A review of 5G/Satellite compatibility studies in C-band

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Executive Summary

As the use of ever higher frequencies for mobile services becomes more widespread, pressure to find spectrum has led to cases where proposed mobile bands need to share spectrum with existing services. In order for this sharing to take place, it is necessary to carefully study the interactions between the mobile service and the incumbent service or services. These studies are called compatibility studies and aim to find a set of parameters which may be technical or practical, or even in some cases political, which will allow the services to co-exist in the same frequency bands without causing harmful interference.

One band which has proven particularly highly contested is the C-band (3400 – 4200 MHz), parts of which have been identified by the International Telecommunications Union (ITU) for International Mobile Telecommunications (IMT) services, more commonly called 5G. This band is home to a large number of (space-to-Earth) satellite transmissions and, in many countries, fixed point-to-point or point-to-multipoint services. Many organisations around the world have examined the question of whether and how 5G systems can co-exist with terrestrial satellite receivers in the band. The results of these studies vary significantly, providing little consistency which others could use to help them reach decisions on if and how the two systems could co-exist side-by-side.

LS telcom has worked with a number of administrations, and industry bodies to consider the compatibility between satellite and mobile services in the band, and have noticed that many of the studies conducted yielded different results. We were curious as to why this was, and whether there were differences in modelling inputs, assumptions or other aspects. In order to better inform our own modelling, we decided to investigate what, if any, the commonalities and differences across the various studies are, and if lessons can be learnt to enable more consistency in future studies. Full details of the analysis are contained within the body of this report, however a summary of the observations is shown below:

- Operating 5G services co-channel with C-band satellite receivers requires separation distances measured in tens to hundreds of km, and the studies have all shown this to be the case. Unless C-band usage is only at a few, very remote sites, this will preclude co-channel spectrum sharing in almost all scenarios.
- Operating 5G service in channels adjacent to wanted C-band satellite signals introduces a range of additional considerations. The out-of-band emissions from 5G transmitters and the potential for overloading the receiver mean that this scenario requires very careful modelling to correctly understand the impacts.
- Emissions masks for the IMT system vary considerably across the studies. A number of studies make use of values from earlier standards, and as such may be of limited use in the current issue of 5G FSS sharing. In addition, it is questionable whether mobile equipment manufacturers would be motivated to exceed requirements beyond those in the 3GPP standards despite some studies assuming that they would.
- LNBs are inherently wideband, being required to operate across the whole of the C-band, and as such would not be expected to significantly attenuate 5G transmissions on adjacent frequencies without additional filtering applied at the input to the LNB. Where filtering is applied to the LNB, it would need to be sufficiently wideband to allow adequate operation within the remaining allocated

FSS spectrum. A concern with the receiver spectral performances identified in a number of the reports is the use of particularly narrow bandwidths. Optimistically narrow filters applied to the LNB are unrealistic, and those applied at IF are not relevant to the issue of compatibility

- All of the thresholds which are defined with respect to satellite receiver performance (e.g. the non-linearity compression point of the LNB, or an increase in I/N) represent limits at, and beyond which, satellite reception will be impacted. As such, they should not be assumed to be targets to be met, and similarly any results based on calculations using these limits will also represent the point at which reception is degraded and not an average value to be used in, for example, determining network roll-out parameters.
- Although higher elevation angles should reduce potential for interference, in practical installations, reflections from nearby structures mean that this is not a usable mitigation to improve compatibility. Considering that studies have shown that the theoretical rejection provided by increased elevation angles does little to mitigate against 5G interference, it can be equally implied that AAS (for which little study has yet been conducted) cannot be used to provide azimuthal protection of satellite receivers as ceasing transmissions in a particular direction will, at best, provide a small reduction in potential interference due to the large number of reflections of the main signals from nearby structures.
- There is a trade-off between the size of any guard-band left between 5G and satellite services, the necessary separation distance between transmitters and receivers, and the performance of any filters fitted to the satellite receivers. Note that it is almost impossible to control the separation distance between user devices and satellite dishes.

Any administrations wishing to conduct a technical compatibility study to determine the extent to which C-band satellite services can co-exist with 5G services in the same band could, on the one hand, take heed of the results of the range of existing studies, or could conduct their own calculations. However, given the wide range of input assumptions used within studies, relying on them at a national level to set sharing criteria is troublesome. As such, administrations wishing to make use of the existing studies would be recommended to take caution to ensure they fully understand the limitations imposed by the assumptions made. Instead, if administrations wish to conduct their own compatibility studies, a set of recommended parameters (considering the conclusions and lessons learnt from the analysis) are presented within the main body of this report.

1 Introduction

1.1 Background

As the use of ever higher frequencies for mobile services becomes more widespread, many organisations around the world have examined the question of whether and how 5G systems can co-exist with satellite receivers in the C-band (3400 – 4200 MHz). The results of these studies vary significantly, providing little consistency which others could use to help them reach decisions on if and how the two systems could co-exist side-by-side.

LS telcom has conducted a number of studies examining these compatibility issues and as a result we have noticed that there are a very wide range of results emanating from them. Such varying outcomes could come from a range of areas including the inputs used, modelling assumptions, and study parameters. To try and bring some clarity to the situation, and thus improve and inform our own modelling, we thought it would be useful to compare the range of studies available to see:

- what the differences between them may be, and whether this might explain their varying results;
- if there are any commonalities amongst them; and
- whether it is possible to draw any conclusions which could then be of assistance to regulators and administrations in taking their own decisions when considering 5G and satellite compatibility in C-band.

The collection of studies has been analysed and high level observations and lessons learnt presented. The outcome of our examination of these studies provides a stark warning to those wishing to better understand the compatibility issues: our findings show that the studies take such a wide range of input assumptions, relying on them at a national level to set sharing criteria is troublesome. We therefore decided to publish the results of our assessments to assist others who may also want to better understand co-existence of 5G and satellite services.

Based on the studies reviews, and our own work on these issues we have provided a recommended set of parameters that provide a solid and repeatable basis for those wishing to conduct the analyses for themselves.

1.2 Structure of this document

This document is structured as follows:

- Section 2 identifies the inputs and outputs, together with the associated modelling scenarios which are required for a full compatibility analysis.
- Section 3 looks at the results of all of the studies and examines how their outputs compare.
- Section 4 discusses the lessons which can be learnt from the studies.
- Section 5 provides recommendations concerning international best practice in conducting compatibility analyses.
- Section 6 documents all the input and output assumptions made in each study.

- Section 7 lists reference documents use in the compilation of this report.
- Section 8 contains a list of acronyms and abbreviations which are used within this report.

2 Inputs and Outputs

2.1 Introduction

The C-band (from 3400 to 4200 MHz) is a mainstay of satellite communications. From relaying the pictures of the first moon landing in 1969 around the world, to providing broadband interconnectivity in remote areas today, satellite use of the band provides crucial connectivity to a variety of commercial and government entities.

In addition to supporting satellites, the band has also historically been used for terrestrial fixed links who can share the band with the satellite downlinks by carefully selecting the location of the links so as not to cause interference. More recently, these fixed services were extended to include fixed wireless access using point-to-multipoint technology. These services typically provide domestic or enterprise broadband internet connectivity and being fixed services could still be largely designed so as not to cause harmful interference to satellite services.

Parts of the band have now been identified for International Mobile Telecommunications (IMT) services at various previous ITU World Radiocommunication Conferences (WRC). Introducing such services into the band is far more complex than for previous fixed services if satellite reception is to be protected as:

- mobile base station transmissions are much higher powered;
- mobile base stations transmit in all directions and not just on a point-to-point basis;
- user devices can be anywhere, making controlling their proximity to satellite receivers nigh on impossible.

A wide range of organisations have tried to determine how mobile services could share spectrum with satellite services (and fixed services) and with a push towards using the band for 5G services, the importance of finding workable solutions has never been greater. In this report we examine some of the compatibility studies which have already attempted to address this issue, to try and tease out international best practice when it comes to the sharing of the band.

There are two axes along which we will compare the various studies:

- the methods employed, and
- the input and modelling assumptions and parameters selected.

2.2 Compatibility methods

C-band satellite transmissions and by dint, receivers, operate across the frequency range 3400 – 4200 MHz. Unmodified, devices called Low Noise Amplifiers (LNAs), also known as Low Noise Blocks (LNBs)[1] are designed to amplify the very weak signals from satellites to ensure that the receiver is sensitive across this whole frequency range. There are two methods by which satellite receivers can be affected such that they are no longer able to receive the satellite signals:

- emissions on the same (wanted) frequency to which the receiver is tuned may be sufficiently strong to cause co-channel interference, or
- emissions anywhere within the LNB's pass-band may be sufficiently strong to overload the LNB, causing it to become non-linear and thereby impeding reception.

Depending on the band selected, 5G transmissions may occupy frequencies from 3300 – 4200 MHz:

- 3GPP Band n78 covers the range 3300 – 3800 MHz and is the band most commonly being considered for wide area mobile services, and
- 3GPP Band n77 which extends the frequency range up to 4200 MHz is being considered in a few countries for low-power campus type networks, and is partially used in the USA for mobile services.

Though the intended transmissions occupy the associated frequency ranges, the transmitters also produce out-of-band emissions which are an unavoidable artefact of digital transmission systems and occupy the spectrum either side of the intended transmission. Thus there are two parts of a 5G transmission which may cause interference to satellite reception:

- the intended transmission, on the frequency on which the 5G transmitter is operating, and
- the out-of-band emissions on frequency adjacent to that on which the 5G transmitter is operating.

There is thus a matrix of possible interference mechanisms between the two systems and it is necessary to consider all four possible results to determine whether a 5G transmission will cause interference to satellite reception. Effectively, results need to be entered in each of the cells of the table below. Note that at this point, the nature of the values which would go into the cells has not been defined. They could be signal thresholds, separation distances, guard-bands, necessary mitigations or other parameters.

	Satellite Receiver	
5G Transmitter	*Co-channel Emissions*	*LNB Overload*
Intended transmissions		
Out-of-band emissions		

[1] The term 'LNB' will be used throughout this report but is interchangeable with LNA.

2.3 Path loss

If the level of 5G transmissions, and the thresholds at which the satellite receiver will suffer interference can be determined (see the section on input parameters below), then assuming that the 5G transmitter and satellite receiver are not co-located, it is necessary to determine the path loss between them. There are several path-loss models which could be used, typically one of the following are usually applied:

- Free space path loss – this is valid, as the name suggests, in free space only (i.e. where there is a clean line of sight between the transmitter and receiver and there are no incursions into the Fresnel zone). In real life situations, free space path loss is typically only valid at distances up to a few tens (or in some cases hundreds) of metres.
- ITU-R Recommendation P.452 [1] "Prediction procedure for the evaluation of interference between stations on the surface of the Earth at frequencies above about 0.1 GHz" - is more appropriate in typical situations where a path is obstructed, but does not provide particularly accurate results at short distances (i.e. <500m).

Many other models exist which may be applicable as long as the author of a study understands their application and limitations.

In addition, if it is assumed that 5G transmitters are operated indoors, it is also necessary to define the additional path loss (if any) which would be provided by the structure and composition of the building including windows and doors. ITU-R Recommendation P.2019 [2] provides one such method.

Finally there is the question of the many or the few. 5G transmitters do not exist in solitude, they are part of a wider network. Considering compatibility between one 5G transmitter and one satellite receiver is therefore not a complete picture and it is necessary to determine how multiple 5G transmitters will impact satellite reception. This is particularly important when understanding that the various thresholds which are often used in compatibility studies represent the points at which harmful interference will occur. Thus, setting parameters in which one site will reach these thresholds will inevitably mean that more than one site will exceed them, and thus interference will occur.

2.4 Input Assumptions and Parameters

For the satellite receiver, there are a wide range of input parameters which need to be considered in order to determine compatibility. These include parameters associated with the reception of the satellite:

- the e.i.r.p. of the satellite being received;
- the size (or gain) of the receiving satellite dish and its efficiency and radiation pattern;
- the noise figure (or noise temperature) of the LNB;
- the angle of elevation and azimuth of the dish;
- the reception bandwidth.

In addition, it is also necessary to understand the performance characteristics of the LNB to determine the point at which it would become overloaded:

- the gain of the LNB;
- its 1 dB compression point (this is the point at which the gain of the LNB falls by 1 dB as it is reaching saturation). Note that it is generally regarded that an LNB will enter a non-linear point at 10 dB below the 1 dB compression point, and that this lower level should never be exceeded;
- the frequency range over which it operates (the ‘pass-band’);
- the performance of any filter fitted before (or built in to) the LNB.

A decision needs to be made concerning the extent to which the 5G interference will be permitted to affect satellite reception. The usual metric for this is the level of additional interference caused by the 5G signal compared to that already experienced by the satellite receiver, measured as C/(I+N) where C is the wanted carrier, I represents interference and N represents noise. Additional 5G interference will increase the ‘I’ in the equation and thus reduce the overall C/(I+N). The extent to which any such reduction is allowed depends on the choice of the administration. The permitted increase in I caused by 5G transmissions is usually referenced to the level of N and may, or may not, include temporal variances (i.e. the percentage of time for which the value is exceeded). Without any temporal variance being specified, the default value is 50% of the time. A requirement not to exceed an increase in I/N of -12 dB for more than 5% of the time is therefore significantly stricter than a limit of just -12 dB.

For the 5G transmitter, the following parameters must be known:

- the intended transmission power (e.i.r.p);
- the intended transmission bandwidth;
- the level of out-of-band emissions and their frequency profile.

It is common to factor transmission bandwidth and transmission power, including for out-of-band emissions, in the form of power per bandwidth (i.e. dBm/MHz). However there can be differences between both the numerator and denominator, such as dBW/MHz, dBW/5 MHz, or dBm/100 kHz and care must be taken to accurately translate between these.

2.5 Outcomes

The results of compatibility studies can be specified in a number of mutually non-exclusive ways:

- an increase in I/N resulting in a reduction in C/(I+N);
- a guard-band which needs to be left between the band in which satellite reception is protected and that in which 5G transmissions are permitted;
- emissions limits on the intended or out-of-band limits of the 5G transmissions;
- interference thresholds which should not be exceeded at a satellite earth station location; and
- separation distances which must be met between any 5G transmitters and any satellite earth stations.

In addition, it may be necessary to introduce mitigations against interference from the 5G transmissions into the satellite receivers (i.e. fitting filters to satellite receivers in order to protect them from 5G transmissions), and the definition and specification of those mitigations may also form part of the results of a study.

3 Analysis of the Results

3.1 Introduction

This section investigates the extent to which trends exist across the compatibility studies examined. Studies were identified through a detailed literature review aiming to find all relevant, published studies from ITU, industry and academic sources. Inclusion in the analysis was dependent on the study quoting results and input parameters which permitted comparisons to be made. Note that a small number of more general recommendation documents, for example ECC Report 254, have not been included on this basis. A detailed consideration of each individual study is given within section 6.2.

The analysis presented here considers a number of areas, looking first to co-channel operation of 5G and FSS systems and the separation distances found to be required, before moving onto adjacent frequency operation of the two systems, and the additional considerations that need to be factored into the studies. The extent to which studies utilise the same parameters is investigated, particularly with regards to 5G emissions masks and FSS receiver masks, before considering the impact on the separation distances and guard bands that are found to be required. Where consensus is not found across the studies, suggestions are made as to how usable recommendations regarding possible 5G implementation within C-band might be found.

3.2 Study Summary

The tables below provide a summary of which studies have considered the issues of spurious emissions, satellite receiver spectral performance and LNB overload.

Reference	Chapter Reference	Organisation	Spurious Emissions	Filter Performance	LNB Overload
[3]	6.2.1	Academia	✓	✓	✓
[4]	6.2.2	Industry	✓	✓	✓
[5]	6.2.3	Industry	✗	✗	✗
[6]	6.2.4	National Administration/ Industry	✓	✓	✓
[7]	6.2.5	Academia	✗	✗	✗
[8]	6.2.6	Academia	✓	✗	✓
[9]	6.2.7	National Administration	✓	✗	✓
[10]	6.2.8	Academia	✗	✗	✗
[11]	6.2.9	National Administration	✓	✓	✗

Reference	Chapter Reference	Organisation	Spurious Emissions	Filter Performance	LNB Overload
[12]	6.2.10.3	ITU	✓	✗	✗
[12]	6.2.10.4	ITU	✓	✗	✗
[12]	6.2.10.5	ITU	✓	✗	✗
[12]	6.2.10.6	ITU	✓	✗	✗
[12]	6.2.10.7	ITU	✓	✗	✗
[12]	6.2.10.9	ITU	✓	✗	✓
[13]	6.2.11.1	ITU	✗	✗	✗
[13]	6.2.11.2	ITU	✓	✗	✓
[13]	6.2.11.3	ITU	✓	✗	✓
[13]	6.2.11.4	ITU	✓	✗	✓
[13]	6.2.11.7	ITU	✓	✓	✗
[13]	6.2.11.8	ITU	✗	✗	✗
[13]	6.2.11.10	ITU	✓	✓	✗
[14]	6.2.12	Industry	✓	✓	✓
[15]	6.2.13	National Administration/ Industry	✓	✓	✓

3.3 Co-Channel Analysis

Within the co-channel studies investigated, there is large variation in both the input and output parameters. EIRPs range from 11dBm/MHz to 57dBm/MHz, with a range of base station and receiver conditions. Studies typically make use of ITU-R P.452 for modelling the propagation related to the IMT service (12, 14, 15 or 16) although one also relies on ITU-R P.2001. Various diffraction models are used, along with various terrain and clutter databases (with some models utilising a smooth Earth approach). There is nominal agreement in parameters within the two ITU study reports that have been considered.

A plot of the worst case separation distance (i.e. the largest co-channel separation distance per study within a given elevation angle range: 0-20º, 20-40º and 40+º) against the highest EIRP for a study (normalised to represent a constant I/N and such that the IMT transmission and FSS receiver bandwidths align) is shown below:

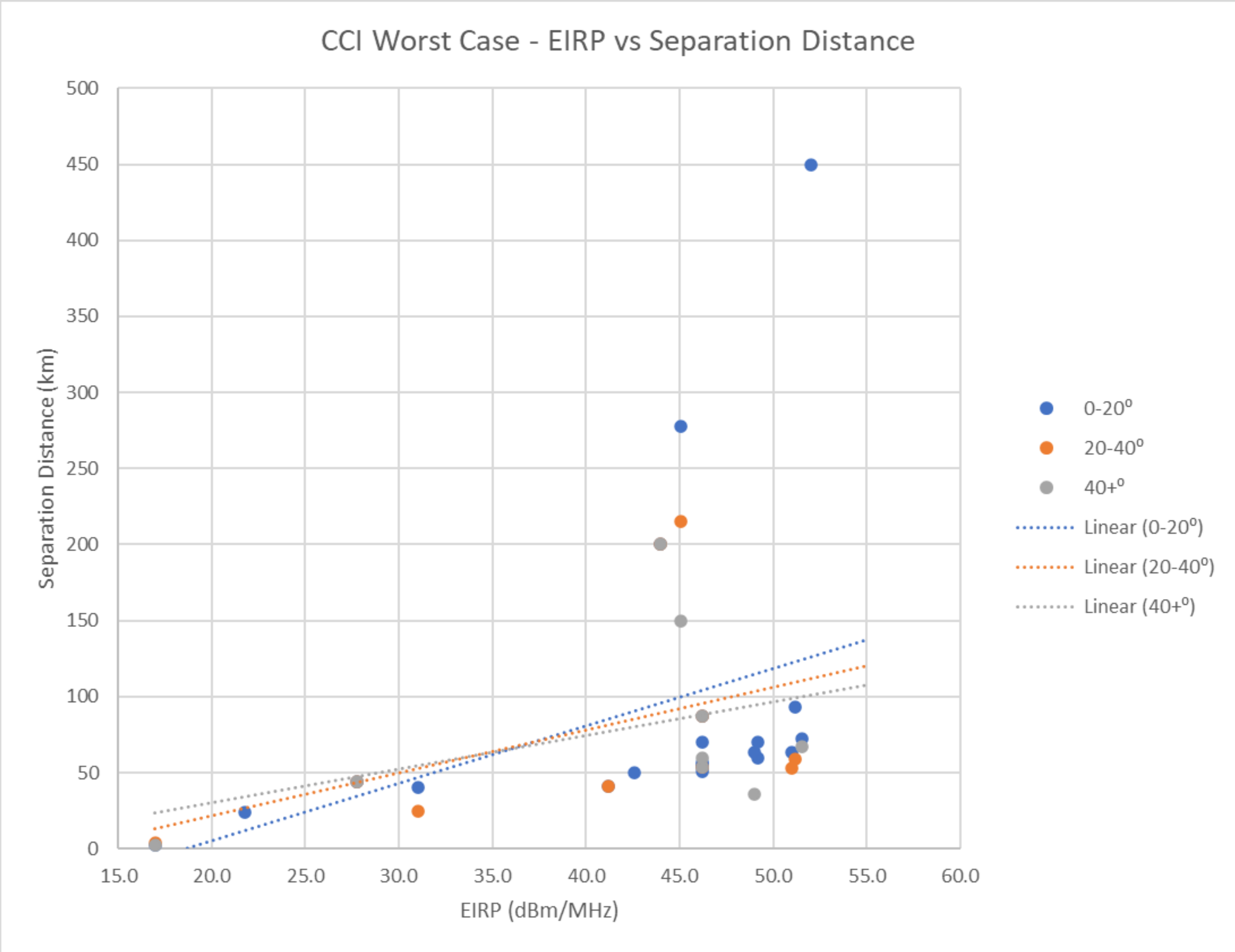

Figure 1: Co-channel studies normalised EIRP vs separation distance for each elevation angle range

Trend lines are included also (least squares fit, standard linear Excel trendline). This may be an oversimplification of the situation, however as a linear relationship exists between distance and free space path loss (in a logarithmic scale such as dB), it is assumed to be valid. Whilst the trend lines do show the expected trend, i.e. an increase in EIRP of an IMT base station results in an increased separation distance between IMT and FSS, the range of values within the studies considered means the fit of the trendline is weak (R^2 of 0.14 to 0.2).

As a number of the study values are grouped, with a small number of values looking to be outliers, there is potentially an argument in omitting these values. Indeed, looking at the studies resulting in outliers, one [7] (considered in 6.2.5) makes use of ITU-R P.2001 rather than ITU-R P.452 for the propagation model. ITU-R P.2001 is applicable for 30MHz to 50GHz, and for distances of 3km to at least 1,000km, and therefore may not be explicitly comparable with results obtained using ITU-R P.452. The results from [8] (considered in 6.2.6) are omitted as the resulting separation distances are significantly larger than for other studies without a clear reason as to why. Earth stations have been chosen in [13] (chapter reference 6.2.11.8) specifically to highlight the effect of terrain close to the FSS earth station on the resulting separation distance. Within the study, the earth station resulting in the large separation distances, Madley in the UK, was chosen precisely because it has little natural terrain screening. Note that the other UK station examined, Brookmans Park, is quoted as having higher levels of terrain screening but does still result in large separation distances also.

If the results of these three studies are omitted, the following plot results.

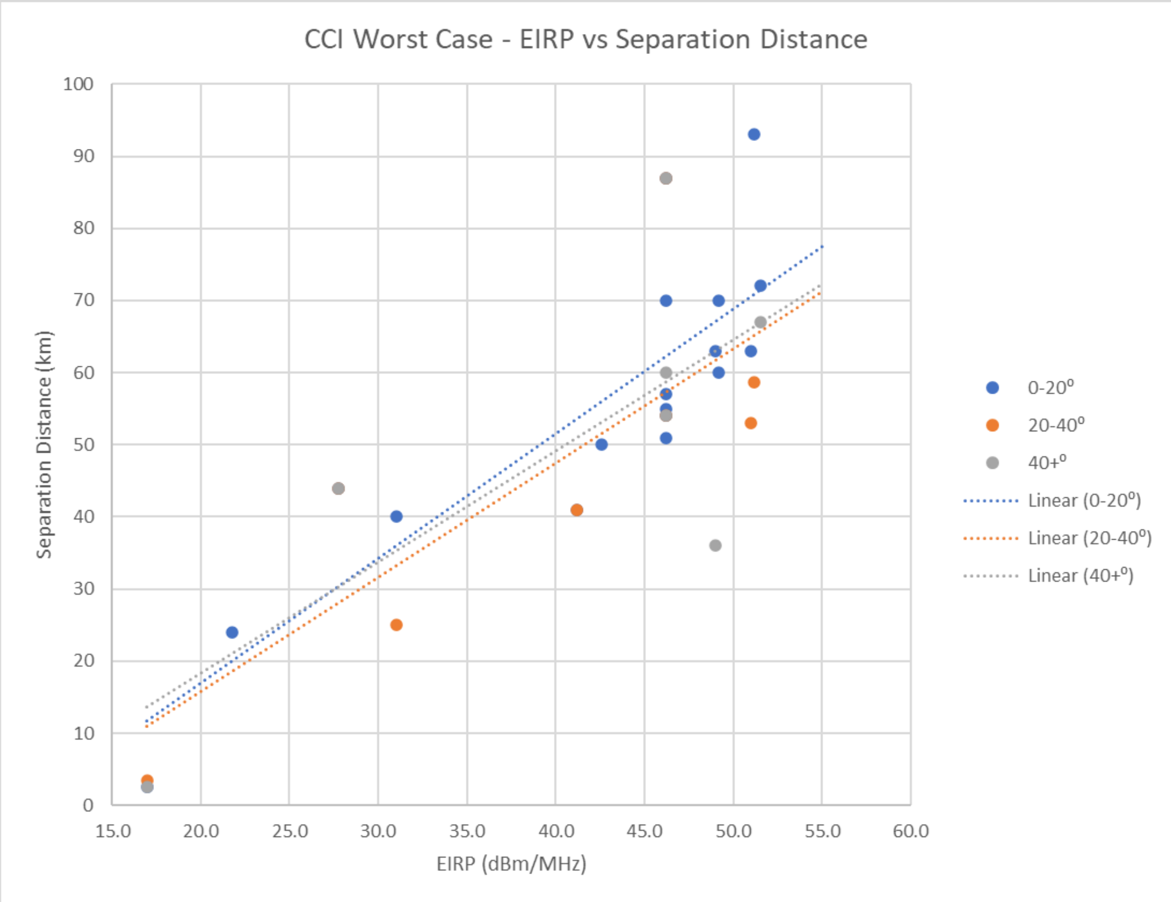

Figure 2: Co-channel studies normalised EIRP vs separation distance for each elevation angle range (some studies omitted)

In this case, the trend line is stronger, with an R^2 of between 0.56 and 0.73 dependent on the elevation angle chosen. It is worth noting, however, that the principle that increasing elevation angles decreases the required separation distance for a given set of input parameters, is not observed. In LS telcom's experience, this effect is also observed in reality whereby reflections of the 5G transmissions from nearby structures negate any benefits that may be achieved by higher satellite elevation angles, and as such higher elevation angles are not a potential mitigation for interference.

The main conclusion from these studies is that for the most part, co-existence of IMT and FSS is only deemed to be possible at large separation distances (e.g. separation distances of over 20km for relatively low EIRPs of 20dBm/MHz). Another point that is made quite consistently throughout a number of the studies is that these separation distances are not necessarily complete exclusion zones within which no IMT may operate, but rather they are areas within which a more detailed study of the interaction between the IMT and FSS systems in question is required. Site specific information, e.g.

terrain and clutter surroundings, exact transmission and receive parameters and so on, are likely to be available in specific cases, and as such these are likely to produce potentially more meaningful and useful results than generic approaches.

3.4 Adjacent Frequency Analysis

Within the adjacent frequency studies investigated, there is large variation in both the input and output parameters. EIRPs range from 11dBm/MHz to 65dBm/MHz, with a range of base station and receiver conditions. Studies typically make use of ITU-R 452 for modelling the IMT service (12, 14, 15 or 16) although one model also makes use of ITU-R 2001. Various diffraction models are used, along with various terrain and clutter databases (with some models utilising a smooth Earth approach). There is nominal agreement in parameters within the two ITU study reports that have been considered.

3.4.1 Emission Masks

A range of standards are used to determine the appropriate IMT emission masks to be used within the studies. For example, the ITU reports ITU-R S.2368 [13] (chapter reference 6.2.11) and ITU-R M.2019 [12] (chapter reference 6.2.10) recommend use of ACLR tables taken from 3GPP Document TS 36.104 v.11.2.0 and 3GPP Document TS 25.104 respectively, reproduced below. There are additional tables within these standards stating operating band limits not specific to adjacent IMT channels. These do not appear to have been used for the most part, however these are the most appropriate values to use in the case of interference to services other than adjacent frequency IMT (i.e. FSS), except in the specific case where the IMT and FSS systems are immediately spectrally adjacent and the spectral separation (including any guard band) is within the ACLR limits stated. In the case of ITU-R S.2368, an absolute limit is also stated for each base station type which is to be taken if it is less stringent than the limits shown below.

Base station ACLR in paired spectrum

Channel bandwidth of E-UTRA lowest (highest) carrier transmitted $BW_{Channel}$ (MHz)	BS adjacent channel centre frequency offset below the lowest or above the highest carrier centre frequency transmitted	Assumed adjacent channel carrier (informative)	Filter on the adjacent channel frequency and corresponding filter bandwidth	ACLR limit
1.4, 3.0, 5, 10, 15, 20	$BW_{Channel}$	E-UTRA of same BW	Square (BW_{Config})	45 dB
	2 x $BW_{Channel}$	E-UTRA of same BW	Square (BW_{Config})	45 dB
	$BW_{Channel}$/2 + 2.5 MHz	3.84 Mcps UTRA	RRC (3.84 Mcps)	45 dB
	$BW_{Channel}$/2 + 7.5 MHz	3.84 Mcps UTRA	RRC (3.84 Mcps)	45 dB

NOTE 1 – BWChannel y BWConfig are the channel bandwidth and transmission bandwidth configuration of the E-UTRA lowest (highest) carrier transmitted on the assigned channel frequency.
NOTE 2 – The RRC filter shall be equivalent to the transmit pulse shape filter defined in TS 25.104, with a chip rate as defined in this Table.

Figure 3: Out of band emissions parameters taken from 3GPP Document TS 36.104 v.11.2.0 used in ITU-R S.2368

IMT-Advanced out-of-band parameters

Offset	ACLR limit
1^{st} adjacent channel	45 dB
2^{nd} adjacent channel	50 dB
3^{rd} adjacent channel and above	66 dB

Figure 4: Out of band emissions parameters taken from 3GPP Document TS 25.104 used in ITU-R M.2019

The more recent 3GPP standard TS 38.104 V16.6.0 requires that, within the operating band, the following must apply for a 'Wide Area category A' base station:

Table 6.6.4.2.1-2: Wide Area BS *operating band* unwanted emission limits (NR bands above 1 GHz) for Category A

Frequency offset of measurement filter -3dB point, Δf	Frequency offset of measurement filter centre frequency, f_offset	*Basic limits* (Note 1, 2)	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}	-13 dBm (Note 3)	1MHz

Figure 5 – Spurious emissions parameters taken from 3GPP Document TS 38.104

Outside of the operating band[2], TS 38.104 V16.6.0 requires that the following spurious emissions limits must apply for a 'Wide Area Category A' base station:

Table 6.6.5.2.1-1: General BS transmitter spurious emission limits in FR1, Category A

Spurious frequency range	*Basic limit*	Measurement bandwidth	Notes
9 kHz – 150 kHz	-13 dBm	1 kHz	Note 1, Note 4
150 kHz – 30 MHz		10 kHz	Note 1, Note 4
30 MHz – 1 GHz		100 kHz	Note 1
1 GHz 12.75 GHz		1 MHz	Note 1, Note 2
12.75 GHz – 5th harmonic of the upper frequency edge of the DL *operating band* in GHz		1 MHz	Note 1, Note 2, Note 3

Figure 6: Out of band emissions parameters taken from 3GPP Document TS 38.104

The limits are varied dependent on the base station type, however only the limits for a 'Wide Area Category A' base station are reproduced here for the sake of brevity. Stricter limits apply for co-located base stations, or for coexistence with IMT systems in different 3GPP bands (e.g. base stations operating in 3GPP band n78 (3.3–3.8GHz), must comply with a limit of -52dBm/MHz within 3GPP band n79 (4.4–5.0GHz). [15] for example makes use of this value, although appears to apply it to unwanted emissions within the same band rather than at the next band. However, as no guarantee can be made within these studies that such a scenario will result, the general limits should be taken.

A comparison of these three sets of limits is shown below for an 'Wide Area Category A' base station with a transmitter power of 59dBm/MHz, operating within a 20MHz bandwidth:

[2] Note that as 3GPP band n77 (3.3 – 4.2 GHz) and n78 (3.3 – 3.8 GHz) occupy at least part of the same spectrum, it could be expected that equipment would be manufactured that is suitable for operation in both bands rather than manufacturers having to produce greater amounts of equipment, i.e. equipment compliant with the limits for n77 could potentially be expected to meet the limits imposed on equipment compliant operation in n78.

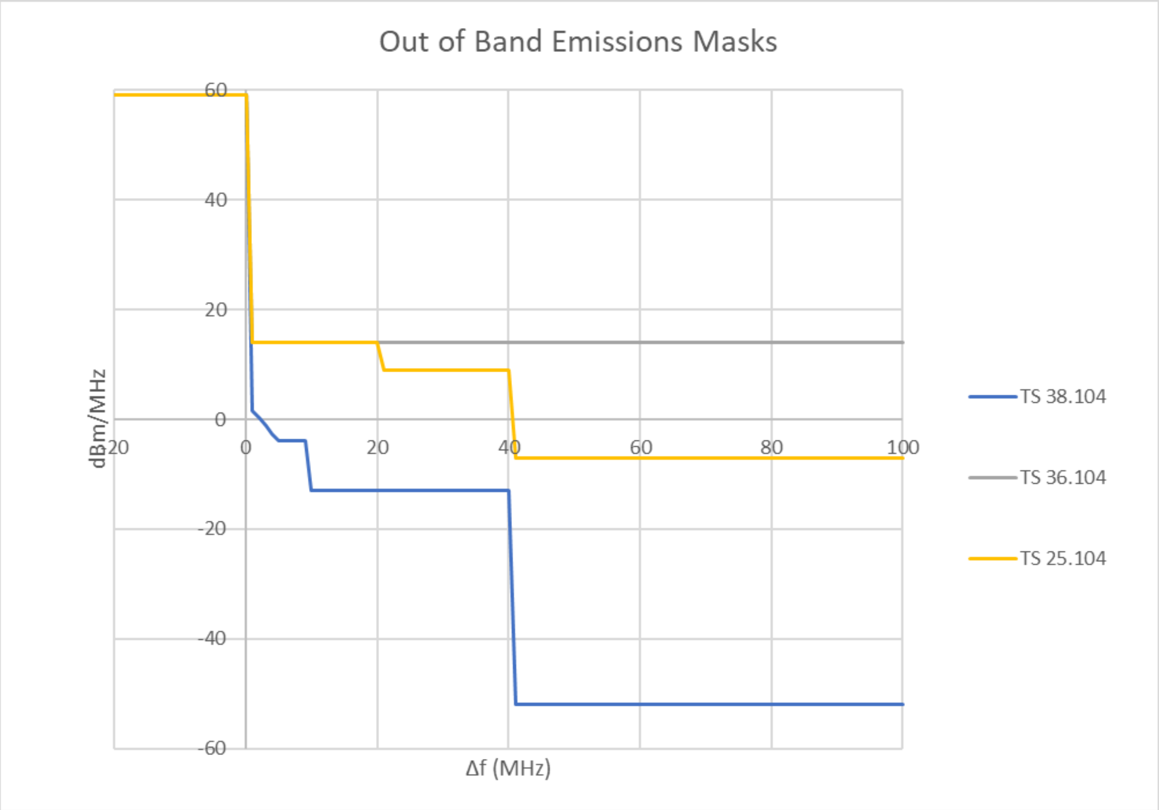

Figure 7: Out of band emissions masks from various 3GPP standards, assuming a 20MHz channel bandwidth and a transmitter power of 59dBm/MHz

As can be seen, the values taken in the ITU studies from the older 3GPP standards in fact require equipment to meet more stringent out of band emissions than those in the more recent TS 38.104 (by over 20dB in some cases). In this regard then, use of the older 3GPP standards within 5G sharing studies (TS 36.104 being relevant to Evolved Universal Terrestrial Radio Access (E-UTRA), and TS 25.104 being relevant to Universal Mobile Telecommunications System (UMTS)) are likely to present a different result to those conducted using TS 38.104 (relevant to 5G NR). The majority of studies (other than a small number of the most recent studies, [3] [6] [14], which make use of at least parts of 3GPP TS 38.104) make use of the older transmission standards, potentially even erroneously, and as such are arguably not applicable to the current issue of 5G FSS sharing.

The same is true of studies making use of masks considered to be more representative of actual equipment. As no general guarantee can be made for the out of band emissions performance of transmission equipment other than the limits set within the relevant 3GPP standards, the standards are the only applicable limits that can be taken.

3.4.2 FSS Receiver Spectral Performance

As with the other parameters investigated, there is little consensus on the appropriate spectrum mask for the FSS receiver. A number of studies either do not quote specific values taken within the analysis or describe the performance as 'ideal'. Within the studies that do quote filter performance, representations of the assumed masks are shown below (normalised for a receiver bandwidth of 20MHz). Note that for the Transfinite studies assuming use of a Gaussian filter, the form of the filter has been estimated based on parameters provided within the report. However, as the report only includes performance up to twice the bandwidth, the values beyond this reproduced here are not necessarily correct.

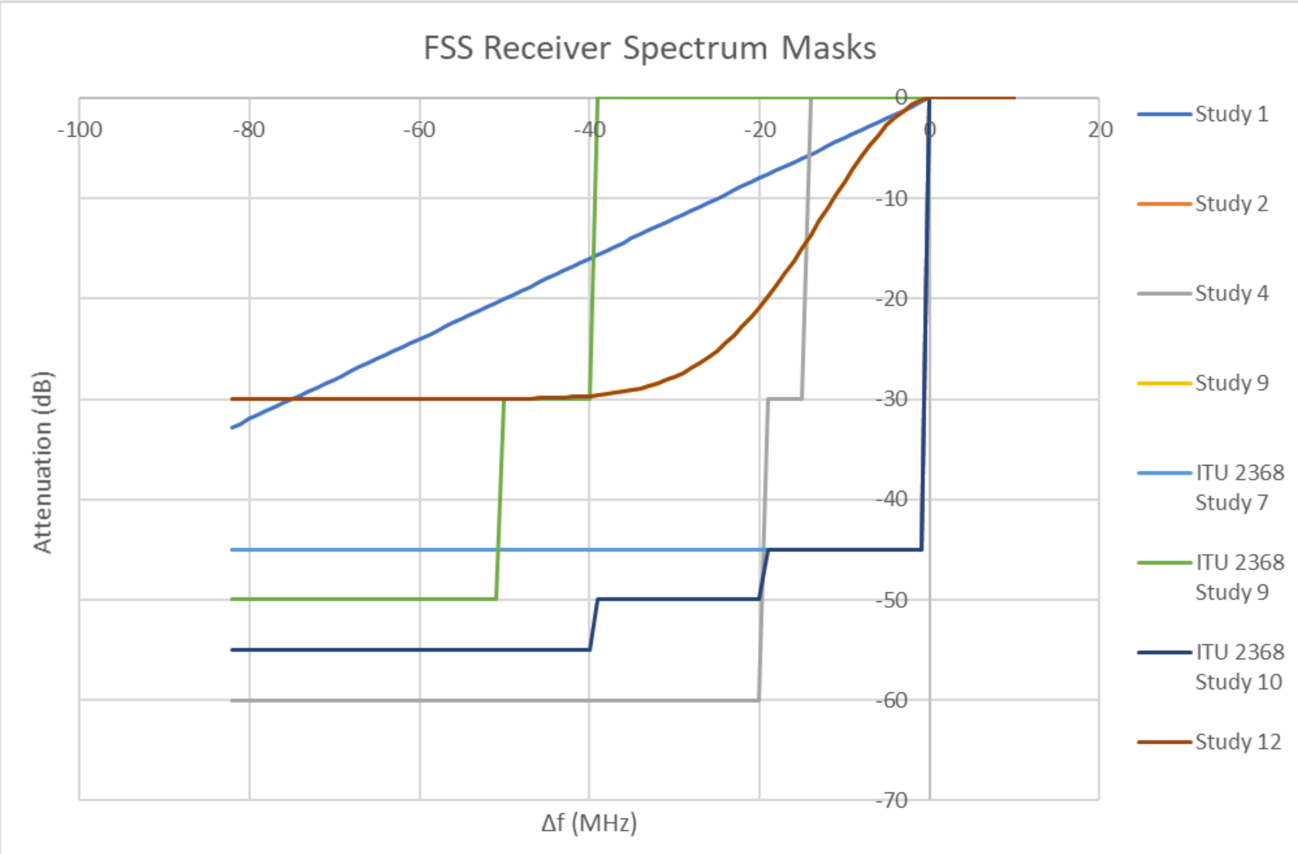

Figure 8: FSS receive spectrum mask representations

As can be seen, the variation in FSS receiver mask performance is large, with some studies assuming a cliff edge transition at the edge of the FSS receiver bandwidth, some assuming a more gradual transition, and some assuming stepped changes a certain spectral distance from the carrier frequency. The studies considered investigate performance of a number of different receivers (small TVRO type installations, VSAT receivers, larger earth station type receivers etc.) and as such it is not surprising that there is a range in assumptions for filter performance.

A number of studies do make the point that representative spectrum masks for FSS receivers are not readily available. This is demonstrative of a potential concern regarding the bandwidth of filters assumed within a number of the studies.

Notwithstanding all of the above, any filters fitted at the intermediate frequency (IF) within satellite receivers themselves will have virtually no impact on compatibility and do not represent valid input assumptions when conducting compatibility studies. This is due to the fact that the interference presented by 5G systems is at the LNB itself, and no amount of filtering after the LNB (i.e. in the receiver) will change the levels at the dish itself. Many of the studies do not make clear whether the filter responses being used are at the receiver or at the LNB.

3.4.3 LNB performance

LNBs are inherently wideband, being required to operate across the whole of the C-band, and as such would not be expected to significantly attenuate 5G transmissions on adjacent frequencies without additional filtering applied at the input to the LNB. As such, some of the responses assumed for the FSS spectral performance in a number of the studies are likely to be overly optimistic when considering unfiltered LNBs.

Where filtering is applied to the LNB, it would need to be sufficiently wideband to allow adequate operation within the remaining allocated FSS spectrum. A concern with the receiver spectral performances identified in a number of the reports is the use of particularly narrow bandwidths, e.g. curves providing high levels of attenuation at twice the receive channel bandwidth as assumed in [14] [11]. Whilst such filtering at either edge of the band may be appropriate, the use of such a narrow filter could not be assumed to provide adequate performance over the rest of the FSS spectrum. Such narrow bandwidth filters may be appropriate if assumed at IF, however, as stated previously, these would not have a bearing on the results of this sort of compatibility analysis.

Across the studies, only a small number specify that the filter is fitted to the LNB [3] [4], the other studies do not specify at what point in the receive chain the filter is fitted, i.e. at RF or IF. As saturation and blocking effects occur prior to the IF section of the receive chain, the RF response of the earth station is the important consideration. A further potential concern then is that as a number of the studies do not explicitly consider LNB saturation, it may be that the exact location in the receive chain of any filter has not been considered.

Hence it is important that studies consider the implications of their assumptions regarding filtering. Optimistically narrow filters applied to the LNB are unrealistic, and those applied at IF are not relevant to the issue of compatibility. In any case, the range of input assumptions mean that general limits and approaches are difficult to produce, and investigation on a case by case basis is likely to be necessary.

3.4.4 Separation Distances

Notwithstanding the differences in study input parameters observed within the previous sections, the same comparison of base station EIRP and resulting separation (as presented within the co-channel case) is shown below for the adjacent frequency case. Again, least squares fit trend lines have been applied on the assumption that a linear fit is appropriate.

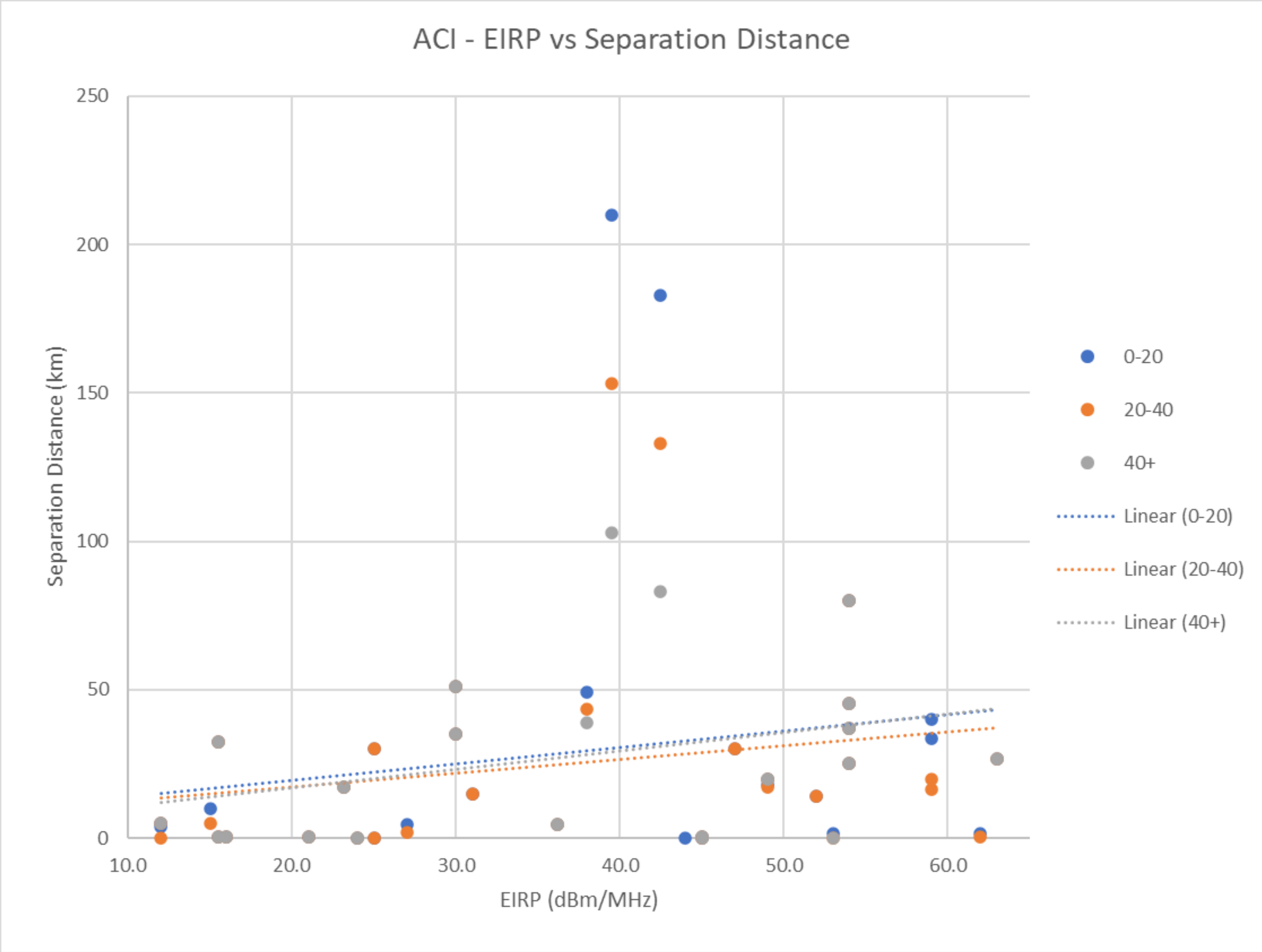

Figure 9: Adjacent frequency studies normalised EIRP vs separation distance for each elevation angle range

As with the co-channel case, the spread of values is such that the trends are unlikely to be of great value in producing recommendations for implementation of 5G and the separation distances that would be required to protect FSS. This is not surprising given the large variation seen in the input parameters, particularly around out of band emissions and satellite filter performance. As with the co-channel case, the removal of outliers helps to strengthen the trend somewhat. Removal of the outliers represented by the results of [7] [8] (chapter reference 6.2.5 and 6.2.6), again on the basis of the use of ITU-R P.2001 rather than ITU-R P.452, results in the following (noting that study [13], chapter reference 6.2.11.8 does not quote adjacent frequency separation distances, and hence is not included in this plot):

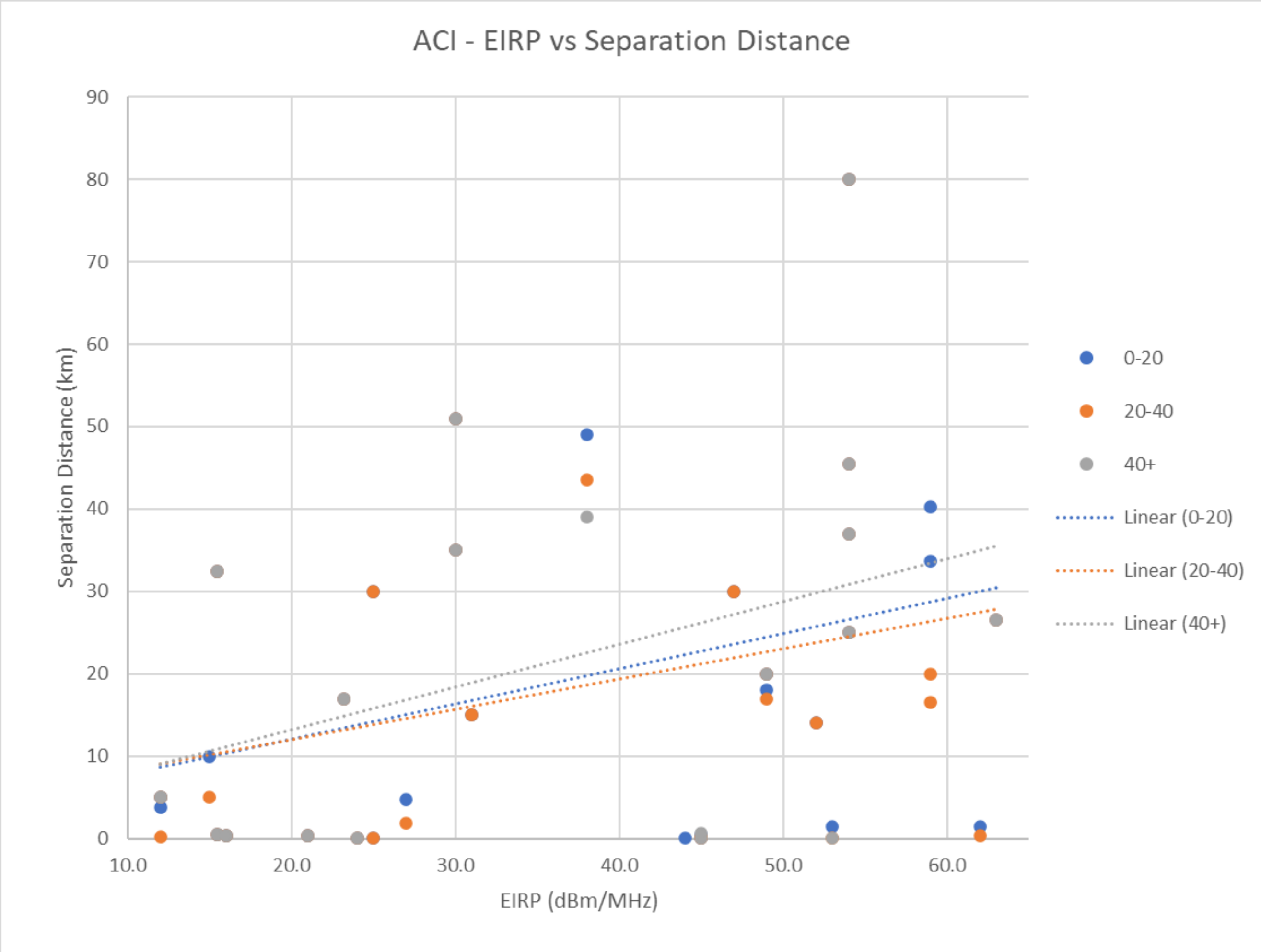

Figure 10: Adjacent frequency studies normalised EIRP vs separation distance for each elevation angle range (some studies omitted)

Removal of the outliers does help to improve the trend, i.e. increasing the EIRP increases the required separation distance. However, considering the range of separation distances quoted across the studies, it is clear that there is unlikely to be sufficient consensus from which to derive actual recommendations to be used in the implementation of 5G systems. Taking just the example of the two data points associated with a corrected EIRP of 25dBm/MHz ([13], chapters 6.2.11.7 and 6.2.11.10), the derived separation distances vary by a factor of around 500. Whilst there are some differences in the studies, such as slightly different out of band emissions for IMT and FSS receiver masks, it is not expected that these could account for such a large difference in results (note that the results here are assumed to correspond to the 0 MHz guard band case, i.e. the highest resulting separating distance).

As such, where studies utilising nearly the same parameters are unable to reach a consensus on the results, it is unlikely that achieving a consensus on generally applicable recommended parameters to be used in actual implementations is likely to be possible. As in the co-channel case, it is more likely that detailed investigation of specific cases is likely to produce the most useful and meaningful results.

3.4.5 Guard Bands

Guard bands between 0 MHz and 100 MHz have been considered within the studies. Plotting the guard band against the separation distance required (again omitting the results from [7] and [8], chapter references 6.2.5 and 6.2.6 respectively), yields the following results:

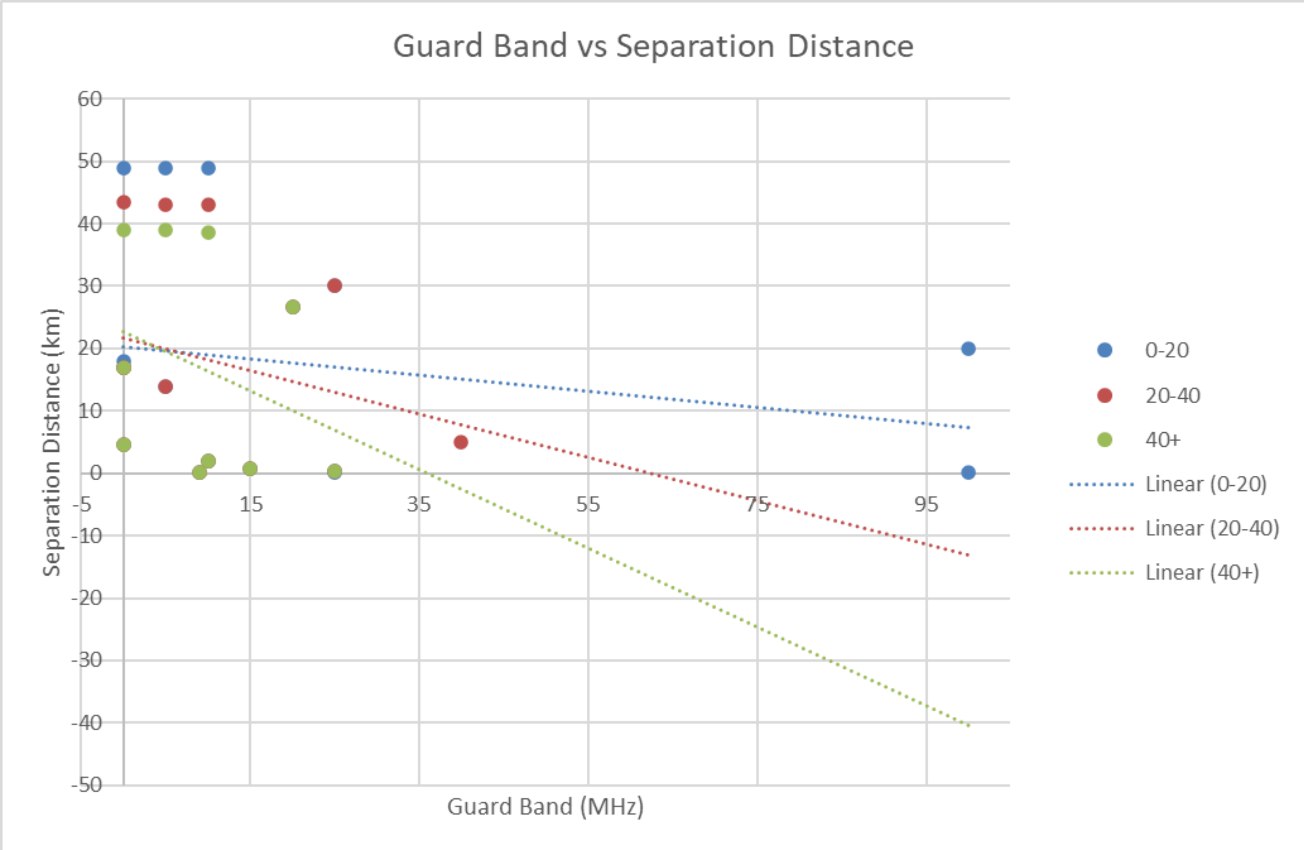

Figure 11: Guard band assumed (MHz) versus resulting separation distance

There is a trend to the data that is as expected, i.e. an increasing guard band decreases the required separation distance. Similarly, the lower the elevation angle, the larger the separation distance required for a given guard band however a number of studies find that the separation distance remains largely constant for increasing guard bands. Indeed, when the frequency separation is such that interference from IMT into the FSS receiver is within the spurious emissions domain, the limit is constant until the next operating band. As such an increase in guard band would not be expected to reduce the emissions or the separation distance required. As the studies have utilised a wide range of values for out of band emissions and FSS receiver masks, a lack of agreement on the relationship between guard band and separation distance would be expected.

In addition, this analysis takes no account of differing EIRPs, and as such only minimal correlation would be expected given the range of input EIRPs considered. As with separation distances, detailed investigation would need to be conducted regarding guard band requirements given the updated parameters.

3.4.6 LNB Saturation

Only a small number of the studies have considered LNB saturation explicitly. Within these, the assumed value for the input power required to saturate the LNB is in the region of -60dBm. An important point to note with regards to LNB saturation however is the implications of the input assumptions. If non-linear behaviour of the LNB is assumed to result at 10dB below the 1dB compression point, and this value is used as an input to the studies, the resultant protection criteria will be generated assuming non-linear operation of the LNB.

LNBs are not designed to operate at this level. Indeed the 1dB compression point is an indicator of departure from linearity and does not in itself provide information as to the level of unwanted mixing or intermodulation products. As such, use of this value represents out of specification performance and any separation distances calculated using this value will allow for 5G implementations that cause satellite systems to be on the edge of failure. As such, separation distances calculated using this value should be regarded as limits, not targets.

Within the studies, the 1dB compression point is typically used and the calculated separation distances vary quite considerably. [9] (considered in 6.2.7) finds, for example, that coexistence of IMT and TVRO FSS receivers is not possible with an LNB saturation point of -60dBm for anything other than small urban cells unless the elevation angle is greater than 40º (noting our previous comment that elevation angles are unlikely to yield useful protection given reflections and other factors). If the saturation point can be increased to -45dBm, coexistence is found to be possible, although never at a separation distance of less than around 100m.

This agrees to some extent with the findings of other studies. [13] (considered in 6.2.11.4, taking a saturation value of -60dBm) finds that separation distances of around 9km are required at lower elevation angles (0-20º), reducing to around 6km when elevation angles increase (20-40º). [12] (considered in 6.2.10.4, taking a saturation value of -61 dBm) finds that separation distances of 9.5km are required for all elevation angles.

Despite only a small number of studies considering the issue however, what is clear is that, in cases where no filters are fitted to satellite receivers, the separation distances required to allow the FSS receiver LNB to operate at the edge of failure are of a similar order to, or sometimes larger than, those required to meet the I/N requirements. Indeed with so few results, any recommendations are unlikely to be generally applicable but the studies completed so far do highlight the issue to be as important as I/N degradation, and highlight the need for it to be considered in detail.

3.4.7 Impact of IMT User Equipment

The majority of the studies examined do not consider user equipment. Those that do typically find that the separation distances required for user equipment are, perhaps not unexpectedly, smaller than those required for base stations. Co-channel analysis finds separation distances of anywhere between 500m and 2.65km are required. For adjacent frequency operation, separation distances between 100m and 32.5km are found. The range of values again does not lend itself to the generation of useful generally applicable recommendations for administrations to use. In addition, enforcing required separation distances for user equipment is likely to be far more challenging for administrations than for base stations. As such, it is again likely that the most useful recommendations will result from specific compatibility studies rather than the general set of studies considered here.

4 Lessons learnt

From the studies examined, co-channel operation of FSS and IMT is considered to be unlikely to be possible in most scenarios. Despite the range of input values to the studies, there is a general consensus that typically 10s of km separation are required for all but the lowest EIRP values for IMT base station transmitters. Whilst in some cases these separation distances might be possible to achieve, or indeed lower separation distances may be feasible due to local effects such as terrain screening, in depth analysis on a case-by-case basis would be required to identify these specific areas.

For out-of-band emissions, various values have been used in the studies, including some thresholds arbitrarily defined by national administrations, and many which use older emissions standards that are not applicable to new 5G systems. However, in order to comply with the 3GPP standards (and thus bring their equipment to market), manufacturers need only meet the requirement specified in the 5G 3GPP standards themselves. For active antenna systems (AAS), where the transmitters are connected directly to the antennas within the antenna casing itself, fitting any additional filtering to reduce out-of-band emissions would be extremely costly, would add to the weight and may impair the operation of the AAS. As such, for the purposes of calculating compatibility, only the emissions specified in the 3GPP standards can be safely applied.

Though national administrations may unilaterally decide to apply different thresholds, it is questionable whether manufacturers would be motivated to meet such requirements. In particular, there is little to no likelihood of manufacturers specially modifying mobile handsets to reduce their out-of-band emissions for one country, unless the market in that country is sufficiently large (i.e. China).

With regards to FSS receiver performance, there is little consensus between the studies, other than to state that representative FSS receiver and filter masks are difficult to obtain. As explored previously, this is likely due to the inherently wideband nature of LNBs. To obtain reliable information applicable within a given country however, it is likely that a more detailed set of FSS parameters will be required, based on measurements of the actual equipment in use which may vary depending on the use to which C-band satellite services are being put. It is also important that the location of any specified filters within the receive chain, and the practicality of their assumed frequency response, are well understood by study authors. Optimistically narrow filters applied to the LNB are unrealistic, and those applied at IF are not relevant to the issue of compatibility

For separation distances for adjacent frequency operation of IMT and FSS, the majority of studies still find large separation distances are required for higher power IMT base stations. While some studies do find shorter separation distances are possible, just as many find that large, multiple kilometre separation distances are required. Regardless, the wide range of input parameters assumed across the studies is unlikely to yield consensus on the appropriate separation distances required.

The same is true of guard bands. There is a slight trend associated with the data that shows increasing guard bands requiring shorter separation distances, but the range of input parameters considered means that useful conclusions are difficult to draw. Rather, it may be better practice to consider real-life implementations around the world of 5G within these bands and consider the levels of success that have been experienced.

Few studies consider the impact of LNB saturation explicitly. Those that do typically find that in cases where no filter is fitted to the LNB, the required separation distances are at least of an order with those required to meet I/N degradation requirements. The importance of the issue is highlighted however, paticularly with regards to the selection of an input value for LNB saturation. Inputs using the 1dB compression point allow for IMT implementations that could result in satellite systems operating at the edge of failure. These values should be regarded as limiting separation distances, rather than targets.

5 Conclusions and Recommendations

5.1 Overview

Any administrations wishing to conduct a technical compatibility study to determine the extent to which C-band satellite services can co-exist with 5G services in the same band, could, on the one hand, take heed of the results of the range of existing studies, or could conduct their own calculations.

As has been indicated in the previous section, the studies available take such a wide range of input assumptions, that relying on them at a national level to set sharing criteria is troublesome. In this section we have tried to summarise the lessons which *can* be learnt from the various compatibility studies, as well as providing a set of parameters which should be used if attempting to revisit or calculate compatibility criteria afresh.

5.2 Points to note from existing studies

If taking heed of the existing studies, the following results represent the most common outcomes:

- Operating 5G services co-channel with C-band satellite receivers requires separation distances measured in tens to hundreds of km, and the studies have all shown this to be the case. Unless C-band usage is only at a few, very remote sites, this will preclude co-channel spectrum sharing in almost all scenarios.
- Operating 5G service in channels adjacent to wanted C-band satellite signals introduces a range of additional considerations. The out-of-band emissions from 5G transmitters and the potential for overloading the LNB mean that this scenario requires very careful modelling to correctly understand the impacts.
- Although higher elevation angles should reduce potential for interference, in practical installations, reflections from nearby structures mean that this is not a usable mitigation to improve compatibility. The ITU standard states that the gain of a dish is -10 dBi at any angle greater than about 45° from the boresight. This may hold true for large dishes, however for smaller ones typical of, for example, direct-to-home television reception, it is an optimistic assumption.
- Considering that studies have shown that the theoretical rejection provided by increased elevation angles does little to mitigate against 5G interference, it can be equally implied that AAS cannot be used to provide azimuthal protection of satellite receivers as ceasing transmissions in a particular direction will, at best, provide a small reduction in potential interference due to the large number of reflections of the main signals from nearby structures which otherwise occur[3].
- There is a trade-off between the size of any guard-band left between 5G and satellite services, the necessary separation distance between transmitters and receivers, and the performance of any

[3] In studies conducted by LS telcom, it was found that the amount of additional path loss between a transmitter and receiver increased by, on average, no more than 6 dB when AAS was used to try and provide azimuthal protection due to scatter and reflections from nearby buildings. In addition, whilst the wanted signal from a 5G AAS transmitter has a defined radiation pattern, the out-of-band emissions are not coherent and are, to all intents and purposes, omnidirectional.

filters fitted to the satellite receivers. Note that it is almost impossible to control the separation distance between user devices and satellite dishes.

- Fitting filters to the LNB to block the impact of 5G transmissions can be effective in reducing the necessary separation distances, assuming these are installed at the correct location within the receive chain and any limitations surrounding the assumptions are well understood. Filters integrated into low-cost LNBs such as may be used in domestic situations have limited rejection of 5G. However, the out-of-band emissions from 5G transmitters remain a limiting factor in the ability to operate 5G and satellite side-by-side.
- Setting an arbitrary, country specific guard-band between 5G and satellite services will not necessarily be successful as the filters available to improve compatibility tend to all operate across the same frequency range.

Whilst much time and effort have been put into trying to calculate compatibility, it is a shame that a more nuanced and precise set of conclusions can not be drawn. In many cases, the studies use incorrect input assumptions and values (such as using earlier out-of-band emission masks) or make best-case assumptions that are unlikely to be achieved in reality.

5.3 Recommended Modelling Parameters

Administrations wishing to produce their own studies on 5G FSS compatibility are recommended to take the following values as inputs. If specific values are available that are more relevant than the general standards, for example measured receive performance of satellite receivers or regional limits on allowable base station EIRPs, these should be used. Note however that the inclusion of specific values rather than general standards, whilst increasing the potential applicability of the study to a given administration's deployment situation, will reduce its general applicability elsewhere.

Parameter		Value/Reference
5G System	Emissions Mask	Base Stations: 3GPP TS 38.104 (V16.6.0, sections 6.6.4.2 Operating Band Basic Limits and 6.6.5.2 Spurious Basic Limits) User Equipment: 3GPP TS 38.101-1 (V16.6.0, sections 6.5.2.2 Operating Band Spectrum Emission Mask and 6.5.3.1 General Spurious Emissions)[4]
	EIRP Limit	Wide Area BS: No Limit Medium Range BS: ≤38dBm Local Area BS: ≤24dBm

[4] Note that the ACLR values can be used in the specific case where the spectral separation (including guard band) between IMT and FSS systems is within the ACLR limits.

Parameter		Value/Reference
FSS System	Receiver Mask	Measured where possible, otherwise filters achieving 45dB rejection at 50MHz from the band edge are practical but expensive. Cheaper filters may require 100 MHz from the band edge to achieve the same rejection. Most currently available commercial filters have a pass-band from 3700 MHz upwards, meaning the guard band should be in the range 3600 – 3700 MHz.
	Dish Parameters	ITU-R S.465-6. In particular this report gives a value for the gain of a dish of -10 dBi at angles greater than around 45° from the boresight.
	LNB Saturation	-60dBm[5]. Note that any interfering signal should be 10 dB lower than this to prevent the LNB becoming non-linear.
Modelling assumptions	Allowable I/N	- 12 dB
	Propagation Model	ITU R P.452-16 for distances > 200m Free Space for distances < 200m

Table 1: Modelling inputs to be used

Three common modelling approaches are:

- **Minimum Coupling Loss** (MCL) Method: The attenuation required at the receiver for a given base station/user equipment (with accompanying EIRP, antenna height etc.) to limit I/N degradation and/or protect the LNB from saturation is known and, given a set of base station/user equipment parameters and environmental conditions (i.e. terrain and clutter), the physical separation (or indeed spectral separation, required filter performance etc.) required to achieve this using a given propagation model (e.g. free space path loss, ITU-R P. 452) can be derived.
- **Deterministic Network Modelling**: Real life, or example representative, networks can be modelled and, given environmental conditions and a propagation model, their impact on a receiver can be determined. This method may require an iterative approach whereby network parameters are modified to determine the requirements (i.e. physical or spectral separation, filter performance etc.) to prevent the I/N degradation or LNB saturation thresholds being broken.
- **Monte Carlo Modelling**: Networks are modelled at random, within a given set of variable value distributions, and the resulting impact on a receiver can be determined for each scenario, i.e. set of variable values. By modelling many scenarios, the analysis can generate a distribution of results from which the requirements to protect I/N degradation or LNB saturation can be determined.

[5] Used across a number of studies and corresponds to a conservative estimate for data taken from a number of LNB manufacturer data sheets.

Typically MCL approaches, whilst relatively straightforward and computationally undemanding, are found to result in spectrally inefficient scenarios when applied to more complex scenarios as they often result in the best case, i.e. the impact of one receiver on one transmitter. Further analysis is then required to assess how a network of transmitters and receivers would respond.

Deterministic network modelling has a benefit in that it can investigate the effect of a real or example network deployment, as opposed to the single site arrangements often considered in MCL. A drawback of both MCL and other deterministic methods however, is the difficulty in being able to take into account parameters that vary in time (e.g. field strengths varying over long distances due to occasional propagation effects) or by receiver (e.g. in accounting for the variety in FSS receiver performance).

Monte Carlo analyses have the benefit that they can consider these more variable parameters. Moreover the need to have a specific network design is reduced, as Monte Carlo analyses are often conducted based on randomly generated networks or indeed regular hexagonal networks. The drawback of course with this method however is the significantly increased complexity and computational requirements.

As all three methods are found to have advantages and disadvantages, it would be rash to recommend just one at the expense of others. Indeed all three methods have been utilised within the studies considered. However, administrations wishing to produce their own compatibility studies would be recommended to fully understand the implications of selecting a specific model, and ensure that the results are valid for the scenario which they are trying to assess.

It is also important to note that the various thresholds identified for study (such as the I/N or LNB saturation requirements) represent the point at which the system will fail. As such, using these as targets for compatibility assessments is a false economy. These values should be treated as extreme limits and real-life operating parameters need to be well below these if harmful interference to satellite reception is to be avoided.

6 Analysis of Studies

6.1 Introduction

This section presents a high-level overview of the objectives, inputs and results of the individual compatibility studies investigated. Where specific input variable to result relationships are clear, e.g. a separation distance is quoted explicitly for each EIRP considered, these are included within the tables. For studies where such relationships have not been explicitly stated, a range of input and result values are presented. For increased granularity in the results, separation distances have been grouped by the satellite receiver elevation angle range (0-20º, 20-40º and 40+º). The results of a number of the ITU study collections either do not quote input values or results, or present them in such a way as to not be entirely comparable with those quoted in other studies. As such, the values from these studies have been omitted from this report. Summary tables of the input and results of all the studies considered are provided also.

6.2 Individual Study Analysis

6.2.1 5G Cellular and Fixed Satellite Service Spectrum Coexistence in C-Band

This study [3] was conducted by a number of IEEE members and supported by the Luxembourg National Research Fund (FNR) and French Agence Nationale de la Recherche under the bilateral CORE project 'SIERRA' – spectrally efficient receivers and resource allocation for cognitive satellite communications. It considers the impact of both co-channel and adjacent frequency emissions from 5G base stations and user equipment into satellite receivers. The 5G system is assumed to utilise a time division duplex (TDD) mode of operation, with perfect synchronisation between a number of different operators (with a 100MHz channel option that overlaps with the satellite receive frequencies by 75MHz, and a 70MHz channel option that leaves a 5MHz guard band). Satellite receivers are assumed to consist of 4.8m or 12m dishes with elevation angles of 10º and 33º respectively.

Separation distances based on the below parameters are derived first for a single base station. An analysis of how many base stations within each of the operators' networks will need to have their power reduced, or be switched off completely, (both in the 70MHz and 100MHz channel options) in order to satisfy the below requirements for both LNB saturation and C/(I+N) degradation is also given. The result of this analysis is a proportion of base stations per operator requiring power modifications and is not included within this report. Some consideration is also given to active antenna systems, with a reduction in the proportion of base stations breaching the LNB saturation criteria of 20-30%.

Finally, a separation distance for user equipment (UE) is derived. In addition, an analysis of how many UEs need to transmit simultaneously to breach either the LNB saturation or C/(I+N) degradation scenarios is presented also.

The assumed input and modelling parameters are shown below, alongside the resulting separation distances.

Input Parameters		
5G	Operating Frequencies	3400 – 3700 MHz OR 3410 - 3620 MHz
	In Band EIRP	54dBm/MHz
	Spurious Emissions	0 MHz <= df < 5 MHz: Min(Pmax-47,14) dBm/MHz 5 MHz <= df < 10 MHz: Min(Pmax-50,8) dBm/MHz 10 MHz <= df <=fmax: Min(Pmax-50,6) dBm/MHz
	Single Cell/Network	Both
Satellite	Operating Frequencies	3625 - 4200 MHz
	Dish Size/Gain	4.8m - 12m
	Wanted Signal EIRP	N/A
	Wanted Signal C/(I+N)	N/A
	Filter Performance	Square root raised cosine (-20dB at 3.55GHz, -60dB at 3.4GHz)
	LNB Overload	-63dBm with added 25dB or 10dB margin
	Single ES/Network	Single

Modelling and Outputs		
Modelling	Path Loss for Terrestrial Service	ITU-R 452-16
	Guard Band	5MHz
	Assumed Degradation in C/(I+N)	I/N = -10dB
Co-Channel Separation Distances (based on elevation angle)	0 - 20º	16km if not aligned with satellite antenna pointing, 41km if aligned with pointing
	20 - 40º	
	≥40º	N/A
Adjacent-Channel Separation Distances (based on elevation angle)	0 - 20º	~14km UE: 550m
	20 - 40º	0
	≥40º	N/A
Dominant Interference Mechanism		Stated OOBE not significant as affects fewest base stations, but has closest separation distance. OOBE critical for UEs

Subsequent references to this study will reference [3] and the chapter reference 6.2.1.

6.2.2 The Interference Mitigation Method and Field Test in C-Band Between 5G System and FSS Receiver

This study [4] was conducted by researchers at the China United Network Communications Group Co. Ltd. and the Beijing University of Post and Telecommunications (BUPT) as an input to a project led by the China Ministry of Industry and Information Technology (MIIT) on the feasibility of the co-existence of 5G and FSS. The study took measurements of a real 17 base station 5G network, deployed by China Unicom at BUPT, aiming to represent the worst case in which an FSS receiver was directly aligned with a base station. Dish sizes of 1.8m and 3m, typical of TVRO installations within China, were used for the satellite receive systems.

The performance of a number of LNB filters were verified under laboratory conditions, before the impact on the levels at the satellite receiver of base station cell loading and the distance of the base station from the satellite receiver were considered. In this way the isolation distance required to meet the LNB saturation criteria is established. Next the impact of the relative angles of the base station transmit and satellite receive antennas, and the aggregation of multiple cells, on receive levels were considered.

The assumed input and modelling parameters are shown below, alongside the resulting separation distances. Note that the spurious emissions within the paper are quoted as 26dBm/MHz and 47dBm/MHz for 3650 – 3700 MHz and 3700 – 4200 MHz respectively. However, as this presents the unlikely situation that the out of band emissions increase when moving further from the transmit band, these are assumed to be -26dBm/MHz and -47dBm/MHz respectively. Note also that no specific channel bandwidth has been provided, so an assumed channel bandwidth of 100MHz has been used to calculate per MHz values.

Input Parameters		
5G	Operating Frequencies	3500 - 3600MHz
	In Band EIRP	~33dBm/MHz (total 53dBm)
	Spurious Emissions	50 MHz <= df > 100MHz: -26dBm/MHz 100 MHz <= df < 600 MHz: -47dBm/MHz
	Single Cell/Network	Both
Satellite	Operating Frequencies	3700 - 4200 MHz OR 3625 - 4200 MHz
	Dish Size/Gain	1.8m - 3m (aligned with BS)
	Wanted Signal EIRP	N/A
	Wanted Signal C/(I+N)	N/A
	Filter Performance	Minimum of -45dB in adjacent band
	LNB Overload	-60dBm

Input Parameters		
	Single ES/Network	Single

Modelling and Outputs		
Modelling	Path Loss for Terrestrial Service	Measured received 5G power
	Guard Band	100MHz OR 25MHz
	Assumed Degradation in C/(I+N)	N/A
Co-Channel Separation Distances (based on elevation angle)	0 - 20º	N/A
	20 - 40º	N/A
	≥40º	N/A
Adjacent-Channel Separation Distances (based on elevation angle)	0 - 20º	90m
	20 - 40º	N/A
	≥40º	N/A
Dominant Interference Mechanism		LNB saturation

Subsequent references to this study will reference [4] and the chapter reference 6.2.2.

6.2.3 IMT-FSS Coexistence Scenarios In C-Band

This study [5] was produced by the GSM Association (Hong Kong) as an input to the 3rd Meeting of the APT Conference Preparatory Group for WRC-15. It makes the argument that a number of compatibility studies have been conducted assuming conservative degradations in I/N without taking into account the actual margin available to FSS systems. Instead, it proposes that an allowable C/(I+N) degradation of ~8dB is reasonable given the margin available to three example systems (receiving Vinasat at 132º East) in Hanoi (elevation angle of 5º), Bangladesh (elevation angle of 34º) and Kuala Lumpur (elevation angle of 54º).

The study makes the argument that C-band spectrum will be required within urban areas only. A base station is positioned at the worst possible interfering location within a 5km circle centred on each of the cities, and the resulting separation distances required to meet the C/(I+N) degradation criteria are then calculated. Note that the study does not take into account LNB saturation.

The assumed input and modelling parameters are shown below, alongside the resulting separation distances.

Input Parameters		
5G	Operating Frequencies	3400 - 3600 MHz
	In Band EIRP	27dBm/MHz
	Spurious Emissions	N/A
	Single Cell/Network	Single
Satellite	Operating Frequencies	3400 - 3600 MHz
	Dish Size/Gain	1.8m, 34.17dBi (peak)
	Wanted Signal EIRP	47.7dBW
	Wanted Signal C/(I+N)	17.01dB
	Filter Performance	N/A
	LNB Overload	N/A
	Single ES/Network	Single

Modelling and Outputs		
Modelling	Path Loss for Terrestrial Service	ITU R 452-15
	Guard Band	N/A
	Assumed Degradation in C/(I+N)	C/(I+N) = 8.69dB (reduction of ~8dB)
Co-Channel Separation Distances (based on elevation angle)	0 - 20º	Hanoi: 2.5km
	20 - 40º	Bangladesh: 3.5km
	≥40º	Kuala Lumpur: 2.5km
Adjacent-Channel Separation Distances (based on elevation angle)	0 - 20º	N/A
	20 - 40º	N/A
	≥40º	N/A
Dominant Interference Mechanism		CCI

Subsequent references to this study will reference [5] and the chapter reference 6.2.3.

6.2.4 Best Practices for Terrestrial-Satellite Coexistence during and after the C-Band Transition

This set of guidelines [6] was produced by TWG-1, a multi stakeholder group consisting of members from a number of companies, both within the satellite and mobile industries. It sets out a number of recommendations with regards to co-existence of IMT and FSS in C-band in the United States. The report investigates a number of topics, including recommended separation distances (for both passive and active antenna systems, with the distances quoted for active antenna systems protecting a given proportion of 1,000 earth stations located randomly within 2.5km of the base station), recommended filter performance, best practices for avoiding interference and best practices for mitigating interference if observed. This section will focus on separation distances and filter performance.

The report considers the FCC mandated OOBE level of -13dBm/MHz and an equipment manufacturer expected level of -40dBm/MHz, and produces a set of separation distances based on an allowable I/N degradation of 6dB (with the associated PFD then adjusted downwards by 4dB). The assumed input and modelling parameters are shown below, alongside the resulting separation distances.

Input Parameters		
5G	Operating Frequencies	3700 - 3980 MHz
	In Band EIRP	65dBm/MHz (rural) 62dBm/MHz (urban)
	Spurious Emissions	-13dBm/MHz -40dBm/MHz
	Single Cell/Network	Single
Satellite	Operating Frequencies	4000 - 4200 MHz
	Dish Size/Gain	N/A
	Wanted Signal EIRP	N/A
	Wanted Signal C/(I+N)	N/A
	Filter Performance	0 MHz <= df < 15 MHz: 0dB 15 MHz <= df < 20 MHz: -30dB 20 MHz <= df < 100MHz: -60dB df > 100MHz: -70dB
	LNB Overload	-16dBW/m^2/MHz
	Single ES/Network	Single

Modelling and Outputs		
Modelling	Path Loss for Terrestrial Service	Free space and ITS Irregular Terrain Model
	Guard Band	20MHz
	Assumed Degradation in C/(I+N)	I/N=-6dB (adjusted down by 4dB)
Co-Channel Separation Distances (based on elevation angle)	0 - 20º	N/A
	20 - 40º	N/A
	≥40º	N/A
Adjacent-Channel Separation Distances (based on elevation angle)	0 - 20º	Passive Antenna: -13dBm/MHz: 26.6km (8.6-20.2km for ITS model) -40dBm/MHz: 1.2km AAS: -13dBm/MHz: 0.2km (7%), 1.5-2km (49%), 5.5km (96%) -40dBm/MHz: <0.2km (7%), <0.2km (49%), <0.3km (96%) LNB: Rural: 102m Urban: 73.2m
	20 - 40º	
	≥40º	
Dominant Interference Mechanism		OOBE

Subsequent references to this study will reference [6] and the chapter reference 6.2.4.

6.2.5 Coexistence for LTE-Advanced and FSS Services in the 3.5GHz Band in Colombia

This study [7] was conducted by researchers at the Colombian School of Engineering and IMEC Ghent University as an input to the Colombia National Spectrum Agency (ANE), a part of the Information, Communication and Technology Ministry (MinTIC), investigation on the availability of new bands for the deployment of 5G IMT services. It investigates the effect of guard band and elevation angle on the required separation distance for co-channel and adjacent frequency IMT and FSS coexistence, based on two known FSS receivers within Bogota, Columbia. IMT base stations are positioned along the axis of each FSS receiver, at regular intervals, to represent a worst case.

The study determines the required separation distance between a single base station and a satellite receiver (assuming an allowable degradation in I/N of 6.5dB), with a guard band of between -28 (i.e. an overlap) and +25MHz and elevation angles of 11, 22 and 42º. The study finds that for any level of overlap, the separation distance remained largely constant. Increasing the guard band however is found to decrease the required separation distance (per 5MHz of additional guard band, a reduction in separation distance in the order of 25km for base stations and 100m for UEs).

The assumed input and modelling parameters are shown below, alongside the resulting separation distances. Note that out of band emissions performance are not explicitly stated within the report. In addition, it is unclear whether ITU-R 2001-2 or ITU-R 452-16 has been used for the propagation modelling of IMT.

Input Parameters		
5G	Operating Frequencies	3664 - 3718 MHz
	In Band EIRP	48dBm/MHz Suburban 45dBm/MHz Urban 13dBm/MHz UE
	Spurious Emissions	N/A
	Single Cell/Network	Single
Satellite	Operating Frequencies	3718MHz
	Dish Size/Gain	-8.6dBi, -1.6dBi, 6.2dBi
	Wanted Signal EIRP	90dBm[6]
	Wanted Signal C/(I+N)	N/A
	Filter Performance	N/A
	LNB Overload	N/A
	Single ES/Network	Single

Modelling and Outputs		
Modelling	Path Loss for Terrestrial Service	ITU R 2001-2 OR ITU-R 452-16
	Guard Band	-28 to +25MHz
	Assumed Degradation in C/(I+N)	I/N = -6.5dB
Co-Channel Separation Distances (based on elevation angle)	0 - 20º	Urban: 278km (BS) 2650m (UE) Suburban: 244km (BS) 2125m (UE)

[6] Note that SES-6 (the satellite assumed for the study) does not have an EIRP of 90dBm.

Modelling and Outputs		
	20 - 40º	Urban: 215km (BS) 1000m (UE) Suburban: 181km (BS) 875m (UE)
	≥40º	Urban: 150km (BS) 750m (UE) Suburban: 141km (BS) 655m (UE)
Adjacent-Channel Separation Distances (based on elevation angle)	0 - 20º	Urban: 210 - 88km (BS) 1000 - 380m (UE) Suburban: 183 - 67km (BS) 975 - 500m (UE)
	20 - 40º	Urban: 153 - 40km (BS) 650 - 200m (UE) Suburban: 133 - 28km (BS) 500 - 465m (UE)
	≥40º	Urban: 103 - 18km (BS) 480 - 200m (UE) Suburban: 83 - 13km (BS) 500 - 265m (UE)
Dominant Interference Mechanism		CCI/ACI

Subsequent references to this study will reference [7] and the chapter reference 6.2.5.

6.2.6 Coexistence Studies between LTE System and Earth Station of Fixed Satellite Service in the 3400-3600 MHz Frequency Bands in China

This study [8] was conducted by researchers at the Beijing University of Posts and Telecommunications. It performs a deterministic analysis, based on ITU-R P.452-12, to determine separation distances for co-channel and adjacent frequency operation of FSS and IMT (a single base station and UE) with a range of guard bands and elevation angles typical for VSAT in China. The paper also investigates the effect to which angular separation helps attenuate incoming IMT signals when a network is considered using Monte Carlo analysis.

The paper recommends that in the instance of China, based on an allowable degradation in I/N of 12dB, a guard band of at least 10MHz should be sufficient to allow reasonable coexistence of IMT base stations and FSS, and a guard band of at least 5MHz should be sufficient to allow reasonable coexistence of IMT UE and FSS.

The assumed input and modelling parameters are shown below, alongside the resulting separation distances. An FSS bandwidth of 60MHz has been assumed based on the receiver noise calculation.

Input Parameters		
5G	Operating Frequencies	3400 - 3600 MHz
	In Band EIRP	36dBm/MHz (BS) 14dBm/MHz (UE)
	Spurious Emissions	BS 0MHz <= df < 5MHz: -4.65dBm/MHz 5MHz <= df <10 MHz: -11dBm/MHz 10MHz <= df: -11dBm/MHz UE 0MHz <= df < 1MHz: -2.7712dBm/MHz 1MHz <= df <5MHz: -16.02dBm/MHz 5MHz <= df <10MHz: -20dBm/MHz 10MHz <= df <15MHz: -32dBm/MHz 15MHz <= df: -84dBm/MHz
	Single Cell/Network	Both
Satellite	Operating Frequencies	3400 - 3600 MHz
	Dish Size/Gain	4m
	Wanted Signal EIRP	N/A
	Wanted Signal C/(I+N)	N/A
	Filter Performance	N/A
	LNB Overload	-60dBm
	Single ES/Network	Single

Modelling and Outputs		
Modelling	Path Loss for Terrestrial Service	ITU R 452-12
	Guard Band	0MHz - 15MHz
	Assumed Degradation in C/(I+N)	I/N = -12.2dB

<table>
<tr><th colspan="3">Modelling and Outputs</th></tr>
<tr><td rowspan="3">Co-Channel Separation Distances (based on elevation angle)</td><td>0 - 20º</td><td rowspan="3">BS: 200km
UE: 5km</td></tr>
<tr><td>20 - 40º</td></tr>
<tr><td>≥40º</td></tr>
<tr><td rowspan="3">Adjacent-Channel Separation Distances (based on elevation angle)</td><td>0 - 20º</td><td rowspan="3">0MHz GB
BS: 4.5km
UE: 450m
5-10MHz GB
BS: 2km
UE: 100m
>10MHz GB
BS: 800m
LNB: 500m</td></tr>
<tr><td>20 - 40º</td></tr>
<tr><td>≥40º</td></tr>
<tr><td colspan="2">Dominant Interference Mechanism</td><td>CCI/ACI</td></tr>
</table>

Subsequent references to this study will reference [8] and the chapter reference 6.2.6.

6.2.7 Coexistence conditions of LTE-advanced at 3400–3600 MHz with TVRO at 3625–4200 MHz in Brazil

This study [9] was conducted by authors at the National Telecommunications Agency, Anatel, in Brazil. It defines operational constraints for LTE-A and FSS based on the protection of LNB (to -45dBm or -60dBm) within typical TVRO (TV receive only) installations in Brazil, using Monte Carlo simulations performed within SEAMCAT (Spectrum Engineering Advanced Monte Carlo Analysis Tool).

The study assumes a typical antenna diameter of 1.5m (32dBi peak gain), but with a number of different off axis gains corresponding to various elevation angles: 0dBi (19º), -4dBi (28º) and -10dBi (48º). It makes use of free space path loss close to the transmitting base station, before linearly interpolating to ITU-R 452-16 at greater distances. OOBE emissions are stated to be as 3GPP TS 36.104 v13.2.0 for base stations, and 3GPP TS 36.101 v14.0.0 for UEs, although the values taken for the analysis are not explicitly stated. The separation distances are given for each type of base station.

The assumed input and modelling parameters are shown below, alongside the resulting separation distances.

<table>
<tr><th colspan="3">Input Parameters</th></tr>
<tr><td rowspan="2">5G</td><td>Operating Frequencies</td><td>3400 - 3600 MHz</td></tr>
<tr><td>In Band EIRP</td><td>Suburban Macro:
34, 40, 45dBm/MHz

Urban Macro:
27, 39, 45dBm/MHz</td></tr>
</table>

Input Parameters		
		Urban Small: 16, 24dBm/MHz
	Spurious Emissions	BS: 3GPP TS 36.104 v13.2.0 UE: 3GPP TS 36.101 v14.0.0
	Single Cell/Network	Both
Satellite	Operating Frequencies	3625 - 4200 MHz
	Dish Size/Gain	0dBi, -4dBi, -10dBi (32dBi peak gain)
	Wanted Signal EIRP	N/A
	Wanted Signal C/(I+N)	N/A
	Filter Performance	N/A
	LNB Overload	-60dBm, -45dBm
	Single ES/Network	TVRO

Modelling and Outputs		
Modelling	Path Loss for Terrestrial Service	ITU R 452-16 (using free space for short distances, 452 for long distances, and linear interpolation between the two for mid range)
	Guard Band	25MHz
	Assumed Degradation in C/(I+N)	N/A
Co-Channel Separation Distances (based on elevation angle)	0 - 20º	N/A
	20 - 40º	N/A
	≥40º	N/A
Adjacent-Channel Separation Distances (based on elevation angle)	0 - 20º	-60dBm LNB: Suburban Macro: not possible Urban Macro: not possible Urban Small: 80-70m -45dBm LNB Suburban Macro: 430-230m Urban Macro: 120-60m Urban Small: 50-30m
	20 - 40º	-60dBm LNB: Suburban Macro: not possible Urban Macro: not possible Urban Small: 70m

Modelling and Outputs		
		-45dBm LNB Suburban Macro: 245-110m Urban Macro: 90-10m Urban Small: 40-15m
	≥40º	-60dBm LNB: Suburban Macro: not possible Urban Macro: 270-95m Urban Small: 60-50m -45dBm LNB Suburban Macro: 75-10m Urban Macro: 55-10m Urban Small: 20-10m
Dominant Interference Mechanism		LNB saturation

Subsequent references to this study will reference [9] and the chapter reference 6.2.7.

6.2.8 Interference Mitigation Technique for the Sharing between IMT-Advanced and Fixed Satellite Service

This study [10] was conducted by researchers at the Radio Research Laboratory (Ministry of Information and Communication, Korea), Yonsei University and Myongji College. It considers the potential for interference reduction at an FSS receiver by means of creating nulls in the IMT transmit antenna pattern. A theoretical model of the technique is considered and validated, and the technique's impact on the separation distances (for both co-channel and adjacent frequency scenarios with a range of guard bands) required to meet an I/N degradation of 12.2dB are considered. Lastly to account for the theoretical nature of the approach, the impact of errors on the separation distances is considered also.

The study finds large reductions in separation distances by using the technique (>99% for the co-channel case and >92% for the adjacent frequency case, dependent on the guard band used), although this is found to be highly dependent on the extent of the error. Note also that the out of band emissions performance used within the study is not stated.

The assumed input and modelling parameters are shown below, alongside the resulting separation distances.

Input Parameters		
5G	Operating Frequencies	4000MHz
	In Band EIRP	26dBm/MHz
	Spurious Emissions	N/A
	Single Cell/Network	Single

Input Parameters		
Satellite	Operating Frequencies	4000MHz
	Dish Size/Gain	3.8m
	Wanted Signal EIRP	N/A
	Wanted Signal C/(I+N)	N/A
	Filter Performance	N/A
	LNB Overload	N/A
	Single ES/Network	Single

Modelling and Outputs		
Modelling	Path Loss for Terrestrial Service	ITU 452-12
	Guard Band	-9 to 9MHz
	Assumed Degradation in C/(I+N)	I/N=-12.2dB
Co-Channel Separation Distances (based on elevation angle)	0 - 20º	W/o Mitigation: 44km W Mitigation: 35m (no error) 7km (2 deg error) 27km (10 deg error)
	20 - 40º	
	≥40º	
Adjacent-Channel Separation Distances (based on elevation angle)	0 - 20º	Without mitigation: 17-0.13km With mitigation:<10m (no error) 5.56km-20m (5deg error) 9.84km-30m (10deg error)
	20 - 40º	
	≥40º	
Dominant Interference Mechanism		CCI/ACI

Subsequent references to this study will reference [10] and the chapter reference 6.2.8.

6.2.9 Geographic Sharing in C-band

This study [11] was conducted by Transfinite Systems on behalf of Ofcom (UK). The study considers the possibility for FSS and fixed links within the UK to share spectrum with IMT, looking to determine which areas have sufficiently few earth stations or fixed links to facilitate sharing. In addition, the study conducts interference zone analysis for specific example FSS and fixed link systems based on an allowable I/N of -10dB. This report will focus on the interference zone analysis results.

The report considers just co-channel operation of the two systems and compares the impact of generic flat Earth modelling and the inclusion of terrain, clutter and polarisation discrimination on the resulting separation distances. The report finds that for an example station at Chalfont Grove in London (with elevation angles 8º and 11º), the required separation distances are anything between 24 and 70km, dependent on the assumptions taken.

The assumed input and modelling parameters are shown below, alongside the resulting separation distances.

Input Parameters		
5G	Operating Frequencies	3800 - 4200 MHz
	In Band EIRP	19dBm/MHz (outdoor) 14dBm/MHz (indoor)
	Spurious Emissions	0MHz <= df < 5MHz: 0dB 5 MHz <= df: -45dB
	Single Cell/Network	Single
Satellite	Operating Frequencies	3800 - 4200 MHz
	Dish Size/Gain	55dBi
	Wanted Signal EIRP	N/A
	Wanted Signal C/(I+N)	N/A
	Filter Performance	Gaussian, -30dB at 2 x transponder bandwidth
	LNB Overload	N/A
	Single ES/Network	Single

Modelling and Outputs		
Modelling	Path Loss for Terrestrial Service	ITU 452-15
	Guard Band	N/A
	Assumed Degradation in C/(I+N)	I/N = -10dB
Co-Channel Separation Distances (based on elevation angle)	0 - 20º	Chalfont Outdoor BS: 25km (1. flat Earth) 73km (2. terrain, but no clutter) 70km (3. as 2, with clutter) 25km (4. as 3, with extra dense urban clutter loss) 24km (5. as 4, with polarisation discrimination, traffic considerations) 3km (indoor BS)
	20 - 40º	N/A

Modelling and Outputs		
	≥40º	N/A
Adjacent-Channel Separation Distances (based on elevation angle)	0 - 20º	N/A
	20 - 40º	N/A
	≥40º	N/A
Dominant Interference Mechanism		CCI

Subsequent references to this study will reference [11] and the chapter reference 6.2.9.

6.2.10 Report ITU-R M.2019 Sharing studies between IMT-Advanced systems and geostationary satellite networks in the FSS in the 3 400-4 200 and 4 500-4 800 MHz frequency bands

This collection of studies [12] was produced by various authors as an input to WRC-07. It provides a summary of sharing studies conducted between IMT and FSS systems in the 3400 – 4200 MHz and 4500 – 4800 MHz band. Only summaries of the studies are included within the report, and these will be presented within this section. Across all studies, a common feature is that co-channel FSS and IMT operation requires a separation distance of typically greater than 10s of km, whereas adjacent frequency operation of FSS and IMT typically requires less than 10s of km separation distance. The distances derived within each of the individual studies will be presented also. Note that a number of the studies within the report do not have specific inputs stated (other than compliance with the general parameters stated within the ITU report). In addition, a number of studies do not quote specific comparable results and as such the results of these studies will not be included. Note also that guard bands have not been quoted.

Channel Arrangement	Separation Distance
Co-Channel Separation Distances	>10s of km
Adjacent-Channel Separation Distances	<10s of km

6.2.10.1 Report ITU-R M.2109 Study 1

This study does not quote specific values for the inputs or results and as such will not be included within this report.

6.2.10.2 Report ITU-R M.2109 Study 2

This study does not quote specific values for the inputs or results and as such will not be included within this report.

6.2.10.3 Report ITU-R M.2109 Study 3

The assumed input and modelling parameters are shown below, alongside the resulting separation distances.

Input Parameters		
5G	Operating Frequencies	N/A
	In Band EIRP	46dBm/MHz (macro) 22dBm/MHz (micro) 7.5dBm/MHz (UE)
	Spurious Emissions	RR Appendix 3
	Single Cell/Network	Single
Satellite	Operating Frequencies	N/A
	Dish Size/Gain	1.8m-3.8m, 11m
	Wanted Signal EIRP	N/A
	Wanted Signal C/(I+N)	N/A
	Filter Performance	N/A
	LNB Overload	N/A
	Single ES/Network	Single

Modelling and Outputs		
Modelling	Path Loss for Terrestrial Service	ITU-R 452-12 with diffraction and ducting models
	Guard Band	N/A
	Assumed Degradation in C/(I+N)	I/N=-12.2dB (long term) I/N=-15.2dB (long term, int apportionment) I/N=-20dB (adjacent)
Co-Channel Separation Distances (based on elevation angle)	0 - 20º	(I/N=-12.2dB) Macro: 55km Mobile: 1km (I/N=-15.2dB) Macro: 70km Mobile: 1.5km
	20 - 40º	
	≥40º	
Adjacent-Channel Separation Distances (based on elevation angle)	0 - 20º	Macro: 18-25km Mobile: 300-450m
	20 - 40º	
	≥40º	

Modelling and Outputs	
Dominant Interference Mechanism	CCI/ACI

Subsequent references to this study will reference [12] and the chapter reference 6.2.10.3.

6.2.10.4 Report ITU-R M.2109 Study 4

The assumed input and modelling parameters are shown below, alongside the resulting separation distances.

Input Parameters		
5G	Operating Frequencies	N/A
	In Band EIRP	46dBm/MHz (macro) 22dBm/MHz (micro) 7.5dBm/MHz (UE)
	Spurious Emissions	1st Adj: -45dB 2nd Adj: -50dB 3rd Adj +:-66dB
	Single Cell/Network	Single
Satellite	Operating Frequencies	N/A
	Dish Size/Gain	2.4m
	Wanted Signal EIRP	N/A
	Wanted Signal C/(I+N)	N/A
	Filter Performance	N/A
	LNB Overload	N/A
	Single ES/Network	Single

Modelling and Outputs		
Modelling	Path Loss for Terrestrial Service	ITU 452-12, LoS with sub-path diffraction
	Guard Band	N/A
	Assumed Degradation in C/(I+N)	I/N=-12.2dB (long term) I/N=-20dB (adjacent)
Co-Channel Separation Distances (based on elevation angle)	0 - 20º	Macro Urban: 37-54km Micro Urban: 15-23km Macro rural: 40-59km
	20 - 40º	
	≥40º	

Modelling and Outputs		
Adjacent-Channel Separation Distances (based on elevation angle)	0 - 20º	N/A
	20 - 40º	N/A
	≥40º	N/A
Dominant Interference Mechanism		CCI

Subsequent references to this study will reference [12] and the chapter reference 6.2.10.4.

6.2.10.5 Report ITU-R M.2109 Study 5

The assumed input and modelling parameters are shown below, alongside the resulting separation distances.

Input Parameters		
5G	Operating Frequencies	N/A
	In Band EIRP	46dBm/MHz (macro) 22dBm/MHz (micro) 7.5dBm/MHz (UE)
	Spurious Emissions	1st Adj: -45dB 2nd Adj: -50dB 3rd Adj +:-66dB
	Single Cell/Network	Both
Satellite	Operating Frequencies	N/A
	Dish Size/Gain	1.8m-3.8m, 11m
	Wanted Signal EIRP	N/A
	Wanted Signal C/(I+N)	N/A
	Filter Performance	N/A
	LNB Overload	N/A
	Single ES/Network	Single

Modelling and Outputs		
Modelling	Path Loss for Terrestrial Service	ITU 452-12
	Guard Band	N/A
	Assumed Degradation in C/(I+N)	I/N=-12.2dB (long term) I/N=-20dB (adjacent)

Modelling and Outputs		
Co-Channel Separation Distances (based on elevation angle)	0 - 20º	Single Entry: Base Station: 45-58km (5-48 deg) Aggregate: Base Station: 51-60km (5-48deg) Mobile Station: 0.5-1.5km
	20 - 40º	
	≥40º	
Adjacent-Channel Separation Distances (based on elevation angle)	0 - 20º	Single Entry: CMDA: 10-34km OFDMA: 0.07-19km Aggregate: CDMA Macro: 15-37km OFDMA Macro: 0.35-21km
	20 - 40º	
	≥40º	
Dominant Interference Mechanism		CCI/ACI

Subsequent references to this study will reference [12] and the chapter reference 6.2.10.5.

6.2.10.6 Report ITU-R M.2109 Study 6

The assumed input and modelling parameters are shown below, alongside the resulting separation distances.

Input Parameters		
5G	Operating Frequencies	N/A
	In Band EIRP	46dBm/MHz (macro) 22dBm/MHz (micro) 7.5dBm/MHz (UE)
	Spurious Emissions	1st Adj: -45dB 2nd Adj: -50dB 3rd Adj +:-66dB
	Single Cell/Network	Single
Satellite	Operating Frequencies	N/A
	Dish Size/Gain	1.8m-3.8m, 11m
	Wanted Signal EIRP	N/A
	Wanted Signal C/(I+N)	N/A
	Filter Performance	N/A
	LNB Overload	N/A
	Single ES/Network	Single

Modelling and Outputs		
Modelling	Path Loss for Terrestrial Service	ITU 452-12, smooth earth with diffraction
	Guard Band	N/A
	Assumed Degradation in C/(I+N)	I/N=-12.2dB (long term) I/N=-15.2dB (long term, int apportionment) I/N=-20dB (adjacent)
Co-Channel Separation Distances (based on elevation angle)	0 - 20º	(I/N=-12.2dB) 5deg: 33-57km 15deg: 33-37km (I/N=-15.2dB) 5deg: 36-60km 15deg: 36-40km
	20 - 40º	
	≥40º	
Adjacent-Channel Separation Distances (based on elevation angle)	0 - 20º	N/A
	20 - 40º	
	≥40º	
Dominant Interference Mechanism		CCI

Subsequent references to this study will reference [12] and the chapter reference 6.2.10.6.

6.2.10.7 Report ITU-R M.2109 Study 7

The assumed input and modelling parameters are shown below, alongside the resulting separation distances.

Input Parameters		
5G	Operating Frequencies	N/A
	In Band EIRP	46-39dBm/MHz (macro) 22-15dBm/MHz (micro) 7.5dBm/MHz (UE)
	Spurious Emissions	1st Adj: -45dB 2nd Adj: -50dB 3rd Adj +:-66dB
	Single Cell/Network	Both
Satellite	Operating Frequencies	N/A
	Dish Size/Gain	1.8m-3.8m, 11m
	Wanted Signal EIRP	N/A
	Wanted Signal C/(I+N)	N/A

Input Parameters		
	Filter Performance	N/A
	LNB Overload	N/A
	Single ES/Network	Single

Modelling and Outputs		
Modelling	Path Loss for Terrestrial Service	ITU 452-12
	Guard Band	N/A
	Assumed Degradation in C/(I+N)	I/N=-12.2dB (long term) I/N=-20dB (adjacent)
Co-Channel Separation Distances (based on elevation angle)	0 - 20º	Single Entry: CDMA Macro: 47-65.6km CDMA Micro: 39-49.5km CDMA Mobile: 0km OFDMA Macro: 43-55km OFDMA Micro: 29-47km OFDMA Mobile: 0km Aggregate: CDMA Macro: 56-87km CDMA Micro: 49-58km CDMA Mobile: 0km OFDMA Macro: 51-61km OFDMA Micro: 46-53km OFDMA Mobile: 0km
	20 - 40º	
	≥40º	
Adjacent-Channel Separation Distances (based on elevation angle)	0 - 20º	Single Entry: CDMA Macro: 10-42.5km CDMA Micro: 2-14km OFDMA Macro: 5-29km OFDMA Micro: 2.4-8.7km Aggregate: CDMA Macro: 27-45.5km CDMA Micro: 11-35km OFDMA Macro: 15-41km OFDMA Micro: 4-8.5km OFDMA Mobile: 0km
	20 - 40º	
	≥40º	
Dominant Interference Mechanism		CCI/ACI

Subsequent references to this study will reference [12] and the chapter reference 6.2.10.7.

6.2.10.8 Report ITU-R M.2109 Study 8

This study does not quote specific values for the inputs or results and as such will not be included within this report.

6.2.10.9 Report ITU-R M.2109 Study 9

The assumed input and modelling parameters are shown below, alongside the resulting separation distances.

Input Parameters		
5G	Operating Frequencies	N/A
	In Band EIRP	46dBm/MHz (macro) 22dBm/MHz (micro) 7.5dBm/MHz (UE)
	Spurious Emissions	3GPP TS 25.104 V7.5.0
	Single Cell/Network	Single
Satellite	Operating Frequencies	N/A
	Dish Size/Gain	1.8m-3.8m, 11m
	Wanted Signal EIRP	N/A
	Wanted Signal C/(I+N)	N/A
	Filter Performance	N/A
	LNB Overload	-60dBm
	Single ES/Network	Single

Modelling and Outputs		
Modelling	Path Loss for Terrestrial Service	ITU 452-12, LoS w/o sub-path diffraction, multipath or focussing effects
	Guard Band	N/A
	Assumed Degradation in C/(I+N)	I/N=-12.2dB (long term) I/N=-20dB (adjacent)
Co-Channel Separation Distances (based on elevation angle)	0 - 20º	N/A
	20 - 40º	N/A
	≥40º	N/A

Modelling and Outputs		
Adjacent-Channel Separation Distances (based on elevation angle)	0 - 20º	Macro: 49.5-80km Micro: 39.5-51km UE: 25-32.5km
	20 - 40º	
	≥40º	LNB Saturation: Mobile station: 170m Micro: 600m Macro: 9.5km
Dominant Interference Mechanism		LNB saturation

Subsequent references to this study will reference [12] and the chapter reference 6.2.10.9

6.2.10.10 Report ITU-R M.2109 Study 10

This study does not quote specific values for the inputs or results and as such will not be included within this report.

6.2.10.11 Report ITU-R M.2109 Study 11

This study does not quote specific values for the inputs or results and as such will not be included within this report.

6.2.11 Report ITU-R S.2368-0 Sharing studies between IMT-Advanced systems and geostationary satellite networks in the FSS in the 3 400-4 200 MHz and 4 500-4 800 MHz frequency bands in the WRC study cycle leading to WRC-15

This collection of studies [13] was produced by a number of authors as an input to WRC-15. It provides a summary of sharing studies conducted between IMT and FSS systems in the 3400 – 4200 MHz and 4500 – 4800 MHz band. Results from each of the studies will be presented individually, but typical findings regarding co-channel and adjacent frequency separation distances are shown below. Values for long term interference (typically co-channel I/N of -10dB and adjacent frequency I/N of -20dB consistent with ITU-R S.1432) and short term interference (I/N of -1.3dB) are presented. In some cases, separation distances based on an aggregate interference are presented also. Note that some studies do make use of slightly different I/N criteria which will be reflected in the summary tables.

Channel Arrangement	Separation Distance
Co-Channel Separation Distances	CCI Macro cell: 10s of km/100s of km (long term/short term int) Small cell: 10s of km Small Indoor: 5 to 10s of km

Channel Arrangement	Separation Distance
Adjacent-Channel Separation Distances	AC Macro cell: 5 to 10s of km Small cell: 900m to 5km LNB/LNA Overdrive Macro cell: 4km to 9km Small cell: 100m to 900m Intermods Macro cell: 2km to 8km Small cell: 100m to 500m

The report also investigates a small number of real interference cases into FSS receivers within the band, including from WiMAX stations in Bangladesh and BWA in Brazil.

6.2.11.1 Report ITU-R S.2368-0 Study 1

This study considers non-site specific conditions through use of a smooth Earth model to determine maximum co-channel separation distances for IMT and FSS. The study considers a number of scenarios in which clutter is either not included, included at just the IMT end of the link, or at both the IMT and FSS ends of the link. Note that the results quoted here reflect the values associated with clutter at both ends of the link for the long term interference criterion. Additional separation distances are quoted also for the case where attenuation of the interfering IMT is higher than initially assumed, although these are not included in this report.

The assumed input and modelling parameters are shown below, alongside the resulting separation distances.

Input Parameters		
5G	Operating Frequencies	3400 - 4200 MHz
	In Band EIRP	48dBm/MHz (Macro Urban & Suburban) 16dBm/MHz (Small Outdoor) 11dBm/MHz (Small Indoor)
	Spurious Emissions	N/A
	Single Cell/Network	Single
Satellite	Operating Frequencies	3400 - 4200 MHz
	Dish Size/Gain	2.4m, 16m
	Wanted Signal EIRP	N/A
	Wanted Signal C/(I+N)	N/A
	Filter Performance	N/A
	LNB Overload	N/A
	Single ES/Network	Single

Modelling and Outputs		
Modelling	Path Loss for Terrestrial Service	ITU 452-14, smooth Earth
	Guard Band	N/A
	Assumed Degradation in C/(I+N)	I/N = -13dB (long term) I/N = -1.3dB (short term, single entry)
Co-Channel Separation Distances (based on elevation angle)	0 - 20º	Long Term: Macro Sub: 61-63km Macro Urban: 46-48km Small Outdoor: 25km Small Indoor: <5km
	20 - 40º	N/A
	≥40º	Long Term: Macro Sub: 35-36km Macro Urban: 20-22km Small Outdoor: 6km Small Indoor: <5km
Adjacent-Channel Separation Distances (based on elevation angle)	0 - 20º	N/A
	20 - 40º	
	≥40º	
Dominant Interference Mechanism		CCI

Subsequent references to this study will reference [13] and the chapter reference 6.2.11.1.

6.2.11.2 Report ITU-R S.2368-0 Study 2

This study investigates the impact of a network of IMT base stations, both outdoor and indoor, on the required separation distances for IMT FSS coexistence within both a co-channel and adjacent frequency band plan. This study assumes a non-site specific scenario, making use of Monte Carlo analysis, with representative terrain and clutter. Deterministic analysis is conducted also, although this isn't presented here. Note that the values quoted here are for the long term interference criterion. The study assumes elevation angles of 5, 15 and 48º.

The assumed input and modelling parameters are shown below, alongside the resulting separation distances.

Input Parameters		
5G	Operating Frequencies	N/A
	In Band EIRP	3dB Less for Aggregate Simulation: 48dBm/MHz (Suburban Macro) 33dBm/MHz (Urban Macro) 16dBm/MHz (Outdoor Small) 11dBm/MHz (Indoor Small)
	Spurious Emissions	3GPP 36.104 v.11.2.0
	Single Cell/Network	Network
Satellite	Operating Frequencies	N/A
	Dish Size/Gain	2.4m, 10m
	Wanted Signal EIRP	N/A
	Wanted Signal C/(I+N)	N/A
	Filter Performance	N/A
	LNB Overload	-55dBm
	Single ES/Network	Single

Modelling and Outputs		
Modelling	Path Loss for Terrestrial Service	ITU 452-14
	Guard Band	0, 5, 10MHz
	Assumed Degradation in C/(I+N)	I/N = -13dB (long term) I/N = -1.3dB (short term, single entry) I/N = -20dB (aggregate, ACI)
Co-Channel Separation Distances (based on elevation angle)	0 - 20º	Long Term: Macro Sub: 60.5km Macro Urb: 72km Small Outdoor: 5km Small Indoor: 4-5km
	20 - 40º	Long Term (15 deg): Macro Sub: 58.2km Macro Urb: 69km Small Outdoor: 1.2km Small Indoor: 1-3km

Modelling and Outputs		
	≥40º	Long Term: Macro Sub: 55.6km Macro Urb: 67km Small Outdoor: 0.53km Small Indoor: 0.55-1.5km
Adjacent-Channel Separation Distances (based on elevation angle)	0 - 20º	0MHz GB: Macro Sub: 1.4km Macro Urb: 49km Small Outdoor: <0.3km Small Indoor: <0.4km 5MHz GB: Macro Sub: 1.3km Macro Urb: 49km 10MHz GB: Macro Sub: 1.3km Macro Urb: 49km
	20 - 40º	0MHz GB (15 deg): Macro Sub: <0.06km Macro Urb: 43.5km Small Outdoor: <0.3km Small Indoor: <0.4km 5MHz GB:Macro Sub: <0.06km Macro Urb: 43km 10MHz GB: Macro Sub: <0.06km Macro Urb: 43km
	≥40º	0MHz GB: Macro Sub: <0.06km Macro Urb: 39km Small Outdoor: <0.3km Small Indoor: <0.4km 5MHz GB: Macro Sub: <0.06km Macro Urb: 39km 10MHz GB: Macro Sub: <0.06km Macro Urb: 38.5km
Dominant Interference Mechanism		CCI/ACI

Subsequent references to this study will reference [13] and the chapter reference 6.2.11.2.

6.2.11.3 Report ITU-R S.2368-0 Study 3

This study considers a specific FSS earth station in Yamaguchi prefecture, Japan, with elevation angles of 6.5 and 36º. It investigates the effect of terrain on the separation distances required for co-channel and adjacent frequency coexistence of FSS and IMT. Whilst separation distances are not explicitly quoted, they are presented on maps, and values read from these are presented within this section. In addition, the effect of base station deployments within a number of cities around the FSS earth station on LNB saturation is considered also, although no separation distance is quoted in this case. Note that no guard band is stated within the adjacent frequency analysis part of the study.

The assumed input and modelling parameters are shown below, alongside the resulting separation distances.

Input Parameters		
5G	Operating Frequencies	3400 - 3600 MHz
	In Band EIRP	33dBm/MHz (Macro Suburban) 17dBm/MHz (Small Outdoor)
	Spurious Emissions	TS 36.104 v.11.2.0
	Single Cell/Network	Single
Satellite	Operating Frequencies	3400 - 4200 MHz
	Dish Size/Gain	18m
	Wanted Signal EIRP	N/A
	Wanted Signal C/(I+N)	N/A
	Filter Performance	N/A
	LNB Overload	-50 to -60dBm
	Single ES/Network	Single

Modelling and Outputs		
Modelling	Path Loss for Terrestrial Service	ITU 452-14
	Guard Band	N/A
	Assumed Degradation in C/(I+N)	I/N=-10dB (long term) I/N=-1.3dB (short term)
Co-Channel Separation Distances (based on elevation angle)	0 - 20º	Macro suburban: 30-40km Small Outdoor: 15-25km
	20 - 40º	Macro suburban: 10-20km Small Outdoor: 15-25km
	≥40º	N/A

Modelling and Outputs		
Adjacent-Channel Separation Distances (based on elevation angle)	0 - 20º	Macro suburban: ~15km Small Outdoor: ~10km
	20 - 40º	Macro suburban: ~15km Small Outdoor: ~5km
	≥40º	N/A
Dominant Interference Mechanism		CCI/ACI

Subsequent references to this study will reference [13] and the chapter reference 6.2.11.3.

6.2.11.4 Report ITU-R S.2368-0 Study 4

This study investigates the required separation distances for both co-channel and adjacent frequency co-existence of IMT and FSS, based on a representative terrain profile. No guard band was assumed within the study for adjacent frequency analysis. For the single base station analysis, the IMT base station is assumed to move along the representative terrain profile until the protection criteria for the FSS receiver is breached. For the network analysis, a network of base stations is positioned around the FSS receiver, with the protection distance increased until the aggregate interference is sufficiently low to meet the protection criteria. The study also considers the protection distances required for the FSS LNB to not be saturated. Brief consideration is also given to the relationship between guard band and separation distance, although this is not presented here.

The assumed input and modelling parameters are shown below, alongside the resulting separation distances. Note that the report assumes filtering for the LNB saturation protection distances, but does not explicitly state the filter performance, although a 'mutual coupling' graph is presented showing the combined effect of the IMT out of band emissions mask and the FSS filter. The exact EIRP used is not explicitly stated either, other than that it is in conformance with a table earlier in the report (i.e. the summary section) that states a range of valid EIRPs. The range of these, over the 10MHz bandwidth stated within the study itself, is quoted.

Input Parameters		
5G	Operating Frequencies	3400 - 4200 MHz
	In Band EIRP	14 - 51dBm/MHz
	Spurious Emissions	TS 36.104 v.11.2.0
	Single Cell/Network	Both
Satellite	Operating Frequencies	3700 - 4200 MHz
	Dish Size/Gain	N/A
	Wanted Signal EIRP	N/A
	Wanted Signal C/(I+N)	N/A
	Filter Performance	N/A
	LNB Overload	-61dBm

Input Parameters		
	Single ES/Network	Both

Modelling and Outputs		
Modelling	Path Loss for Terrestrial Service	ITU 452-14
	Guard Band	N/A (stated 0MHz for LNB)
	Assumed Degradation in C/(I+N)	ITU-R S.1432 and ITU-R SF.1006
Co-Channel Separation Distances (based on elevation angle)	0 - 20º	Long Term (5-10deg): Macro Suburban: 58.1-50.5km Macro Urban: 51.2-45.2km Small Urban: 20.3-9km Aggregated: Macro Suburban: 63-55km Macro Urban: 53-48km Small Urban: 20.3-10km
	20 - 40º	Long Term (20-30deg): Macro Suburban: 45.7-44.6km Macro Urban: 40-35.7km Small Urban: 8.3-6.2km Aggregated: Macro Suburban: 53-52km Macro Urban: 45-44km Small Urban: 9km
	≥40º	N/A
Adjacent-Channel Separation Distances (based on elevation angle)	0 - 20º	Long Term (5-10deg): Macro Suburban: 13.4-9.4km Macro Urban: 9.3-8.4km Small Urban: 3.8-2.8km Aggregated: Macro Suburban: 18-17km Macro Urban: 12-10km Small Urban: 3.8-2.8km LNB: Macro Suburban: 8.8-8.1km Macro Urban: 8.5-6.4km Small Urban:0.9-0.4km

Modelling and Outputs		
	20 - 40º	Long Term (20-30deg): Macro Suburban: 8.6-8.2km Macro Urban: 6.4-5km Small Urban: 1.4-0.9k Aggregated: Macro Suburban: 17-15km Macro Urban: 9km Small Urban: 1.4-0.9km LNB: Macro Suburban: 6.2-4.8km Macro Urban: 4.9-4.4km Small Urban: 0.2-0.1km
	≥40º	N/A
Dominant Interference Mechanism		LNB saturation

Subsequent references to this study will reference [13] and the chapter reference 6.2.11.4.

6.2.11.5 Report ITU-R S.2368-0 Study 5

This study considers a specific FSS earth station in Orlando, Florida, with elevation angles of 5 and 30º. The location chosen corresponds to a flat terrain profile. Within the analysis, a single base station is positioned within a pre defined area around the FSS receive earth station. FSS filter performance is described as 'ideal', although the performance is not explicitly stated within the report.

The assumed input and modelling parameters are shown below, alongside the resulting separation distances.

Input Parameters		
5G	Operating Frequencies	3400 - 4200 MHz
	In Band EIRP	51dBm/MHz (Macro Urban, Suburban) 19dBm/MHz (Small Outdoor)
	Spurious Emissions	TS 36.104 v.11.2.0
	Single Cell/Network	Single
Satellite	Operating Frequencies	3400 - 4200 MHz
	Dish Size/Gain	2.4m
	Wanted Signal EIRP	N/A
	Wanted Signal C/(I+N)	N/A
	Filter Performance	'Ideal'
	LNB Overload	N/A

Input Parameters		
	Single ES/Network	Single

Modelling and Outputs		
Modelling	Path Loss for Terrestrial Service	ITU 452-14
	Guard Band	N/A
	Assumed Degradation in C/(I+N)	I/N=-12.2dB (100% worst month) I/N=-10dB (20% any month I/N=-20dB (aggregate)
Co-Channel Separation Distances (based on elevation angle)	0 - 20º	Long Term: Macro Sub: 57.1-87.1km Macro Urban: 45.5-93km Small Outdoor: 4.9-35.1km
	20 - 40º	Long Term: Macro Sub:51.8-58.6km Macro Urban: 45.4-52.9km Small Outdoor: 3.4-15.8km
	≥40º	N/A
Adjacent-Channel Separation Distances (based on elevation angle)	0 - 20º	Long Term: Macro Sub: 13.6-33.6km Macro Urban: 11-40.2km Small Outdoor: 4.7km
	20 - 40º	Long Term: Macro Sub: 13.6-16.5km Macro Urban: 10.9-20km Small Outdoor: 1.8km
	≥40º	N/A
Dominant Interference Mechanism		CCI/ACI

Subsequent references to this study will reference [13] and the chapter reference 6.2.11.5.

6.2.11.6 Report ITU-R S.2368-0 Study 6

This study considers exclusion zones around a specific FSS earth station in Madley, UK. It presents maps showing the exclusion zones, as well as discussion of the results, but does not quote specific separation distances. As such, it will not be included within this report.

6.2.11.7 Report ITU-R S.2368-0 Study 7

This study considers adjacent frequency compatibility analysis between FSS and IMT. Elevation angles of 5, 15 and 48º are assumed for the FSS receiver. A representative network has been simulated, with the FSS receiver at the centre.

The assumed input and modelling parameters are shown below, alongside the resulting separation distances.

Input Parameters		
5G	Operating Frequencies	3300 - 3400 MHz
	In Band EIRP	14 - 51dBm/MHz
	Spurious Emissions	3GPP 36.104 v.11.2.0 45dB ACLR or -15dBm/MHz (wide area) 45dB ACLR or -32dBm/MHz (local)
	Single Cell/Network	Network
Satellite	Operating Frequencies	3400 - 4200 MHz
	Dish Size/Gain	2.4m, 11m
	Wanted Signal EIRP	N/A
	Wanted Signal C/(I+N)	N/A
	Filter Performance	45dB ACS
	LNB Overload	N/A
	Single ES/Network	Single

Modelling and Outputs		
Modelling	Path Loss for Terrestrial Service	ITU 452-15
	Guard Band	N/A
	Assumed Degradation in C/(I+N)	I/N=-23dB
Co-Channel Separation Distances (based on elevation angle)	0 - 20º	N/A
	20 - 40º	N/A
	≥40º	N/A
Adjacent-Channel Separation Distances (based on elevation angle)	0 - 20º	5-15deg Macro Sub and Urb: 1400-467m Small Outdoor: 50m Small Indoor: 60-60m

Modelling and Outputs		
	20 - 40º	Macro Sub and Urb: 315m Small Outdoor: 50m Small Indoor: 60m
	≥40º	N/A
Dominant Interference Mechanism		CCI/ACI

Subsequent references to this study will reference [13] and the chapter reference 6.2.11.7.

6.2.11.8 Report ITU-R S.2368-0 Study 8

This study investigates the required separation distances for three example FSS earth stations: Madley (7.7º) and Brookmans Park (9.4º) in the UK, and Yamaguchi in Japan (6.5º). In particular, it aims to investigate the extent to which terrain close to the earth station helps to reduce the separation distances required for co-existence of IMT and FSS. Note that the study assumes use of 3400 – 3600 MHz for the earth stations, despite the band not being allocated to FSS in the UK. In addition, whilst the FSS antenna pattern references ITU-R S.465, no information is given with regards to dish size, peak gain etc.

The assumed input and modelling parameters are shown below, alongside the resulting separation distances.

Input Parameters		
5G	Operating Frequencies	3400 - 3600 MHz
	In Band EIRP	51dBm/MHz (Macro Suburban and Urban) 22dBm/MHz (Small Outdoor) 17dBm/MHz (Small Indoor)
	Spurious Emissions	N/A
	Single Cell/Network	Single
Satellite	Operating Frequencies	3400 - 3600 MHz
	Dish Size/Gain	N/A
	Wanted Signal EIRP	N/A
	Wanted Signal C/(I+N)	N/A
	Filter Performance	N/A
	LNB Overload	N/A
	Single ES/Network	Single

Modelling and Outputs		
Modelling	Path Loss for Terrestrial Service	ITU 452-14 (with Aster terrain)
	Guard Band	N/A
	Assumed Degradation in C/(I+N)	I/N=-13dB (long term) I/N=-1.3dB (short term)
Co-Channel Separation Distances (based on elevation angle)	0 - 20º	Brookmans Park: Macro Sub: 300-350km (sea), 270-300km (land) Macro Urban: 350km (sea), 250-300km (land) Small Outdoor: 70km (land) Small Indoor: 20-55km (land) Madley: Macro Sub: 450km (sea), 300-350km (land) Macro Urban: 420-450km (sea), 250-350km (land) Small Outdoor: 300km (sea), 120km (land) Small Indoor: 240km (sea), 7-120km (land) Yamaguchi: Macro Sub: 110km (sea), 60km (land) Macro Urban: 90-125km (sea), 25-60km (land) Small Outdoor: 15km (land) Small Indoor: 10-15km (land)
	20 - 40º	N/A
	≥40º	N/A
Adjacent-Channel Separation Distances (based on elevation angle)	0 - 20º	N/A
	20 - 40º	N/A
	≥40º	N/A
Dominant Interference Mechanism		CCI

Subsequent references to this study will reference [13] and the chapter reference 6.2.11.8.

6.2.11.9 Report ITU-R S.2368-0 Study 9

This study considers adjacent frequency interference from a network of IMT base stations centred around an FSS dish receiving from one of two satellites. The study aims to quantify the size of the guard band required to reduce interference below the co-ordination trigger level. It convolutes a number of possible IMT out of band emissions masks and FSS receiver masks to produce a net filter discrimination function. From this, the required guard band can then be determined. It finds that a guard band of 4MHz is sufficient for small outdoor deployments, and a guard band of 26MHz is sufficient for macro cell networks. Whilst this is a useful output, it is not directly comparable to the majority of the other studies considered within this report, and as such the detailed results will not be presented here.

6.2.11.10 Report ITU-R S.2368-0 Study 10

This study considers co-existence between IMT and FSS, aiming to derive both separation distances and the required frequency dependent rejection of the IMT and FSS spectrum masks. The study considers both base stations and user equipment. The study assumes a smooth Earth profile. For the co-channel case, the FSS receiver is positioned next to a single IMT base station, and the distance varied to determine the required separation distance. For the adjacent frequency case, the distance between an FSS receiver and the IMT network is varied to determine the required attenuation of the IMT signal at each distance. The attenuation is then combined with the derived frequency dependent rejection to determine the guard band required for each separation distance.

The assumed input and modelling parameters are shown below, alongside the resulting separation distances. Note that in the below tables, where a range is given for the separation distances, it either depends on the extent of the misalignment between the IMT and FSS antennas in the horizontal plane, or the guard band which is shown in brackets.

<table>
<tr><th colspan="3">Input Parameters</th></tr>
<tr><td rowspan="4">5G</td><td>Operating Frequencies</td><td>3400 – 4200 MHz</td></tr>
<tr><td>In Band EIRP</td><td>36dBm/MHz (Macro Suburban and Urban)
14dBm/MHz (Small Outdoor and Indoor)
14 to -50dBm/MHz (UE)</td></tr>
<tr><td>Spurious Emissions</td><td>BS
1st Adj: -45dB
2nd Adj: -45dB
Spurious: -54dB
UE
1st Adj: -30dB
2nd Adj: -33dB
Spurious: -53dB</td></tr>
<tr><td>Single Cell/Network</td><td>Network</td></tr>
<tr><td rowspan="5">Satellite</td><td>Operating Frequencies</td><td>3400 – 4200 MHz</td></tr>
<tr><td>Dish Size/Gain</td><td>3m</td></tr>
<tr><td>Wanted Signal EIRP</td><td>N/A</td></tr>
<tr><td>Wanted Signal C/(I+N)</td><td>N/A</td></tr>
<tr><td>Filter Performance</td><td>1st Adj:-45dB
2nd Adj:-50dB
>2nd Adj:-55dB</td></tr>
</table>

Input Parameters		
	LNB Overload	N/A
	Single ES/Network	Single

Modelling and Outputs		
Modelling	Path Loss for Terrestrial Service	ITU 452-14
	Guard Band	0-103.3MHz
	Assumed Degradation in C/(I+N)	I/N=-13dB (co-channel) I/N=-23dB (adj channel)
Co-Channel Separation Distances (based on elevation angle)	0 - 20º	BS: Macro Sub: 27.7-50km Macro Urban: 28.3-48km Small Outdoor: 2.8-16km Small Indoor: <1km UE: Macro Sub: <1km Macro Urban: <2km Small Outdoor: <1km Small Indoor: <1km
	20 - 40º	N/A
	≥40º	N/A
Adjacent-Channel Separation Distances (based on elevation angle)	0 - 20º	BS: Macro Sub: 20-30km (103.3-25MHz) Macro Urban: 20-30km (98.7-25MHz) Small Outdoor: 1-30km (40-16.3MHz) Small Indoor: 1-30km (22-4.8MHz) UE: 0MHz GB for all distances
	20 - 40º	BS: Macro Sub: 5-30km (39.8-24.5MHz) Macro Urban: 5-30km (25-24.7MHz) Small Outdoor: 1-30km (25-5MHz) Small Indoor: 1-30km (4.8-4.6MHz) UE: 0MHz GB for all distances
	≥40º	N/A

Modelling and Outputs	
Dominant Interference Mechanism	CCI/ACI

Subsequent references to this study will reference [13] and the chapter reference 6.2.11.11.

6.2.11.11 Report ITU-R S.2368-0 Study 11

This study considers the co-existence of BWA services with FSS. Interfering signal level limits have not been calculated. Rather levels measured in typical LNBs in Brazil have been used, and additional attenuation stated that would be required on a typical installation in order for coexistence to be possible. As this is not comparable with the majority of studies considered within this report, the detailed results will not be presented here.

6.2.12 Report for GSMA on the mitigations required for adjacent frequency compatibility between IMT and ubiquitous FSS Earth Stations in the 3.4 – 3.8 GHz frequency band

This study [14] was completed by Transfinite Systems on behalf of GSMA. It considers the spectral separation required, based on a fixed set of parameters, to allow adjacent frequency coexistence of IMT and FSS. The study focusses on a single test point FSS earth station in Pretoria, South Africa, with links to two satellites, giving different elevation angles (5º and 27.5º) and azimuths. Monte Carlo simulations are used to position the earth station randomly within a 300m hexagonal area surrounding the centre of the IMT network deployment. Each base station is assumed to transmit at full power at a single user terminal located randomly within its cell.

The study utilises the net frequency discrimination (NFD) method to determine the required guard band based on an allowable I/N degradation of 10dB for at least 50% of all possible deployments, although the results are presented such that guard bands for other degradation values are available also. A number of different spectrum masks are included in the net frequency discrimination analysis. Full details of the results are available within [14], with results for an I/N=-10dB included here.

The assumed input and modelling parameters are shown below, alongside the resulting guard band required.

Input Parameters		
5G	Operating Frequencies	3400 - 3600 MHz
	In Band EIRP	27dBm/MHz (Macro Urban) 5dBm/MHz (Small Outdoor)
	Spurious Emissions	Macro: 0 MHz <= df < 1 MHz: 2dBm/MHz 1 MHz <= df <= 5MHz: interpolate 2 to -4dBm/MHz 5 MHz <= df <= 10MHz: -4dBm/MHz > 10MHz: -13dBm/MHz Small 0 MHz <= df <= 1MHz: interpolate 5 to -43dBm/MHz

Input Parameters		
		1 MHz <= df <= 5MHz: interpolate -43 to -49dBm/MHz > 5MHz: -49dBm/MHz
	Single Cell/Network	Network
Satellite	Operating Frequencies	3600 - 3800 MHz
	Dish Size/Gain	1.8m
	Wanted Signal EIRP	N/A
	Wanted Signal C/(I+N)	N/A
	Filter Performance	IDA, or Gaussian (2 x bandwidth at -30, -40, -50 and -60dB)
	LNB Overload	-60dBm
	Single ES/Network	Single

Modelling and Outputs		
Modelling	Path Loss for Terrestrial Service	ITU 452-16
	Guard Band	18MHz
	Assumed Degradation in C/(I+N)	I/N=-10dB
Co-Channel Separation Distances (based on elevation angle)	0 - 20º	N/A
	20 - 40º	N/A
	≥40º	N/A
Adjacent-Channel Separation Distances (based on elevation angle)	0 - 20º	N/A
	20 - 40º	N/A
	≥40º	N/A
Dominant Interference Mechanism		ACI

Subsequent references to this study will reference [14] and the chapter reference 6.2.12.

6.2.13 Assessments on and Recommendations to Enable the Electromagnetic Compatibility between Public Mobile Services and Fixed Satellite Service Operating in the C-Band

This study [15] was conducted by Rohde & Schwarz on behalf of The Office of Communications Authority (OFCA), Hong Kong. It considers the mitigation measures required to allow compatibility of existing FSS systems with future public mobile services. The study investigates the RF performance of a number of FSS system components, before considering a theoretical set of scenarios to determine the possibility for compatibility. It then goes on to verify these test cases through the use of field testing.

The assumed input and modelling parameters are shown below.

Input Parameters		
5G	Operating Frequencies	3700 - 4200 MHz
	In Band EIRP	38dBm/MHz (Macro) 16dBm/MHz (Outdoor small) 11dBm/MHz (Small indoor)
	Spurious Emissions	-52dBm/MHz
	Single Cell/Network	Single/Two
Satellite	Operating Frequencies	3700 - 4200 MHz
	Dish Size/Gain	3m, 40dBi
	Wanted Signal EIRP	N/A
	Wanted Signal C/(I+N)	N/A
	Filter Performance	3600, >55dB rejection 4200, >50dB rejection
	LNB Overload	-52dBm
	Single ES/Network	Single

Modelling and Outputs		
Modelling	Path Loss for Terrestrial Service	Free space, diffraction as per ITU-R P.526-7, insertion loss
	Guard Band	50MHz or 100MHz
	Assumed Degradation in C/(I+N)	N/A
Co-Channel Separation Distances (based on elevation angle)	0 - 20º	N/A
	20 - 40º	N/A
	≥40º	N/A
Adjacent-Channel Separation Distances (based on elevation angle)	0 - 20º	N/A
	20 - 40º	N/A
	≥40º	N/A
Dominant Interference Mechanism		LNB saturation

Subsequent references to this study will reference [15] and the chapter reference 6.2.13.

6.3 Summary of Studies

6.3.1 Studies

Reference	Chapter Reference	Study	Authors	Date	Organisation	Country
[3]	6.2.1	5G Cellular and FSS Spectrum Coexistence in C-Band	EVA LAGUNAS, CHRISTOS G. TSINOS, SHREE K. SHARMA, and SYMEON CHATZINOTAS	2020	University of Luxembourg	Luxembourg
[4]	6.2.2	The Interference Mitigation Method and Field Test in C-Band Between 5G System and FSS Receiver	Yushan Pei, Fuchang Li, Yao Zhou, Yi Feng and Yuande Tan	2020	China United Network Communications Group Co. Ltd	China
[5]	6.2.3	IMT-FSS Coexistence Scenarios IN C-Band	GSM Association (Hong Kong)	2014	GSM Association (Hong Kong)	Hong Kong
[6]	6.2.4	BEST PRACTICES FOR TERRESTRIAL-SATELLITE COEXISTENCE DURING AND AFTER THE C-BAND TRANSITION	TECHNICAL WORKING GROUP #1	2020	TECHNICAL WORKING GROUP #1	USA
[7]	6.2.5	Coexistence for LTE-Advanced and FSS Services in the 3.5GHz Band in Colombia	German Castellanos, Guillermo Teuta, Hernan Paz Penagos and Wout Joseph	2019	Colombian School of Engineering	Columbia
[8]	6.2.6	COEXISTENCE STUDIES BETWEEN LTE SYSTEM AND EARTH STATION OF FIXED SATELLITE SERVICE IN THE 3400-3600 MHZ FREQUENCY BANDS IN CHINA	Weidong Wang, Fei Zhou, Wei Huang, Ben Wang, Yinghai Zhang	2010	Beijing University of Posts and Telecommunications	China
[9]	6.2.7	Coexistence conditions of LTE-advanced at 3400–3600 MHz with TVRO at 3625–4200 MHz in Brazil	Leandro Carı´sio Fernandes, Agostinho Linhares	2017	National Telecommunications Agency Brazil	Brazil

Reference	Chapter Reference	Study	Authors	Date	Organisation	Country
[10]	6.2.8	Interference Mitigation Technique for the Sharing between IMT-Advanced and Fixed Satellite Service	JaeWoo Lim, Han-Shin Jo, Hyun-Goo Yoon, and Jong-Gwan Yook	2007	Various Universities	China
[11]	6.2.9	Geographic Sharing in C-band	Transfinite	2015	Transfinite, Ofcom	UK
[12]	6.2.10	Rep. ITU-R M.2109 Sharing studies between IMT-Advanced systems and geostationary satellite networks in the fixed-satellite service in the 3 400-4 200 and 4 500-4 800 MHz frequency bands	ITU	2007	ITU	Various
[12]	6.2.10.3	Rep. ITU-R M.2109 Study 3	ITU	2007	ITU	Various
[12]	6.2.10.4	Rep. ITU-R M.2109 Study 4	ITU	2007	ITU	Various
[12]	6.2.10.5	Rep. ITU-R M.2109 Study 5	ITU	2007	ITU	Various
[12]	6.2.10.6	Rep. ITU-R M.2109 Study 6	ITU	2007	ITU	Various
[12]	6.2.10.7	Rep. ITU-R M.2109 Study 7	ITU	2007	ITU	Various
[12]	6.2.10.9	Rep. ITU-R M.2109 Study 9	ITU	2007	ITU	Various
[13]	6.2.11	Report ITU-R S.2368-0 Sharing studies between International Mobile Telecommunication-Advanced systems and geostationary satellite networks in the fixed-satellite service in the 3 400-4 200 MHz and 4 500-4 800 MHz frequency bands in the WRC study cycle…	ITU	2015	ITU	Various
[13]	6.2.11.1	Report ITU-R S.2368-0 Study 1	ITU	2015	ITU	Various
[13]	6.2.11.2	Report ITU-R S.2368-0 Study 2	ITU	2015	ITU	Various
[13]	6.2.11.3	Report ITU-R S.2368-0 Study 3	ITU	2015	ITU	Various
[13]	6.2.11.4	Report ITU-R S.2368-0 Study 4	ITU	2015	ITU	Various

Reference	Chapter Reference	Study	Authors	Date	Organisation	Country
[13]	6.2.11.7	Report ITU-R S.2368-0 Study 7	ITU	2015	ITU	Various
[13]	6.2.11.8	Report ITU-R S.2368-0 Study 8	ITU	2015	ITU	Various
[13]	6.2.11.10	Report ITU-R S.2368-0 Study 10	ITU	2015	ITU	Various
[14]	6.2.12	Report for GSMA on the mitigations required for adjacent frequency compatibility between IMT and ubiquitous FSS Earth Stations in the 3.4 – 3.8 GHz frequency band	Transfinite	2019	Transfinite, GSMA	South Africa
[15]	6.2.13	Assessments on and Recommendations to Enable the Electromagnetic Compatibility between Public Mobile Services and Fixed Satellite Service Operating in the C-Band	Rohde & Schwarz	2018	OFCA	Hong Kong

6.3.2 5G Input Assumptions

Ref No	Chapter No	Band	In Band EIRP	Spurious Emissions	Single Cell/Network
[3]	6.2.1	3400 - 3700 MHz OR 3410 - 3620 MHz	54dBm/MHz	0 MHz <= df < 5 MHz: Min(Pmax-47,14) dBm/MHz 5 MHz <= df < 10 MHz: Min(Pmax-50,8) dBm/MHz 10 MHz <= df <=fmax: Min(Pmax-50,6) dBm/MHz	Both
[4]	6.2.2	3500 - 3600MHz	~44dBm/MHz	50 MHz <= df > 100MHz: -26dBm/MHz 100 MHz <= df < 600 MHz: -47dBm/MHz	Both
[5]	6.2.3	3400 - 3600 MHz	27dBm/MHz	N/A	Single
[6]	6.2.4	3700 - 3980 MHz	65dBm/MHz (rural) 62dBm/MHz (urban)	-13dBm/MHz -40dBm/MHz	Single
[7]	6.2.5	3664 - 3718 MHz	48dBm/MHz Suburban 45dBm/MHz Urban 13dBm/MHz UE	N/A	Single
[8]	6.2.6	3400 - 3600 MHz	36dBm/MHz (BS) 14dBm/MHz (UE)	BS 0MHz <= df < 5MHz: -4.65dBm/MHz 5MHz <= df <10 MHz: -11dBm/MHz 10MHz <= df: -11dBm/MHz UE 0MHz <= df < 1MHz: -2.7712dBm/MHz 1MHz <= df <5MHz: -16.02dBm/MHz 5MHz <= df <10MHz: -20dBm/MHz 10MHz <= df <15MHz: -32dBm/MHz 15MHz <= df: -84dBm/MHz	Both
[9]	6.2.7	3400 - 3600 MHz	Suburban Macro: 34, 40, 45dBm/MHz Urban Macro: 27, 39, 45dBm/MHz	BS: 3GPP TS 36.104 v13.2.0 UE: 3GPP TS 36.101 v14.0.0	Both

Ref No	Chapter No	Band	In Band EIRP	Spurious Emissions	Single Cell/Network
			Urban Small: 16, 24dBm/MHz		
[10]	6.2.8	4000MHz	26dBm/MHz	N/A	Single
[11]	6.2.9	3800 - 4200 MHz	19dBm/MHz (outdoor) 14dBm/MHz (indoor)	0MHz <= df < 5MHz: 0dB 5 MHz <= df: -45dB	Single
[12]	6.2.10	See individual studies	46dBm/MHz (macro) 22dBm/MHz (micro) 7.5dBm/MHz (UE)	6.6.2 from the 3GPP Document TS 36.104 v.11.2.0	See individual studies
[12]	6.2.10.3	N/A	46dBm/MHz (macro) 22dBm/MHz (micro) 7.5dBm/MHz (UE)	RR Appendix 3	Single
[12]	6.2.10.4	N/A	46dBm/MHz (macro) 22dBm/MHz (micro) 7.5dBm/MHz (UE)	1st Adj: -45dB 2nd Adj: -50dB 3rd Adj +:-66dB	Single
[12]	6.2.10.5	N/A	46dBm/MHz (macro) 22dBm/MHz (micro) 7.5dBm/MHz (UE)	1st Adj: -45dB 2nd Adj: -50dB 3rd Adj +:-66dB OFDMA different (theoretical mask with rolloff factor 0.2 used)	Both
[12]	6.2.10.6	N/A	46dBm/MHz (macro) 22dBm/MHz (micro) 7.5dBm/MHz (UE)	1st Adj: -45dB 2nd Adj: -50dB 3rd Adj +:-66dB	Single
[12]	6.2.10.7	N/A	46-39dBm/MHz (macro) 22-15dBm/MHz (micro) 7.5dBm/MHz (UE)	1st Adj: -45dB 2nd Adj: -50dB 3rd Adj +:-66dB	Both

Ref No	Chapter No	Band	In Band EIRP	Spurious Emissions	Single Cell/Network
[12]	6.2.10.9	N/A	46dBm/MHz (macro) 22dBm/MHz (micro) 7.5dBm/MHz (UE)	3GPP TS 25.104 V7.5.0	Single
[13]	6.2.11	See individual studies	24dBm - 61dBm	6.6.2 from the 3GPP Document TS 36.104 v.11.2.0	See individual studies
[13]	6.2.11.1	3400 - 4200 MHz	48dBm/MHz (Macro Urban & Suburban) 16dBm/MHz (Small Outdoor) 11dBm/MHz (Small Indoor)	N/A	Single
[13]	6.2.11.2	N/A	3dB Less for Aggregate Simulation: 48dBm/MHz (Suburban Macro) 33dBm/MHz (Urban Macro) 16dBm/MHz (Outdoor Small) 11dBm/MHz (Indoor Small)	3GPP 36.104 v.11.2.0	Network
[13]	6.2.11.3	3400 - 3600 MHz	33dBm/MHz (Macro Suburban) 17dBm/MHz (Small Outdoor)	TS 36.104 v.11.2.0	Single
[13]	6.2.11.4	3400 - 4200 MHz	14 - 51dBm/MHz	TS 36.104 v.11.2.0	Both
[13]	6.2.11.7	3300 - 3400 MHz	14 - 51dBm/MHz	3GPP 36.104 v.11.2.0 45dB ACLR or -15dBm/MHz (wide area) 45dB ACLR or -32dBm/MHz (local)	Network
[13]	6.2.11.8	3400 - 3600 MHz	51dBm/MHz (Macro Suburban and Urban) 22dBm/MHz (Small Outdoor) 17dBm/MHz (Small Indoor)	N/A	Single
[13]	6.2.11.10	3400 – 4200 MHz	36dBm/MHz (Macro Suburban and Urban) 14dBm/MHz (Small Outdoor and Indoor) 14 to -50dBm/MHz (UE)	BS 1st Adj: -45dB 2nd Adj: -45dB Spurious: -54dB UE	Network

Ref No	Chapter No	Band	In Band EIRP	Spurious Emissions	Single Cell/Network
				1st Adj: -30dB 2nd Adj: -33dB Spurious: -53dB	
[14]	6.2.12	3400 - 3600 MHz	27dBm/MHz (Macro Urban) 5dBm/MHz (Small Outdoor)	Macro: 0 MHz <= df < 1 MHz: 2dBm/MHz 1 MHz <= df <= 5MHz: interpolate 2 to -4dBm/MHz 5 MHz <= df <= 10MHz: -4dBm/MHz > 10MHz: -13dBm/MHz Small 0 MHz <= df <= 1MHz: interpolate 5 to -43dBm/MHz 1 MHz <= df <= 5MHz: interpolate -43 to -49dBm/MHz > 5MHz: -49dBm/MHz	Network
[15]	6.2.13	3700 – 4200 MHz	38dBm/MHz (Macro) 16dBm/MHz (Outdoor small) 11dBm/MHz (Small indoor)	-52dBm/MHz	Single/Two

6.3.3 FSS Input Assumptions

Ref No	Chapter No	Band	Dish Size/Gain	Wanted Signal EIRP	Wanted Signal C/(I+N)	Filter Performance	LNB Overload	Single ES/Network
[3]	6.2.1	3400 - 3700 MHz OR 3410 - 3620 MHz	4.8m - 12m	N/A	N/A	Square root raised cosine (-20dB at 3.55GHz, -60dB at 3.4GHz)	-63dBm with added 25dB or 10dB margin	Single
[4]	6.2.2	3500 - 3600MHz	1.8m - 3m (aligned with BS)	N/A	N/A	Minimum of -45dB in adjacent band	-60dBm	Single
[5]	6.2.3	3400 - 3600 MHz	1.8m, 34.17dBi (peak)	47.7dBW	17.01dB	N/A	N/A	Single
[6]	6.2.4	3700 - 3980 MHz	N/A	N/A	N/A	0 MHz <= df < 15 MHz: 0dB 15 MHz <= df < 20 MHz: -30dB 20 MHz <= df < 100MHz: -60dB df > 100MHz: -70dB	-16dBW/m^2/MHz	Single
[7]	6.2.5	3664 - 3718 MHz	-8.6dBi, -1.6dBi, 6.2dBi	90dBm	N/A	N/A	N/A	Single
[8]	6.2.6	3400 - 3600 MHz	4m	N/A	N/A	N/A	-60dBm	Single
[9]	6.2.7	3400 - 3600 MHz	0dBi, -4dBi, -10dBi (32dBi peak gain)	N/A	N/A	N/A	-60dBm, -45dBm	TVRO
[10]	6.2.8	4000MHz	3.8m	N/A	N/A	N/A	N/A	Single
[11]	6.2.9	3800 - 4200 MHz	55dBi	N/A	N/A	Gaussian, -30dB at 2 x transponder bandwidth	N/A	Single
[12]	6.2.10	See individual studies						
[12]	6.2.10.3	N/A	1.8m-3.8m, 11m	N/A	N/A	N/A	N/A	Single
[12]	6.2.10.4	N/A	2.4m	N/A	N/A	N/A	N/A	Single
[12]	6.2.10.5	N/A	1.8m-3.8m, 11m	N/A	N/A	N/A	N/A	Single

Ref No	Chapter No	Band	Dish Size/Gain	Wanted Signal EIRP	Wanted Signal C/(I+N)	Filter Performance	LNB Overload	Single ES/Network
[12]	6.2.10.6	N/A	1.8m-3.8m, 11m	N/A	N/A	N/A	N/A	Single
[12]	6.2.10.7	N/A	1.8m-3.8m, 11m	N/A	N/A	N/A	N/A	Single
[12]	6.2.10.9	N/A	1.8m-3.8m, 11m	N/A	N/A	N/A	-60dBm	Single
[13]	6.2.11	See individual studies						
[13]	6.2.11.1	3400 - 4200 MHz	2.4m, 16m	N/A	N/A	N/A	N/A	Single
[13]	6.2.11.2	N/A	2.4m, 10m	N/A	N/A	N/A	-55dBm	Single
[13]	6.2.11.3	3400 - 3600 MHz	18m	N/A	N/A	N/A	-50 to -60dBm	Single
[13]	6.2.11.4	3400 - 4200 MHz	N/A	N/A	N/A	N/A	-61dBm	Both
[13]	6.2.11.7	3300 - 3400 MHz	2.4m, 11m	N/A	N/A	45dB ACS	N/A	Single
[13]	6.2.11.8	3400 - 3600 MHz	N/A	N/A	N/A	N/A	N/A	Single
[13]	6.2.11.10	3400 – 4200 MHz	3m	N/A	N/A	1st Adj:-45dB 2nd Adj:-50dB >2nd Adj:-55dB	N/A	Single
[14]	6.2.12	3400 - 3600 MHz	1.8m	N/A	N/A	IDA, or Gaussian (2 x bandwidth at -30, -40, -50 and -60dB)	-60dBm	Single
[15]	6.2.13	3700 – 4200 MHz	3m, 40dBi	N/A	N/A	3600, >55dB rejection 4200, >50dB rejection	-52dBm	Single

6.3.4 Modelling Assumptions

Ref No	Chapter No	Path Loss for Terrestrial Service	Guard Band (MHz)	Assumed Degradation in C/(I+N)
[3]	6.2.1	ITU-R 452-16	5MHz	I/N = -10dB
[4]	6.2.2	Measured received 5G power	100MHz OR 25MHz	N/A
[5]	6.2.3	ITU R 452-15	N/A	C/(I+N) = 8.69dB (reduction of ~8dB)
[6]	6.2.4	Free space and ITS Irregular Terrain Model	20MHz	I/N=-6dB (adjusted down by 4dB)
[7]	6.2.5	ITU R 2001-2 OR ITU-R 452-16	-28 to +25MHz	I/N = -6.5dB
[8]	6.2.6	ITU R 452-12	0MHz - 15MHz	I/N = -12.2dB
[9]	6.2.7	ITU R 452-16 (using free space for short distances, 452 for long distances, and linear interpolation between the two for mid range)	25MHz	N/A
[10]	6.2.8	ITU 452-12	-9 to 9MHz	I/N=-12.2dB
[11]	6.2.9	ITU 452-15	N/A	I/N = -10dB
[12]	6.2.10	See individual studies		
[12]	6.2.10.3	ITU 452-12 with diffraction and ducting models	N/A	I/N=-12.2dB (long term) I/N=-15.2dB (long term, int apportionment) I/N=-20dB (adjacent)
[12]	6.2.10.4	ITU 452-12, LoS with sub-path diffraction	N/A	I/N=-12.2dB (long term) I/N=-20dB (adjacent)
[12]	6.2.10.5	ITU 452-12	N/A	I/N=-12.2dB (long term) I/N=-20dB (adjacent)
[12]	6.2.10.6	ITU 452-12, smooth earth with diffraction	N/A	I/N=-12.2dB (long term) I/N=-15.2dB (long term, int apportionment) I/N=-20dB (adjacent)

Ref No	Chapter No	Path Loss for Terrestrial Service	Guard Band (MHz)	Assumed Degradation in C/(I+N)
[12]	6.2.10.7	ITU 452-12	N/A	I/N=-12.2dB (long term) I/N=-20dB (adjacent)
[12]	6.2.10.9	ITU 452-12, LoS w/o sub-path diffraction, multipath or focussing effects	N/A	I/N=-12.2dB (long term) I/N=-20dB (adjacent)
[13]	6.2.11	See individual studies		
[13]	6.2.11.1	ITU 452-14, smooth Earth	N/A	I/N = -13dB (long term) I/N = -1.3dB (short term, single entry)
[13]	6.2.11.2	ITU 452-14	0, 5, 10MHz	I/N = -13dB (long term) I/N = -1.3dB (short term, single entry) I/N = -20dB (aggregate, ACI)
[13]	6.2.11.3	ITU 452-14	N/A	I/N=-10dB (long term) I/N=-1.3dB (short term)
[13]	6.2.11.4	ITU 452-14	N/A (stated 0MHz for LNB)	ITU-R S.1432 and ITU-R SF.1006
[13]	6.2.11.7	ITU 452-15	N/A	I/N=-23dB
[13]	6.2.11.8	ITU 452-14 (with Aster terrain)	N/A	I/N=-13dB (long term) I/N=-1.3dB (short term)
[13]	6.2.11.10	ITU 452-14	0-103.3MHz	I/N=-13dB (co-channel) I/N=-23dB (adj channel)
[14]	6.2.12	ITU 452-16	18MHz	I/N=-10dB
[15]	6.2.13	Free space, diffraction as per ITU-R P.526-7, insertion loss	50MHz, 100MHz	N/A

6.3.5 Co-Channel Separation Distances

Ref No	Chapter No	0 - 20º Co-channel Separation Distance	20 - 40º Co-channel Separation Distance	≥40º Co-channel Separation Distance
[3]	6.2.1	16km if not aligned with satellite antenna pointing, 41km if aligned with pointing		N/A
[4]	6.2.2	N/A	N/A	N/A
[5]	6.2.3	Hanoi: 2.5km	Bangladesh: 3.5km	Kuala Lumpur: 2.5km
[6]	6.2.4	N/A	N/A	N/A
[7]	6.2.5	Urban: 278km (BS) 2650m (UE) Suburban: 244km (BS) 2125m (UE)	Urban: 215km (BS) 1000m (UE) Suburban: 181km (BS) 875m (UE)	Urban: 150km (BS) 750m (UE) Suburban: 141km (BS) 655m (UE)
[8]	6.2.6	BS: 200km UE: 5km		
[9]	6.2.7	N/A	N/A	N/A
[10]	6.2.8	W/o Mitigation: 44km W Mitigation: 35m (no error) 7km (2 deg error) 27km (10 deg error)		

Ref No	Chapter No	0 - 20º Co-channel Separation Distance	20 - 40º Co-channel Separation Distance	≥40º Co-channel Separation Distance
[11]	6.2.9	Chalfont Outdoor BS: 25km (1. flat Earth) 73km (2. terrain, but no clutter) 70km (3. as 2, with clutter) 25km (4. as 3, with extra dense urban clutter loss) 24km (5. as 4, with polarisation discrimination, traffic considerations) 3km (indoor BS)	N/A	N/A
[12]	6.2.10	>10s of km		
[12]	6.2.10.3	(I/N=-12.2dB) Macro: 55km Mobile: 1km (I/N=-15.2dB) Macro: 70km Mobile: 1.5km		
[12]	6.2.10.4	Macro Urban: 37-54km Micro Urban: 15-23km Macro rural: 40-59km		
[12]	6.2.10.5	Single Entry: Base Station: 45-58km (5-48 deg) Aggregate: Base Station: 51-60km (5-48deg) Mobile Station: 0.5-1.5km		

Ref No	Chapter No	0 - 20º Co-channel Separation Distance	20 - 40º Co-channel Separation Distance	≥40º Co-channel Separation Distance
[12]	6.2.10.6	(I/N=-12.2dB) 5deg: 33-57km 15deg: 33-37km (I/N=-15.2dB) 5deg: 36-60km 15deg: 36-40km		
[12]	6.2.10.7	Single Entry: CDMA Macro: 47-65.6km CDMA Micro: 39-49.5km CDMA Mobile: 0km OFDMA Macro: 43-55km OFDMA Micro: 29-47km OFDMA Mobile: 0km Aggregate: CDMA Macro: 56-87km CDMA Micro: 49-58km CDMA Mobile: 0km OFDMA Macro: 51-61km OFDMA Micro: 46-53km OFDMA Mobile: 0km		
[12]	6.2.10.9	N/A	N/A	N/A
[13]	6.2.11	CCI Macro cell: 10s of km/100s of km (long term/short term int) Small cell: 10s of km Small Indoor: 5 to 10s of km		

Ref No	Chapter No	0 - 20º Co-channel Separation Distance	20 - 40º Co-channel Separation Distance	≥40º Co-channel Separation Distance
[13]	6.2.11.1	Long Term: Macro Sub: 61-63km Macro Urban: 46-48km Small Outdoor: 25km Small Indoor: <5km	N/A	Long Term: Macro Sub: 35-36km Macro Urban: 20-22km Small Outdoor: 6km Small Indoor: <5km
[13]	6.2.11.2	Long Term: Macro Sub: 60.5km Macro Urb: 72km Small Outdoor: 5km Small Indoor: 4-5km	Long Term (15 deg): Macro Sub: 58.2km Macro Urb: 69km Small Outdoor: 1.2km Small Indoor: 1-3km	Long Term: Macro Sub: 55.6km Macro Urb: 67km Small Outdoor: 0.53km Small Indoor: 0.55-1.5km
[13]	6.2.11.3	Macro suburban: 30-40km Small Outdoor: 15-25km	Macro suburban: 10-20km Small Outdoor: 15-25km	N/A
[13]	6.2.11.4	Long Term (5-10deg): Macro Suburban: 58.1-50.5km Macro Urban: 51.2-45.2km Small Urban: 20.3-9km Aggregated: Macro Suburban: 63-55km Macro Urban: 53-48km Small Urban: 20.3-10km	Long Term (20-30deg): Macro Suburban: 45.7-44.6km Macro Urban: 40-35.7km Small Urban: 8.3-6.2km Aggregated: Macro Suburban: 53-52km Macro Urban: 45-44km Small Urban: 9km	N/A
[13]	6.2.11.7	N/A	N/A	N/A

Ref No	Chapter No	0 - 20º Co-channel Separation Distance	20 - 40º Co-channel Separation Distance	≥40º Co-channel Separation Distance
[13]	6.2.11.8	Brookmans Park: Macro Sub: 300-350km (sea), 270-300km (land) Macro Urban: 350km (sea), 250-300km (land) Small Outdoor: 70km (land) Small Indoor: 20-55km (land) Madley: Macro Sub: 450km (sea), 300-350km (land) Macro Urban: 420-450km (sea), 250-350km (land) Small Outdoor: 300km (sea), 120km (land) Small Indoor: 240km (sea), 7-120km (land) Yamaguchi: Macro Sub: 110km (sea), 60km (land) Macro Urban: 90-125km (sea), 25-60km (land) Small Outdoor: 15km (land) Small Indoor: 10-15km (land)	N/A	N/A
[13]	6.2.11.10	BS: Macro Sub: 27.7-50km Macro Urban: 28.3-48km Small Outdoor: 2.8-16km Small Indoor: <1km UE: Macro Sub: <1km Macro Urban: <2km Small Outdoor: <1km Small Indoor: <1km	N/A	N/A
[14]	6.2.12	N/A	N/A	N/A
[15]	6.2.13	N/A	N/A	N/A

6.3.6 Adjacent Frequency Separation Distances

Ref No	Chapter No	0 - 20º Adjacent Frequency Separation Distance	20 - 40º Adjacent Frequency Separation Distance	≥40º Adjacent Frequency Separation Distance
[3]	6.2.1	~14km UE: 550m		N/A
[4]	6.2.2	90m	N/A	N/A
[5]	6.2.3	N/A	N/A	N/A
[6]	6.2.4	Passive Antenna: -13dBm/MHz: 26.6km (8.6-20.2km for ITS model) -40dBm/MHz: 1.2km AAS: -13dBm/MHz: 0.2km (7%), 1.5-2km (49%), 5.5km (96%) -40dBm/MHz: <0.2km (7%), <0.2km (49%), <0.3km (96%) LNB: Rural: 102m Urban: 73.2m		
[7]	6.2.5	Urban: 210 - 88km (BS) 1000 - 380m (UE) Suburban: 183 - 67km (BS) 975 - 500m (UE)	Urban: 153 - 40km (BS) 650 - 200m (UE) Suburban: 133 - 28km (BS) 500 - 465m (UE)	Urban: 103 - 18km (BS) 480 - 200m (UE) Suburban: 83 - 13km (BS) 500 - 265m (UE)

Ref No	Chapter No	0 - 20º Adjacent Frequency Separation Distance	20 - 40º Adjacent Frequency Separation Distance	≥40º Adjacent Frequency Separation Distance
[8]	6.2.6	0MHz GB BS: 4.5km UE: 450m 5-10MHz GB BS: 2km UE: 100m >10MHz GB BS: 800m LNB: 500m		
[9]	6.2.7	-60dBm LNB: Suburban Macro: not possible Urban Macro: not possible Urban Small: 80-70m -45dBm LNB Suburban Macro: 430-230m Urban Macro: 120-60m Urban Small: 50-30m	-60dBm LNB: Suburban Macro: not possible Urban Macro: not possible Urban Small: 70m -45dBm LNB Suburban Macro: 245-110m Urban Macro: 90-10m Urban Small: 40-15m	-60dBm LNB: Suburban Macro: not possible Urban Macro: 270-95m Urban Small: 60-50m -45dBm LNB Suburban Macro: 75-10m Urban Macro: 55-10m Urban Small: 20-10m
[10]	6.2.8	Without mitigation: 17-0.13km With mitigation:<10m (no error) 5.56km-20m (5deg error) 9.84km-30m (10deg error)		
[11]	6.2.9	N/A	N/A	N/A
[12]	6.2.10	<10s of km		
[12]	6.2.10.3	Macro: 18-25km Mobile: 300-450m		
[12]	6.2.10.4	N/A	N/A	N/A

Ref No	Chapter No	0 - 20º Adjacent Frequency Separation Distance	20 - 40º Adjacent Frequency Separation Distance	≥40º Adjacent Frequency Separation Distance
[12]	6.2.10.5	Single Entry: CMDA: 10-34km (5-48deg) OFDMA: 0.07-19km Aggregate: CDMA Macro: 15-37km (5-48deg) OFDMA Macro: 0.35-21km		
[12]	6.2.10.6	N/A	N/A	N/A
[12]	6.2.10.7	Single Entry: CDMA Macro: 10-42.5km CDMA Micro: 2-14km OFDMA Macro: 5-29km OFDMA Micro: 2.4-8.7km Aggregate: CDMA Macro: 27-45.5km CDMA Micro: 11-35km OFDMA Macro: 15-41km OFDMA Micro: 4-8.5km OFDMA Mobile: 0km		
[12]	6.2.10.9	Macro: 49.5-80km Micro: 39.5-51km UE: 25-32.5km LNB Saturation: Mobile station: 170m Micro: 600m Macro: 9.5km		

Ref No	Chapter No	0 - 20º Adjacent Frequency Separation Distance	20 - 40º Adjacent Frequency Separation Distance	≥40º Adjacent Frequency Separation Distance
[13]	6.2.11	AC Macro cell: 5 to 10s of km Small cell: 900m to 5km LNB/LNA Overdrive Macro cell: 4km to 9km Small cell: 100m to 900m Intermods Macro cell: 2km to 8km Small cell: 100m to 500m		
[13]	6.2.11.1	N/A	N/A	N/A
[13]	6.2.11.2	0 MHz GB: Macro Sub: 1.4km Macro Urb: 49km Small Outdoor: <0.3km Small Indoor: <0.4km 5MHz GB: Macro Sub: 1.3km Macro Urb: 49km 10MHz GB: Macro Sub: 1.3km Macro Urb: 49km	0 MHz GB (15 deg): Macro Sub: <0.06km Macro Urb: 43.5km Small Outdoor: <0.3km Small Indoor: <0.4km 5MHz GB: Macro Sub: <0.06km Macro Urb: 43km 10MHz GB: Macro Sub: <0.06km Macro Urb: 43km	0 MHz GB: Macro Sub: <0.06km Macro Urb: 39km Small Outdoor: <0.3km Small Indoor: <0.4km 5MHz GB: Macro Sub: <0.06km Macro Urb: 39km 10MHz GB: Macro Sub: <0.06km Macro Urb: 38.5km
[13]	6.2.11.3	Macro suburban: ~15km Small Outdoor: ~10km	Macro suburban: ~15km Small Outdoor: ~5km	N/A

Ref No	Chapter No	0 - 20º Adjacent Frequency Separation Distance	20 - 40º Adjacent Frequency Separation Distance	≥40º Adjacent Frequency Separation Distance
[13]	6.2.11.4	Long Term (5-10deg): Macro Suburban: 13.4-9.4km Macro Urban: 9.3-8.4km Small Urban: 3.8-2.8km Aggregated: Macro Suburban: 18-17km Macro Urban: 12-10km Small Urban: 3.8-2.8km LNB: Macro Suburban: 8.8-8.1km Macro Urban: 8.5-6.4km Small Urban:0.9-0.4km	Long Term (20-30deg): Macro Suburban: 8.6-8.2km Macro Urban: 6.4-5km Small Urban: 1.4-0.9km Aggregated: Macro Suburban: 17-15km Macro Urban: 9km Small Urban: 1.4-0.9km LNB: Macro Suburban: 6.2-4.8km Macro Urban: 4.9-4.4km Small Urban: 0.2-0.1km	N/A
[13]	6.2.11.7	5-15deg Macro Sub and Urb: 1400-467m Small Outdoor: 50m Small Indoor: 60-60m	Macro Sub and Urb: 315m Small Outdoor: 50m Small Indoor: 60m	N/A
[13]	6.2.11.8	N/A	N/A	N/A
[13]	6.2.11.10	BS: Macro Sub: 20-30km (103.3-25MHz) Macro Urban: 20-30km (98.7-25MHz) Small Outdoor: 1-30km (40-16.3MHz) Small Indoor: 1-30km (22-4.8MHz) UE: 0MHz GB for all distances	BS: Macro Sub: 5-30km (39.8-24.5MHz) Macro Urban: 5-30km (25-24.7MHz) Small Outdoor: 1-30km (25-5MHz) Small Indoor: 1-30km (4.8-4.6MHz) UE: 0MHz GB for all distances	N/A
[14]	6.2.12	N/A	N/A	N/A
[15]	6.2.13	N/A	N/A	N/A

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8 Acronyms and Abbreviations

AAS	Active Antenna System
ACI	Adjacent Channel Interference
ACLR	Adjacent Channel Leakage Ratio
BS	Base Station
CCI	Co-Channel Interference
CDMA	Code Division Multiple Access
DTH	Direct To Home
ECC	Electronic Communications Committee
EIRP	Effective Isotropic Radiated Power
E-UTRA	Evolved - UMTS Terrestrial Radio Access
FDD	Frequency Division Duplex
FSS	Fixed Satellite Service
GB	Guard-band
IMT	International Mobile Telecommunications
ITU	International Telecommunications Union
LNA	Low Noise Amplifier
LNB	Low Noise Block
LTE	Long Term Evolution (4G)
MCL	Minimum Coupling Loss
NR	New Radio (5G)
OFDMA	Orthogonal Frequency Division Multiple Access
OOB[E]	Out-of-Band [Emissions]
TDD	Time Division Duplex
TVRO	Television Receive Only
UE	User Equipment
UMTS	Universal Mobile Telecommunication System (3G)
VSAT	Very Small Aperture Terminals
WRC	World Radiocommunications Conference