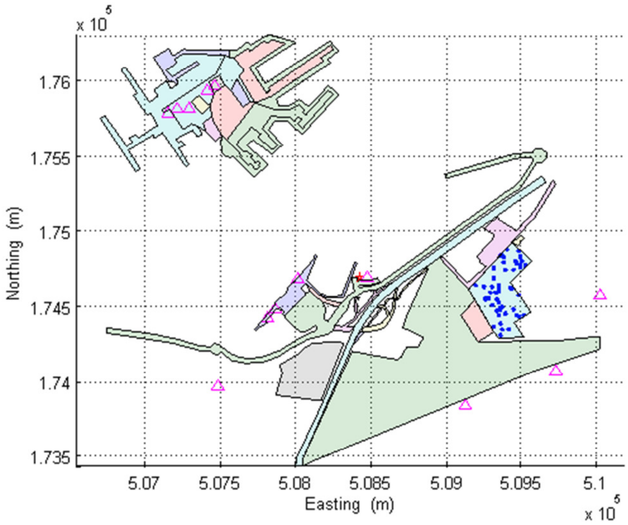
Figure 10-24 shows the different polygon areas that correspond to each position that were chosen for the analysis. The aim of the investigation, similar to the initial investigation for the base station, was to determine the increase of interference from the mobile as the distance was reduced towards the radar. This was achieved by simulating random deployments of the mobile station in a range of polygon areas at distances closer to the radar.



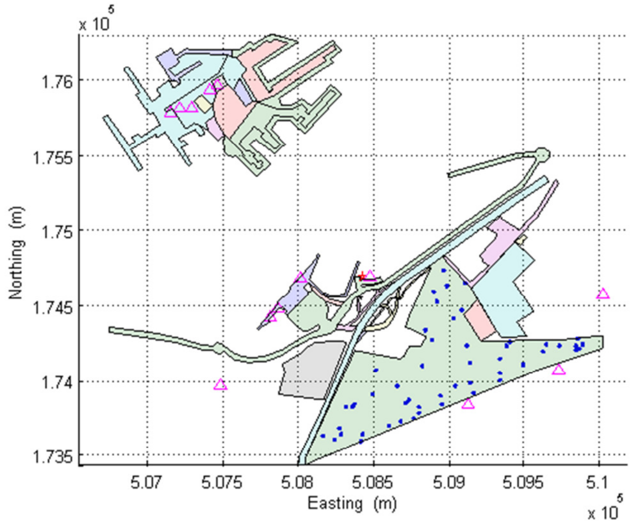
Mobile station position 1 (Polygon 15)



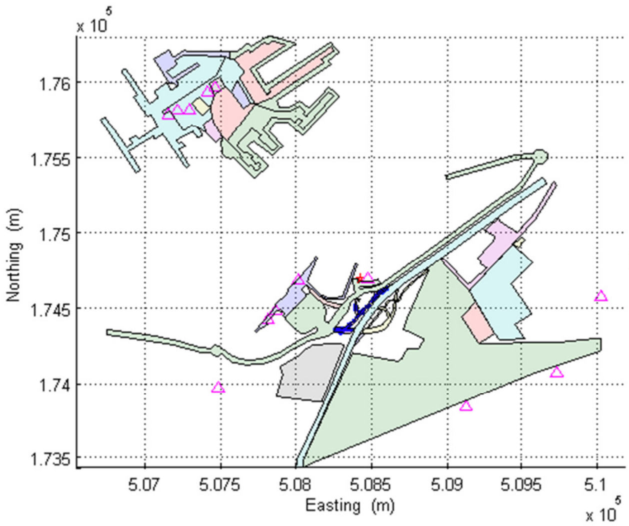
Mobile station position 2 (Polygon 24)



Mobile station position 3 (Polygon 11)



Mobile station position 4 (Polygon 9)



Mobile station position 5 (Polygon 5)

Figure 10-24 Polygon positions for mobile station investigation. Blue dots represent the mobile station random location. See Table 6 for the distance of the polygon to the radar location.

Figure 10-25 and Figure 10-26 show the CDF of interference levels at point A and point B in the receiver chain for each modelled position. Within each figure it shows the combined statistical output from the Monte Carlo simulations for a single mobile station at different locations for a given polygon.

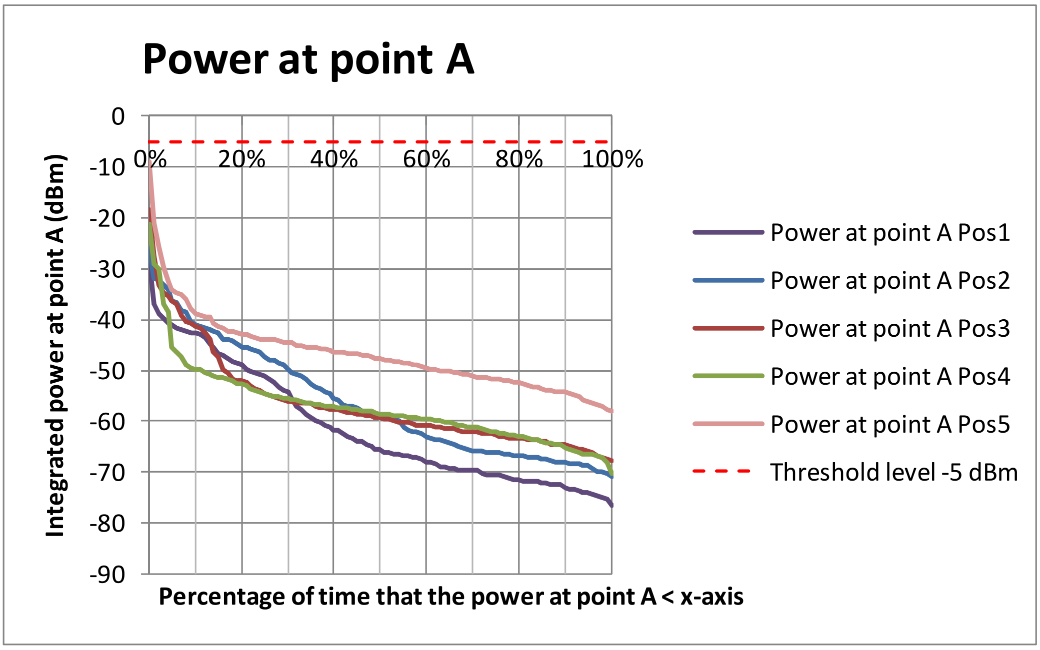


Figure 10-25 Average interference blocking levels at point A positions 1 to 5

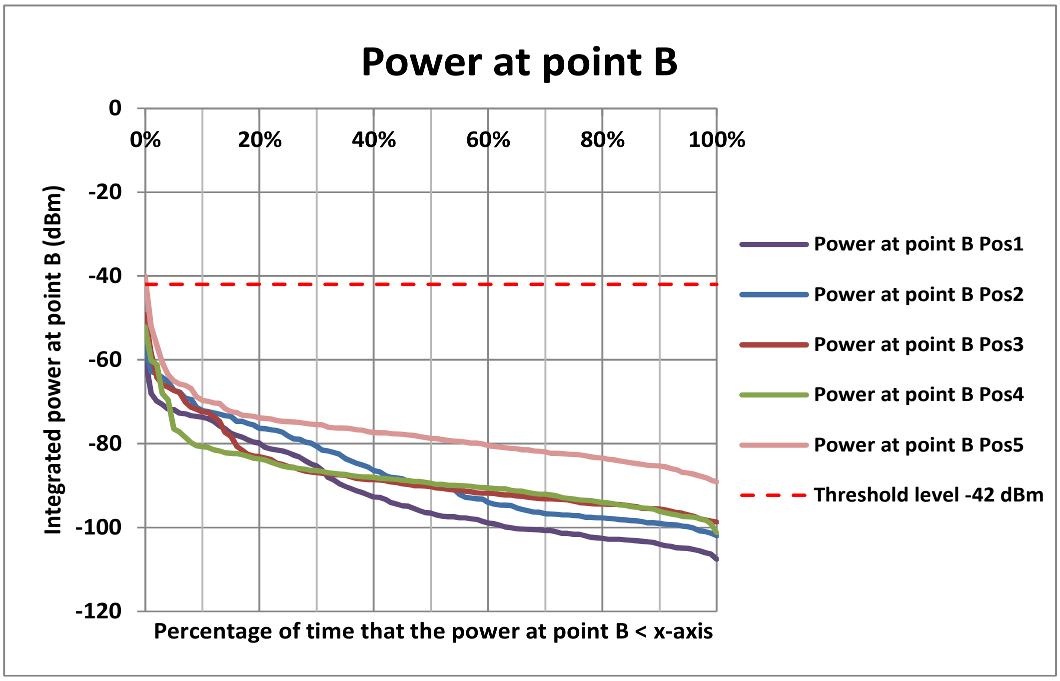


Figure 10-26 Average interference blocking levels at point B positions 1 to 5

It can be seen from the results that blocking of the radar does not occur at any of the positions for points A and B in the radar as the blocking threshold level is not exceeded at those points in the receiver. Note that for percentages of time greater than 20%, there is a clear distinction between the interference levels that are the result from the different mobile station polygons. This is in contrast to percentages less than 20%, where the position that generates the highest levels of interference is less consistent which is due to:

- Variability in the peak envelope power
- Variability due to shadowing
- In Position 4 the polygon area extends in a wide range of distances from the radar location

A steep rise in interference occurs for small percentages of time (<1% time) due to the variability in the shadowing and the signal envelope power, and the radar receiver appears to be blocked for a small fraction of time.

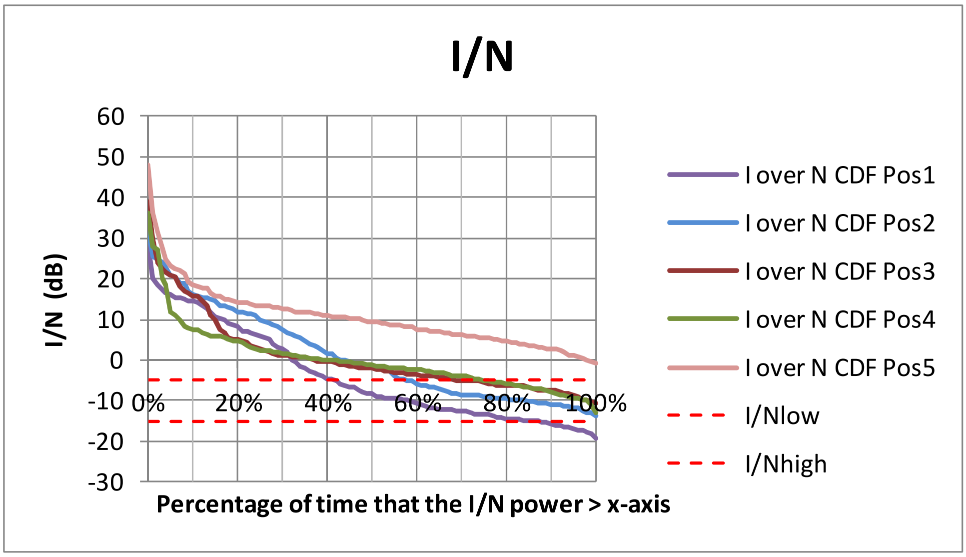


Figure 10-27 Average I/N levels for positions 1 to 5

The results from the I/N simulations in Figure 10-27 show that under the challenging case conditions the interference noise power is exceeded for 100% of the time the radar is pointing at the area of highest interference. Interference from position 5 shows the highest levels with positions 1 to 4 exceeding the threshold limit from 60% of the time the radar is pointing towards the area of worst interference. These results show that mobile station unwanted emission (3GPP/IEEE see section 8.2.3) will cause a problem to the co-channel interference to the radar. At position 5 under challenging case conditions a margin of 63.1 dB is required to reduce the interference noise power to within the acceptable threshold limits of the radar. This result has helped establish the extent of interference that could be generated from the mobiles and introduced the dynamic aspect of the mobile environment that would be apparent from interference from the uplink portion of the 2.6 GHz band.

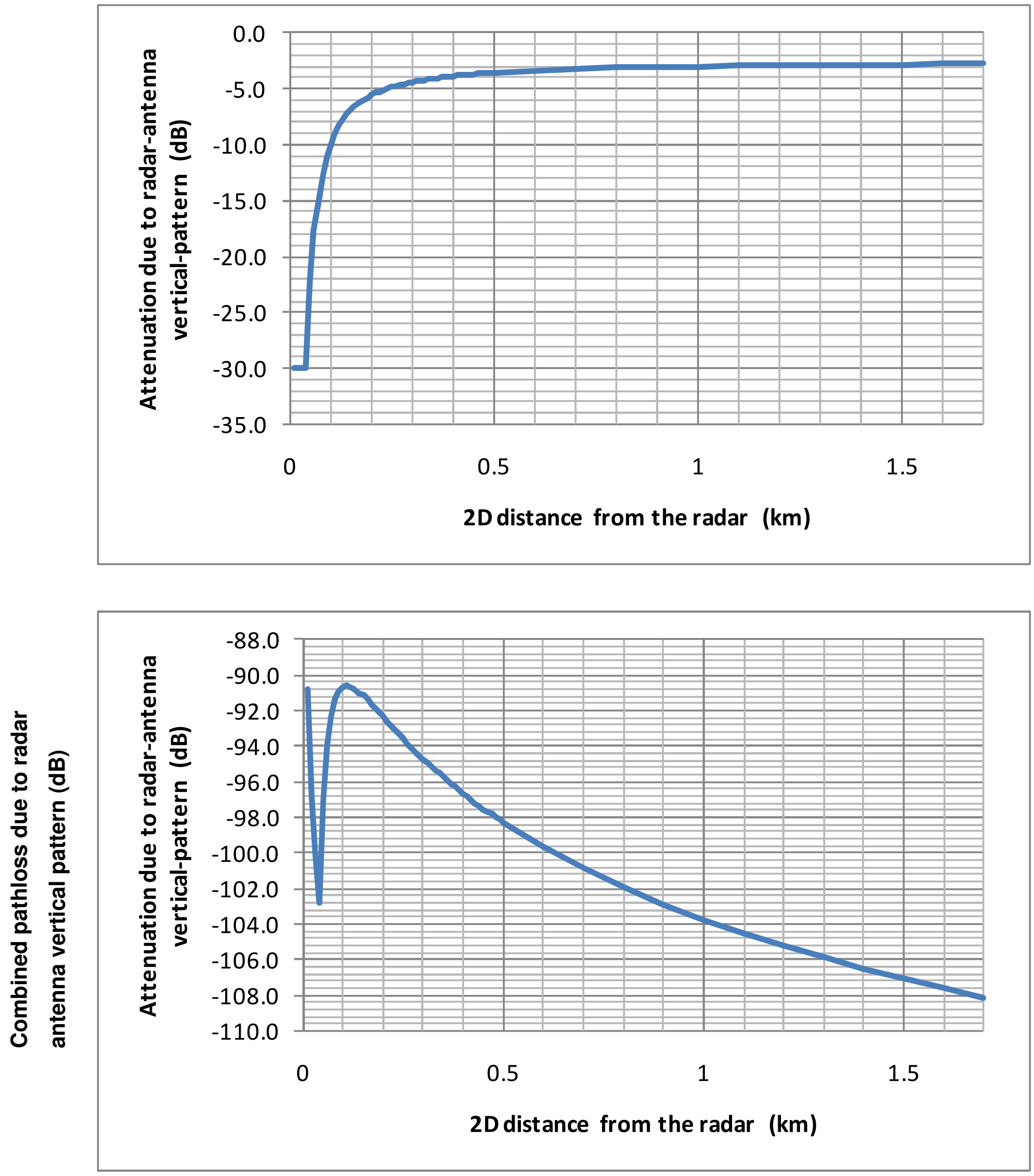


Figure 10-28 Combined pathloss and vertical-pattern attenuation vs distance from the radar. Radar effective vertical HPBW= 4.4deg, radar height= 5m, radar uptilt = 2deg, MS height = 1.5m.

10.7 Mobile station to radar – Challenging case

The mobile station to radar challenging case scenario aims to investigate the interference caused by all the modelled mobile stations in the simulation area. The input parameters used for this scenario have been selected to create severe interference conditions using challenging values. The main input parameter values can be seen in Table 10-11.

Parameter	Value
MS max EIRP	23dBm
MS power control	All mobiles at maximum power
MS location	Outdoor
MS antenna height	1.5 m
MS body loss	0 dB
MS spurious emissions	-30 dBm/MHz (3GPP/IEEE)
Number of mobiles	53 simultaneously active per iteration
BS channels	All channels at 100% loading[24]
Propagation model	Free space path loss+ 6 dB
Building penetration losses	0 dB (outdoor)
Shadowing standard deviation	8.3 dB
Radar height	5 m

Table 10-11 Challenging case parameters for mobile station

Figure 10-29 shows the blocking levels calculated at each point in the receiver chain, when the radar was pointing at the angle of highest interference. Blocking of the radar does not occur when the radar is pointing in the direction of highest interference. Note that the steep rise in the blocking level occurs at percentages of time 10% and below.

The average blocking level at point A is -33.9 dBm which is 28.9 dB below the -5 dBm threshold limit and thus blocking does not occur at this stage. The next stage in the receiver through which the signal passes, is the RF filter stage. It can be seen that the RF filter attenuates the signal by just over 30 dB which brings the blocking level down below the threshold of input to sub-system 2. At point B the level is -64 dBm for 1% time the radar points at the worst interference which still provides a 22 dB margin below the threshold. It can also be seen from Figure 10-29 the interference levels at percentage time below 1% are well below the threshold at point B which means no blocking occurs.

[24] The site locations 1 and 2 are sufficiently close together to justify the assumption that different mobile network operators are operating in each site. Therefore sites 1 and 2 are partially loaded. The same was assumed for sites 3 and 4.

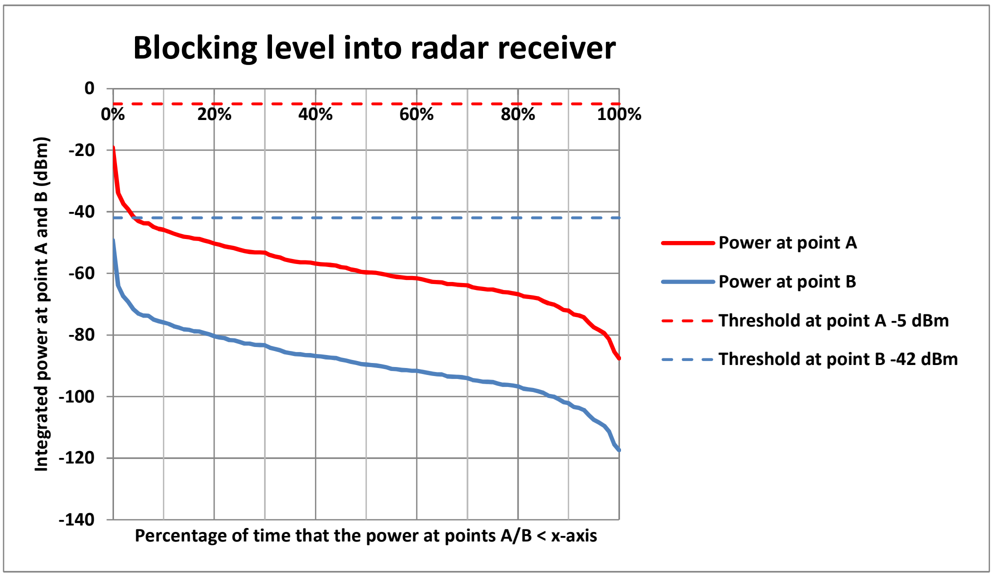


Figure 10-29 Average blocking levels from MS into radar – Challenging case

The radar receiver suffers severe interference noise rise from the spurious emissions of the MS under the challenging case conditions as can be seen in Figure 10-30. The results show that the interference noise power exceeds the minimum threshold for 90% of the time the radar is pointing at the area of highest interference. The interference level steadily increases across the statistical range up to a maximum 24.2 dB for 1% of the time the radar is pointing at the area of highest interference. The margin by which the mobile stations exceed the minimum threshold limit is 39.2 dB for 1% of the time. The simulated I/N level causes unacceptable levels of interference and would degrade the performance of the radar.

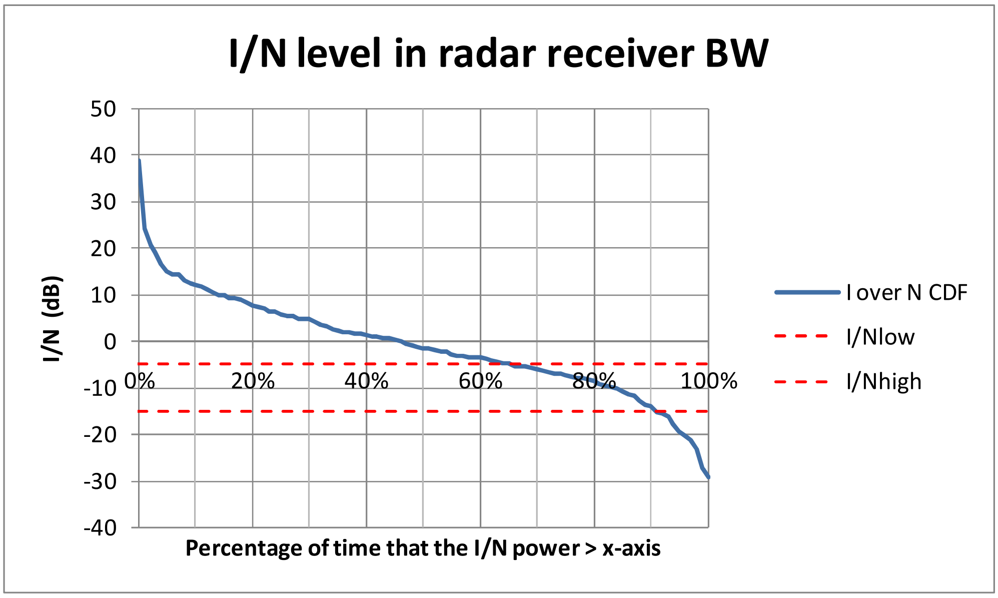
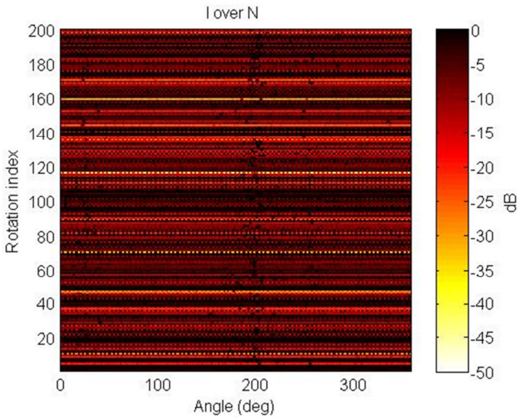


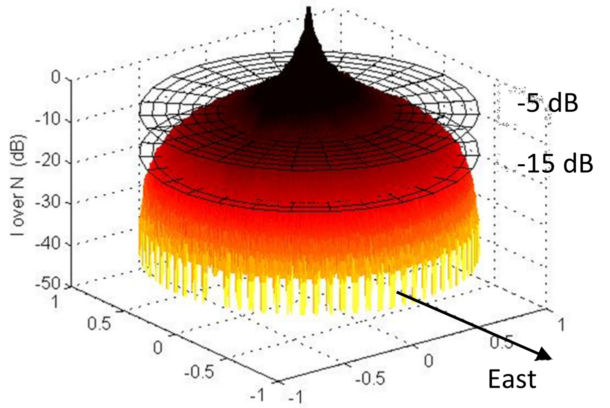
Figure 10-30 I/N level from MS into radar receiver – Challenging case

It can be seen that the CDF curve in Figure 10-30 is plotted for the angle of the radar pointing in the direction of highest interference. As the radar rotates the interference varies. Full appreciation of the interference environment generated by the mobile stations is captured more clearly in Figure 10-31, where the noise rise is plotted for variable rotation-angle and for different radar rotations. This figure assists to interpret the angles where the highest interference levels occur.

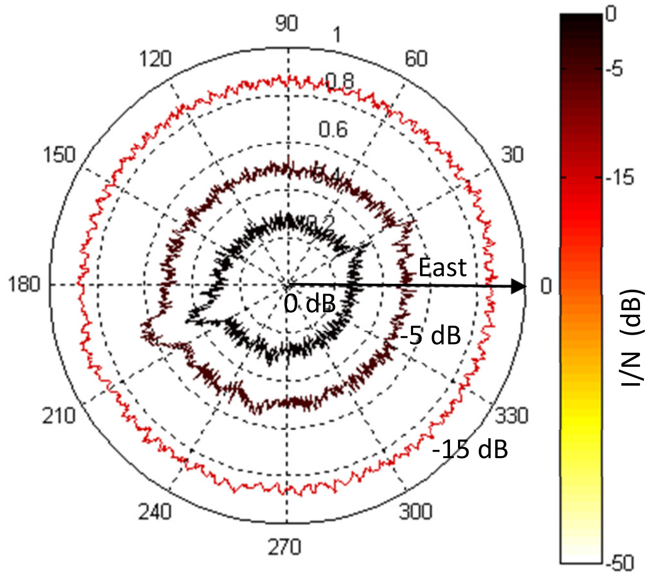
Subplot (a) shows the noise rise I/N as the radar rotates. The noise rise appears to be practically invariable with the rotation angle, apart from when the radar points to an interferer location, which is represented by a noise rise peak at that angle, i.e. a higher power level is displayed. It is reminded that for time efficiency purposes, the mobile station locations are constant in the simulation area throughout the radar rotation. Note that in some rotations the same noise rise level is recorded regardless of the rotation angle. This is most probably due to strong interferers spread evenly in several angles. Subplot (b) shows the same information of the noise rise I/N as subplot (a) but in a cylindrical coordinate system. It plots the probability of the noise rise exceeding several threshold levels (CDF) in the polar dimension. Subplot (b) shows that the noise rise exceeds the lower threshold (-15 dB) regardless of the rotation angle. Subplot (c) shows the same information of the noise rise I/N as subplots (a) and (b) but as contours in polar axes. It is a top-down view of subplot (b) to identify angles of highest interference and their corresponding percentage of time the interference exceeds the threshold level. Three contour levels are plotted, e.g. the contour labelled -5 dB shows that the noise rise exceeds the higher threshold (-5 dB) for about 50% of the time and that the sector between 190° and 200° shows stronger interference which is translated into slightly higher percentages. This suggests that this sector contributes with the highest interference. At the worst angle the percentage of the time that the radar exceeds the threshold is about 65%, which agrees with the value shown in Figure 10-30. The lower threshold limit (-15 dB) is exceeded at about 85% of the time, irrespective of the rotation angle. The signal variability causes small fluctuations in this percentage, which peaks at the worst angle at about 90%, in agreement with Figure 10-30. This confirms that from all angles under challenging case conditions the radar suffers from a rise in noise.



(a) Noise rise level at the radar receiver as the radar rotates. Colour intensity is used as scale of the noise rise value. The starting rotation angle is when the radar points east. The radar rotates counter-clockwise. Different rows depict the noise rise for varying mobile locations. For each angle (column of values) the CDF of the noise rise can be assessed, see subplot (b).



(b) CDF of the noise rise level at the radar receiver as the radar rotates (3D view). The noise rise values are positioned on the longitudinal-axis. The percentage of time that the noise rise exceeds the level of the longitudinal-axis is given by the polar-axis. The further the horizontal cut, at a given threshold value in the longitudinal-axis, is from the longitudinal-axis, the higher the probability of the noise rise exceeding this threshold value. Two horizontal cuts are plotted at the maximum and minimum I/N thresholds. Each radar rotation-angle corresponds to a column of values from subplot (a). Colour intensity is used as scale of the noise rise value.



(c) CDF of the noise rise level at the radar receiver as the radar rotates (contour view). This is a top-down view of subplot (b), and it plots the horizontal cuts at different contour levels. The percentage of time that the noise rise exceeds the contour-level is given by the polar-axis. The further the cut is from the pole, the higher the probability of the noise rise exceeding this contour level value. Colour intensity is used as scale of the noise rise value in the plotted contours.

Figure 10-31 Plots to identify angles of highest interference – Challenging case

10.8 Mobile station to radar – Typical case

This section studies the interference from mobile stations to radar under typical case assumptions. The input parameters used for this scenario have been selected to create a Heathrow-specific 2.6 GHz mobile deployment. The technical parameter values of the mobile stations are more realistic when compared to the challenging case, see Table 10-12.

Parameter	Value
MS max EIRP	23dBm
MS power control	Activated
MS location	Outdoor and indoor
MS antenna height	Variable according to the polygon
MS body loss	5 dB
MS spurious emissions	-50 dBm/MHz (assumption for typical value)
Number of mobiles	53 simultaneously active per iteration
BS channels	All channels at 80% loading[25]
Propagation model	Given by the polygon to radar propagation model
Building penetration losses	0 dB (outdoor), 14 dB (indoor)
Shadowing standard deviation	8.3 dB
Radar height	40 m

Table 10-12 Typical case parameters for mobile station

Figure 10-32 shows the average blocking levels calculated by the software model and it can be seen from the plot that the blocking level at point A is below the first threshold level of -5 dBm for all percentages of time under the typical case conditions. The blocking levels recorded at point A that occur for 1% of the time the radar was pointing at the area of highest interference was -48.8 dBm which is 43.8 dB below the first threshold level.

[25] The site locations 1 and 2 are sufficiently close together to justify the assumption that different mobile network operators are operating in each site. Therefore sites 1 and 2 are partially loaded. The same was assumed for sites 3 and 4.

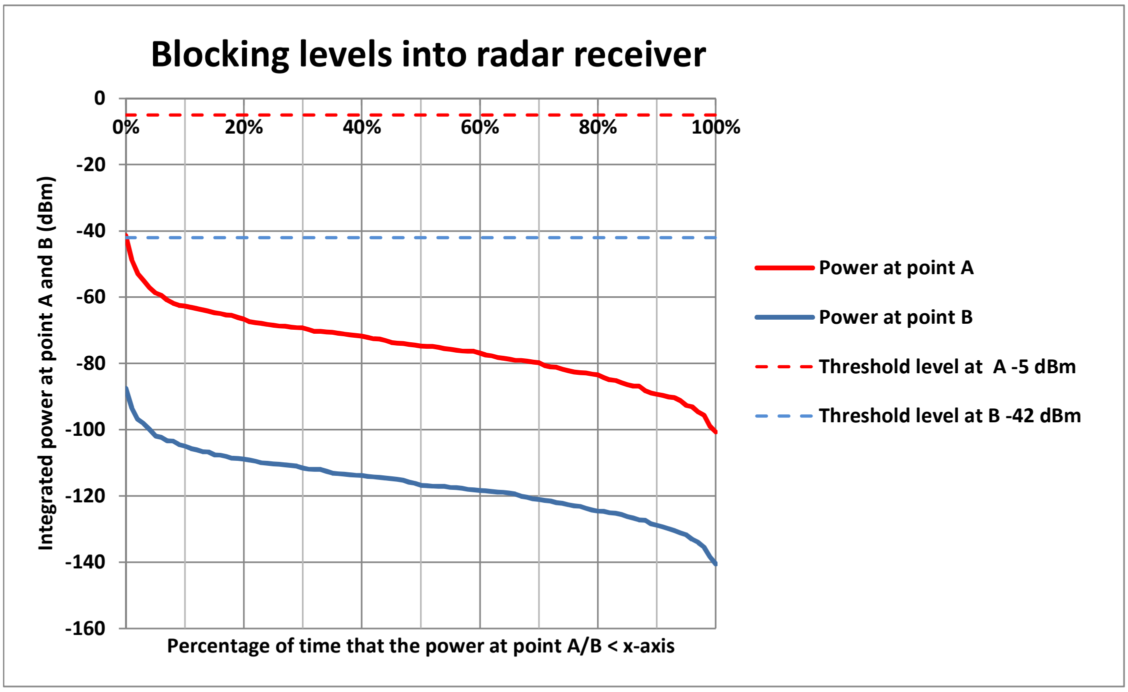


Figure 10-32 Average blocking from MS into radar - Typical case

The blocking levels recorded at point B shows increased attenuation as the signal passes through the RF filter. These filters provide approximately 40 dB of rejection after the first RF filters thus eliminating any blocking effects from the in band mobile emissions. This demonstrates no blocking occurs in the radar from mobile station emissions under typical case conditions.

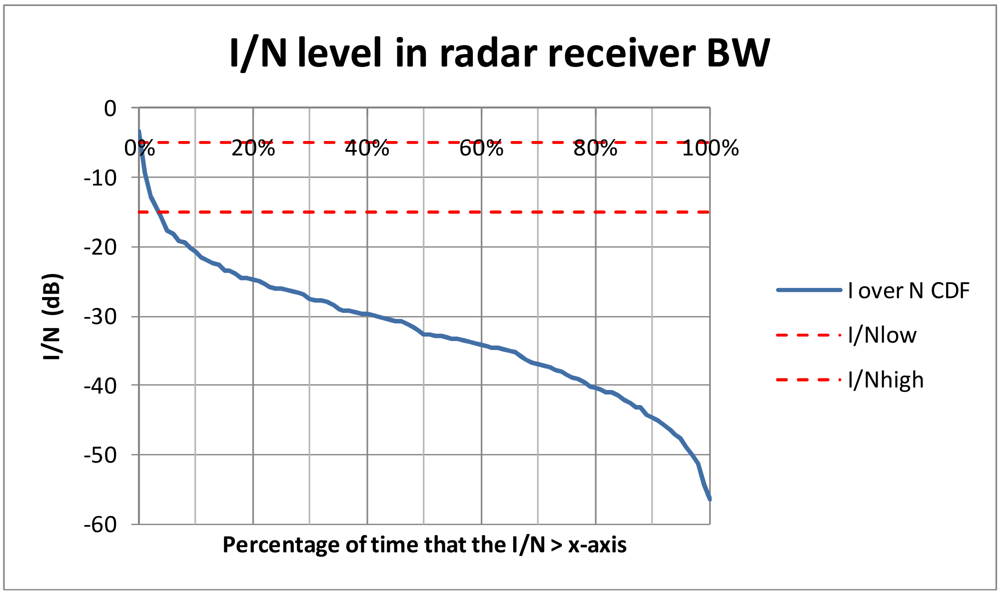
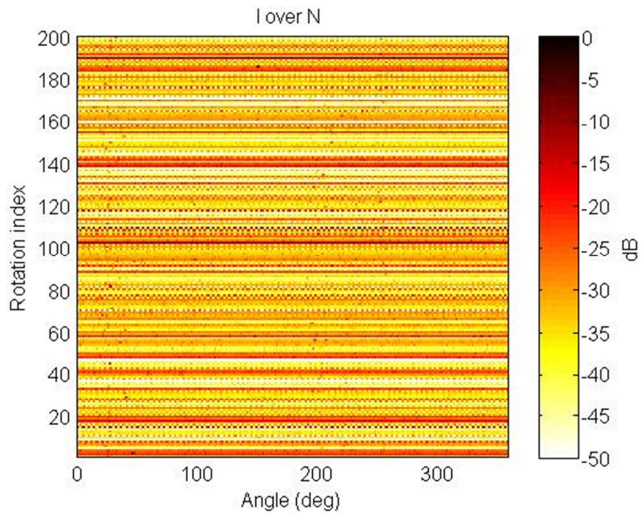


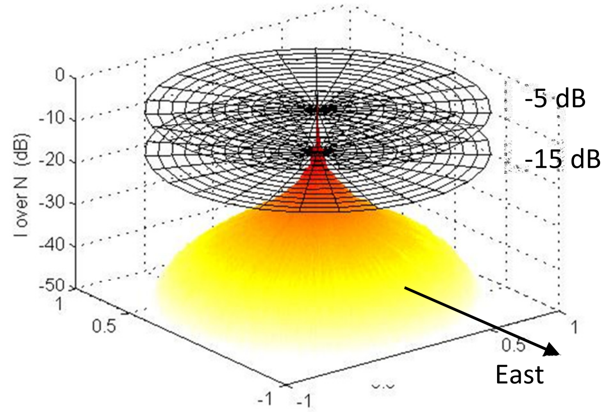
Figure 10-33 Average I/N levels from MS into radar - Typical case

Similar to the challenging case the results in Figure 10-33 for the I/N interference into the radar receiver show interference noise power from the mobile stations exceeds the minimum threshold level at <3% of the time the radar is pointing at the area of highest interference. In this scenario it was expected the resulting I/N level would be reduced compared to the challenging case I/N levels due to the improvement to the simulation environment parameters; the I/N level recorded was -9.3 dB for 1% time the radar is pointing to the area of highest interference. This has been demonstrated from the results. However, there is still a margin of 5.7 dB the level exceeds the threshold at 1% of the time the radar is pointing at the area of highest interference. This indicates a requirement for additional mitigations to be incorporated to reduce the 5.7 dB margin below the maximum threshold limits of the radar receiver.

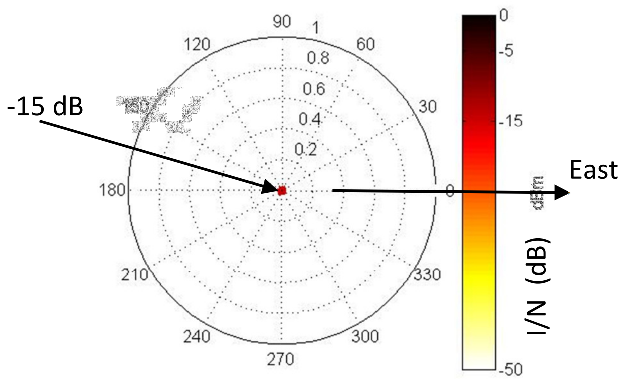
It can also be seen from the plot in Figure 10-33 for interference levels below 1% time there is up to 6 dB additional interference which therefore means up to 11.7 dB (maximum) may be required to bring the excess interference below the threshold level for 0.01% of the time and below.



(a) Noise rise level at the radar receiver as the radar rotates. Colour intensity is used as scale of the noise rise value. The starting rotation angle is when the radar points east. The radar rotates counter-clockwise. Different rows depict the noise rise for varying mobile locations. For each angle (column of values) the CDF of the noise rise can be assessed, see subplot (b).



(b) CDF of the noise rise level at the radar receiver as the radar rotates (3D view). The noise rise values are positioned on the longitudinal-axis. The percentage of time that the noise rise exceeds the level of the longitudinal-axis is given by the polar-axis. The further the horizontal cut, at a given threshold value in the longitudinal-axis, is from the longitudinal-axis, the higher the probability of the noise rise exceeding this threshold value. Two horizontal cuts are plotted at the maximum and minimum I/N thresholds. Each radar rotation-angle corresponds to a column of values from subplot (a). Colour intensity is used as scale of the noise rise value.



(c) CDF of the noise rise level at the radar receiver as the radar rotates (contour view). This is a top-down view of subplot (b), and it plots the horizontal cuts at different contour levels. The percentage of time that the noise rise exceeds the contour-level is given by the polar-axis. The further the cut is from the pole, the higher the probability of the noise rise exceeding this contour level value. Colour intensity is used as scale of the noise rise value in the plotted contours.

Figure 10-34 Plots to identify angles of highest interference – Typical case

Figure 10-34 shows the interference environment at all angles. As the radar rotates the noise rise is lower compared to the challenging case, see Figure 10-31. In each full rotation the radar sweeps through angles of high interference of noise rise levels of about -15 dB, see subplot (a). This suggests a much improved interference environment compared to the challenging case. Subplot (b) shows that the noise rise levels exceed the threshold for a smaller percentage of time for all angles, at the peak of the plotted surface. Subplot (c) shows that the interference exceeds the threshold (-15 dB) for about 3% of the time regardless of the radar angle. This suggests a significant reduction in interference at all angles compared to the challenging case conditions.

10.9 Mobile station to radar – Measured emissions case

Measurements of a commercially available 2.6 GHz FDD LTE mobile device were produced to capture the behaviour of mobile noise emissions in the S-band (blocking has been ignored due to limited impact from mobiles). The aim of the measurements was to provide some material evidence of the emissions that would either support our view for the mobile spurious emission assumptions or not. In parallel, the measurements also give the most representative indication of how spurious emissions from a mass produced commercially available mobile device may behave in the S-band in practice.

The mobile emission measurements became available in the latter stages of the project and therefore, results from this analysis have not been incorporated into the mitigation assessment.

The plots in Figure 10-35 show two close up samples of the mobile emission measurements that were performed by RFI Global on the LTE mobile device. One at full transmit power of the device and the other at a reduced (by 4 dB) transmit power. The basic parameters used to produce the result in Figure 10-35 are as follows:

- Max transmit power = 21 dBm
- Reduced transmit power = 17 dBm
- Transmission bandwidth = 10 MHz (50 Resource Blocks)
- Modulation scheme = QPSK

It can be seen from the plots that the peak measured spurious emissions from the mobile device are around -87 dBm/MHz which is about 40 dB lower than our assumption of the typical case spurious emissions parameter. At this level there is a negligible increase in noise into the radar receiver.

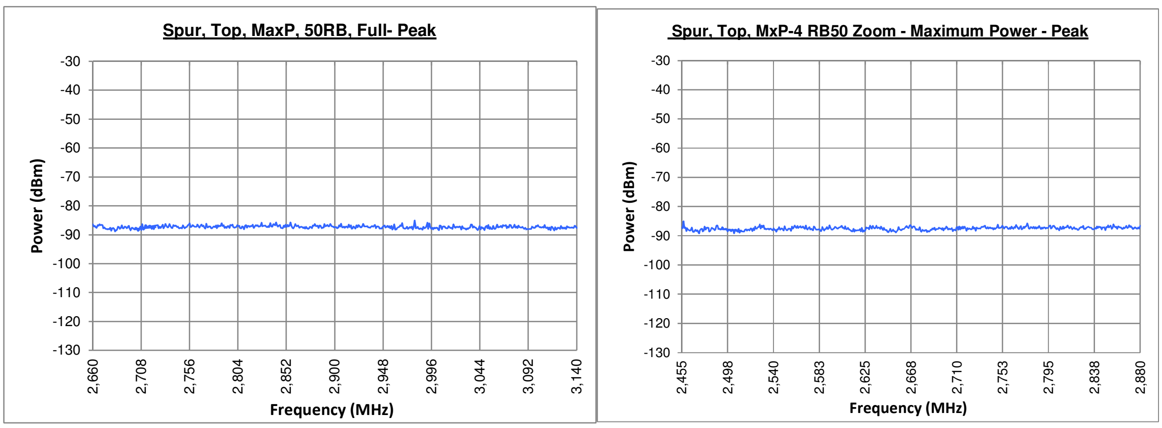


Figure 10-35 Peak spurious emission measurements of LTE FDD device in the S-band

The spurious emission levels between the two plots are practically the same but for different in-band power levels (4dB difference) indicating no correlation between in-band power and spurious emissions of the particular device. The shape of the emissions plot is generally flat with many very small peaks but there is no sign of a discrete spurious occurring within this measurement. Therefore, using the measurement plot data we imposed a discrete spurious occurring on the centre frequency of the radar receiver into our model, to capture any effects from the likelihood of it appearing.

10.9.1 Assumptions for discrete spurious

The lowest measured level of -89 dBm/MHz was set as the reference and from this level we increased the amplitude of the discrete spurious from 0 dB to 50 dB in 10 dB increments since we did not anticipate significant change in the output with smaller levels. We then increased the amplitude from 50 dB to 59 dB in 1 dB increments because these levels are approaching the 3GPP specification limit and could potentially be a level that exceeds the threshold. The model treats the spurious as if it was a function of the in band channel power of the mobile and therefore only occurs on a specific frequency (2560 MHz) with a 20 MHz bandwidth. However, the amplitude of the discrete spurious does not vary with power control due to the limited fluctuation in noise from any change in in-band power. Furthermore, the bandwidth of the discrete spurious is twice the bandwidth of the transmission of the mobile if we assume it is in an image of the mobile centre frequency.

We also assumed that the discrete spurious would not occur on all mobiles from all base stations and the following list of base stations were used in the model to serve the mobiles which produced the discrete spurious. Refer to Figure 10-6 for the position with respect to radar in each case.

- BS6
- BS10
- BS11
- BS13

These base stations were chosen randomly based on the mix of distances from the radar with those in close proximity likely to cause more interference than those further away. (Note BS7, BS8 and BS9 are indoor and serve indoor mobiles which are unlikely to be of sufficient power to cause a problem)

10.9.2 Results from modelling discrete spurious emissions

The results were generated using parameters from the typical case, the only change in parameters were the, radar height (increased to 40m) spurious emission levels and discrete spurious. Table

10-13 shows the discrete spurious not exceeding the -10 dB I/N threshold in most cases over the range of increased amplitude, except for levels approaching the 3GPP limit of -30 dBm/MHz. This means in the event of a discrete spurious appearing on the centre frequency of the radar receiver it is at risk of excessive noise rise (from this particular device) when the level is within at least 2 dB of the 3GPP limit.

Power level of discrete spurii modelled in S-band (dBm/MHz)	Exceeds -10 dB I/N threshold level at 1% time?
-89 (Flat response) to -39	No
-38	No
-37	No
-36	No
-35	No
-34	No
-33	No
-32	Yes

Table 10-13 Summary of measurement case analysis

Furthermore, the results suggest that for a commercially available mass produced LTE device spurious emissions performance is good and in the event of a discrete spurious appearing under the circumstances modelled then the amplitude must be within 2 dB of the 3GPP limit to cause a problem to the radar. Therefore, considering this to be a possible corner case the discrete spurious would need to occur under the following conditions to cause excessive noise rise into the radar receiver:

- Amplitude near to the 3GPP limit
- Appear on the centre frequency of the radar
- Generated by the combination of effects of the circuitry in the mobile device on the right in-band frequency
- Connected to a base station that is close to the radar
- Duration of the spurious must be long enough to be captured in the main beam

Although all of these events are unlikely to occur simultaneously, there is a very small risk a spike in the spurious emissions could appear and under the right circumstances could cause excessive interference to the radar. However, this situation can be compared to mobile devices already operating in the vicinity of an S-band radar but in other licensed frequency bands such as 2.1 GHz where successful co-existence between 3G devices and radars is already taking place. Detailed results for this analysis can be found in appendix A of the appendices document.

10.10 Summary of findings for mobile station to radar

10.10.1 Mobile station to radar – Single mobile station transmitter at variable distance from the radar with challenging case conditions

The findings from the initial investigation has shown that a single mobile station transmitting a single carrier at full power, using challenging case values, at various distances to the radar will cause blocking in the radar receiver. The blocking effect does not occur at point A of the radar receiver, which is at the input to sub-system 1, as the level recorded for all positions were below the -5dBm threshold level. The front-end RF filter provides additional attenuation in the order of 30-40 dB which reduces the signal further into the latter stages of the radar receiver. In particular there is 22 dB of margin below the threshold at point B in the receiver.

Position	Blocking at point A (dBm) (1% of the time the radar points at the worst interference angle) dB	Threshold at A (dBm)	Average distance km
1	-37	-5	1.86
2	-31.8	-5	1.4
3	-27.4	-5	0.96
4	-29.1	-5	0.87
5	-21	-5	0.25

Table 10-14 Blocking level summary

Position	I/N level (1% of the time the radar points at the worst interference angle) dB	Threshold (dB)	Margin to max threshold	Average distance km
1	20.2	-5 to -15	35.2	1.86
2	25.4	-5 to -15	40.4	1.4
3	29.8	-5 to -15	44.8	0.96
4	28.1	-5 to -15	43.1	0.87
5	36.2	-5 to -15	51.2	0.25

Table 10-15 I/N level summary

The interference caused by a rise in noise co-channel with the radar receiver centre frequency exceeds the maximum threshold limits for 80% of the time the radar is pointing at the interference. At relatively long distances (the maximum modelled distance is about 2km) emissions based on the 3GPP/IEEE mask can yield noise rise values that exceed the threshold levels. Several mitigation techniques can be investigated:

a) Improved spectrum emission masks from mobiles
b) Introduction of coordination zones around the radar
c) Introduction of a base station antenna that is positioned close to the radar location with a view to reduce the mobile output power based on the power control mechanism
d) Cap the maximum output power of mobiles in the vicinity of the airport

e) Cap the number of simultaneously active connections in the 2.6 GHz band in the vicinity of the airport

The aim of this investigation was to determine that sensible results were being produced by the software model and it was expected that as a single mobile station moved towards the radar the interference levels would increase which would validate the model calculations. It can be seen this has been confirmed from the results.

10.10.2 Mobile station to radar – Challenging case, typical case and measured emissions case

The findings from the main investigation of mobile station to radar show the impact of interference to the radar under the different scenario conditions. The scenario conditions analysed included:

- The challenging case technical parameters
- The typical case technical parameters

The summary results for blocking at point A and the I/N levels from the mobile stations are summarised in the tables below:

Scenario	Blocking at point A (dBm) (1% time)	Threshold at A (dBm)	Margin (dB)
Challenging case	-33.9	-5	-28.9
Typical case	-48.8	-5	-43.9

Table 10-16 Challenging and typical case summary blocking results

Scenario	I/N level (dB) (1% time)	Threshold (dB)	Margin to max threshold(dB)
Challenging case	24.2	-5 to -15	39.2
Typical case	-9.3	-5 to -15	5.7

Table 10-17 Challenging and typical case I/N summary results

The blocking levels in both cases did not exceed the first threshold limit at point A in the receiver due mainly to reduced EIRP compared to the base stations in order of 40 dB and also due to the frequency separation of the uplink band which is a minimum 140 MHz from the centre frequency of the radar that was investigated. The attenuation due to the frequency separation is based on the filters used for both the mobile station and the radar. For example, the maximum attenuation of the radar RF filter reach their limit of about -40 dB in the uplink portion of the 2.6 GHz band (see Figure 8-16 in section 8.3). Even with the contribution of the aggregate effects of multiple mobiles did not impact upon the blocking at point A.

In the challenging case scenario the noise rise from the mobile stations exceeded the threshold for more than 97% of the time that the radar was pointing at the highest interference angle. In other words the radar noise rise exceeds the threshold at least once in every rotation, with a probability of 97%. The noise rise level recorded for 1% of the time the radar was pointing at the area of highest interference was 24.2dB, which exceeds the lower threshold (-15 dB) by 39.2 dB. It is this margin which requires further analysis in order to reduce the interference level to below the threshold limit so that no degradation to the radar performance occurs.

This challenging case results were produced based on the out-of-band and spurious emission mask set to the minimum specified levels (-30 dBm/MHz) from the equipment standards. This means mobile equipment built to operate up to the specification limits with little improvement to the filter components could cause a problem with a rise in noise to S-band radars within an airport environment. It was expected under typical case conditions the interference levels would be reduced below the threshold limits for both interfering mechanisms and occur at levels either below or much closer to the threshold limits.

The improvement to the interference for both mechanisms was demonstrated under typical case conditions and described in more detail below. The analysis required changes to the main parameter settings for both the mobile station and the radar. For example settings such as the activation of power control, improvement to the OOB/spurious emission mask and increase to the radar height were made to represent a more realistic Heathrow-specific scenario.

The findings from the analysis under typical case conditions showed a 15 dB improvement to the blocking level and a 33.5 dB improvement to the interference noise power. The problems identified for blocking under the challenging case conditions were eliminated in this scenario. In addition a major contributor to the improvement to the interference noise power was due to the 20 dB reduction below the challenging case limits of the OOB and spurious mask. This was further improved when implementing the measured emission levels and increasing the radar height to 40m. The outcome showing no impact from 2.6 GHz mobiles for both blocking and noise rise in a Heathrow airport environment.

The combined analyses are put into perspective based on the rationale listed below which describes a number of contributing factors that must be considered for such a reduction in interfering signal to occur at the radar receiver:

1. Uplink power control – The mobiles adjust their EIRP in accordance to the path loss to their serving base station. Thus a base station close to the radar location would result in reduced output power for its connected mobiles.

2. Use of noise estimated/measured spectrum emission mask – The roll-off of spurious emissions once in the radar band is significant to the order of 50 dB. Therefore the margin of 20 dB below the 3GPP specification assumed for the typical case was conservative. The reduction in unwanted emissions had a significant impact to the I/N levels recorded and meant the noise occurred well below the acceptable threshold limits.
3. Increased radar height – Increasing the radar height has the effect of limiting the opportunity of interference to be captured in the main beam of the radar. As the height increases so does the clearance distance between the main beam and the ground.
4. Body loss – The impact of the body loss can be the difference between exceeding the threshold of interference or not. Usage of handsets and other mobile devices will be subject to body loss due to the user obstructing the path between the mobile station and the radar, and in this case contributed a small effect to the overall interference level.

The impact of the interference from mobile stations under typical case conditions does not cause a problem to the radar from a blocking perspective but did exceed the maximum threshold for the noise rise using assumed spurious emission level. It is therefore necessary to identify the source of interference in order to address the reduction of interference and apply the mitigations. This can be done by using the polar plots shown in Figure 10-31 and Figure 10-34 (c) to identify the angles of the highest levels of interference and the origin area. The polar plots show that the worst interference is coming mainly from all angles, see Figure 10-36, which is suggestive of high interference arising from locations very close to the radar. A small increase in the interference levels is identified when the radar points at the terminal or the airport perimeter roads.

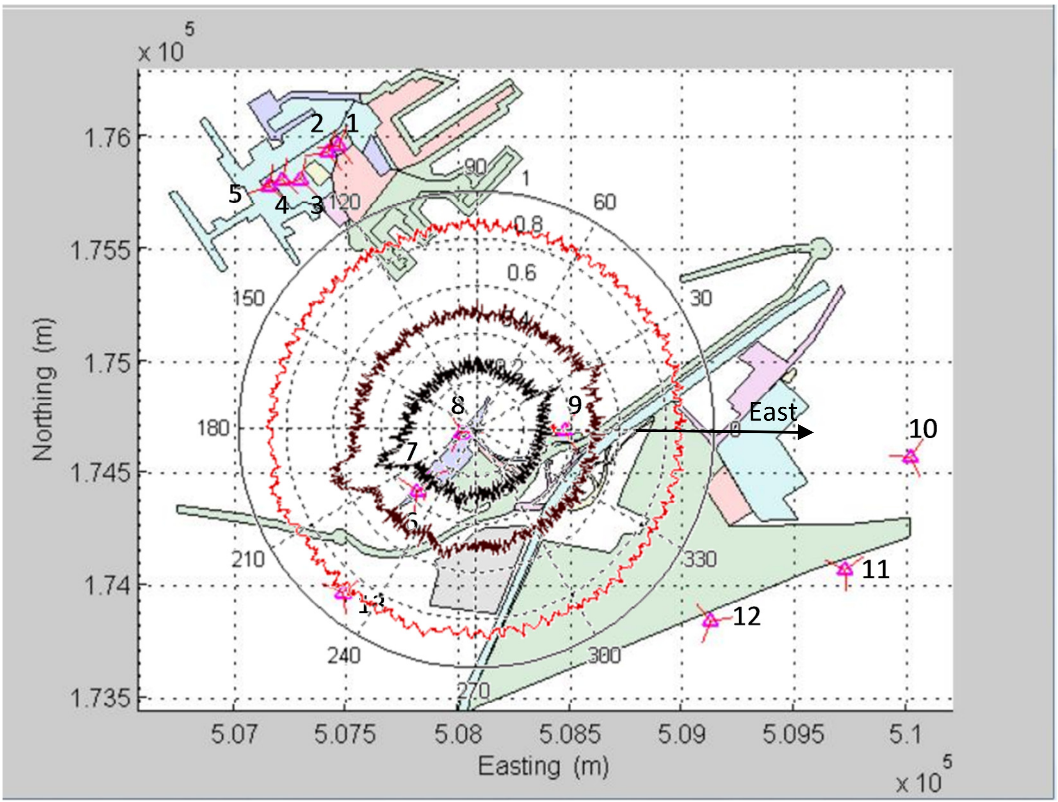


Figure 10-36 Polar plot of the CDF of the noise rise (I/N) under challenging case technical parameters, overlaid on the simulation area. The radar location is at the pole of the polar plot.

The findings from the challenging case and typical cases analysis support the need for further investigation into mitigation techniques for mobile stations specifically in relation to reducing the out-of-band and spurious emissions levels occurring into the radar band (when ignoring the measured emission levels). Furthermore, it is recognised that the results may be quite different under alternative scenario conditions which supports the need to understand the improvement the mitigation techniques are likely to have to the Heathrow layout case.

The investigation aims to identify which parameters can be modified and to what extent so that certain measures can be taken by 2.6 GHz operators within a variety of different airport environments.

10.11 Mitigation techniques identified from interference analysis

10.11.1 Base station to radar mitigation techniques

The findings from the results suggest that mitigation techniques are required to address the issue of interference noise power increasing the noise floor of the radar. The mitigation techniques identified for further investigation to reduce the impact of the interference noise power include:

Mitigation technique	Description	Comments
Reduce BS EIRP level	The reduced EIRP results in reduced unwanted emissions	Linear relationship between the reduction of EIRP and BS emission power levels is assumed. However a reduction in the EIRP has a non-linear relationship with the reduction of the service area of that BS.
Null of the BS antenna pattern towards the radar	Pointing the null of the antenna pattern towards the radar contributes to reducing the emissions in that direction as the null of the pattern will exhibit reduced gain towards the radar	Shaping of the antenna pattern is possible so that a null is introduced at the direction to the radar location
Reduce BS antenna height	The strongest interference occurs when the radar and the BS antennas have the same height	Changing the antenna height may provide attenuation of the unwanted emissions, however the reduced height may be combined with decreased downtilt (see below) to reshape the coverage area, so that the combined effect on the interference may be abortive
Increase BS antenna downtilt	The strongest interference occurs when the antenna points at zero elevation	Typical value for the downtilt used in industry planning exercises is 6 deg, which is also a reasonable assumption for suburban deployments where the Heathrow airport is situated. In more rural airports the interference problem may be intensified due to the decreased downtilt value. For the mobile network operator, an increase in the downtilt value is translated into additional sites or poorer coverage.
Improve unwanted BS spectrum emission mask	This is a direct mitigation technique that would adopt the use of high specification cavity filters to ensure sufficient rejection in the order 70 -80 dBc was realised in the unwanted emission levels	The cost associated with improvement to the base station filtering is dependent on the quality of the transmitter equipment and site specific engineering. Estimated costs for external high specification cavity filters are in the order of £500. This would need to be applied to all transmitters within the defined coordination zone in and around the airport
Power control the transmitter as the radar sweeps past the BS	Switching off the base station effectively means the radar is receiving interference from the sidelobes of its antenna, and thus at an attenuated level	This is a theoretical technique that is considered a plausible mitigation technique. For the mobile network operator, switching off the site is translated into loss of service. However, the percentage of time the site is required to be 'off' is relatively small.

Coordination zone for BSs	The coordination zone is an area around the radar, e.g. a disc where BSs are not allowed to be deployed	For the mobile network operator, a coordination zone may interfere with the optimisation of the network and in proving additional capacity for the passenger users. For a 2.6 GHz -only network, the coordination zone may result in a high loss of revenue.

Table 10-18 Summary of mitigation techniques for base stations

It is acknowledged that the application of the mitigation techniques to the base station will also cause a certain amount of degradation in performance to the 2.6 GHz networks. The types of impact this could cause to network operations include:

i. A reduction in the downlink coverage area from base stations
ii. Limit the availability or number of resources available to network users
iii. Limit the throughput available on the downlink
iv. Reduction in Quality of Service such as Guaranteed Bit Rate
v. Potentially de-value the spectrum around airports

The values identified for each of the mitigation techniques are adjusted to the most practical yet appropriate level possible with the aim of minimising the impact caused to the deployment of the network. Furthermore, this approach will help minimise cost per base station to the essential components which would likely include the addition of a cavity filter.

10.11.2 Mobile station to radar mitigation techniques

The analysis of the mobile station interference into a radar receiver has found there is no requirement for additional mitigation techniques to be applied in order to reduce blocking under the typical case scenario investigated. However it might be the case for other deployment scenarios that mobile stations cause blocking or more likely cause interference noise power increase that does exceed the threshold levels of the radar under different scenario conditions.

The mitigation techniques that have been considered are listed below:

Mitigation technique	Description	Comments
Reduce MS maximum EIRP level	Limit maximum EIRP level to 20 dBm	Linear relationship between the reduction of EIRP and MS emission power levels is assumed. However a reduction in the EIRP has a non-linear relationship with the reduction of throughput and/or quality of service. Especially for high power mobiles, which are at the cell edge, reduction of power may lead to dropped calls and coverage holes.

Improve MS unwanted spectrum emission mask	This is a direct mitigation technique that would require the adoption of improved ceramic filtering within the mobile device to ensure sufficient rejection in the order 70 -80 dBc into the radar band	There is little published evidence of spurious emissions performance for different device types into the S-band. Mobile devices are already entering the market and understanding their spurious emissions performance is critical for the deployment of mobiles at airports.
Coordination zone for MSs	The coordination zone is an area around the radar, e.g. a disc where MSs are not allowed to be on the 2.6 GHz band	This may be achievable by careful planning from the mobile network operator so that the signal level is below the handover threshold when the MS is within the predefined coordination zone. A signal jammer may also be deployed to shape the coordination zone. For a 2.6 GHz -only network, the coordination zone may result in a high loss of revenue.
Additional BS	Introduce an additional site or coupled antenna close to areas of high interferers to minimise the output power of the mobile via the power control mechanism	The mitigation of introducing additional sites may be difficult in practice, because of potential saturation in the site locations. Further, the reduction in power levels is rather local, and the number of new sites that are required to lower the emissions may be large. Introduction of coupled antennas does not contribute to additional capacity, so that transmission takes place in a small quantity of spectrum with a high power.
Cap the maximum number of 2.6 GHz users	Cap the maximum number of simultaneously active connections in the vicinity of the airport	At the cell-edges there are clusters of high emitting users that are captured within the main horizontal beam as the radar rotates. In more rural airports, compared to Heathrow, the number of active connections will be reduced, compared to the simulation value, which provides an inherent mitigation to the interference problem. This mitigation may require further analysis on its applicability, taking into account the complex resource allocation mechanisms in LTE and WiMAX.

Table 10-19 Summary of mitigation techniques for mobile stations

The values to be used for each of the mitigation techniques should be adjusted to the most practical yet appropriate level possible. However, it has been recognised that adjustments to the mobile station technical parameters or to the uplink can impact upon the performance of the 2.6 GHz network. For example, limiting the EIRP of the mobile station will reduce the throughput per mobile which may cause a noticeable reduction in performance. In addition there is a limit to the adjustments that can be made to mass produced equipment such as mobiles, built to a standardised specification. Therefore, e.g. improvement in the spectrum emissions mask may in practice be difficult to implement as national interface requirements may stipulate tighter limits on the masks would usually be developed at a regional or International level. This analysis considered all mitigations listed above and therefore it was expected each one to contribute some reduction to the interference levels in close proximity to the radar.

11 Interference modelling results with mitigations

11.1 Discussion of mitigation approaches

The mitigation techniques identified for further investigation are analysed in this section. The mitigation techniques were derived from Section 10 based on the analysis of interference from a challenging case and typical case perspective for both the base- and the mobile-stations. The analysis highlighted the particular parameters that could be adjusted further and improve the interference environment so that the noise rise is reduced to levels within the acceptable threshold limits of the radar receiver. In addition to that, resolving the noise rise problem ascertains resolution to blocking problems at the various stages of the receiver chain for both base- and mobile-stations.

The aim of introducing the mitigation techniques was to establish that even under specific deployment conditions the variety of scenarios will vary widely. Using the Heathrow Airport as one example demonstrates how under typical case conditions for the specific deployment environment greatly minimises the potential for interference from blocking and interference noise power. However, these conditions may not apply under different deployment circumstances, therefore the mitigations offer a set of generic parameters that can be modified further for different deployment conditions.

Reducing the interference into the radar receiver comes at a cost to the deployment of 2.6 GHz networks. The cost implications arise from making adjustments to the network parameters to satisfy an additional (mobile operator exclusive) requirement. The introduction of mitigation techniques could have the following impact on 2.6 GHz network deployments:

- Additional CAPEX and OPEX per base station to the deployment of 2.6 GHz networks in and around airports
- Further engineering complexity required to manage the interference situation
- Introduction of new approval processes required for 2.6 GHz network equipment to be implemented by the airport authority

The mitigation techniques that were identified for both the base- and the mobile-stations in section 10 are shown in Table 11-1 and Table 11-2.

No.	Mitigation parameter	Non-mitigated value	Mitigation value	Comment
1	EIRP	63 dBm/ 20MHz	57 dBm/20 MHz	Reduction in EIRP reduces the interference by the same amount in decibels
2	Antenna downtilt	6°	10°	Reduces the gain of the BS antenna towards the radar
3	Antenna height	Any permitted (max 25m)	15m (5m below the typical radar height)	Reduces gain of the vertical antenna pattern towards the radar
4	Antenna orientation optimisation towards radar	Random orientation	Null towards the radar	Reduces gain of the horizontal pattern towards the radar
5	Power control the transmitter as radar sweeps past BS	N/A	E.g.< -85dBm/MHz	Potentially eliminate interference at the angle when the base station is illuminated by the radar main beam
6	OOB/Spurious emission mask (EIRP)	-13 dBm/MHz	-39 dBm/MHz	Reduction in the emissions mask in the OOB/spurious domain reduces the interference by the same amount in decibels
7	Coordination zone	N/A	600 - 700m	No 2.6 GHz deployment around the radar from outdoor (and indoor) base stations

Table 11-1 Mitigation techniques for base stations

No.	Mitigation parameter	Non-mitigated value	Mitigation value	Comment
1	Max EIRP	23 dBm	20 dBm	Reduced EIRP reduces the OOB/spurious with aim to reduce I/N level
2	Coordination zone (indoor and outdoor)	N/A	300m (outdoor) 70m (indoor)	To minimise the I/N levels impacting in close proximity to the radar
3	OOB/spurious emission mask	-30 dBm/MHz	-56dBm/MHz	To further reduce impact to the I/N levels in close proximity to the radar
4	Additional base station in the area of high interference	N/A	Additional site	Reduce EIRP from mobiles by introducing lower signal losses between the BS and MS
5	Cap the number of users on the 2.6 GHz network	53 (100%)	44 (83%)	Reduce overall interference from aggregate power of clusters of mobiles

Table 11-2 Mitigation techniques for mobile station

11.2 Performance of Mitigation solutions

The following sections present the results from the simulations of the mitigation techniques and establish to what extent any improvement to the interference environment has been made by introducing the different mitigation techniques.

11.2.1 Base station to radar

The following results show the impact each mitigation technique contributes to the net reduction in interference noise power into the radar receiver from the base stations. The challenging synthetic layout case scenario was used to establish a coordination zone for modelling the mitigations. The investigation included running the simulation for each mitigation mechanism to determine the improvement of the interference over the non-mitigated case. The parameters used were set to challenging yet realistic values as shown in Table 10-5.

The tables below show each mitigation technique and the parameter value used in the analysis against the results without mitigation and the result with mitigation. In addition, the tables show the impact of introducing each mitigation to the overall 2.6 GHz network deployments paying particular attention to the service as a percentage of resources available to users. In the outdoor case Table 11-3 shows that from the mitigation techniques modelled there are four which contribute up to 23 dB reduction to the I/N level and have the lowest combined impact on the availability of network resources. Mitigations 4, 5, 6 and 7 are likely to be the most attractive to implement based on the amount of improvement to the interference levels and to their minimal impact to the network resource availability.

No.	Mitigation technique	Parameter value without mitigation	Parameter value with mitigation	Improvement in I/N when the radar points at the angle of BS 8 (BS 8 is situated 1 km from the radar)	Improvement in I/N when the radar points at the angle of BS 1 (BS 1 is situated 50 m from the radar)	Impact for 2.6 GHz deployments
1	Reduced EIRP	63 dBm/ 20MHz	57 dBm/20 MHz	6 dB	6 dB	6 dB in reduced EIRP is translated into 25% availability of resources
2	Antenna downtilt	6°	10°	9 dB	9 dB	The coverage area shrinks to 16% of its original size

3	Antenna height	20 m	15m	3.2 dB	30.4 dB	The coverage area shrinks to 53% of its original size
4	Antenna orientations	0, 120,240° 0 deg = East	12 dB max attenuation	8.4 dB	8.4 dB	100% availability of resources
5	Power control the transmitter as radar sweeps past BS	63 dBm/20 MHz	-85dBm/MHz	3.1 dB	30.5 dB	99% availability of resources
6	Improved OOB/Spurious emissions (EIRP)	-13 dBm/MHz	-37 dBm/MHz	24dB	24 dB	100% availability of resources
7	Coordination zone	N/A	600 - 700m	-2 dB	45.1 dB	The area that the MNO can deploy shrinks to 84% of its original size
8	Combined mitigations 4-7			41.6 dB	63.5 dB	83%

Table 11-3 Comparison of mitigation techniques in reducing the noise rise I/N. The required I/N threshold is -15 dB. MNO: Mobile Network Operator – Outdoor base stations

Figure 11-1 and Figure 11-2 show the improvement in noise rise when introducing mitigations for two rotation angles: when the radar points at the angle of BS 1 and BS 8. Note that the impact of introducing a mitigation technique is dependent on the angle. For example introducing a coordination zone eliminates BS 1 which results in great reduction of received interference, when the radar points at the angle of BS 1. This is because with the coordination zone mitigation the radar interference is attenuated from the side lobes of its antenna horizontal pattern. At the angle of BS 8 the received interference remains at about the same level, because the interfering BS 8 is outside the coordination zone and therefore contributing with the same amount of interference regardless of the mitigation.

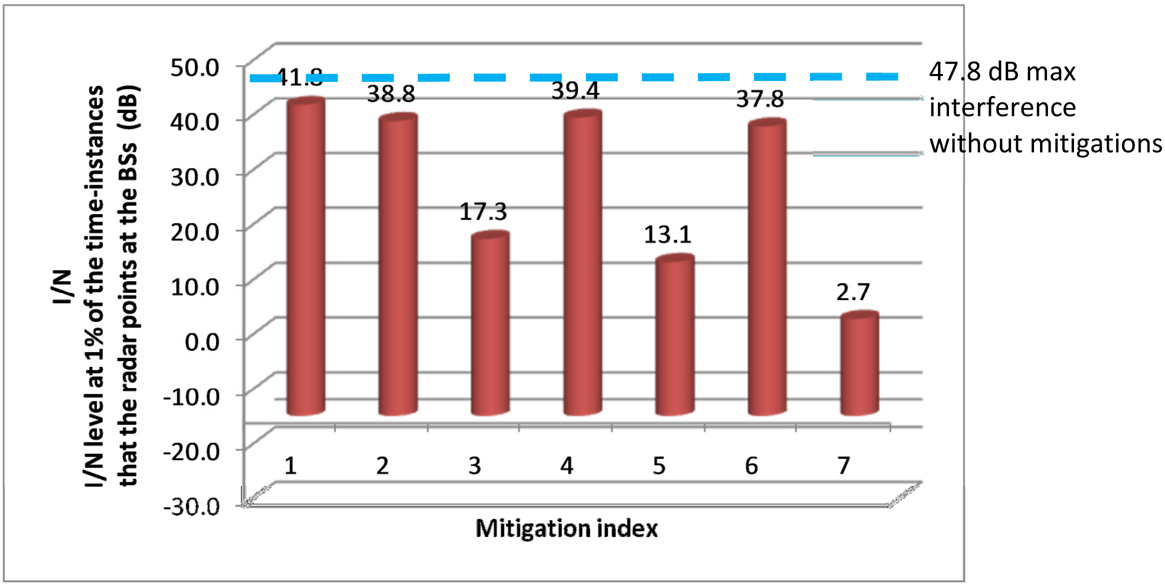


Figure 11-1 Peak I/N results difference when the radar points at the angle of BS 1

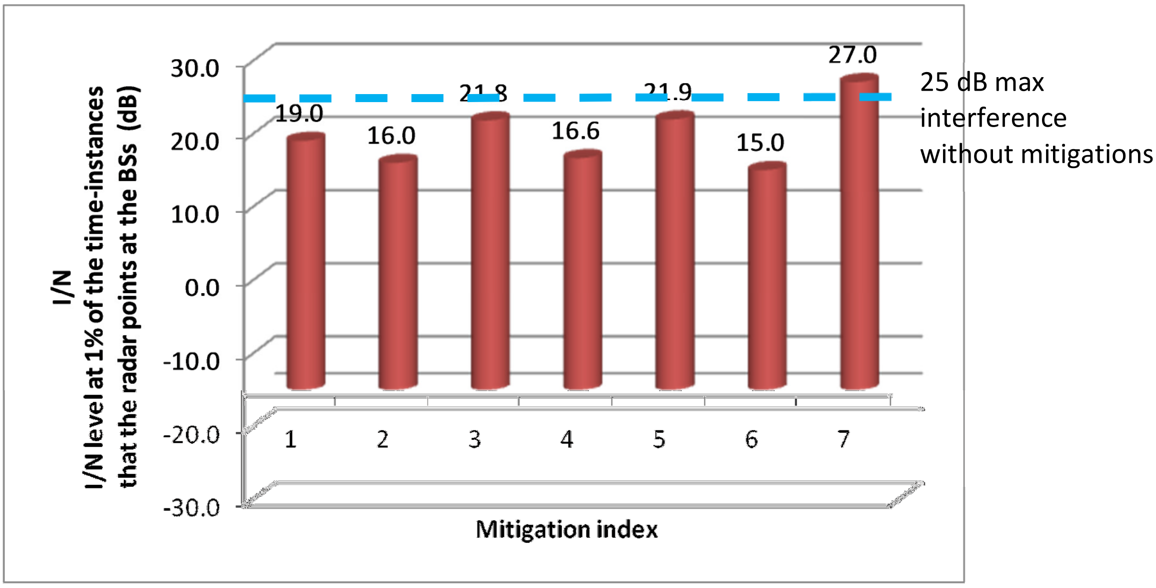


Figure 11-2 Peak I/N results difference when the radar points at the angle of BS 8

The mitigations applied individually do not contribute enough to bring the interference noise power to within the acceptable limits. Therefore, using a combination of mitigations 4 to 7 produces mitigation 8 which shows there is sufficient reduction to the overall interference noise power and thus can be tested against the Heathrow layout scenario. The results of implementing the combined mitigations can be seen in Figure 11-3 which shows the I/N levels from all base stations below the -15 dB threshold.

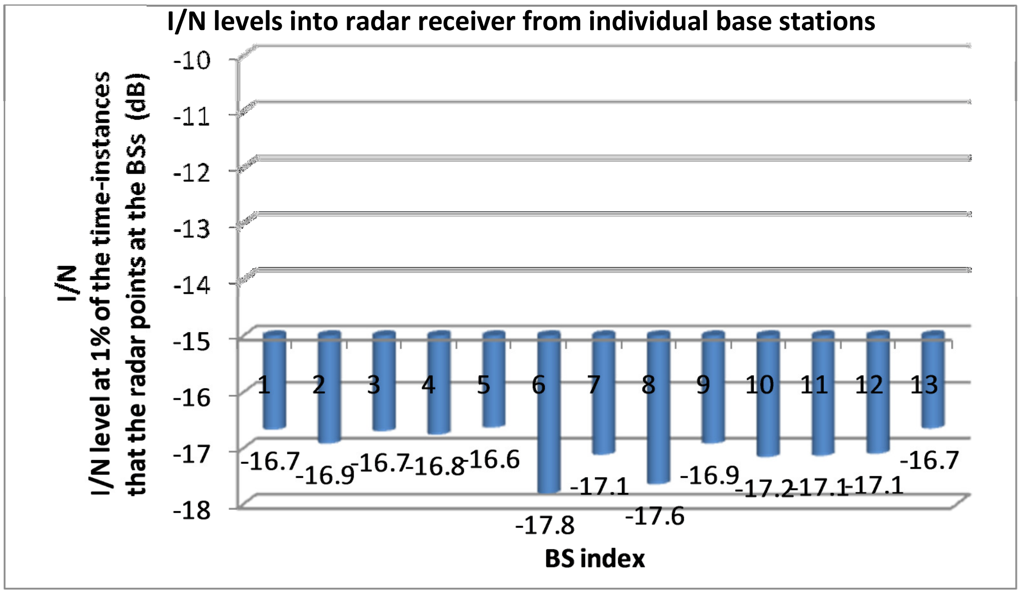


Figure 11-3 Peak I/N levels with Outdoor Mitigation 8 applied to the challenging synthetic layout (outdoor base stations), see Figure 10-15

Having identified a combination of mitigations that reduces the peak I/N levels, the next step is to introduce them into the Heathrow specific layout of outdoor base stations to test the validity. The results in Figure 11-4 show the impact of introducing the combined mitigations into the Heathrow layout which shows how using the mitigations improves the interference noise situation by a margin range of 7.5 to 16 dB. This solution also has the added benefit of resolving the blocking at point A as shown in Figure 11-5.

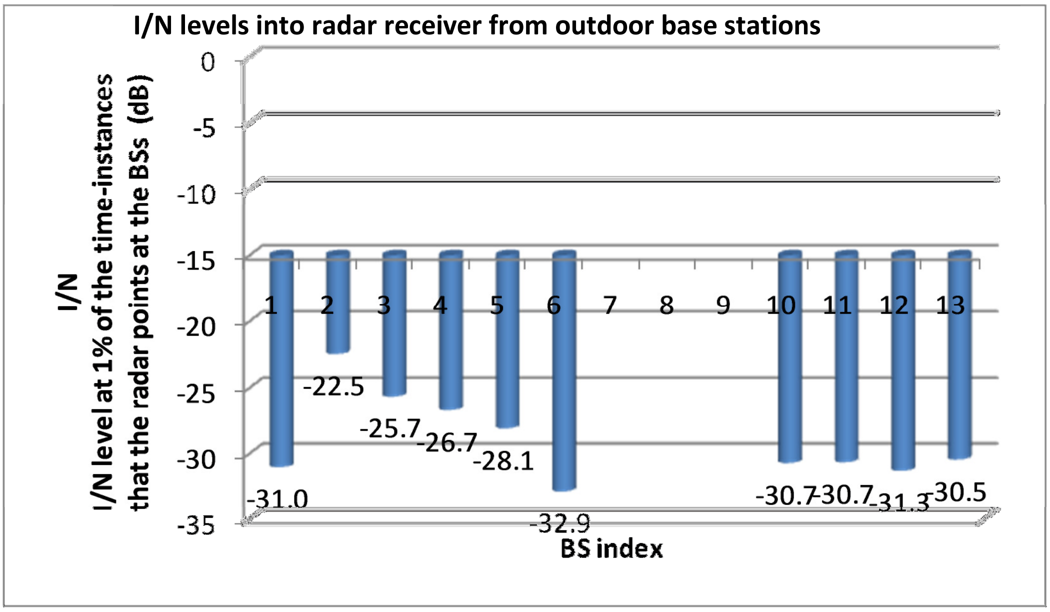


Figure 11-4 Peak I/N levels with Outdoor Mitigation 8 applied to the Heathrow-specific layout (outdoor base stations where BS 7, 8, 9 are indoors), see Figure 10-6

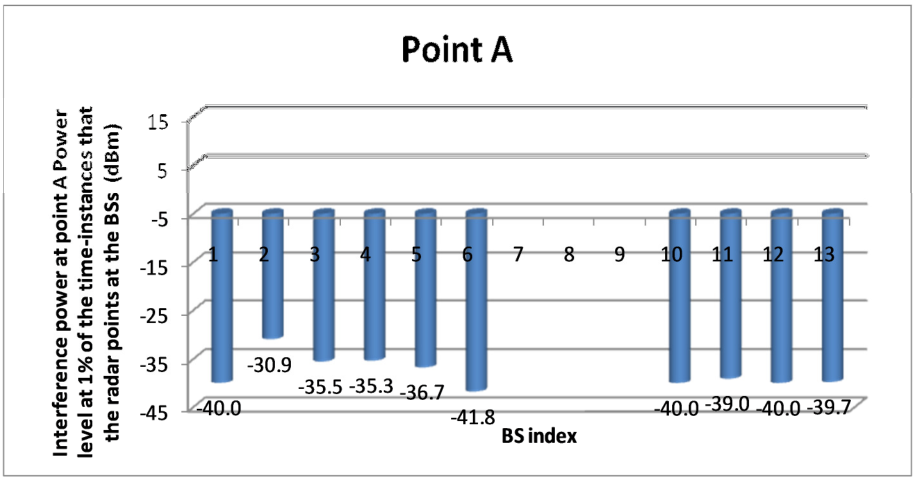


Figure 11-5 Peak blocking levels at point A in receiver chain

The challenging synthetic layout case scenario was used to establish an indoor coordination zone and other mitigation techniques. The non-mitigated challenging synthetic layout showed that the noise rise I/N generated from indoor base stations exceeded the threshold at all modelled distances. Table 11-4shows the mitigations used to reduce the margin of interference and the improvement from the simulations in each case. Compared to the outdoor required mitigations, due to the lower EIRP, omni-directional antennas and building penetration losses the number of mitigations for indoors stations was lower.

No.	Mitigation technique	Parameter value without mitigation	Parameter value with mitigation	Improvement in I/N when the radar points at the angle of BS 8 (BS 8 is situated 1 km from the radar)	Improvement in I/N when the radar points at the angle of BS 1 (BS 1 is situated 50 m from the radar)	Impact for 2.6 GHz deployments
1	Antenna height	20m	See Figure 11-6	7.9 dB	19 dB	85%
2	Improved OOB/Spurious emissions (EIRP)	-13 dBm/MHz	-37 dBm/MHz	24 dB	24 dB	100% availability of resources
3	Coordination zone	N/A	120m	12.4 dB	22.5 dB	The area that the MNO can deploy shrinks to 95% of its original size
4	Combined mitigations 1 to 3			25.7 dB	58.7 dB	

Table 11-4 Comparison of mitigation techniques in reducing the noise rise I/N. The required I/N threshold is -15 dB. MNO: Mobile Network Operator – Indoor base stations

Each mitigation alone does not contribute adequately to the reduction of the noise rise level so that the I/N level changes to within its threshold limit. Therefore several mitigations should be combined to create an aggregate effect on the interference. There are an infinite number of combinations of base station height and coordination zone considerations, and many can be the solution that reduces the interference below the threshold level. With the aim to achieve the lowest possible impact to the 2.6 GHz deployments, the height restriction for the indoor base stations are shown in Figure 11-6.

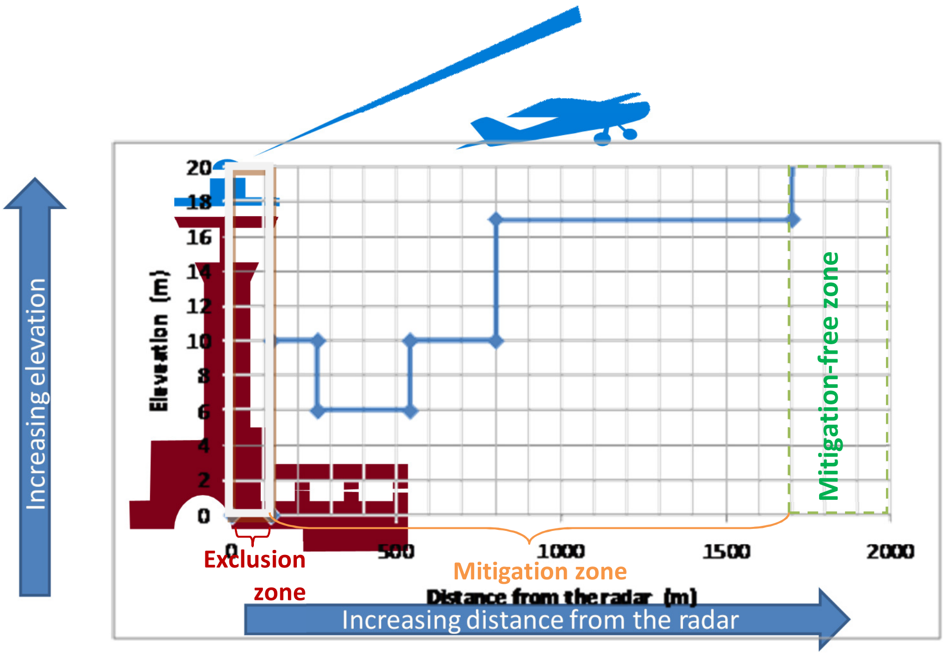


Figure 11-6 Indoor BS antenna height chart

Mitigation 4 was tested on the challenging synthetic layout. The simulation results show that when the radar was pointing at the locations of each indoor base station noise rise levels did not exceed the minimum threshold limit, see Figure 11-7. This was considered to be an acceptable outcome.

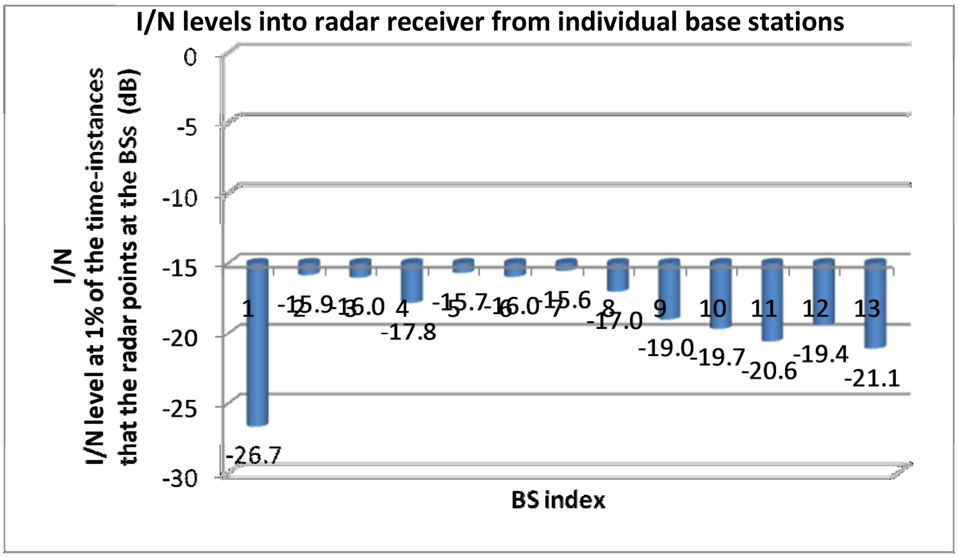


Figure 11-7 Peak I/N levels with Indoor Mitigation 4 applied to the challenging synthetic layout (indoor base stations), see Figure 10-15

Figure 11-8shows the results from the Heathrow specific layout using Mitigation 4. Only two out of the three original base stations can be deployed under these mitigation conditions, this is due to the introduction of the coordination zone of 120m. Therefore, base station 9 (see Figure 10-6) is no longer allowed to transmit (under the specific conditions modelled) on 2.6 GHz due to its close proximity to the radar and the interference that would cause at this distance. However, exclusion of this base station does not have an impact on the Heathrow-specific layout, because this base station is intended to provide coverage only in its close proximity and to non-passengers.

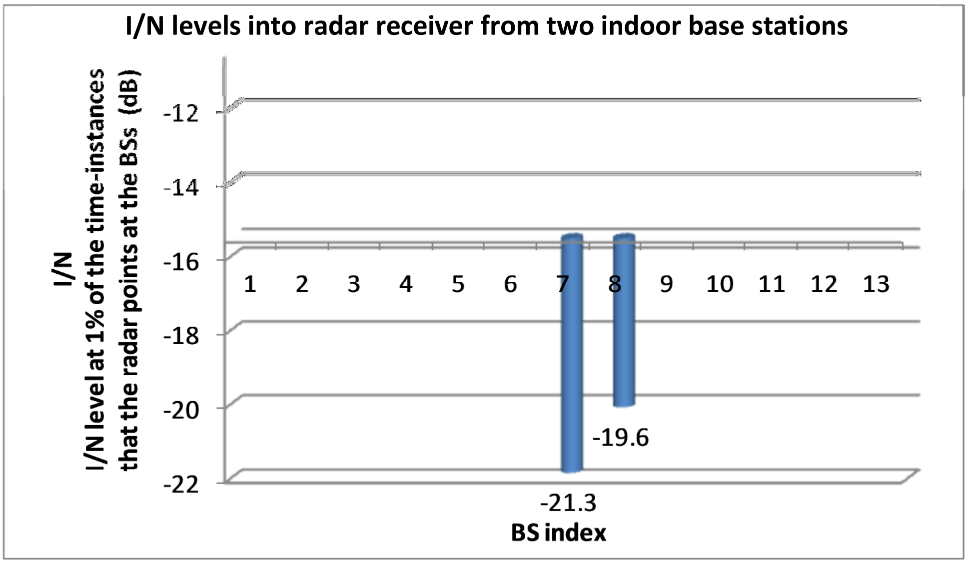


Figure 11-8 Peak I/N levels with Indoor Mitigation 4 applied to the Heathrow specific layout (indoor base stations), see Figure 10-6

The outcome of applying the combined mitigation techniques reveals the following:

- The types of modifications required to 2.6 GHz deployments so that co-existence can take place between the mobile networks and the radar within an airport environment
- The parameters which were not adjusted for the mitigations but can still be considered to improve the situation further where necessary. Such as the antenna heights of base station, antenna tilts, EIRP reduction which all still contribute to the impact to radar
- Improvement to the interference to within the threshold limits, provides an industry-wide protection level to minimise interference to radars within acceptable limits

11.2.2 Mobile station to radar

The following results show the impact each mitigation technique contributes to the net reduction in interference into the radar receiver from the mobile stations. It has already been established that blocking does not occur under both the challenging case and typical case conditions therefore, the metric in this analysis is the reduction of the noise power in the radar receiver it is reminded that the simulation is designed to capture the statistical effects from the variability of the mobile emissions. This includes the fluctuations in the signal envelope, the shadowing and the building penetration losses variability.

The table below shows each mitigation technique modelled and the parameter used in the analysis against the results without mitigation and the result with mitigation and the improvement to the interference margin in dB. The table also shows the impact the mitigation has to the 2.6 GHz network deployment.

No.	Mitigation technique	Parameter value without mitigation	Parameter value with mitigation	Improvement in I/N when the radar points at the worst interference	Impact for 2.6 GHz deployments
1	Cap maximum EIRP	23 dBm	20 dBm	~0 dB	83% of the users are unaffected
2	Coordination zone (outdoor /indoor users)	No coordination zone	70m I/D 300m O/D radius around radar	4.4 dB	The coverage area shrinks to 97% of its original size
3	Improved OOB/Spurious emissions (EIRP)	-30 dBm/MHz	-56 dBm/MHz	26 dB	Cost of equipment that satisfies the more strict emissions mask 100% availability of resources
4	Additional BS located in highest interference area	12 BSs	13 BSs	~0 dB	Additional site cost
5	Cap number of users on 2.6 GHz network around airports	53 users (100%)	44 users (83%)	1.2 dB	83% of the users are unaffected, the rest served by another band OR reduced throughput for 100% of the users

Table 11-5 Comparison of mitigation techniques in reducing the noise rise I/N. The required I/N threshold is -15 dB. MNO: Mobile Network Operator – Mobile stations

It can be seen in Table 11-5 that for each of the modelled mitigation techniques only one reduces the interference noise power into the radar significantly. Improvement to the spectrum emission mask lowers the spurious emission levels in the radar band and contributes the majority of the reduction to the interference. The introduction of a coordination zone provides a further 4.4 dB improvement to the interference situation.

It was found from the simulations that capping the maximum EIRP, introducing a new base station and capping the maximum number of users had <=1.2 dB improvement to the interference situation and therefore not considered as useful mitigations.

The improvement of the unwanted noise emission mask for mobiles would require tighter filter limits to be applied. There is an inherent problem with applying tighter filter limits to mobile stations which is due to the mass production of the equipment. As discussed in Section 4 handset manufacturers produce equipment to the lowest price point which would generally exclude high specification and likely high cost components such as ceramic filters that can provide up to 75 dBc rejection into the radar band.

11.3 Findings

The aim of investigating the mitigation techniques for both the base and mobile station and the radar was to determine what further improvement can be made by adjusting the transmission and simulation parameters to protect the radar from interference in any deployment scenario.

11.3.1 Base station to radar

The findings from introducing the various mitigation techniques showed a spread of improvements in the interference margin. The mitigations are discussed individually below to justify the choice of the preferred set.

Mitigation 1 – Reduced EIRP

Reduced EIRP of the base station by 6 dB gave a 6 dB reduction to the interference power level as expected. This reduction would impact upon the 2.6 GHz network service such as coverage and/or capacity. E.g. A reduction of 6 dB to the EIRP results in 25% of the resources being available to the network, given that the coverage area does not vary, and therefore would require four times more base stations to fill the shortfall in service. Therefore this was not considered a viable option for mitigation purposes.

Mitigation 2 – Antenna downtilt

The increased antenna downtilt showed a 9 dB noise rise reduction. Mobile operators optimise their networks based on specific antenna orientation criteria, therefore adjustment of downtilt too much or not enough may impact on service provision to the cell edge such as throughput performance. A 10° downtilt results in a coverage area shrink to 16% compared to the size of a 6° downtilt. Thus it would require 5 to 6 times more sites to fill the shortfall in service. The increased antenna downtilt was not implemented for the mitigation scenarios and remained a 6°.

Mitigation 3 – Lower antenna height

The base station antenna height was reduced 5m below the radar antenna height. The impact of this reduction was to introduce the effects of the combined antenna patterns of the base station and the radar. The interference reduction is dependent on the radar rotation angle, see Table 11-3. The 2.6 GHz network service area was reduced to 53% of its original size, which would require twice as many sites to fill the shortfall. Thus this mitigation is not likely to be desirable to implement and it was not utilised in further analysis.

Mitigation 4 – Antenna orientation so that nulls occur towards radar

This mitigation may suggest that there is a substantial dip in the antenna pattern that can be directed towards the radar. However, cellular network operators plan their networks based on a 3 sector antenna pattern and attempt to avoid any reduction in antenna gain in every direction. The point of this mitigation was to rotate the antenna to the point where the edge of the sectors meet. This meant directing the antenna with the lowest gain (10-12 dB) towards the radar.

The knock on effect of this mitigation means that the operator may need to adjust other base station antenna orientations to maintain the optimum cell re-use plan.

Mitigation 5 – Power control the transmitter as radar sweeps passed base station

This mitigation[26]was considered to be a theoretical yet plausible method using a more novel (rather than standard) approach to avoid causing interference into the radar as the main beam sweeps

[26] Although no standard exists for this mitigation technique the concept is plausible. The ability to power control the base station by whatever means is technically possible, the challenging part is to synchronise this with the rotation of the radar.

passed the transmitter. The interference reduction is dependent on the radar rotation angle, see Table 11-3. Consider the following example for the explanation of the reduction's dependence on the distance: Assume the base station locations as in the Challenging synthetic layout, see Figure 10-15. Without implementation of the switch-off mitigation, when the radar points at the angles of BS 1 and BS 8, let the received powers be I_1 and I_8. Due to the propagation model: $I_1>I_8$. With the switch-off mitigation, when the radar points at the angle of:

i) BS 1, the received interference is I_8-30, thus the reduction of interference is I_1-I_8+30
ii) BS 8, the received interference is I_1-30, thus the reduction of interference is I_8-I_1+30

The reduction of interference is greater when the radar points at the angle of BS 1: $I_1-I_8+30 > I_8-I_1+30$.

This mitigation has small footprint on the 2.6 GHz network. Switching the base station power off for the interval that it is illuminated by the radar is translated to 98%[27] availability of network resources in the Heathrow base station layout. In less mobile network congested airports the effect of switching off the power to the network will be even smaller. At a practical level the operator should synchronise the base station with the rotation of the radar and consider switching off the particular sector facing the radar rather than all sectors.

Mitigation 6 – Improved spectrum mask OOB/spurious emissions

An improvement to the spectrum emission mask over the 3GPP/IEEE specifications reduced the noise rise. A 10 dB reduction to the emission mask produced a 10 dB reduction to the interference noise levels. It is possible to reduce the noise rise with the introduction of high specification cavity filters at the base station sites. The impact to the 2.6 GHz network service is trivial as the wanted emissions are not affected. There is however the cost of procurement, installation and commissioning of the cavity filter to consider for this mitigation technique. This is a required mitigation technique.

Mitigation 7 – Coordination zone

The coordination zone was not established in isolation. Mitigations 4, 5 and 6 were applied to derive the coordination zone. This is apparent since the coordination zone would be many tens of kilometres without additional mitigations to contribute to minimising interference closer to the threshold limits. The base stations located closest to the radar were systematically removed to establish a coordination zone. Simulations were conducted on a step by step basis starting by

[27] It was assumed that the base station is illuminated when the attenuation due to the horizontal pattern > 30 dB

removing the closest base station to the radar and then removing the next closest base station and so on until the interference noise levels satisfied the desired margin. The results showed a 660m coordination zone is necessary to minimise the interference noise power to a point it will not exceed the threshold and must be applied in combination with the following mitigations:

- Power control the base station transmitter when illuminated by the radar
- Use of improved out-of-band and spurious emission mask
- Orientation of base station antenna pointing lowest gain at the radar

Table 11-2 summarises the mitigations chosen for implementation. It should be noted that all mitigations must be used in combination for the full effects to the radar to be realised. The mitigations in Table 11-2 it can be seen that an attempt has been made to minimise the cost to 2.6 GHz network deployments. Mitigations 4, 6 and 7 which are the antenna optimisation, switching off the base station and a coordination zone around the radar are considered to be relatively low cost solutions to implement. For example antenna optimisation is undertaken at commissioning of the station and can form part of the overall installation costs. The base station switch-off may require some specific base station engineering or technology add-on to introduce this mitigation but it is not deemed very high cost compared to building to a new site.

No	Mitigation	Practical value range	Impact to 2.6 GHz deployments
4	Optimise antenna orientation to lowest gain facing radar	10-12 dB attenuation	The reduction in availability of network resources is trivial. The adjustment to the antenna orientation may impact the re-use pattern adopted to surrounding sites.
5	Improve unwanted spectrum emission mask	-46 dBm/MHz	Will require the addition of high specification cavity filter which would mean additional cost per site. This has trivial impact to the 2.6 GHz network service availability.
6	Power control the transmitter as radar sweeps past base station	-85dBm/MHz	Estimated percentage of network resource availability is98%
7	Coordination zone	660 m	Estimated percentage of network resource availability is84%

Table 11-6 BS mitigations

The introduction of a coordination zone is an administrative matter for the airport authority and Ofcom depending on where the coordination zone lies. In the case of Heathrow, the coordination zone is partly on airport land and partly on public land, which may require some joined up policy on how to apply the coordination zone in practice.

The only significant cost, therefore will be the installation of a high specification cavity filter at the base station sites to reduce the out-of-band and spurious emissions. The analysis has been confined to the airport environment which will assist the airport operators to understand and implement the required mitigations to ensure satisfactory operation of the networks in proximity to the radar. However, the impact cannot be treated in isolation as the interference is generated from base stations beyond the airport perimeter which is out of the control of the airport operator and becomes the responsibility of the mobile operator and the technical licence conditions set by Ofcom.

The following chart shows how the additional requirement for filtering drops with distance based on free space pathloss. The required level of attenuation reduces from a radius distance of 1.7 km to 26.7 km away from the radar and suggests that even for the highest levels of filtering the additional attenuation requirements are likely to be deemed achievable using some standard equipment types.

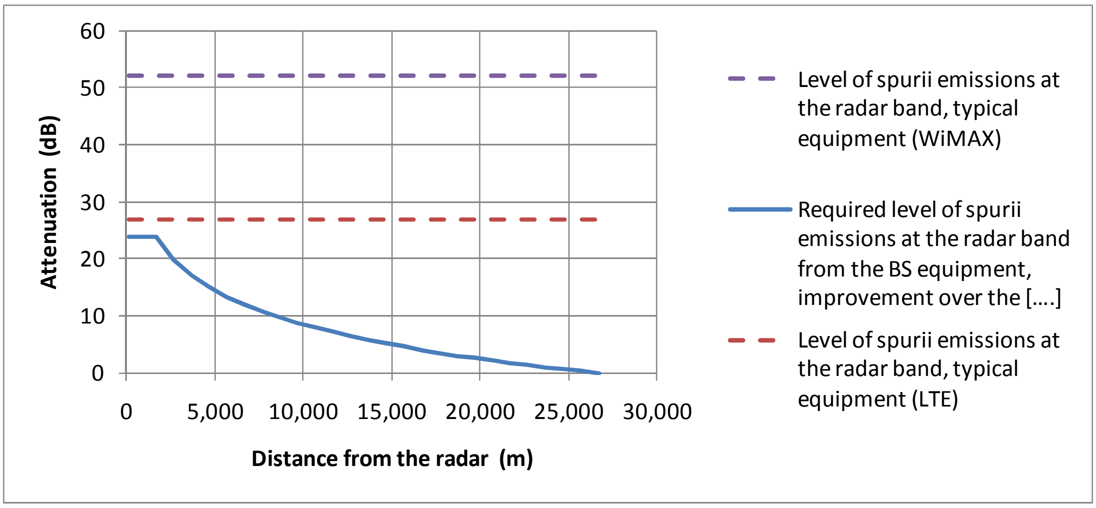


Figure 11-9 Unwanted emission attenuation versus distance from radar

11.4 Mobile station to radar

The findings from introducing the various mitigation techniques showed a spread of noise rise reduction. The majority of the improvements were found to be <1.2 dB and the following section gives an explanation of why these findings occurred.

Mitigation 1 – Restricted maximum EIRP

A cap on the maximum EIRP from the mobile has a dual impact. Reduced in band power helps to reduce blocking of the radar receiver in addition to reducing the noise emissions from the out-of-band and spurious domain.

The improvement from restricting the maximum EIRP was about 0 dB. This could be due to the distance of the highest interferers from the radar, see also the reduction of interference vs. distance in the Mitigation 5 example in Section 11.3.1. 83% of the users were not affected by the maximum power capping. This means that users at cell-edge will be subject to low throughputs and/or coverage holes. This mitigation was not considered to be an effective technique.

Mitigation 2 – Implementation of a coordination zone

A coordination zone was derived for both indoor and outdoor users around the radar based on trial and error. The coordination zone was derived with the implementation of a 22 dB improved filter mask as without it the radius would have been > 1.7 km from the radar location. The radius of the outdoor coordination was found to be 300m and the radius of the indoor coordination zone was 70m. These coordination zones were derived based on the optimum improvement to the interference level that that can be gained whilst limiting the impact to the 2.6 GHz network users. For example the combined indoor and outdoor coordination zone yields to a service area that is 97% of its original size.

Mitigation 3 – Improved spectrum mask OOB/spurious emissions

An improvement to the spectrum emission mask over the 3GPP/IEEE specifications reduced the noise rise. A 10 dB reduction to the emission mask produced a 10 dB reduction to the interference noise levels.

It is suggested that this mitigation alone can reduce the interference noise power levels below the threshold limits if 26 dB or more improvement over the 3GPP/IEEE masks, can be obtained from the practical filter. This will remove the requirement for a coordination zone or any other mitigation for the mobile stations. However, the emission requirements can be relaxed by 4.4 d B if a coordination zone as identified above is implemented.

Mitigation 4 – Low power base station antenna in area of worst interference or deployed close to the radar

The deployment of a low power base station antenna within an area of the worst mobile station interference has the effect of powering down the mobiles in the vicinity of highest interference. The location of the base station could also be close to the radar position.

Using the model it was possible to produce a snapshot of the area with the highest interference and identify an optimum position for the low power base station. It was found that the highest interference occurred at various distances from the radar from different combinations of snapshots. The highest interferer could be a single mobile close to the radar or a cluster of mobiles far away from the radar. Therefore, this solution would require adopting a planned network of additional base stations to cover all eventualities of interference which is not a cost effective mitigation strategy for consideration.

In the case of uncontrolled mobile stations roaming close to the radar, a single low power base station can be deployed in close proximity to the radar as a final backstop. This low power base station could be used to control or reduce the emissions output from the mobile stations thus minimising interference within a given radius from the base station/radar. A more in-depth analysis of the mechanism to reduce the mobile emissions is captured in appendix H.

Mitigation 5 – Cap the maximum number of users on 2.6 GHz network around airports

Capping the maximum number of users of the 2.6 GHz network aimed to reduce the total active users that contribute interference at the radar receiver. It was found from that a 1.2 dB improvement was gained by reducing the number of users by 17% which, as a mitigation alone, does not contribute enough of a reduction to the interference. Furthermore, limiting the number of users for such a small improvement has a negative cost impact and therefore, effort in obtaining gains elsewhere is more worthwhile than implementing this mitigation.

11.4.1 Summary

It can be deduced that the improved spectrum emission mask is the most appropriate and effective mitigation from those modelled. It is not worth considering the introduction of a coordination zone if improved spectrum emissions can be achieved from the mobile handsets. If it transpires that the mobile station filters used in 2.6 GHz equipment cannot achieve the maximum reduction in emissions then further investigation into the coordination zones is required.

Table 11-7 summarises the findings and those mitigations identified for implementation.

No	Mitigation	Practical value range	Impact to 2.6 GHz deployments
1	Cap maximum EIRP of mobiles	Not considered	Will require intervention from operators but at a technical and operational level. Will limit service such as capacity and throughput but only in certain areas, on certain sectors to a limited number of mobiles
2	Coordination zone around the radar	300 m outdoor 70 m indoor for 22 dB mask improvement No coordination for 26 dB mask improvement	Requires restricted use of phones near to radar that may be costly and complex to implement. Could be managed function by airport authority such as BAA's ECAP
3	Improve the OOB/Spurious emission mask	See row above	May require regulatory intervention which could be time consuming and difficult to implement and ultimately equipment vendors would burden the cost
4	Introduce coupled antenna from a BS into area of worst mobile interference, direct sector towards mobiles and away from radar	Not considered	Will require some additional engineering from the operators perspective and may also increase the interference to radar from the base station antenna
5	Cap the maximum number of users on 2.6 GHz network around airports	Not considered	Will require intervention from the mobile operators and possible cost due to reduced subscribers active on the network

Table 11-7 Summary of mobile station mitigations

Implementing the mitigation identified above under the Heathrow specific layout will enable the co-existence of mobile stations and radars within an airport environment.

The following chart shows how the additional requirement for filtering drops with distance based on free space pathloss.

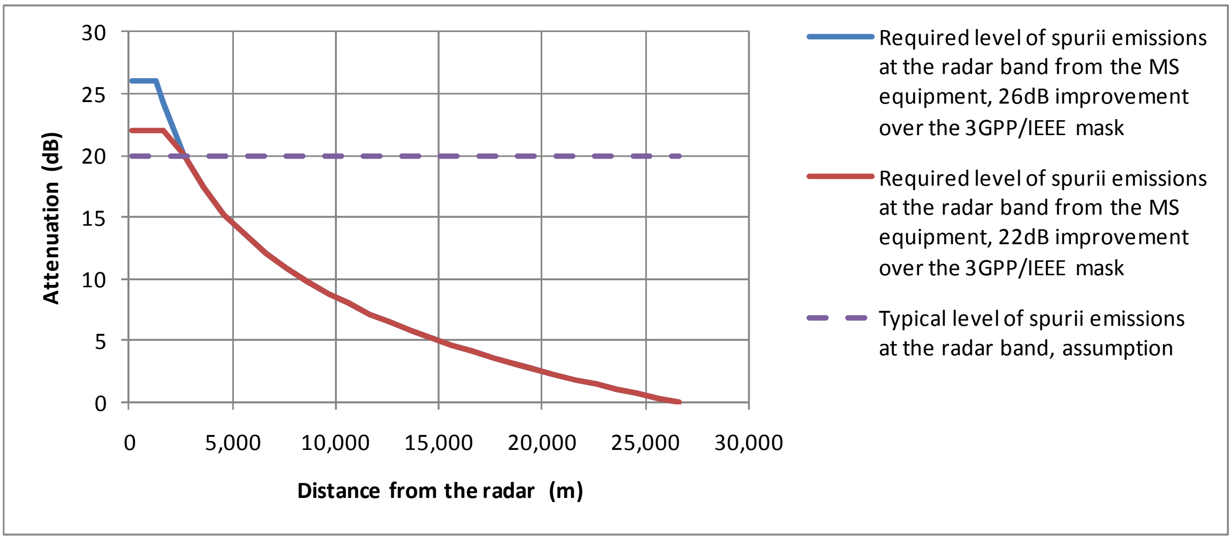


Figure 11-10 Unwanted emission attenuation versus distance from radar

The mitigation to improve the spectrum emission mask is a challenging one to adopt based on the potential for manufacturers to amend the filtering designs within their handsets. However, at the present time it is not known the extent of quality of handsets in terms of their actual out-of-band and spurious emission levels and it would be very useful to understand the measured emissions radiated from mobile devices into the radar band to determine to what extent development of handset design is required.

Measured data from mobile device emissions could usefully inform the study and help provide more accurate results in terms of the interference noise power received at the radar receiver.

11.5 Impact on cost to 2.6 GHz deployments

This chapter has investigated the implementation of mitigation techniques to help reduce the interference from base stations and mobile stations and introduced the cost implications that would also impact on 2.6 GHz deployments when incorporating the mitigation techniques.

The following section discusses the high level cost to licensees and the airport authorities when planning 2.6 GHz deployments in and around airports.

One main consideration is the cost impact that applies to outdoor sites that are built within the airport perimeter. Site acquisitions within airports are likely to be scarce and are resourced and managed by the airport owner. This also applies to indoor sites where shared common infrastructure is used and the addition of new services may introduce complex engineering work to already heavily loaded infrastructure.

The types of cost that are likely to be applicable under the circumstances modelled in the study include:

- Capital costs, such as new hardware components, software upgrades etc
- Operational costs, such as additional site rental
- Site engineering re-design

The mitigations identified for both indoor and outdoor base stations sought to minimise the cost burden to operators as much as possible. This was mainly to avoid the requirement to build additional base sites to fill any shortfall in coverage which is considered to be the greatest expense. It is possible that under certain circumstances not building new sites is unavoidable and therefore this will be the greatest cost. Under the conditions modelled in the study the greatest cost to operators will be the installation of the high specification cavity filters for the base stations which will need to be installed for the co-existence of 2.6 GHz network within an airport environment.

11.5.1 Impact to base stations

The significant costs are realised if the addition of new base station sites are required. New sites would have been proposed based on the requirement to fill in gaps in coverage, capacity, service created by the degradation in service due to the mitigations.

Based on the analysis of the mitigations and the possible shortfall in service provision from 2.6 GHz network operators the following estimates have been considered:

No	Mitigation	Impact to 2.6 GHz deployments	Estimated cost to 2.6 GHz deployment
1	Reduce EIRP levels of BS	May require additional low power sites to maintain coverage/capacity	For example if four times the number of base stations are required to fill a capacity shortfall at up to 100,000 GBP a site could result in a negative cost/benefit ratio and be prohibitively expensive.
2	Improve unwanted spectrum emission mask	May require the addition of high spec cavity filter which would mean additional cost per site	Cost of cavity filter up to £500 per transmitter for an operator with 10 to 20 transmitters in and around the airport this becomes a significant cost
3	Optimise antenna orientation to lowest gain facing radar	Adjustment to antenna orientation will not only impact coverage to the network but will affect the re-use pattern adopted to surrounding sites which could mean extensive on-going optimisation to an operators network	Cost neutral. Site specific engineering would be included at the point of installation
4	Increase downtilt of antenna	Adjustment to antenna downtilt will have an impact to coverage of the network which may require the addition of fill in sites to cover the shortfall	Cost neutral. Site specific engineering would be included at the point of installation
5	Lower antenna height	Adjustment to antenna height will have an impact on coverage and require more power to compensate	Cost neutral. Site specific engineering would be included at the point of installation
6	Power control transmitter as radar sweeps past base station	Estimated percentage of service reduction between 0.4% and 0.8%. This would be negligible to users of the network	Cost neutral. Site specific engineering would be included at the point of installation
7	Coordination zone	Estimated percentage of network resource availability is84%. Users may notice some reduction in network quality such as throughput to users of the network	Cost neutral. Requires mobile operator, airport operator and regulator intervention to coordinate specific coordination zone around airports

Table 11-8 Cost impact to the deployment of base stations

Another major cost is the incorporation of a high specification cavity filter which can greatly reduce the out-of-band and spurious emission levels transmitted from the base station and improving the interference situation at the radar receiver. This requirement is based on 2.6 GHz base station equipment no longer designed with high specification filtering in mind to reduce size of the units and reduce cost of production. Furthermore, reduced sized components requires less cooling and thus cuts costs of cooling systems installed into base sites.

The types of filters expected to be used in the 2.6 GHz band have been estimated by Ofcom in the 2.6 GHz auction statement[3] at a cost of around £500. This was based on providing enough selectivity to protect in band TDD/FDD systems. The advantage of this will be the additional selectivity the filters will provide into the upper adjacent S-band. Furthermore, the additional filters will only need to be installed at the sites in areas that cause an impact to the radar.

11.5.2 Impact to mobile stations

No	Mitigation	Impact to 2.6 GHz deployments	Estimated cost to 2.6 GHz industry
1	Cap maximum EIRP of mobiles	Will require intervention from operators but at a technical and operational level. Will limit service such as capacity and throughput but only in certain areas, on certain sectors to a limited number of mobiles	Cost neutral. Site specific engineering would be included at the point of installation
2	Coordination zone around the radar	Requires restricted use of phones near to radar that may be costly and complex to implement. Could be managed function by airport authority such as BAA's ECAP	Cost neutral. This will require mobile operator, airport operator coordination and regulatory intervention
3	Improve the OOB/Spurious emission mask	May require regulatory intervention which could be time consuming and difficult to implement and ultimately cost to equipment vendors	Potential development costs to handsets, dongles and integrated laptops. Cost could be significant based on inclusion of higher specification components
4	Introduce coupled antenna from a BS into area of worst mobile interference, direct sector towards mobiles and away from radar	Will require some additional engineering from the operators perspective and may also increase the interference to radar from the base station antenna	Additional site or relay build required at cost of new antennas, and feeders approximately £20,000 to £50,000
5	Cap number of active users on 2.6 GHz network	Will require specific network engineering to cap users and switch them to alternative spectrum resources, where available	Medium to low cost based on software and NOC upgrades. Potential revenue impact based on reduced number of users and inefficient use of spectrum

Table 11-9 Cost impact to the deployment of mobile stations

12 Conclusions and summary recommendations

12.1 Conclusions

This study has addressed the interference environment from 2.6 GHz systems into the adjacent 2.7 GHz radar band at an airport and found that under more realistic scenarios the interference levels were below the acceptable threshold limits and the overall impact to the radar minimal thus enabling the deployment of 2.6 GHz systems for both base stations and mobile stations within an airport environment.

However, in specific challenging corner case deployment conditions severe interference can be generated causing degradation to the performance of the radar that required further investigation on a more detailed basis.

12.2 Summarised conclusions

The summarised conclusions from this study are as follows:

1. Interference from LTE and WiMAX base stations and mobile stations operating in the 2.6 GHz band to Air Traffic Control radars operating in the adjacent 2.7 GHz band has been analysed via simulations representative of installations in and around Heathrow airport.
2. The analysis examined two types of layout environments for the base stations. 1) A layout representing the Heathrow airport environment, 2) a synthetic layout representing base stations at equidistant intervals from the generic modified radar. The two layouts were used to establish the extent of interference from base stations with the synthetic layout used to further analyse the required mitigations. The *challenging case* which could in principle occur in practice but is relatively extreme was used in both layouts, while the *typical case,* which is considered more realistic, was used in the Heathrow layout only. Both layouts consist of 13 base stations at distances ranging between 50m and 1700m.
3. Mobile stations were modelled within the Heathrow layout for both the *challenging* case and the *typical case* at a density consistent with levels of usage which could occur in the airport environment. Spurious emissions of the mobiles are assumed to be at the standard specification limits and transmitting at full power in the challenging case. Under the *typical case* the spurious emission of the mobiles were assumed to be at 20 dB below the standard specification limits with power control activated.
4. Mobile stations were also modelled using measured emissions data from tests performed to determine the behaviour of a commercially available FDD LTE mobile device. We found that negligible noise rise occurred from the measured emissions, this was due to -87 dBm/MHz spurious level across the S-band. Even when imposing a discrete spurious emission co-channel with the radar centre frequency, the amplitude required to exceed the I/N threshold of the radar receiver, was 57 dB.
5. Base stations were found to cause blocking of the radar receiver at the radar antenna connector input and a rise in noise under the *challenging case conditi*ons from locations inside and outside the airport perimeter and from both in-buildings and outdoors. Blocking

from the base stations at a distance of 50 m from the radar exceeded the -5 dBm threshold by 9.9 dB. The noise rise from the base stations was as high as 47.8 dB for small percentages of time, which exceeded the desired threshold of between -5 and -15 dB.

6. Mobile station spurious emissions under *challenging case* conditions, did, generate a noise rise in the radar receiver which exceeded the maximum (-15 dB) threshold by 39.2 dB for small percentages of time. However, the spurious emission levels were set to -30 dBm/MHz (3GPP limit) to achieve this.
7. The blocking situation for both base stations and mobile stations is substantially improved when under these *typical case* conditions. For example blocking levels arising from base stations are reduced to -16 dBm compared to the -5 dBm threshold, and from mobile stations to -107 dBm compared to the -80 dBm threshold.
8. The noise rise was not completely resolved under the *typical case* for base stations or mobile stations. The maximum threshold limit of -15 dB I/N was exceeded by 8 dB for base stations and 5.7 dB for mobile stations, for small percentages of time. This result led to the determination of specific mitigation techniques, such as 2.6GHz base stations not transmitting for the small period of time when the main radar beam is known to be pointing directly at it, to reduce the noise rise to below the threshold limits.
9. The noise rise at the generic modified radar receiver was reduced by introducing several mitigation techniques. These techniques showed various degrees of improvement, when compared to the interference of the Synthetic Challenging layout (base stations base line scenario) and the Challenging case technical parameters (mobile stations base line scenario). The criterion assumed to avoid interference is that the noise rise is allowed to exceed -15dB for 1% of the time for which the radar antenna is oriented towards the most significant interferer. For a single dominant interferer, such a condition only occurs for around 1% of the time, leading to an overall interference instance of around 0.01%.
10. To achieve this level of protection, a combination of mitigations is required. This will include an improvement of the spurious emissions of 2.6 GHz equipment over the 3GPP/IEEE standards by 24 dB for base stations and 26 dB for mobile stations which are considered reasonable levels from discussions with vendors. If, however, a higher level of interference or an increased percentage of time could be tolerated, other mitigations can be used on their own, such as creating a coordination zone around the radar and preventing base station transmissions when the radar is oriented towards the base station.
11. For any individual deployment, the application of site-specific mitigation techniques can reduce the risk of interference to minimal levels. Such mitigation techniques vary in their efficacy and impact on the 2.6 GHz deployment, but taken in combination with appropriate initial network design they can ensure appropriate coexistence. Such mitigations should be monitored to ensure they are appropriate via an appropriate approvals process, via a calculation methodology which is accepted by the 2.6 GHz operators, the airport authorities and the CAA. This methodology could potentially use the simulation framework developed for this study. This process could be incorporated into existing arrangements, such as BAA's Electronic Communications Approval Process.

The study found that the dominant interfering mechanism is the interference noise power generated from both base stations and mobile stations. The increase in peak noise levels exceeded the acceptable limits in the challenging case and required further investigation into mitigation techniques.

Under typical case conditions the blocking and I/N levels caused by base stations at an airport were quite dramatically reduced compared to challenging case conditions. This is due to the reduced in-band emission levels, the attenuation due to the antenna patterns and the radar antenna height positioned above the base station antenna height.

Applying the mitigations led to the satisfactory outcome of deployment of 2.6 GHz systems at both a synthetic layout and Heathrow layout. The tradeoffs from applying mitigations included:

- Further coordination required for base stations deployed within the coordination zone, that could lead to the introduction of unacceptable deployment parameters to satisfy requirements
- The use by operators of high specification cavity filters on the base stations
- Introduction of the theoretical concept for transmitter ‘switch-off’ as the radar sweeps passed the base station for which there is no standard technique available at present
- The use by operators of handsets and mobile devices with ceramic filters whose spurious performance levels are 40 -50 dB below the 3GPP limit
- Optimised orientation of BS antenna with lowest gain of the pattern pointing towards the radar

It was identified that combining four out of the seven mitigations contributed the most to reducing the interference whilst minimising the performance and service quality impact on the 2.6 GHz network deployments was the solution. This has the effect of bringing the interference noise power to within the threshold limits considered to be acceptable to the regulatory authorities. The mitigation options; the coordination zone, transmitter power control, improved spurious emissions and antenna orientation, modelled were considered to be the most cost effective solution without having to build new sites at very high cost.

The study revealed that emissions from shared sites do cause a problem to radar receivers which in an airport environment, is a common deployment technique. BAA, the owner of Heathrow Airport uses its electronic equipment approvals requirements to manage the use of sites on their property which includes shared site infrastructure. Therefore site specific solutions could be adopted by the airport operator to address this problem.

Similar to the base station analysis, the mobile stations do not cause blocking to the radar under typical case conditions and would co-exist with radars at an airport on that basis. This means that for the blocking interference mechanism mobile stations do not cause a problem to the radar.

The interference noise increase generated by multiple mobiles in the vicinity of the radar receiver under the typical case marginally exceeded the desired I/N threshold and is considered to be manageable with careful network planning. Upon identifying the mitigations in the challenging case, it was found that mitigations such as coordination zone and improved spurious emissions had a neutral effect on the performance and service quality of 2.6 GHz network deployments and did reduce the interference level below the acceptable limit.

There was negligible noise rise from the spurious emissions of a commercial off the shelf FDD LTE mobile device. This one example device suggests good emissions performance with very low risk to the satisfactory operation of radars at airports under the particular scenario conditions of this study. There is a strong likelihood of mass deployment of this particular device type or, future generations of it by LTE networks operators in the UK and in particular at airports. However with only one example 2.6 GHz device measured, we cannot assume the same positive effects will occur for other mobile devices such as laptops, tablet PC's and smartphones. As 2.6 GHz networks mature the mix of devices will increase and thus the uncertainty in performance of mobile devices. Therefore, a deeper understanding of the performance of a wider selection of mobile device types would provide a more representative sample of the environment to be found in future.

Furthermore, the results show that upgrading the radars such as the one used in the model attenuates the blocking levels from 2.6 GHz emissions by up to 40 dB at the RF front end. The modified design of the generic modified radar receiver used in the model shows that co-existence is possible in the presence of 2.6 GHz systems and that attention on reducing the interference before the filtering, i.e. at the antenna connector is of more concern.

12.3 Recommendations

This section makes the recommendations that have been identified from the outcome of the study and that are applicable to the deployment of 2.6 GHz networks within an airport environment in close proximity to an S-band radar.

These recommendations are supported by the findings of the study that will help meet Ofcom's objectives with regard to the award of 2.6 GHz spectrum in the medium term.

12.3.1 Recommendations to improve the interference situation at airports

Base stations:

Implementing the mitigation techniques outlined in section 11.2.1 will provide maximum reduction in interference for both blocking and interference noise rise. The following recommendations are based on the conclusions found from this study.

1. Extending the -45 dBm/MHz EIRP limit of the Ofcom specified Block Edge Mask from 2720 MHz to 2750 MHz and above to protect radar frequencies beyond those specified by Ofcom
2. Coordination and collaboration with the airport authority. It is anticipated that as part of the planning of new mobile communications networks that coordination and collaboration between the airport operator and the mobile network operator will be necessary for the deployment of 2.6 GHz networks. Findings from this report can inform the approval procedures of 2.6 GHz networks at airports.
3. Airport operators to implement a coordination zone for the deployment of 2.6 GHz base stations dependent on the layout and specific deployments. It is recommended that operators seeking to deploy base stations within the coordination zone would need to further reduce the values such as EIRP or use lower antenna heights.
4. Implementation of a high specification filter for the base stations located within the airport perimeter to meet the desired limits specified in section 11.2.1
5. Careful selection and design of base station locations taking into account the typical case conditions used for modelling as a benchmark for further study and analysis
6. Optimisation of the antenna pattern with the lowest gain of the pattern pointing towards the radar
7. Adoption of alternative deployment strategies, for example, operators limit 2.6 GHz deployments indoors and mobiles can roam to an alternative spectrum band when outdoors.

Mobile stations:

The following recommendations are based on the findings from the investigation of interference generated by mobile stations with assumed spurious emissions within an airport environment.

1. The introduction of an outdoor and indoor coordination zone around the radar. The simulations found that a 300m outdoor coordination and a 70m indoor coordination zone are sufficient to reduce interference to below the threshold for each mechanism. For smaller coordination zones parameters such as EIRP should be reduced further or investigate in detail the specific building penetration loss for the particular airport which may offer more attenuation than the 14 dB assumed in the model.
2. Appreciation of the typical case conditions used for modelling as a benchmark for further study and analysis of the interference within an airport environment For example the activation of power control for the uplink in the model helped reduce the interference levels into the radar.
3. Where possible identify the mobiles manufacturers with the best and worst out-of-band and spurious emissions and re-model using the measured data. This will establish a set of mobiles (and vendors) whose equipment will operate within the threshold limits of interference and can co-exist in an airport environment.

The addendum to this report provides details of the recommendations of the analysis of measured emissions from a commercially available LTE FDD mobile device into a second modified radar design.

12.3.2 Recommendations for further analysis

The results from the study suggest that there is merit in further detailed analysis of the airport environment using more specific conditions. The following recommendations are given for further analysis:

1. In order to understand the combined interference from base stations and mobile stations further analysis should be undertaken to establish the blocking and interference noise levels incorporating both base stations and mobile stations operating simultaneously.
2. Appropriate design parameters should be determined on an airport-specific basis and coordinated with the relevant authorities as appropriate as many different deployment parameters can materially affect the interference performance of 2.6 GHz base stations in and around airports[28]
3. Analysis of low power a base station located close to the radar to minimise interference from roaming mobiles that could potentially cause significant interference
4. Consideration of the type of action to be taken by the mobile operators or airport owner to restrict use of 2.6 GHz emissions within the coordination zone in the case for mobile stations.
5. Radar heights at other UK airports should be catalogued to ensure they have been covered by this study. The radar heights found at other UK airports vary widely from 5m at the lowest height up to 40m for the greatest height. There are increased levels of interference from 2.6 GHz deployments into radars with antenna heights below that of the 2.6 GHz transmitter
6. Consideration of a mobile station's ability to hand over to a spectrum band other than 2.6 GHz for outdoor deployments at airports when the conditions for avoiding radar interference cannot be satisfied.
7. Commercial and technical factors in site sharing should be reviewed as suggested mitigations applied by the airport owners could include the restriction on the number of base stations transmitting from a single site.
8. Spurious emission measurements of a wider selection of mobile device types, such as smartphones, tablet PC's and laptops to determine their behaviour in the S-band.

[28] These are specified in Section 8.

13 Glossary

3GPP	Third Generation Partnership project
ACLR	Adjacent Channel Leakage Ratio
CAA	Civil Aviation Authority
CDF	Cumulative Distribution Function
dB	Decibels
dBc	Decibels relative to carrier power
dBm	Decibels relative to 1mW
D/L	Downlink
ECC	Electronic Communications Committee
EIRP	Equivalent Isotropic Radiated Power
FDD	Frequency Division Duplex
FSPL	Free Space Path Loss
GHz	Gigahertz
IEEE	Institute of Electronic and Electrical Engineers
IF	Intermediate Frequency
IMT	International Mobile Telecommunications
I/N	Interference to Noise ratio
LNA	Low Noise Amplifier
LOS	Line of Sight
LTE	Long Term Evolution
MCA	Maritime and Coast Guard Agency
MHz	Megahertz
MOD	Ministry of Defence
NLOS	Non-Line of Sight
OFDM	Orthogonal Frequency Division Multiplexing
OOB	Out-of-band emissions
PDF	Probability Distribution Function
RF	Radio Frequency
TDD	Time Division Duplex
U/L	Uplink
WiMAX	Worldwide interoperability for Microwave Access

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