ITUPublications

International Telecommunication Union
Radiocommunication Sector

Report ITU-R S.2546-0

(11/2024)

S Series: Fixed satellite services

Mitigation measures between FSS and IMT in the frequency band 3 400-3 600 MHz

Foreword

The role of the Radiocommunication Sector is to ensure the rational, equitable, efficient and economical use of the radio-frequency spectrum by all radiocommunication services, including satellite services, and carry out studies without limit of frequency range on the basis of which Recommendations are adopted.

The regulatory and policy functions of the Radiocommunication Sector are performed by World and Regional Radiocommunication Conferences and Radiocommunication Assemblies supported by Study Groups.

Policy on Intellectual Property Right (IPR)

ITU-R policy on IPR is described in the Common Patent Policy for ITU-T/ITU-R/ISO/IEC referenced in Resolution ITU-R 1. Forms to be used for the submission of patent statements and licensing declarations by patent holders are available from https://www.itu.int/ITU-R/go/patents/en where the Guidelines for Implementation of the Common Patent Policy for ITU-T/ITU-R/ISO/IEC and the ITU-R patent information database can also be found.

Series of ITU-R Reports

(Also available online at https://www.itu.int/publ/R-REP/en)

Series	Title
BO	Satellite delivery
BR	Recording for production, archival and play-out; film for television
BS	Broadcasting service (sound)
BT	Broadcasting service (television)
F	Fixed service
M	Mobile, radiodetermination, amateur and related satellite services
P	Radiowave propagation
RA	Radio astronomy
RS	Remote sensing systems
S	**Fixed-satellite service**
SA	Space applications and meteorology
SF	Frequency sharing and coordination between fixed-satellite and fixed service systems
SM	Spectrum management
TF	Time signals and frequency standards emissions

***Note**: This ITU-R Report was approved in English by the Study Group under the procedure detailed in Resolution ITU-R 1.*

Electronic Publication
Geneva, 2025

REPORT ITU-R S.2546-0

Mitigation measures between FSS and IMT in the frequency band 3 400-3 600 MHz

(2024)

TABLE OF CONTENTS

Page

Related ITU-R Recommendations, Reports and Handbooks

Recommendation ITU-R BO.790

Recommendation ITU-R S.733

Recommendation ITU-R S.1541

Recommendation ITU-R S.1061

Recommendation ITU-R S.2131

Recommendation ITU-R F.1766

Report ITU-R M.2109

Report ITU-R S.2368

Report ITU-R S.2150

ITU-R Handbook on satellite communications

1 Scope

The purpose of this Report is to describe techniques that may assist administrations deploying IMT stations in the frequency range 3 400-3 600 MHz, interested in mitigation measures to enhance coexistence between IMT base stations and FSS earth stations in order to avoid potential interference. The frequency range 3 400-3 500 MHz is allocated to the mobile service with primary status in Regions 1 and 2 and with secondary status in Region 3 (except those countries listed in RR No. **5.432B** which have mobile as primary), and the frequency range 3 500-3 600 MHz is allocated to the mobile service with primary status in the three ITU Regions. The relevant footnotes for IMT identification in this band can be found in RR Nos. **5.430A**, **5.431B**, **5.432B** and **5.433A**. The frequency band 3 400-3 600 MHz is allocated to the fixed-satellite service (FSS) (space-to-Earth) globally on a primary basis. For further details see the Table of Frequency Allocations.

ITU-R studies conducted for World Radiocommunication Conferences in 2007 and 2015 illustrated how IMT systems operating within 3 400-3 600 MHz could have an impact on receiving earth stations of the FSS unless certain mitigation measures were considered, including natural terrain shielding, geographical or frequency separation in order to achieve coexistence. Further, these studies[1] analysed, among other issues, cross border scenarios to establish coordination distances between administrations.

Considering that many countries in all three regions are deploying IMT and/or satellite services in C-band, a Report highlighting relevant techniques and/or guidelines to facilitate coexistence between IMT stations and FSS earth stations in these countries should be considered carefully and implemented.

Therefore, this ITU-R Report describes additional mitigation techniques that can be applied to either the FSS earth station and/or the IMT base station to facilitate the coexistence of both services in the same or in an adjacent part of the band.

WRC-23 decided on the matter of identification of IMT in the frequency band 3.6-3.8 GHz, or parts thereof, in some countries of Region 1 and Region 2. Although this Report focuses on the frequency

---

[1] Report 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. Report ITU-R S.2368 – 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 leading to WRC-15".

band 3.4-3.6 GHz, the mitigation techniques presented in this ITU-R Report are also implementable to the frequency range 3.6-3.8 GHz, where applicable.

2 Introduction

TABLE 1 reproduces the current allocations and status in the frequency band 3 400-3 600 MHz as per Article **5** of the Radio Regulations.

TABLE 1

Allocations in the frequency band 3 400-3 600 MHz as per RR Article 5

<table>
<tr><td rowspan="2">3 400-3 600
FIXED
FIXED-SATELLITE (space-to-Earth)
MOBILE except aeronautical mobile 5.430A
Radiolocation

5.431</td><td>3 400-3 500
FIXED
FIXED-SATELLITE (space-to-Earth)
MOBILE except aeronautical mobile 5.431A 5.431B
Amateur
Radiolocation 5.433
5.282</td><td>3 400-3 500
FIXED
FIXED-SATELLITE (space-to-Earth)
Amateur
Mobile 5.432 5.432B
Radiolocation 5.433

5.282 5.432A</td></tr>
<tr><td>3 500-3 600
FIXED
FIXED-SATELLITE (space-to-Earth)
MOBILE except aeronautical mobile 5.431B
Radiolocation 5.433</td><td>3 500-3 600
FIXED
FIXED-SATELLITE (space-to-Earth)
MOBILE except aeronautical mobile 5.433A
Radiolocation 5.433</td></tr>
</table>

Conditions for the use of the frequency band by IMT in different Regions are contained in RR Nos. **5.430A**, **5.431B**, **5.432B** and **5.433A**.

The following ITU-R Reports contain results of sharing studies between IMT and receiving FSS earth stations conducted for WRC-07 and WRC-15:

– Report 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 MHz and 4 500-4 800 MHz frequency bands

– Report ITU-R S.2368 – 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 leading to WRC-15.

This Report summarizes the principles on coexistence between IMT systems and receiving FSS stations.

FSS (s-E), FS, and MS are allocated as co-primary in the frequency band 3.4-4.2 GHz, or portions thereof. FSS has been in use for satellite operations for the past 40 years. As discussed in later sections of this Report, this provides context to explain the design choices applicable to the radio frequency elements of the earth station, e.g. the low noise amplifier, which are capable of receiving in the entire frequency band 3.4-4.2 GHz.

The characteristics of the C-band spectrum (also referred to as mid-band spectrum) deliver a range of benefits for terrestrial and space communications solutions. For IMT deployments, use of this spectrum results in a balance between the ability to achieve coverage objectives in various deployment scenarios, and to provide high capacity and high throughput services. In a similar fashion, frequencies in the C-band spectrum enable satellite operators to deliver various types of coverage from the space stations, ranging from global to spot beams and to benefit from the reduced impact that tropospheric impairments such as rain can cause on the Earth-to-space path. The benefits perceived by both mobile and fixed-satellite services illustrate the attractiveness of the frequency band for the delivery of communication services.

For a number of administrations, C-band represents a solution to connectivity with over several hundred satellites serving all three ITU Regions worldwide with a range of critical services. These cover applications including video broadcasting, with thousands of TV channels delivered via satellite to communities, backhaul infrastructure providing connectivity in areas where fibre is not available.

3 Functional descriptions of an earth station and earth station characteristics

3.1 Overview of an earth station

This section provides an overview of the general configuration of an FSS earth station focusing on the components that play a role in the analysis of the impact of interference onto the earth station.

Earth stations, whether large or small (VSATs), can be described from a functional perspective, in two sections:

– An outdoor section, which is the name given to that portion of the earth station located outdoors. It is comprised of the antenna system, the low noise amplifier (LNA) or block-downconverter (LNB) and in some earth station designs, the power amplifier.

– An indoor section, containing signal translation and processing equipment such as up/down converters, and interfaces to user equipment such as modems and routers, and, in some earth station designs, ancillary devices such as tracking systems, beacon receivers, or uplink power control systems.

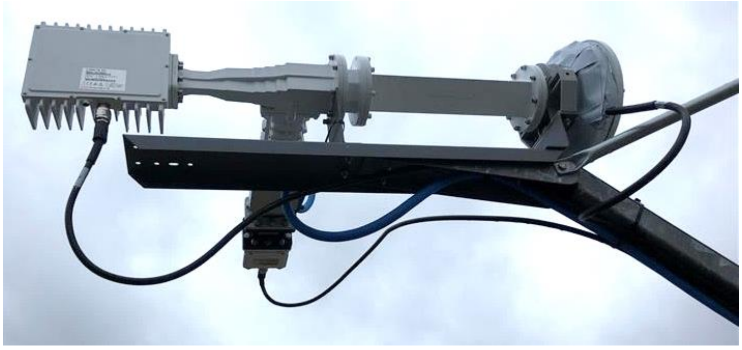
The outdoor section operates in the radio frequency (RF) domain which in the case of C-band is the frequency range 3.4-4.2 GHz, in the space-to-earth direction, while the indoor section typically operates in the intermediate frequency domain, which could be 70±18 MHz, 140±36 MHz or 950-2 000 MHz. The most popular kind of antenna used in FSS earth stations in the C-band is a parabolic reflector antenna with offset feed. Large earth stations frequently use reflector systems incorporating sub-reflector assemblies of the Cassegrain or Gregorian type. Additionally, large earth stations may house the low noise amplification stage in a dedicated enclosure at the back of the antenna, directly coupled to the antenna feed ports.

Large earth station designs may perform frequency conversion as part of the first stage (that is, by means of LNB devices) or may transfer the RF signals directly after amplification, to a dedicated device located indoor for down-conversion.

Small earth stations such as some TVROs and VSATs follow the same construction principle, with the outdoor equipment contained in compact assemblies known as integrated transceivers (which combine in a single unit a solid-state amplifier and an LNB) or as a discrete set of amplifier and LNB located in close proximity to the antenna feed in the outdoor unit, and connected to it by means of an orthomode transducer (OMT) or polarisation duplexer. In some cases, for instance terminals used for reception of video signals, the feed horn component of the antenna system and the low noise block (LNB) are integrated into one unit called Low Noise Block converter with Feed (LNBF). Signals in the intermediate frequency range are delivered via an inter-facility cable (IFL link) to the devices typically located inside user premises, known as indoor unit (IDU), which contains usually either a MODEM or a TV set-top box, depending on the application.

FIGURE 1

Outdoor components for a VSAT terminal



Note to Fig. 1: Shown in the picture are the feed, a transmit reject filter, an OMT, a solid-state power amplifier (SSPA) and an LNB. The output from the LNB and the input to the SSPA are L-band signals.

FIGURE 2

An example of an integrated feed and LNB device (LNBF)

Note to Fig. 2: The signal at the output of the device is delivered in L-band.

The IDU demodulates one of the carriers, de-multiplexes the retrieved bit stream and decodes the digitally-modulated signal for delivery to a variety of other devices.

The following Figures are provided to represent a schematic of the main subsystems which commonly compose an earth station. A picture is provided next to each schematic to show an example of the type of earth station relating to the configuration diagram. Figure 3 provides a block description of a large earth station configuration with a split between RF (outdoor section) and IF (indoor section) and with separate up/down conversion stages. Figure 4 provides an illustration of a smaller earth station (Tx/Rx VSAT) with direct conversion to IF by means of an LNB device, but without integrating the feed and LNB.

FIGURE 3

Example of a large earth station configuration (e.g. a Feeder link or a gateway) including redundant elements in the transmit and receive RF chains. Not shown are the baseband equipment (Uplink power control (UPC), modulators, demodulators, etc.)

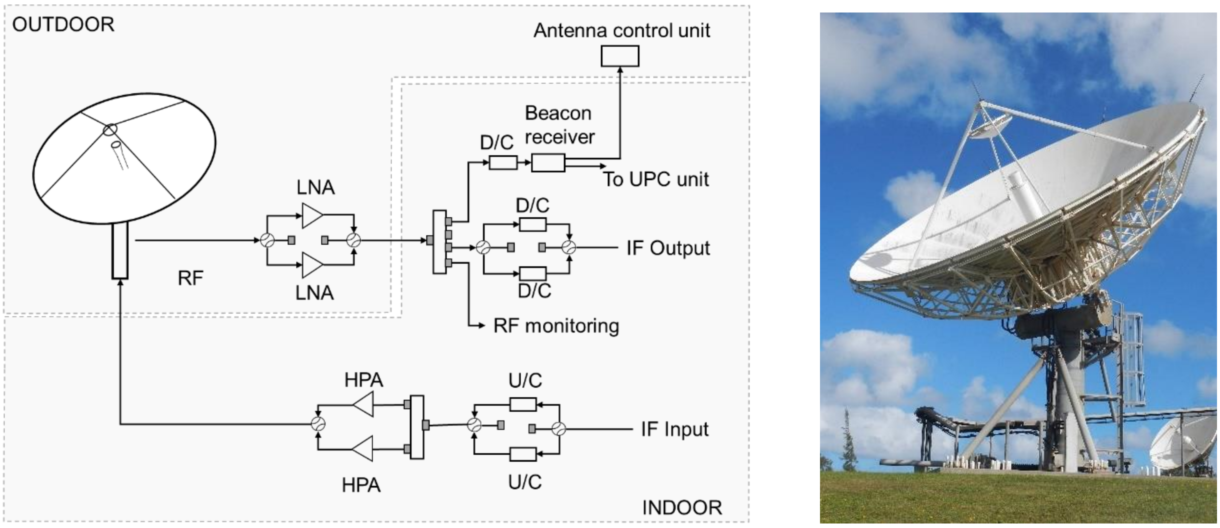
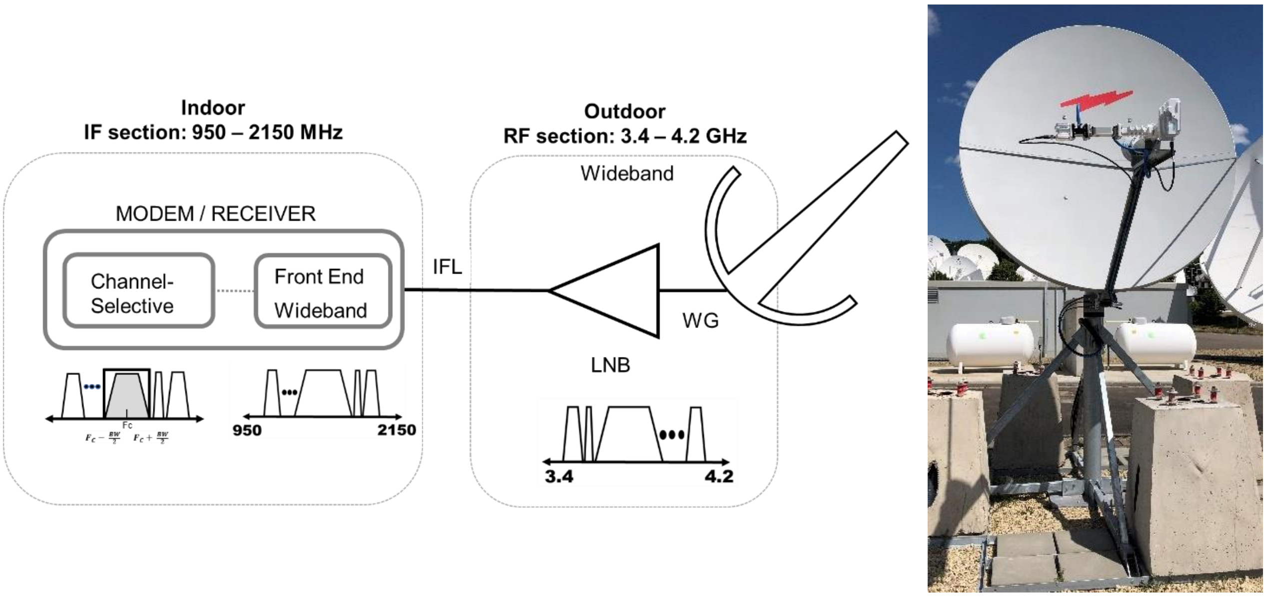


FIGURE 4

Illustration of the two main blocks in a small earth station (TVRO, VSAT): the outdoor and indoor blocks



This Report will focus on describing measures available to system designers of both IMT networks as well as FSS networks, to mitigate the impact of IMT emissions into the FSS receiving earth stations to ensure their nominal operation. The suitability of a mitigation measure will depend on the interference mechanism considered.

3.2 High gain and low noise as design objectives of an earth station

The distance that signals transmitted by geostationary satellites towards earth stations must travel lies between 35 800 and 42 500 km, for high and low elevation angle cases respectively, which results in path losses in the order of 195 dB, and power flux density levels at the input of the antenna in the order of[2] -136 dB(W/(m^2 · MHz)). Therefore, earth stations in the fixed-satellite service have design objectives that may differ from those of terrestrial services.

– High gain: in order to be able to detect the low power signals from the GSO space station at the surface of the Earth.

  In C-band, high gain antenna systems are achieved using an arrangement of a feed antenna, a reflector and, in some cases, a sub-reflector.

– Low noise: to receive the signals from the satellite, it is necessary to maximize the sensitivity of the receive chain and therefore reduce the inherent noise.

  A low noise amplifier is used to amplify the signals received by the antenna. This device should be connected as close as possible to the antenna diplexer flange to minimize any losses in between this antenna output port and the LNB itself, which will result in increased noise temperature in the earth station. In practice, the LNB is connected directly to the feed port, making the losses in the order of a tenth of a dB (0.1 dB).

3.3 Figure of merit of the earth station and earth station noise temperature

The figure of merit of the earth station, or *G*/*T* ratio of an earth station, is a measure of its ability to receive the signals transmitted by the satellite and also of the amount of noise power that the earth station itself will contribute to the overall noise budget.

The *G*/*T* in absence of pointing losses, with impedance and polarisation matching, with the system gain at its maximum value, can be expressed as:

$$\frac{G}{T} = G - 10\log_{10}(T_{ES}) \qquad (1)$$

where:

G : earth station gain, in the direction of the received signal

T_{ES} : earth station system noise temperature.

The usable *G*/*T*, defined in Recommendation ITU-R BO.790, includes effects associated to pointing and polarisation mismatch, as well as the increase in noise temperature due to atmospheric attenuation.

The *G*/*T* of the earth station plays a key role in the determination of the carrier to noise power ratio of the satellite link, and in the determination of the satellite resources (satellite power and bandwidth) required to provide a service at the desired quality.

3.3.1 Computing the *G*/*T* ratio for an earth station

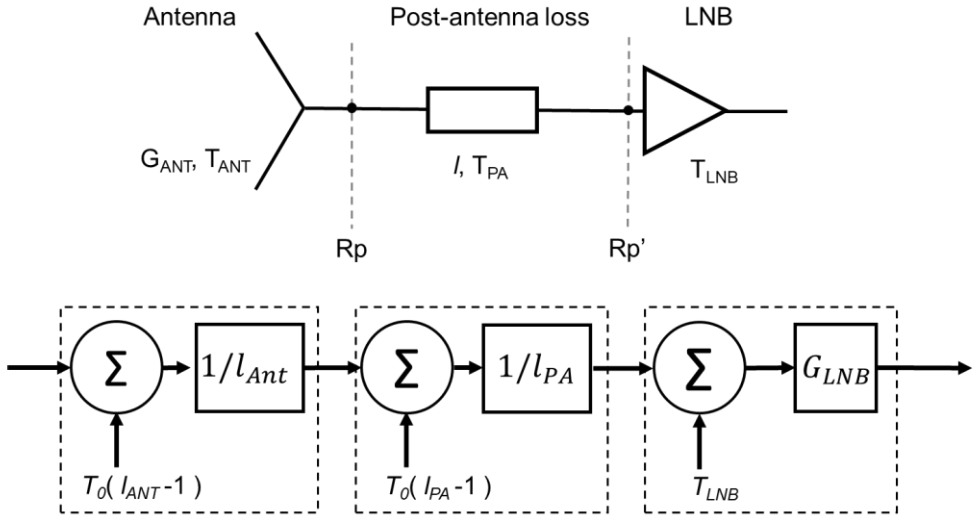
A simplified earth station gain and noise temperature model is shown in Fig. 5. Since the noise temperature analysis requires the definition of a reference plane, the example illustrates the differences that arise with a modification of the reference plane location. A typical choice of location for the reference plane is at the input of the LNB [5], [7], [9].

---

[2] Based on an e.i.r.p. density from the GSO space station of -32.5 dBW/Hz and distances ranging from 35 786 km at subsatellite point to 40 500 km at elevation angles around 10 degrees.

FIGURE 5

Schematic of the earth station for system noise and gain calculations and equivalent circuit model



The model includes the antenna and associated losses, the LNB, and post-antenna losses due to a passive component (e.g. a waveguide, an RF filter or a switching network or combinations thereof) connecting those two elements.

With regards to the earth station system gain:

– When referred to the plane *RP*, the gain elements up to the plane include only the antenna system gain, which includes any effects introduced by the feed system such as illumination function or losses. Thus,

$$G_{ES,RP} = G_{ANT} \tag{2}$$

– When referred to the plane *RP'*, the total gain is the antenna system gain minus the losses (ratio) of the passive component, l_{PA}.

$$G_{ES,RP'} = G_{ANT} - 10\log_{10}(l_{PA}) \tag{3}$$

The computation of the earth station noise temperature considers the cascaded noise contribution from the devices part of the chain.

The system net temperature is:

$$T_{ES} = T_{ant} \cdot G_{\text{LNB}} \cdot \frac{1}{l_{ANT}} \cdot \frac{1}{l_{PA}} + T_0(l_{ANT} - 1) \cdot \frac{1}{l_{ANT}} \cdot \frac{1}{l_{PA}} \cdot G_{\text{LNB}} + T_0(l_{PA} - 1) \cdot \frac{1}{l_{PA}} \cdot G_{\text{LNB}} + T_{LNB} \cdot G_{\text{LNB}} \tag{4}$$

The system temperature, referred to a plane at the LNB input, is the net temperature divided by the gain of the LNB:

$$T_{ES,RP'} = T_{ant} \cdot \frac{1}{l_{ANT}} \cdot \frac{1}{l_{PA}} + T_0(l_{ANT} - 1) \cdot \frac{1}{l_{ANT}} \cdot \frac{1}{l_{PA}} + T_0(l_{PA} - 1) \cdot \frac{1}{l_{PA}} + T_{LNB} \tag{5}$$

Referred to a plane at the antenna output, the system noise temperature is the net temperature without the impact of the LNB and the passive component:

$$T_{ES,RP} = T_{ant} \cdot \frac{1}{l_{ANT}} + T_0(l_{ANT} - 1) \cdot \frac{1}{l_{ANT}} + T_0(l_{PA} - 1) \cdot \frac{1}{l_{PA}} + T_{LNB} \tag{6}$$

In equations (3) to (6):

l_{ANT}, l_{PA} : losses (l > 1) of the antenna system and of the passive component, expressed as a power ratio

T_0 : physical temperature of the passive components

T_{ant}, T_{LNB} : equivalent noise temperatures of the antenna system and LNB device

$T_{ES,RP}$: system temperature with the reference plane set at RP, the antenna output

$T_{ES,RP'}$: system temperature with the reference plane set at RP', the input of the LNB

Therefore, the *G*/*T* ratio, computed at the reference plane *RP* or at the plane *RP'*, will be numerically identical.

In compact systems, in which the LNB and the antenna feed system are integrated into a single device called LNBF (see Fig. 2) and where the coupling losses remain low, the earth station system temperature computation can be further simplified to

$$T_{ES} = T_{ant} + T_{LNB} \quad (7)$$

with the losses introduced by passive components in the device folded into the equivalent temperature of the LNBF itself.

From the total system noise perspective, and as can be deduced from the cascaded noise temperature expression, minimizing the losses between the output of the antenna and the input to the LNB is a fundamental design principle, since the noise introduced by passive networks will affect directly both the total gain of the system and increase the total noise temperature. This observation will be of relevance whenever RF filters are introduced in the RF section of the receive chain, since those filters need to be placed in between the antenna and LNB, thus impacting the earth station noise and gain budget.

More detailed information regarding the computation and measurement of the *G*/*T*, and the contributors to the earth station system noise temperature, can be found in Recommendation ITU-R S.733.

3.3.2 Contributors to earth station noise temperature

3.3.2.1 Antenna noise temperature

The main contributors to antenna noise are:

– exoatmospheric (background cosmic) radiation;

– the atmosphere, via atmospheric attenuation originating from gas and clouds;

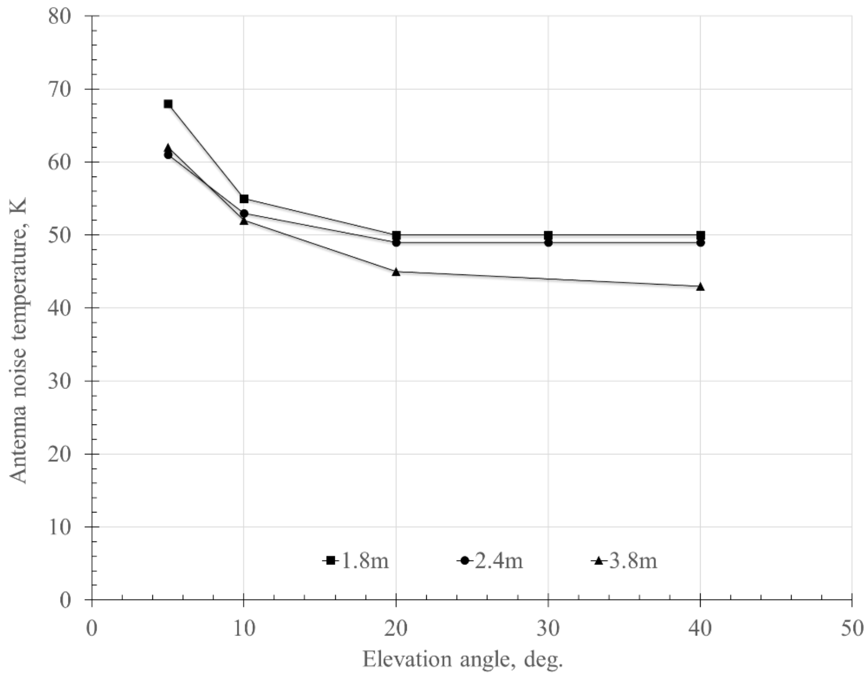
– emission and scattering from the ground.

The precise calculation of the equivalent antenna noise temperature is complex and requires detailed knowledge of the antenna radiation pattern: it involves the integration of the product of the radiation pattern of the antenna with the surrounding scene brightness temperature over the sphere [1].

Manufacturers of antennas provide equivalent noise temperature curves as a function of the elevation angle (see for example [2], [3], [4]). A summary of some of the available data for typical antenna diameters, is provided in Fig. 6.

FIGURE 6

Antenna noise temperature versus elevation angle, for various antenna diameters, based on data made available by antenna manufacturers



As expected, higher antenna temperatures are associated with lower elevation angles. This is because:

a) a larger amount of ground emissions is being captured by the antenna via both its main and side lobes when the elevation angle is close to the horizon; and

b) the path through the atmosphere is longer, and therefore the atmospheric contribution is higher. As the elevation angle increases, antenna noise temperature starts to flatten, and the dominant contributor to the noise temperature is the atmosphere.

The antenna noise temperature can be extrapolated to other elevation angles if necessary, with some accuracy degradation, using as input the known values of the manufacturer curve and by developing the zenith transmission coefficient discussed in Recommendation ITU-R S.733 [5] and considering the dependence of the atmospheric attenuation in clear sky with the elevation angle.

The antenna noise temperature must be low, by design, to support the objective of a high figure of merit (G/T).

3.3.2.2 LNA/LNB Noise temperature

Considering that the TVRO and VSAT installations in C-band use LNB devices, this section will focus on the equivalent noise temperatures of LNB devices.

TABLE 2 contains a non-exhaustive survey of available LNB technical data from manufacturers. From the sample captured it is possible to observe that:

i) the equivalent noise temperature of LNBs in the frequency band 3.4-4.2 GHz does not change when compared against devices limited to an operating frequency band of 3.8-4.2 GHz;

ii) the differences between devices of the Dielectric Resonator Oscillator (DRO) type and those that include Phased Locked Loop (PLL), in terms of equivalent noise temperature, is not appreciable;

iii) a typical noise temperature for an LNB in the frequency range 3.4-4.2 GHz is ~25 K.

TABLE 2

Survey of noise temperature for a set of C-band LNB products in the market

	Type	Operating range (GHz)	Noise temperature (K)
Prod-A	DRO	3.625-4.8	30 K typ. / 35 K max.
Prod-B	DRO	3.4-4.2	25
Prod-C	PLL	3.4-4.2	15 K typ. / 30 K max.
Prod-D	PLL	3.4-4.2	25
Prod-E	PLL	3.4-4.2	30 K typ. / 32 K max.
Prod-F	PLL	3.4-4.2	30
Prod-G	PLL	3.70-4.20	25
Prod-H	PLL	3.70-4.20	30
Prod-I	LNA	3.4-4.2	30
Prod-J	LNA	3.4-4.2 / 3.625-4.2	50

3.3.3 Sample values of earth station temperature and figure of merit

Considering the data and principles described in previous sections, typical values of the earth station system temperature for compact systems such as TVRO or VSAT terminals are:

– at 5 degrees: circa 85 K for 2.4-m and 3.8-m antennas, and

– above 25 degrees: circa 50 K for 1.8-m antennas and 75 K for 2.4-m antennas.

Figure 7 and Table 3 present estimates of earth station noise temperature and figure of merit for a compact system, as a function of elevation angle.

FIGURE 7

Earth station noise temperature for various elevation angles and antenna diameters, based on an LNB temperature of 25 K and the antenna temperature data reported by various antenna manufacturers

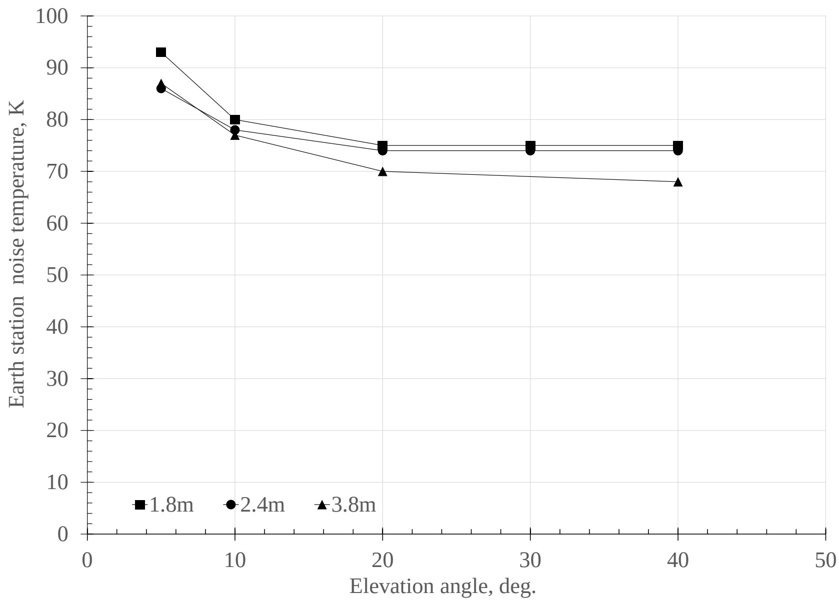


TABLE 3

Illustrative values of earth station figure of merit (dB/K) as a function of elevation angle. Earth station temperature computed using equation (6) with T_{LNA}=25 K

Elevation angle (degree)	1.8 m Gant = 35.6 dBi	2.4 m Gant = 38.2 dBi	3.8 m Gant = 41.8 dBi
5	15.9	18.9	22.4
10	16.6	19.3	22.9
20	16.8	19.5	23.3
40	16.8	19.5	23.5

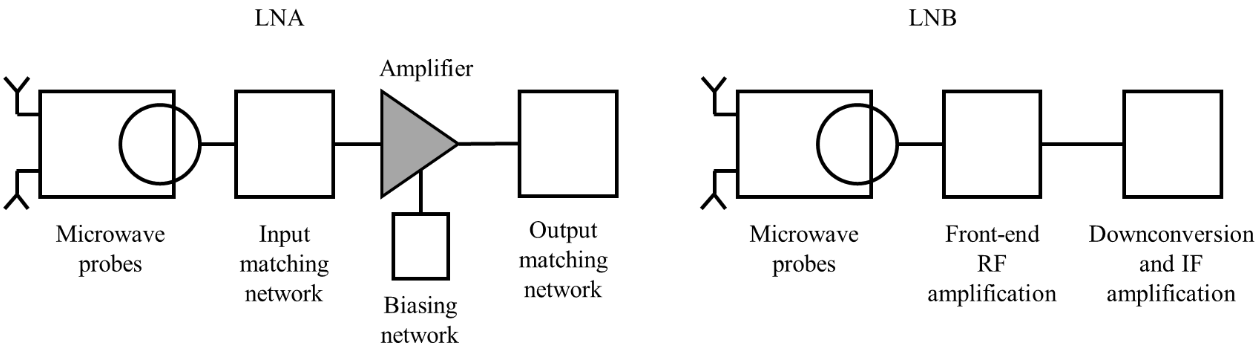
3.4 Low noise amplifier and its intended operating point

3.4.1 Basic block diagrams

Figure 8 presents the block diagram of a single stage LNA. It includes the RF probe block, which is responsible for receiving the microwave radio signal, the amplifier block which incorporates all the microwave components of the receiving chain amplifier and appropriate biasing network, and the input and output matching networks. Matching networks are passive, built using inductors, capacitors, resistors, and stripline elements. A multi-stage LNA is composed of two or more of these basic blocks.

FIGURE 8

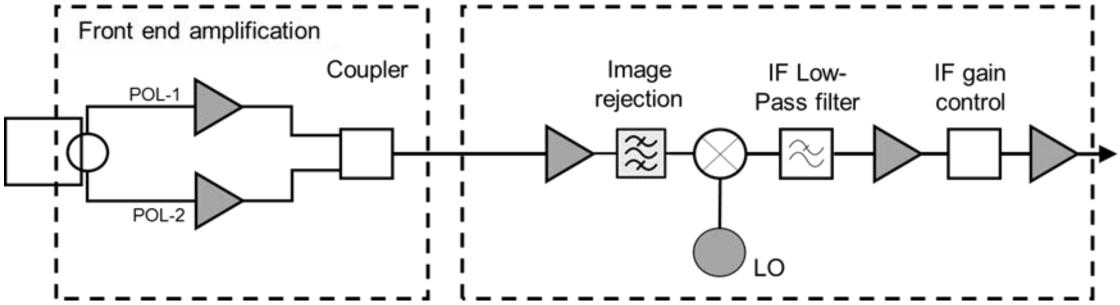
Reference block diagrams of an LNA and an LNB



The basic LNB block diagram, shown in Figs 8 and 9, is composed of three blocks: the microwave probe section, which may include the antenna feed in the case of LNBF devices, the front-end block (FE), which includes the amplifier itself and which provides low noise amplification and ensures sensitivity of the LNB, and the down-converter (DNC) which translates in frequency and provides additional amplification capabilities to the IF signal.

FIGURE 9

Reference block diagram of an LNB device



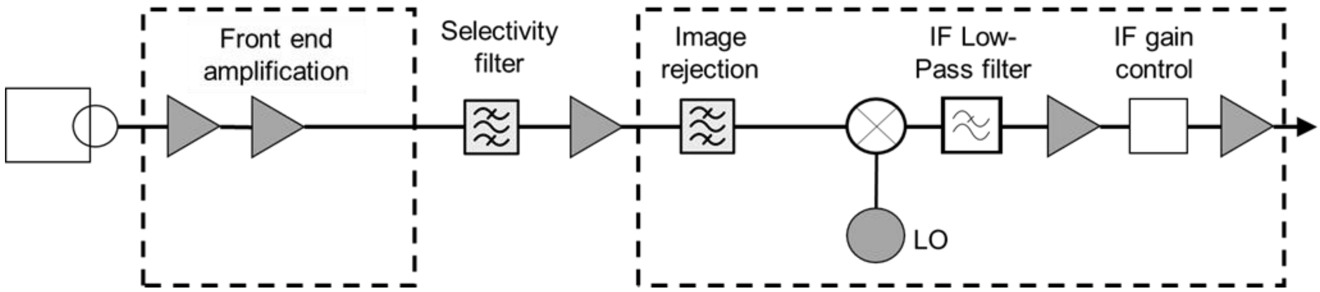
In Fig. 10, the front-end (FE) is the core block that dictates the noise performance of the device, and its critical performance parameters are the noise figure and gain. The FE could have two independent first-stages, one per polarisation, or a single first stage, where an OMT has provided initial polarisation selectivity.

In the classic LNB architecture, the selectivity is driven by the response of the front end and, within it, dictated by the response of the amplifiers. There are no filtering stages associated to this architecture, which makes the front-end wide-band.

Other LNA and LNB design approaches introduce a filtering stage and modified mixing stages to increase its robustness in the presence of high-powered signals at the input. Figure 10 presents an example for the case of an LNB [6]. The addition of a filtering stage contributes to limit the amount of power that the LNB device will receive outside of its intended passband but comes at the expense of a degradation in the device's noise performance.

FIGURE 10

LNB architecture modified to incorporate an RF filtering stage after the front-end block

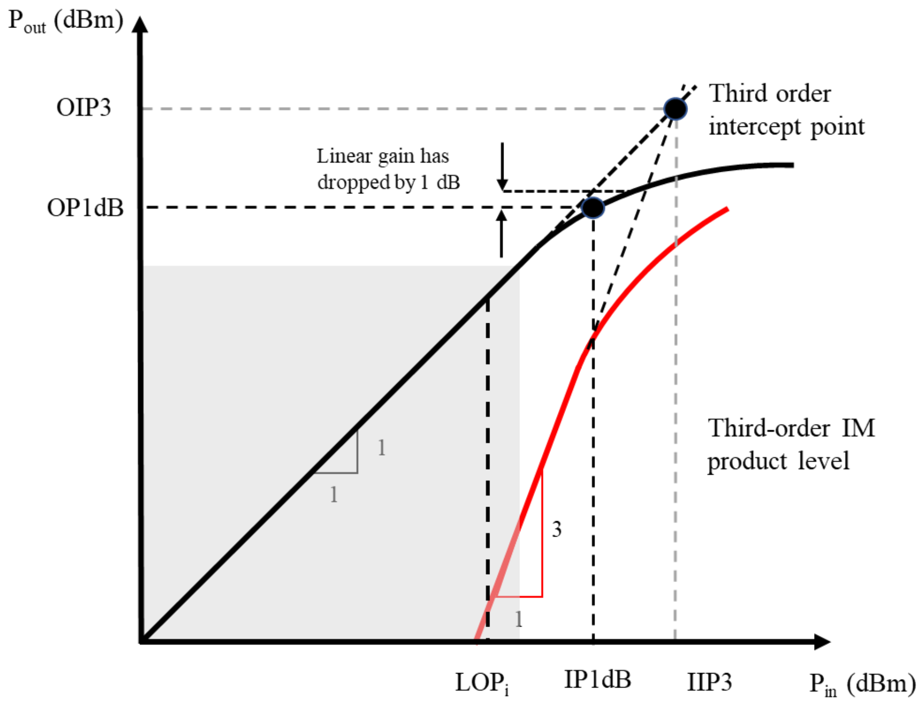


3.4.2 Linear region as a target operating point for the LNA/LNB

Figure 11 illustrates the different operating regions in the gain transfer of an LNA/LNB.

FIGURE 11

Schematic of the gain transfer curve of a solid-state amplifier device and the third-order intermodulation response



Note to Fig. 11: The wanted signal rises with a slope of gain G in dB, while the third-order IM products rise with a slope of gain 3G in dB (60 dB/decade).

The nonlinear behaviour in solid state amplifiers such as LNA or LNB can be characterized by means of the third order intermodulation level, and the third order intercept parameter. The third order intercept represents a virtual point in the gain transfer of the amplifier where the magnitude of the wanted signal level and the resulting third-order intermodulation products is the same. The value of input power at this point is called the input third-order intercept point (IIP3), and the corresponding output power is called the output third-order intercept point (OIP3). Devices with higher values of OIP3 have better large signal capabilities.

Operating in the linear region of the LNA/LNB device guarantees that the distortion introduced by gain compression is minimized and that the combination of multiple signals at the input of the LNB (wanted and unwanted) does not result in the generation of unwanted products (either from reciprocal mixing or from intermodulation) with a large magnitude.

To ensure that the device operates in its linear region, the total power into it must be below a threshold denoted the linear operating point (LOP). The LOP referred to the LNB input can be computed as:

$$LOP_i = OIP3 - 0.5 * \left(\frac{C}{IM}\right) - G_{LNB} \quad (8)$$

where:

*OIP*3: third order intercept point at the output of the amplifier, in dBm

C/IM: target value of the carrier-to-intermodulation product level ratio for operations of the LNB, dB

G_{LNB}: LNB gain, dB

Table 4 illustrates values of the linear operating point threshold for various low noise amplifier types. The computed values consider a design criterion for *C*/*IM* in the LNB of 30 dB that ensures that unwanted third-order products do not become a limiting factor in the performance of the device.

TABLE 4

Example of the operating parameters of LNB products

LNB product	*OIP*3 (dBm)	Gain (dB)			LOP_i (typical, dBm)
		min	typical	max	
LNB Consumer Product 1	9.6		60		−65.4
LNB Consumer Product 2	12.6		58		−60.4
LNB Consumer Product 3	14.6		65		−65.4
LNB Prof. Product 1	12.6	55	60	70	−62.4
LNB Prof. Product 2	19.6	55	62	70	−57.4
LNB Prof. Product 3	25	55	60		−50
LNB Prof. Product 4	14.6		62		−62.4
LNB Prof. Product 5	15	59	61		−61
LNA Product 1	14.6	55	60	65	−60.4
LNA Product 2	20	60	64	66	−59
LNA Product 3	30	60	64	66	−49
Transceiver Product 1	14.6		60		−60.4

From Table 4 the typical values of LOP_i are observed to vary between −60 dBm and −65.4 dBm for LNB devices, and around −60 dBm to −49 dBm for LNAs. Values of LOP_i as low as −72 dBm are possible, depending on device gain. Devices to be installed with large antennas (LNAs) exhibit higher linear operating points, as expected, given their coupling with a large gain antenna resulting in the delivery of higher-powered signals to the low noise amplifier.

Considering the variability of the values of parameters such as device gain and its impact on the value of *OIP*3, and noting Report ITU-R S.2368, which expresses that non-linear behaviour becomes apparent when the input level exceeds a value 10 dB below the input 1 dB compression point, it is suggested to use as a reference a LOP_i value of −68 dBm.

3.4.3 Amplifier desensitization and blocking

Desensitization of a receiver is the condition where the receiver is unable to receive a weak intended signal due to the presence of stronger unwanted signals. Receiver desensitization originates in the intermodulation products (second and third-order) arising from the combinations between *a)* interfering signals and *b)* interfering signals and the wanted signal, which lead to gain compression, carrier suppression and degradation of the noise performance of the receiver circuit. Desensitization due to a single large interferer is called blocking [11]. Section 4.1 reviews the potential for LNB desensitization and blocking arising from the presence of IMT signals within the passband of the earth station low noise amplifier, in the context of spectrum sharing.

3.5 Wideband operation as a design objective of an earth station

Considering the current allocations for fixed-satellite service in the Radio Regulations: the frequency range 3 400 to 4 200 MHz has historically included the fixed-satellite service, fixed service and mobile service as a primary allocation.

The design of earth stations has used a wideband approach. In this scenario, wideband operations refer to the need for the earth stations to be able to tune to any individual carrier within an 800 MHz frequency range. This is a challenging objective considering that it is necessary that the radiofrequency devices operate correctly not only in the frequency range 3 400 to 4 200 MHz of the space-to-earth link, but for transmit/receive devices, also over large portions of the complementary frequency range 5 725 to 7 075 MHz used for the earth-to-space path.

A consequence of this objective is that the devices part of the earth station operating the radio frequency domain are designed to be able to receive and amplify signals in the entire 3 400 to 4 200 MHz bandwidth, and any selectivity is implemented in the devices operating in the intermediate frequency range, at the end of the receive chain.

Refer to the functional structure of the earth station discussed in § 3.1. In the outdoor context, the LNB operates its front-end in the radiofrequency (RF) domain, while in the indoor context the devices operate in the Intermediate Frequency (IF) domain. In both contexts the first stage is wideband, meaning that its intended operating range in the corresponding domain is much wider than the bandwidth of the wanted carriers. Carrier selection and demodulation is performed by the modem or receiver equipment located in the indoor premises or IDU. This happens in a second stage within the IDU receiver device, after the IDU front-end. This stage is the only stage in the receive chain of the earth station that can be characterised by having selectivity.

The total earth station selectivity is the multiplication of the frequency response, followed by integration (over the desired frequency range), of the equipment composing the ODU and the IDU.

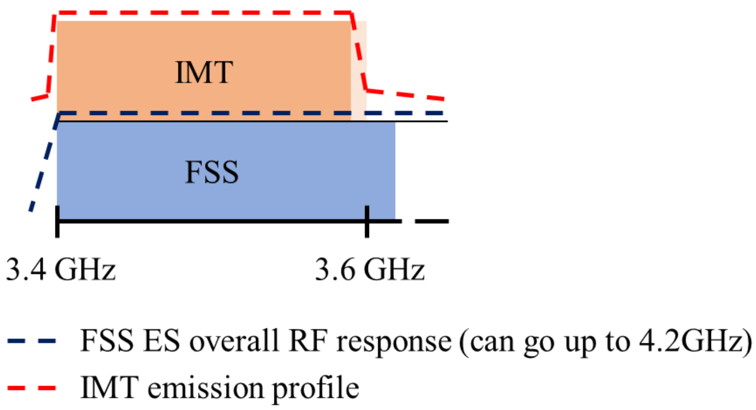
4 Description of the mechanisms involved in interference into the FSS earth station

As mentioned in the previous section, there are two scenarios to identify for which the mitigation measures may be different.

4.1 Co-frequency scenario: IMT and FSS sharing the same frequency band 3.4-3.6 GHz

FIGURE 12

Illustration of a co-frequency spectrum sharing scenario



This scenario considers that the IMT transmitter and the FSS ES operate in overlapping portions of the 3.4-3.6 GHz frequency band, as shown in Fig. 12. The FSS earth station receiver can therefore perceive the IMT in-band emissions within its operating receiving range.

If the wanted FSS signal and IMT signal are using overlapping frequencies, the interfering signal will reach the receiver demodulator, if sufficiently high causing errors in signal demodulation. The impact of such interference is typically assessed in terms of a maximum interference-to-noise power ratio.

In addition, as discussed in § 3, the IMT emissions can cause the aggregate input power into the LNB to exceed its linear operating point threshold.

When receiving from an FSS GSO satellite, the signal levels at the input of the LNB device are weak (with power flux spectral density levels in the range of −136 dB(W/(m^2 · MHz)) compared to terrestrial IMT emission levels. The total power into the LNB, arising from IMT emissions and wanted signals (aggregation of emissions over the LNB passband of 800 MHz) can therefore cause the LNB to operate in the non-linear domain, leading to desensitization and degradation to the output signal from the LNB. Strong interfering IMT in-band emissions can cause the LNB to experience severe non-linear effects, increased noise floor levels and blocking, leading to inability to deliver a usable signal to the devices on the receive chain.

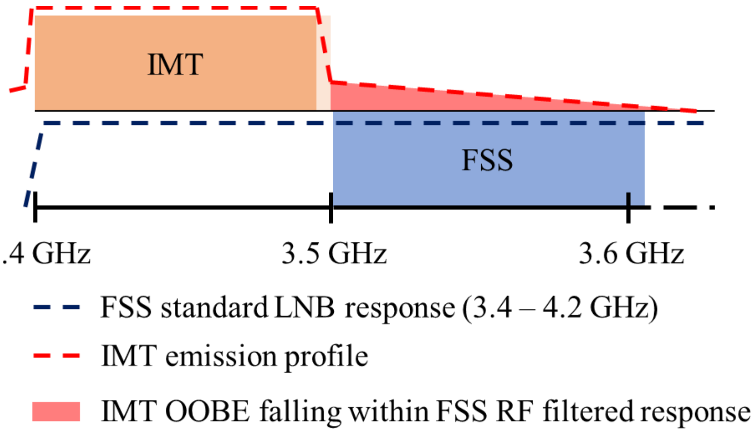
Both these interference mechanisms should be separately assessed.

4.2 Adjacent band scenario example: IMT operating in 3.4-3.5 GHz and FSS in 3.5-3.6 GHz with a standard LNB response starting at 3.4 GHz

This section provides an example of an adjacent band scenario with IMT operating in 3.4-3.5 GHz and FSS in 3.5-3.6 GHz with a standard LNB response starting at 3.4 GHz.

FIGURE 13

Illustration of the adjacent band spectrum sharing scenario



Potential interference arises from two mechanisms in this adjacent band scenario:

– Impact of IMT emissions in the frequency band 3.4-3.5 GHz falling inside the passband of the FSS LNB response.

– Unwanted emissions from IMT stations falling within the operating frequency band 3.5-3.6 GHz of the FSS earth station.

The following sub-sections explain in more detail the mentioned interference mechanisms.

4.2.1 Impact of IMT emissions in the frequency band 3.4-3.5 GHz falling within the FSS LNB response

As described in § 3, the earth stations of the fixed-satellite service are designed to operate on the basis of the current allocations to the FSS in the frequency range 3.4-4.2 GHz. With reference to Fig. 13, in which operations of IMT and FSS are shown as being adjacent in assignments, given the wideband nature of the LNB response and although the FSS wanted signal falls within the frequency band 3.5-3.6 GHz, the LNB will be exposed to the IMT emissions in the frequency range 3.4-3.5 GHz and to the OOB and spurious emissions above 3.5 GHz. In absence of additional mechanisms to mitigate the incoming signals outside the FSS assignment, the LNB will experience an operational condition similar to that of the co-frequency scenario: the aggregate input levels into the LNB can exceed the target linear operating point and the ability to demodulate and decode the signal delivered by the LNB to the user baseband devices will be compromised.

4.2.2 Unwanted emissions falling within the operating frequency band 3 500-3 600 MHz of the FSS

4.2.2.1 General definitions

Article **1** of the ITU-R Radio Regulations (RR) defines unwanted, out of band and spurious emissions as follows:

> «**1.146** *unwanted emissions**: Consist of spurious emissions and out-of-band emissions.»
>
> «**1.145** *spurious emission*: Emission* on a frequency or frequencies which are outside the *necessary bandwidth* and the level of which may be reduced without affecting the corresponding transmission of information. Spurious emissions include harmonic *emissions*, parasitic *emissions*, intermodulation products and frequency conversion products, but exclude *out-of-band emissions*.»
>
> «**1.144** *out-of-band emission*: Emission* on a frequency or frequencies immediately outside the *necessary bandwidth* which results from the modulation process, but excluding *spurious emissions*.»

From the above definitions, Recommendation ITU-R S.1541-6 [12] identifies two specific domains within the unwanted emissions.

– The out-of-band domain: this represents the frequency range immediately adjacent to the necessary bandwidth in which the OOBE will predominate.

– The spurious domain: the frequency range beyond the OOB domain in which the spurious emissions will predominate.

A typical value of cut-off between OOB domain and spurious emissions is around 250% of the necessary bandwidth (see Annex 1 to RR Appendix **3**). Controlling the levels of both the OOB and the spurious emissions originated by radiocommunication systems is fundamental to maintain a controlled level of interference into adjacent band services. The ITU-R, through the implementation of RR Appendix **3** and Recommendation ITU-R S.1541, provides generic limits for all services to follow.

4.2.2.2 Potential impact into the FSS receiver

Through their out-of-band emissions, interference into FSS reception in the frequency band 3 500-3 600 MHz arising from IMT emissions operating in part of the frequency band 3 400-3 500 MHz may appear. Since in this case the scenario considers that the IMT and FSS services are operating in the adjacent band, it is expected that the OOB emissions would have the predominating impact into the FSS receiver performance, which will perceive any power from IMT in the frequency band 3 500-3 600 MHz as interference. Depending on the level of OOB emissions experienced by the FSS receiver, the impact to the FSS earth station performance can vary from negligible, when the perceived OOB emissions level are low, to moderate and impacting the service $C/(N+I)$ and as a consequence reducing the effective link margin available to the service supported by the earth station.

The impact incurred to the FSS ES reception is dependent on several factors such as OOB emission levels, separation distance between services, and relative antenna alignment.

4.3 Overview of applicable ITU-R sharing study results

Spectrum sharing between IMT and FSS earth stations operating in the same band has been studied in the past at the ITU under different agenda items. Report ITU-R S.2368 developed during the WRC-

15 cycle, contains various sharing studies between International Mobile Telecommunication-Advanced systems and geostationary-satellite networks in the fixed-satellite service in the frequency bands 3 400-4 200 MHz and 4 500-4 800 MHz. Some conclusions relative to the in-band sharing scenario are quoted below:

> "Sharing studies have been performed to assess the technical feasibility of deploying IMT-Advanced systems using the characteristics in Tables 1 to 5 of this Report. To provide protection of the FSS receive earth stations operating in the 3 400-4 200 MHz and 4 500-4 800 MHz bands, required separation distances were derived relative to the IMT-Advanced base station location. As can be seen from the results found in § 6, the magnitude of those required separation distances to protect the FSS receive earth stations depend on the topography, parameters of the networks and the deployment of the two services. The results found in this study show that:
>
> – for in-band, co-channel operations, the minimum separation distances associated with long-term interference criterion have been found to be at least several kilometres for the small cell outdoor scenario and at least in the tens of kilometres for the macro cell scenario. The minimum separation distances associated with short term interference criterion have been found to be at least tens of kilometres and extend up to several hundred kilometres in the considered cases with similar assumptions as the ones used for the long term;
>
> – for adjacent-band operations, to ensure that the FSS receiving earth station is not subjected to excessive levels of out-of-band emissions from the transmitting IMT-Advanced base station, the minimum separation distances have been found to be at least several kilometres for the small cell outdoor scenario and at least in the tens of kilometres for the macro cell scenario.
>
> It may be concluded that macro urban, macro suburban and small cell outdoor IMT deployments in this band would likely face sharing problems for the scenarios studied."

4.4 Summary of impact to FSS in absence of mitigation measures

Considering the above-mentioned sharing scenarios and without implementing adequate additional mitigation measures, interference can cause degradation of the services provided by the FSS earth stations including:

– Outage in the services due to suppression, blocking, or saturation (§ 3.3.2) of the earth station LNB.

– Reduction of the service $C/(N+I)$ ratio due to the increased value of interference (I) in the operating band of the earth station, leading to increased BER, the apparition of video artifacts in digital video signals (such as pixelation, freezing) and reaching the cliff effect[3].

5 Mitigation techniques applicable to the FSS earth stations

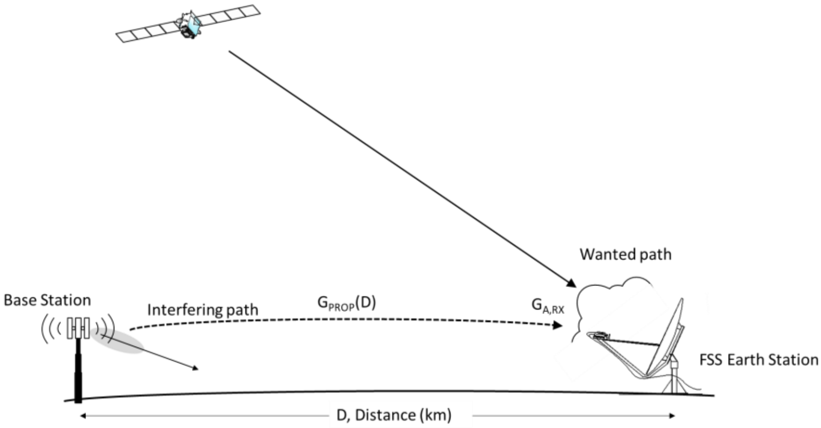
This section discusses the techniques applicable to the FSS earth stations and designed to increase the potential to coexist with IMT operating co-frequency or in adjacent bands. To do this, one must understand the various components that come into play in an interference analysis. Figure 14 provides a graphical representation of the radio paths between an IMT base station and the victim FSS earth station. These earth stations could be either operating co-frequency or in adjacent band (see § 4).

---

[3] The cliff effect is the name given to the loss of video signals in digital transmissions that occurs when the E_s/N_o of the signal falls below the minimum threshold.

FIGURE 14

Example of the radio paths in an FSS – IMT sharing scenario



5.1 Mitigating techniques for co-frequency sharing

This section focuses on the elements that affect the level of interference that can be managed on the FSS receiver side for the co-frequency scenario described in § 4.1. A list below provides an overview of deployment parameters that come into play when assessing the interference received by the FSS earth station in a co-frequency sharing scenario:

– The FSS earth station receiver antenna gain towards the IMT BS ($G_{A,RX}$). This will depend on several factors such as the FSS earth station target satellite, which dictates its pointing in elevation and azimuth, as well as the relative angular alignment of the IMT base station with regards to the FSS earth station.

– The separation distance of the IMT base station and the FSS earth station receiver (D). The larger the separation distance between the two services, the higher the propagation losses and therefore the lower the potential interference perceived by the FSS earth station receiver. See § 7.1.1 for more detail.

– The specific terrain layout around the considered geographic position of the FSS earth station. See § 7.1.1 for more detail.

– Any man-made structure blocking or shielding the FSS earth station from the incoming interfering IMT signals. See § 5.1.1 for more information on site shielding principles.

5.1.1 RF Shielding of earth stations

The principle behind the radio-frequency shielding of an earth station is the attenuation by diffraction or blocking of the incoming interference signals by means of the installation of an artificial barrier. Although this section focuses on artificial barriers, it is also possible to use pits and terrain features and other natural clutter (e.g. trees) to act as natural barriers to achieve the purposes of protection. This use of natural barriers has already been mentioned in § 5.1.1 in the context of the development of protection and exclusion zones considering local terrain information and propagation models.

Among the positive aspects of shielding are that it is useful to prevent interference from any number of surrounding sources and is insensitive to the characteristics of the interfering signals, whilst negative aspects include the inability of the technique to mitigate interference coming into the antenna via its main beam, dimensions and weight associated to some configurations of shields and fences, difficulties in constructing the fence itself, arising for instance from the need to excavate or construct supporting elements, and availability of space to install the barrier itself.

5.1.1.1 Quantifying the benefits of shielding: Site shielding factor (SSF)

The site shielding factor, SSF, is a coefficient that quantifies the degree of isolation provided by an obstacle. A general definition of the factor is [13]:

$$SSF = 20\log_{10}(\frac{D_{with\,obstacle}}{D}) + 20\log_{10}(\frac{I}{I_{with\,obstacle}}) \quad (9)$$

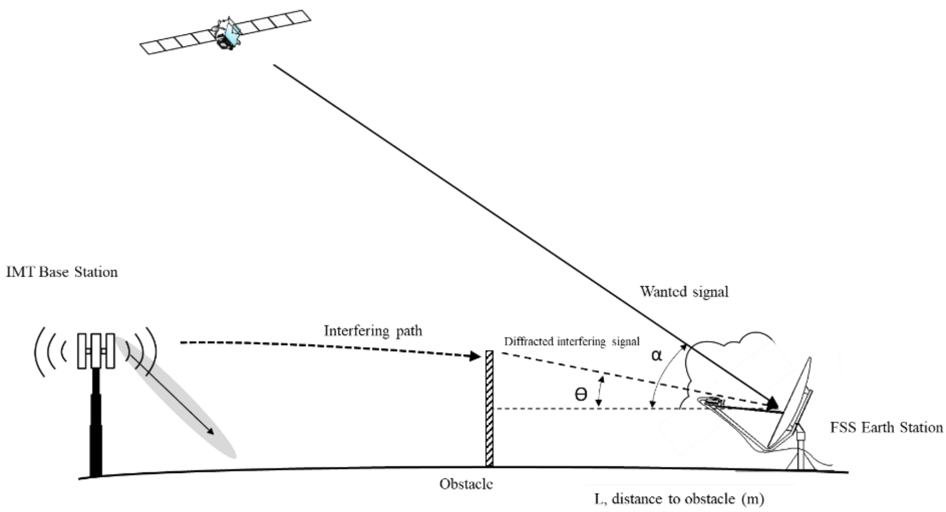
where *D* and *I* are the desired (wanted) and interfering electric field strength at the receiver.

When the presence of the obstacle has no effect on the desired signal, the factor reduces to $20\log_{10}(\frac{I}{I_{with\,obstacle}})$, matching the traditional definition of SSF as the ratio of the received unwanted powers in absence and presence of the obstacle [14].

The general geometry of the system is shown in Fig. 15. For a given site, the SSF may be determined by evaluating the signal level incident at the earth station, with and without the obstacle on the path, as a function of the distance *L* between the obstacle and the antenna, the elevation angle α of the path to the satellite and the elevation angle θ towards the obstacle.

FIGURE 15

General diagram for site shielding using a single artificial barrier



The analysis of both the desired and interfering signal levels in the presence of the obstacle requires computations of the diffraction of the signals over the edge of the obstacle, as well as an analysis of the radiation characteristics of the antenna under analysis in presence of the obstacle, which may be in the near field region of the antenna.

The magnitude of the SSF is dependent on various parameters such as the structure of the earth station antenna, and parameters of the geometry of the path antenna-to-obstacle such as the obstacle elevation angle as seen from the antenna and its distance to the earth station antenna.

The CCIR in Report 390-6 [15] proposed a method derived from the calculation of the diffraction loss caused by a single knife-edge obstacle, which permits calculations of the SSF for obstacles located at distances meeting the Rayleigh far-field criterion ($L > d^2/2\lambda$ where *d* is the antenna diameter).

A more detailed treatment of the impact of the shield upon the system needs to consider that the obstacle could be in the near field region of the victim earth station, and that a general diffraction model will be required for accurate characterisation of the obstacle including accounting for finite conductivity, modifications to the edges (serrations, slots) or the use of absorbing materials to line the obstacle edges. An overview of the elements involved in the calculation of the SSF is presented in 0.

5.1.1.2 Shielding structure and materials

The simplest shielding structure consists of a wall or fence surrounding the sides of the antenna to be protected. These fences can be constructed using wire mesh, with openings that are dependent on the wavelength of the interfering signal to be attenuated. To mitigate the field diffracted at the top of the structure, the top of the fence is rounded (to reduce similarities to a knife-edge obstacle), or serrated [16], [17].

In addition, for cases where the earth stations are shielded from interference from sources in opposite sides of the antenna using two structures opposite each other, the barrier could be installed with a slope or with a sloped section added to the top of the shielding obstacle or fence, in order to minimize the impact arising from diffracted rays from one shielding structure being reflected into the antenna by the second shielding structure. In certain cases, where the installation of sloped section or tilting the barrier is impractical, the addition of absorptive material on a portion of the shielding structure facing the antenna may be a viable alternative.

5.1.1.3 Side effects of the shielding structure on system performance

Depending on the characteristics of the shielding structure such as material, shape, height, width, distance to FSS earth station and blockage of the main lobe of the reflector, the addition of this shielding structure can cause the following effects [16]:

– Modifications to the radiation pattern and gain reduction: arising from the superposition of the desired field with the field diffracted from the shielding structure.
– Increase in antenna noise temperature.
– Depolarization of the incoming wanted and interfering signals.

5.1.1.4 Practical limitations associated to shielding of an RF earth station

One major drawback associated to the installation of RF shields around earth stations is that the dimensions of the shielding structure can become large. The structure would need to be generally higher than height of the earth station antennas, but not so high as to restrict the visibility to a satellite and be sufficiently wide. Installation of shielding is complicated where multiple earth stations are present on a site whereby individual screening may be required around each earth station or around the site. Furthermore, the environmental impact of having large shielding structures around earth stations needs to be considered, together with any operational restrictions that may result in limiting the visibility of the GSO arc from the earth station or the ability to receive inclined orbit satellites for which the resulting elevation angle may be low. In case of teleports and large earth stations, given that the size of the area to be protected could be considerable, shielding as a mitigation technique may not be practical.

From a construction perspective, the required building materials, the overall shape of the shielding structure (e.g. concrete, mesh grid made of aluminum or steel, etc.) and the methods and requirements for its installation, may impose civil engineering constraints that could also render impractical the installation of shielding structures even for small or medium size earth stations.

5.1.2 Mitigation of interference by adaptive signal processing

Advances in signal processing and signal detection and reduction permit its use as a technique to facilitate coexistence of services both in co-frequency and adjacent band scenarios.

Interference cancelling algorithms can deliver a processed version of the wanted signal that has portions of the overlapping interfered signal removed or highly attenuated.

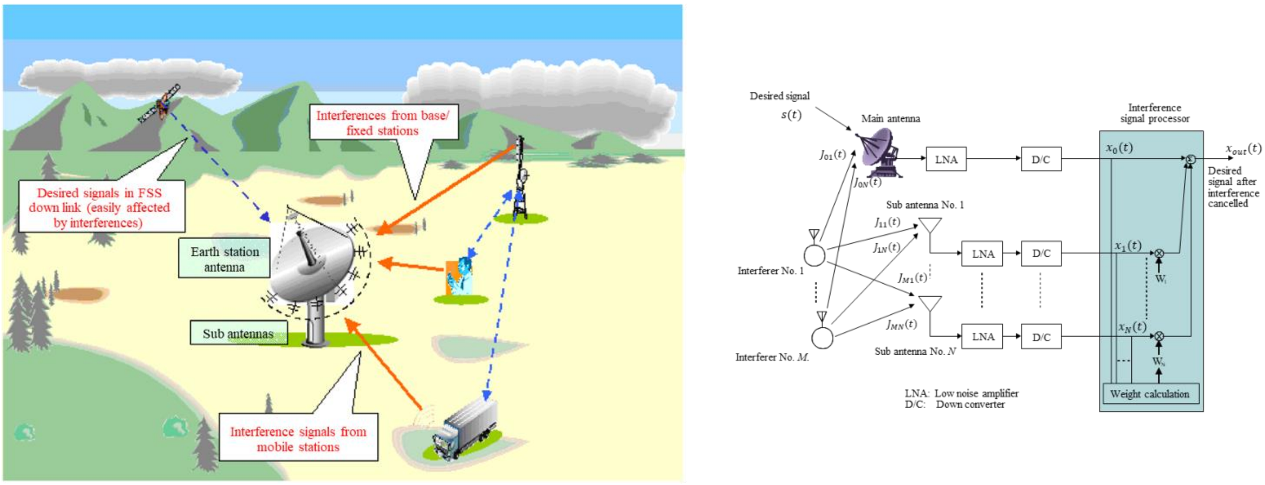
The algorithms take as input at least two signals, the primary input corresponding to the combined desired plus interference signal received by the main antenna, and secondary inputs corresponding to samples of the interfering signal received by secondary antennas or probes. The output is a digitally filtered signal, using a filter with adaptive weights, in which the information from the secondary inputs is used to remove the interference present in the primary input.

In the context of FSS / IMT coexistence, the antenna in the FSS earth station is the main antenna, and a series of secondary antennas, directed horizontally, with a gain pattern that minimizes the signal level received from the space-earth path, and receiving the interfering signal from the IMT stations correspond to the secondary antennas.

Report ITU-R M.2150 [18] describes the use of an interference cancellation algorithm in the context of coexistence of the FSS and IMT application. Figure 16, extracted from the Report, illustrates the basic diagram of the system.

FIGURE 16

Overall concept and principles of the interference reduction by adaptive cancellation technique



Given the principles of operation of the system, requiring samples of the interfering signal which do not contain a large component of wanted signal, the benefits of such a system are limited when the interference arrives near the direction of boresight of the main FSS antenna. Therefore, the technique may have limited benefits when the operational elevation angle of the FSS earth station is low.

5.2 Mitigating techniques for adjacent band sharing

In the case where IMT operates in a band adjacent to FSS, interference from out-of-band IMT station emissions can cause signal quality degradation and even interruption of FSS service unless adequate protection measures are considered.

5.2.1 Mitigating received IMT in-block interference and LNB blocking

To protect the LNB from desensitisation and blocking, as discussed in § 3, it is necessary to reduce the amount of unwanted signal power arriving at the input of the device. This can be achieved by the introduction of a frequency selective device, that is, a device whose frequency response 'selects' certain frequencies above others. An example of such device is a radio-frequency filter. The introduction of RF filters in the receive chain of the FSS earth stations is an effective technique to reduce the amount of power from a specific frequency range present at the input of the earth station LNB.

Filters can be added to existing earth stations either as independent devices, with the appropriate waveguide interface to match the feed and LNB flanges or, via the use of an LNB with integrated filtering (see § 3). Figure 17 illustrates a receive chain with the addition of an RF filter before the LNB. RF Filters can also be incorporated into the LNA/LNB device. In these cases, additional challenges arising from the amount of space available in the device housing appear, which may limit the complexity and achievable selectivity of the filter.

FIGURE 17

The receive chain of an FSS earth station with an RF filter installed.
The right-hand side picture illustrates a dual polarisation configuration

In addition to modifying the frequency response of the receive chain of the earth station, as discussed in § 3.3, the introduction of a filter will increase the losses in the receive path, reducing the total gain of the receive chain by its insertion loss factor l and increasing the noise temperature of the system by a factor of $T_0\left(1-\frac{1}{l}\right)$.

5.2.1.1 Filtering of RF signals

Filters can have one of five responses low-pass, high-pass, band-pass, band-stop (including notch filters), and all-pass. In the discussion that follows, the focus will be on band-pass filters, as it is the required response in the context of the coexistence of IMT and FSS systems in adjacent bands.

The response of a band-pass filter is composed of three regions:

– Upper and lower rejection regions: characterised by high attenuation and designed to limit the contribution of signals with frequencies inside the limits of those regions into the load. These are the continuous ranges of frequencies that the filter is expected to stop, with some minimum specified attenuation value;

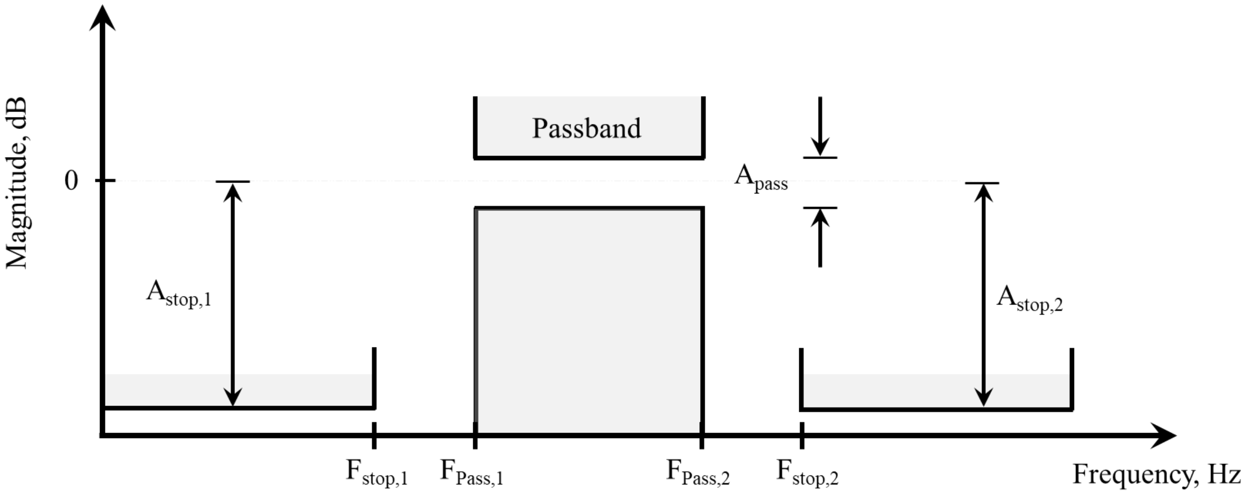
– Pass-band region: characterised by low attenuation, and with a width equal to that of the desired bandwidth, it is the continuous set of frequencies which the filter is expected to let through without excessive attenuation or distortion;

– Transition bands: regions in between the passband and the rejection bands, in which the response of the filter is decreasing in attenuation, from the rejection levels (high) to the passband levels (low). Within this region, the filter's response does not meet neither the rejection nor the passband criteria. The width of the transition region is a critical design parameter and influences the characteristics of the transfer function and the methods used in the design of the filter.

The main trade-off in filter design is between constraining the width of the transition bands and the filter order –its complexity[4]–, related to the number of components or discernible structures required to implement a filter [19]. Figure 18 illustrates the main parameters describing the frequency response of a band-pass filter.

FIGURE 18

Illustration of the regions in a band-pass filter frequency response. Regions between specification values such as $F_{stop,1}$ and $F_{pass,1}$ are transition regions where the filter response is not explicitly defined



The parameters are defined as follows:

– A_{Pass}: Maximum variation of attenuation (dB) allowed in the passband response. Also referred to as insertion loss.

– $A_{Stop,1}$, $A_{Stop,2}$: Attenuation (dB) associated to the stop-bands or rejection bands.

– $F_{Stop,1}$, $F_{Stop,2}$: Cut-off frequencies (MHz) to transition out of and into the lower rejection and upper rejection bands, respectively.

– $F_{Pass,1}$, $F_{Pass,2}$, the begin and end frequencies (MHz) of the filter's passband, defining its operational bandwidth.

5.2.1.1.1 Selectivity

The selectivity of a filter is its ability to suppress the signals outside the intended passband. The selectivity of a filter can be represented through parameters such as the shape factor, which indicates the ability of the filter to transition from the stop band region to the passband.

$$SF = \left(\frac{F_{Pass,2} - F_{Pass,1}}{F_{Stop,2} - F_{Stop,1}}\right) \quad (10)$$

A low value of the shape factor is associated to narrow transition regions.

5.2.1.1.2 Parameters defining the behaviour in the passband: Insertion loss and insertion loss ripple

The insertion loss (IL) is the amount of power lost as the signal traverses the filter. It can be computed as:

[4] The order, N, is the number of poles in the filter's transference function.

$$IL_{dB} = 10\log_{10}\left(\frac{P_{Out}}{P_{In}}\right) \quad (11)$$

where P_{out} and P_{in} are the output and input power, respectively.

An insertion loss specification is necessary to provide a target for what is considered an acceptable value of attenuation within the filter intended passband.

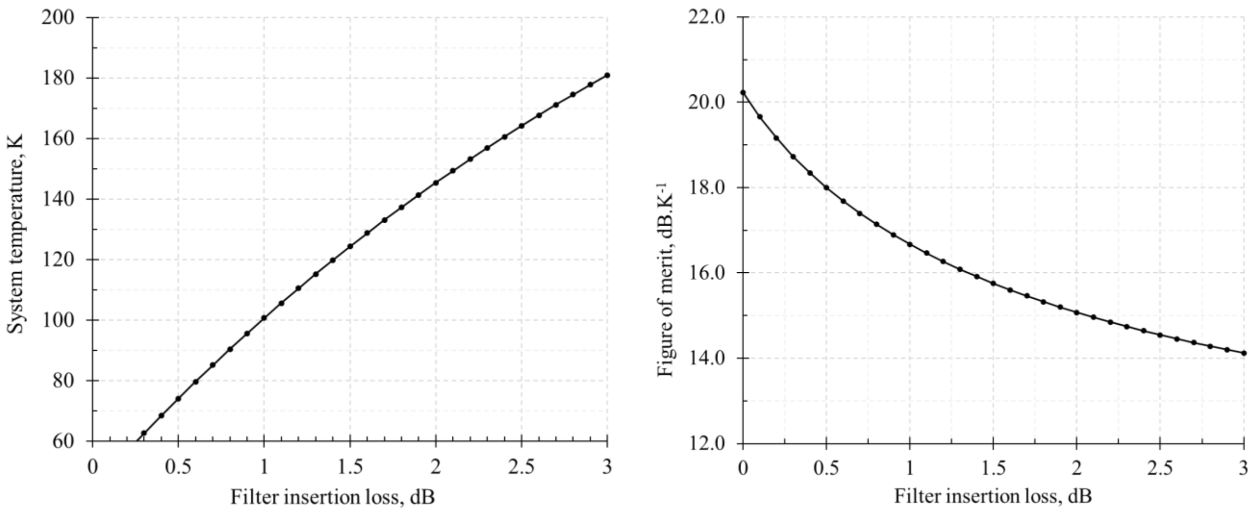
A related parameter is the insertion loss ripple, defined as the peak-to-peak variation of the insertion loss within the passband (flatness of the signal as it passes through the passband).

5.2.1.1.3 Increase in earth station noise temperature

Following the model in equation (6), the impact of the introduction of a filter on the earth station *G*/*T* can be computed. Figure 19 presents some illustrative results. The calculations assume a physical temperature of 20° Celsius, and a 2.4-m reflector antenna with gain of 38.2 dBi and operating at an elevation angle of 30 degrees.

FIGURE 19

Illustration of the impact of the insertion loss of a filter on the earth station noise temperature and its figure of merit



5.2.1.1.4 Phase and group delay

The phase response of a filter is of particular importance, considering that the decomposition of a signal in its various frequency components and subsequent faithful reconstruction relies on the amplitude and phase of those components remaining unmodified. The phase response of a filter could introduce changes to the phase of the frequency components of the input signal, thus affecting the characteristics of the signal at the output of the device. Another metric is the group delay, which is defined as the change of phase with frequency. Phase and group delay have an impact on the performance of digital modulations, as they are linked to inter-symbol interference. For modulations using amplitude and phase to encode information, uncompensated changes in the phase will distort the resulting constellation, shifting the position of a symbol from is intended location and resulting in erroneous decoding of the symbol at the receiving end. In consequence, the introduction of a filter will not only affect the service by an insertion loss penalty, but digital carriers may experience degraded BER if the overall group delay profile of the transmission path exceeds the equalization capability of the demodulator.

Ideally, a linear phase response -and in consequence a flat group delay response- are desired to minimize distortion of the digital signal. Since group delay variation over frequency degrades any signal, it is desirable that the filter's contribution to the overall group delay of the transmission chain is low. Group delay specifications must be prepared considering the characteristics of the FSS modulations, including symbol rate ranges.

It must be noted that the equalizers on modern satellite receivers are able to compensate for some of the issues introduced by group delay but may not be able to accommodate large variations such as those present around the edges of the passband of filters exhibiting sharp transition regions, as illustrated in Figs 22 and 23.

5.2.1.1.5 Other parameters

Finally, there are other environmental parameters that affect filter performance. For example, depending on the materials used to construct the microwave filter, changes in temperature will cause variations in the geometry of the filter structure. Such changes will give rise to variations in the frequency response of the device, known as frequency drifts. Temperature-induced drift is thus the fractional frequency change with respect to temperature change.

The frequency after a temperature change ΔT, $f(\Delta T)$, can be expressed as:

$$f(\Delta T) = \frac{f}{1+\alpha\Delta T} \tag{12}$$

and Δf, the change in frequency with respect to a reference value f_r arising from a change in temperature ΔT, can be expressed as:

$$\Delta f = f(\Delta T) - f_r = \frac{-\propto\Delta T f_r}{1+\alpha\Delta T} \tag{13}$$

where α is the coefficient of thermal expansion (CTE) of the material. The change in frequency is proportional to the coefficient of thermal expansion of the materials used to construct the filter and approximately linear with temperature [20], [21]. Temperature induced drift, δ is finally expressed as:

$$\delta = \frac{\Delta f}{f_o\Delta T} = \frac{-\alpha}{1+\alpha\Delta T} \tag{14}$$

The accuracy of the simplified expressions above increases as the product $\alpha\Delta T$ approaches zero [21].

Temperature-induced drift is a critical factor to consider when high selectivity and steep transition bands are required in a filter response, as any shift on the cut-off frequencies of the rejection bands will result in additional interference into the system, and any shift (positive or negative) of the passband can result in undesired attenuation of the wanted signal.

Table 5 provides an example of the parameters required to fully specify a filter.

TABLE 5

Example of a table of specifications of an RF filter, including electrical and mechanical parameters

Electrical specifications	Value
Pass band limits	MHz
Insertion loss within the passband	dB
Return loss within passband	dB
Group delay variation ±0.5 MHz from any frequency within pass band	ns
Rejection below FS,1	dB
Rejection below FP,1	dB
Rejection above FP,2	dB

TABLE 5 (*end*)

Electrical specifications	Value
Rejection above FS,2	dB
Mechanical specifications	**Value**
Interfaces (waveguide, coaxial)	INPUT/OUTPUT
Maximum dimensions (LxWxH). Length inclusive of flanges. Width and Height exclusive of flanges.	Cm/mm
Operating temperature	deg. C

For a more detailed discussion of RF filters, refer to [19].

5.2.1.2 Quantifying filter improvement from specifications: effective rejection and net filter discrimination

The effective filter rejection is the measure of the total rejection provided by a filter and is needed to determine the type of filter to install. It can be understood as the insertion loss computed within the rejection regions, outside the filter's pass band, relative to the insertion loss experienced in the passband.

The magnitude of the required minimum filter rejection will depend on the emission profile of the IMT application, any frequency separation between services (which should dictate the width of the filter's transition region), and other parameters such as the relative angle of alignment between interfering stations and FSS stations, distance separation between IMT and FSS stations beyond which they are considered compatible, etc.

The minimum rejection required for a victim-interferer link configuration can be determined by considering the following parameters:

– the magnitude of emissions from IMT stations;

– the number of interfering stations;

– discrimination of the FSS station antennas;

– the magnitude of the desired FSS signal level in the band 3 400-4 200 MHz.

Considering the step-wise specification of the filter device, the effective rejection *Eff.Rej* (with values in the range [0, 1]) is defined as:

$$Eff.Rej = \frac{P_{out,Tot}}{P_{in,Tot}} = \frac{\sum_{i=1}^{n} \mathrm{rej}_i.(\mathrm{PSD}_i \cdot \mathrm{BW}_i)}{\sum_{i=1}^{n} \mathrm{PSD}_i \cdot \mathrm{BW}_i} = \frac{1}{P_{in,Tot}} \cdot \sum_{i=1}^{n} \mathrm{rej}_i.(\mathrm{PSD}_i \cdot \mathrm{BW}_i) \qquad (15)$$

where:

i :	section in the filter frequency response specification
rej_i :	rejection for step i
BW_i :	bandwidth of step i
PSD_i :	power spectral density for step i
$P_{out,Tot}$:	total output power
$P_{in,Tot}$:	total input power.

The effective filter rejection is useful to compute the total input power into the earth station LNB when the filter specification is known. When the magnitude response of the filter device is available, numerical integration of the response is recommended.

5.2.1.3 Filter response design trade-offs

Once the performance requirements have been established, e.g. width of the reference bands and required rejection, a filter reference class can be selected.

For example, filters of the Butterworth class deliver flat pass band response at the expense of selectivity, as a sharper transition between rejection and passband has immediate effect on the magnitude of the passband ripple. Pass-band ripple is an undesired side effect of a filter design response, as it will cause a degradation in performance of any signal present within the bandwidth where ripple is appreciable. In the specific case of satellite services, it will cause additional attenuation within the bandwidth of the satellite service that may not be present in other frequencies closer to the centre of the passband.

An alternative is the Chebyshev class, in which gain ripple is sacrificed at the expense of sharpness of the transition. In this case, the greater the ripple allowed, the faster the transition from the stop-band to passband can be. Chebyshev class filters are also called ‘equiripple’. Equiripple in this context means that the maximum deviation from the desired gain response due to ripple within the passband or stopband is kept at a value less than a design objective (constant). With Chebyshev class filters, as the order increases, the ripple increases and the transition between passband and stopband becomes narrower.

5.2.1.4 Comparison of filter functional class for two different transition region widths

Comparing the behaviours illustrated in Figs 20 to 23:

– For a given frequency in the transition region, there is a large variation in rejection. For the configuration in the illustration, Chebyshev functions of type I provide more rejection than the others. In consequence, it is recommended to include at least an additional rejection requirement inside the passband, to ensure a minimum of rejection of any emission within the transition region.

– The realisation functions exhibit different passband ripple behaviour. A Chebyshev type II function exhibits –ideally– 0 dB of ripple in the passband, while the other classes exhibit higher amounts of ripple.

– Filters with larger transition region width exhibit less ripple, at the same peak-to-peak amplitude. For the example, compare the Chebyshev Type I design with 40 MHz transition region to the design with 20 MHz transition region width: the wider transition region design exhibits fewer ripples within the passband.

– From the group delay perspective, a reduction in the transition region width results in double the amount of group delay at the start of the passband and in additional ripple within the passband.

FIGURE 20

A comparison of the magnitude response for various types of filter realisation function. Transition region of 40 MHz

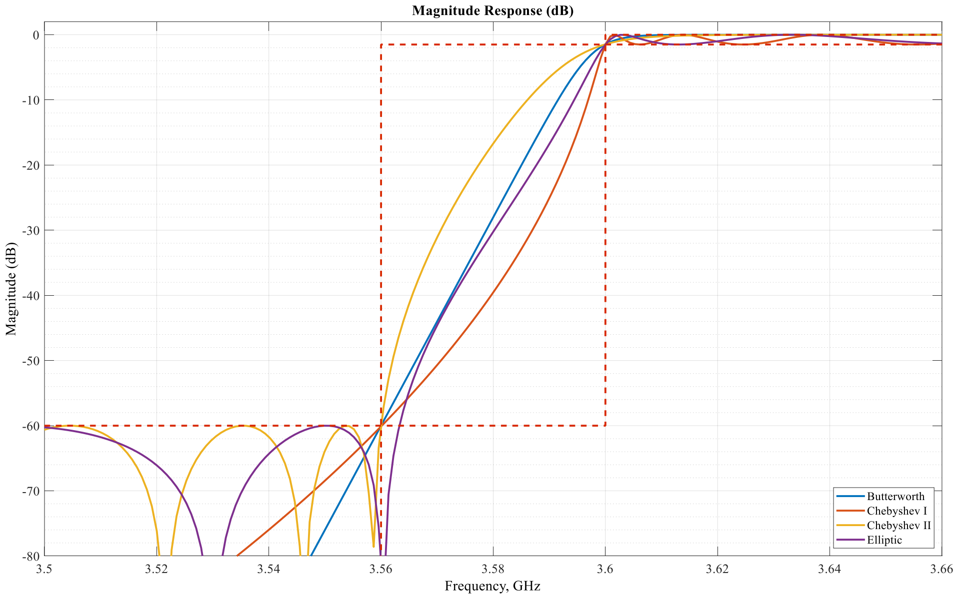


FIGURE 21

A comparison of the magnitude response for various types of filter realisation function. Transition region of 20 MHz

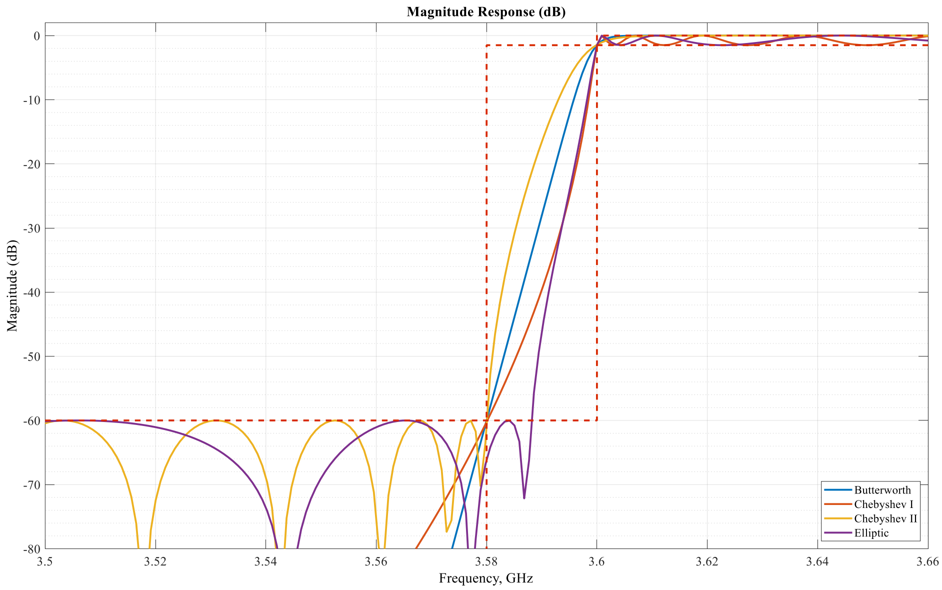


FIGURE 22

A comparison of the group delay response for various types of filter realisation function. Transition region of 40 MHz

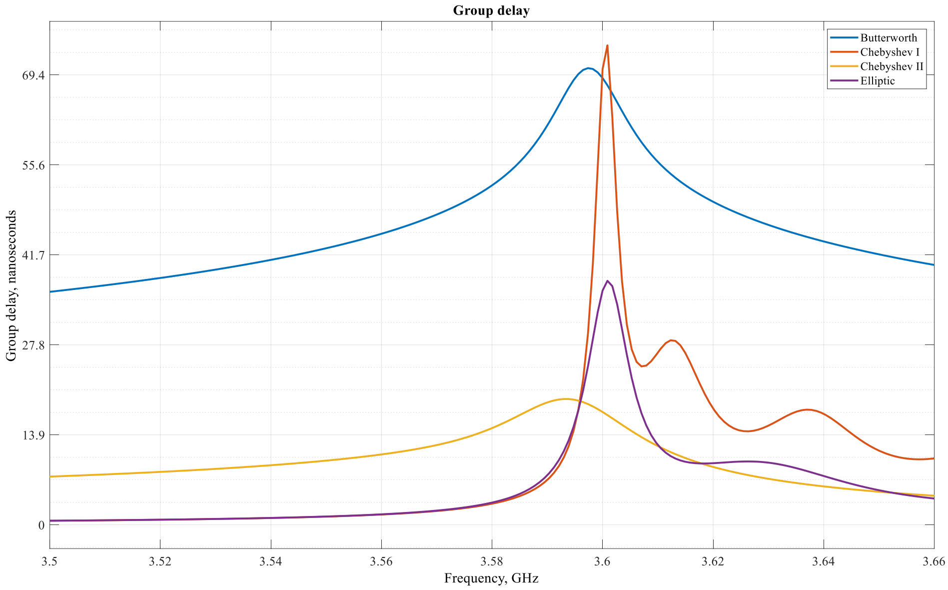
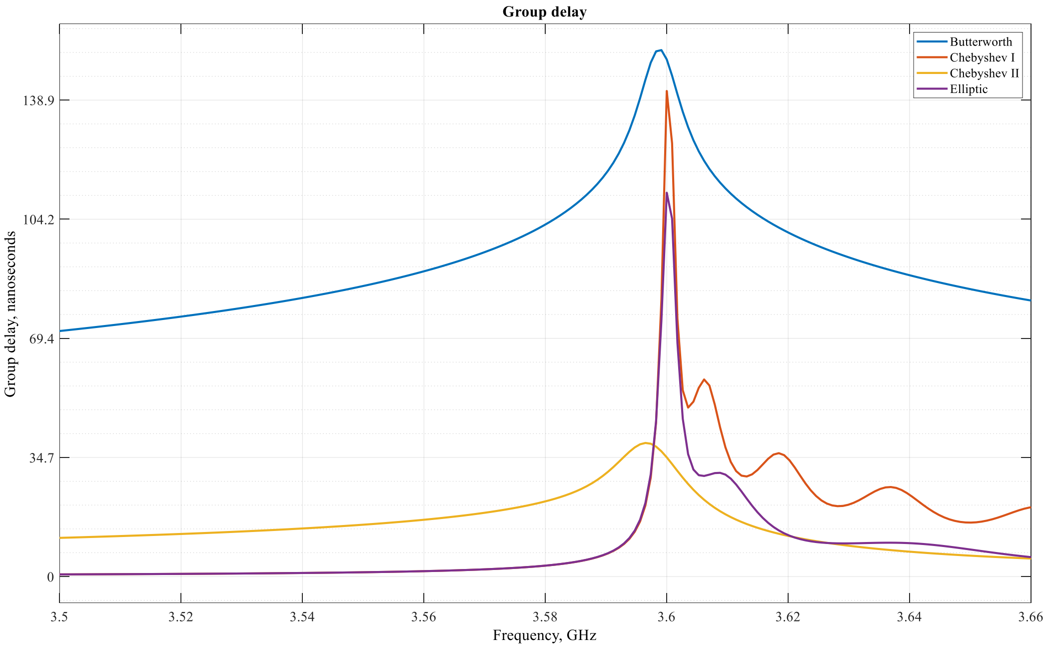


FIGURE 23

A comparison of the group delay response for various types of filter realisation function. Transition region of 20 MHz



5.2.2 Reducing the level of IMT unwanted emissions into the FSS earth stations operating band

As described in § 4.2.2, the unwanted emission signals falling within the FSS earth station operating frequency band 3.5-3.6 GHz originate from the IMT unwanted emissions in the out-of-band (OOB) and spurious domains. These unwanted emissions fall into the FSS operating band and cannot be removed using RF filters at the FSS earth station without impacting the FSS signal in the process. Considering this, the mitigation techniques for this type of interference are similar to those presented for the mitigation of unwanted emissions in the co-frequency sharing scenario in § 5.1, i.e. combinations of separation distances and shielding of the FSS earth station.

An aspect to consider, compared to the co-frequency case, is the magnitude of the IMT out of band emissions. Limits on unwanted emissions out of the intended operating block can be set by means of a Spectrum Emission Mask (SEM, see § 8). The out of block portions of a SEM are usually related to device's OOB emissions and thus the IMT unwanted emissions in the out-of-block segments and out of band domain, falling within the FSS operating band, could be mitigated/reduced when the out-of-block domain contains levels defined considering the adjacent band coexistence parameters. An SEM can be defined at national or regional level, to mitigate the degradation of services in the adjacent band where unwanted emissions are dominant in the interference scenario compared with receiver selectivity / blocking. Where receiver selectivity/blocking is the dominant issue, reducing unwanted emissions will be of limited benefit.

5.3 Use of adaptive waveform as an interference mitigation technique

Some FSS links are capable of adapting their waveforms depending on the carrier to noise (*C*/*N*) levels received. This technique is known as adaptive coding and modulation and is further described in Recommendations ITU-R S.1061 and ITU-R S.2131. Interfering signals increase the noise present in the system (thermal or due to non-linearities in the devices part of the system), giving origin to the carrier-to noise plus interference ratio, $C/(N+I)$, which will decrease with increasing impact of interference coming from IMT emissions. With links supporting adaptive waveforms, a more robust modulation scheme, i.e. one requiring a lower value of $C/(N+I)$ to reach the desired BER, will be automatically selected by the system, in response to the $C/(N+I)$ of the received signal and used to ensure the continued operation of the service and to maintain service uptime. However, the use of a more robust modulation scheme in the link also results in a reduced spectral efficiency, i.e. a lower user information rate, and therefore a reduction in the throughput of the service which may cause a violation of service level agreements based on link throughput.

Whether adaptive waveforms are beneficial from the interference management perspective will depend upon the type of service provided and the available link margin: some links may require operating at fixed throughput or constant bit rate therefore not able to benefit from adaptive waveforms or may operate at $C/(N+I)$ values such that adaptation may not bring material benefits. In addition, while signal adaptation could be an effective way to mitigate transient interference events, it may not be suitable as a permanent mitigation technique to accommodate time-invariant or long-term interference as this would mean a continuous degradation of the FSS service, which can be more effectively mitigated using alternative methods.

6 Mitigation techniques applicable to IMT networks

This section discusses possible techniques applicable to the IMT networks and designed to increase the potential to coexist with FSS earth stations operating co-frequency or in adjacent bands. It is noted that the implementation of a national registry of receiving FSS earth stations can be considered by regulators, to help to ensure their protection and to identify areas where to apply the mitigation techniques listed in this section.

6.1 Sector pointing to reduce emission power towards FSS earth station

The aim of this technique is to reduce the base station emissions in the direction of the interfered-with FSS earth station. Generally, IMT base stations utilize sectoral antennas (e.g. 3- and 6-sector configuration) pointing in different directions. Accordingly, one way to reduce base station emission in the direction of an interfered-with FSS earth station is to avoid having the antenna sector pointing towards the FSS earth station, noting that such an area would need to be served by a different sector that is not pointing towards FSS earth station. Section 8.1.5.1.1 of Report ITU-R M.2109 presents some results on the potential improvement of the coexistence scenario through consideration of sector pointing between IMT-Advanced and FSS earth station receivers. However, the feasibility and practicability of implementing this technique has not been captured in this Report.

The application of this method will require careful network planning to mitigate the introduction of coverage gaps. This approach will depend greatly on the operating parameters of both the IMT base station and the receiving FSS earth station, e.g. the earth station's pointing angle and location.

6.2 Adaptive beam forming for active antennas

Downlink antenna beam-forming is a technique in which the gain pattern of an adaptive array is steered in a desired direction through either beam steering or null steering signal processing algorithms. When these algorithms are implemented using a digital signal processor, we refer to them as digital beam-forming. This allows the antenna system to focus the maxima of the antenna pattern towards the desired user while minimizing the impact of noise, interference and other effects from undesired transmitters that can degrade signal quality. The effectiveness of adaptive beam-forming will depend on the application and the number of nulls (or beams) to be created. The beam-forming technique is also a composite part of Multiple Input Multiple Output (MIMO) space division multiple access (SDMA) and is sometimes referred to as the MIMO SDMA mitigation technique.

In a multi-user environment, an improvement in performance is observed due to the fact that an adaptive beam forms the maxima towards the desired signal and at the same time tries to steer nulls towards the interfering signals, thus reducing co-channel interference. Note that the beam pattern of both receive and transmit antennas can vary. Therefore, the set of nodes with which a given node can close a direct link depends on the beam patterns for both transmission and reception.

When considering the protection of a potential FSS earth station victim receiver at a known location, adaptive beam forming can be considered as a possible mitigation technique by steering the nulls in the direction of the FSS earth station. This would indeed help to minimise interference towards the victim receiver.

This technique would require replanning of the IMT network to serve areas created by the null steering.

6.3 Multiple input, multiple output (MIMO) technique

With this method, a sensing device/circuit is installed on each FSS earth station to be protected and channel propagation conditions (i.e. amplitude and phase variations on propagation from an IMT base station to the FSS earth station) are fed back to the IMT base station. More flexible MIMO configurations can be utilized in order to reduce the interference power from IMT base station into the FSS earth station. The required reaction time for changing the transmit antenna pattern at the IMT base station should be decided on a case-by-case basis. Such a MIMO configuration with feedback information could be applied to multiple antennas within a sector of an IMT base station (i.e. intra-sector), multiple antennas of different sectors in an IMT base station (i.e. inter-sector), and multiple antennas among multiple IMT base stations (i.e. inter-site).

This method may be used to estimate the propagation losses between a transmitting IMT base station and the potentially interfered-with FSS receiving earth station. This would in turn enable the IMT base station to adjust its power accordingly in order to minimize its interference to the interfered-with receiving FSS earth station.

It should be noted that this mitigation technique provides high interference suppression in areas where the IMT base station signal can achieve accurate channel estimations. With large propagation losses, due to a large separation distance, channel estimation accuracy will degrade and the application of this technique would not lead to any substantial interference reduction. As a result, this method is efficient in cases where high levels of interference are accepted by the FSS earth station or in cases where accurate channels estimation is obtained by using and accumulating a high number of low power pilot symbols for channel estimation.

It should be noted that the feedback technique requires installation of equipment at each FSS earth station location to estimate propagation channel information (i.e. amplitude and phase information of propagation channel between the IMT base station and the FSS earth station) and to provide the estimated channel information to the IMT base station. The equipment used needs to be able to detect the IMT signal with sufficient sensitivity at the level necessary to protect the interfered-with FSS earth station.

6.4 Antenna downtilting

A possible technique to improve sharing is antenna downtilting at the IMT base stations. Although antenna tilting is often applied to all base stations of an IMT network, it can be additionally used as a mitigation technique and it leads to additional protection if its application is tailored to the location of a specific FSS receiving earth station.

In the deployment scenarios envisaged for IMT systems, the cell size will be reduced to support high-speed transmissions assuming a limitation of transmission power. The deployment based on the small cell size is also indispensable for IMT systems in order to achieve high frequency efficiency. Since the degree of antenna downtilting will be increased in the case of small cell size in order to avoid inter-cell interference in IMT systems using the frequency reuse, this will also result in the reduction of interference from an IMT base station to FSS earth stations and the reduction of the required minimum distance.

By increasing the downtilt of the base station antenna, there is a potential:

– for an increase of the number of IMT base stations required to provide service in a given area; and

– for a decrease of transmission power per IMT base station.

Accordingly, when computing aggregate interference into an FSS receive earth station, these two offsetting elements would have to be taken into account.

6.5 Low/medium power networks for local coverage

Low/medium power transmission, instead of conventional IMT network as described in Report ITU-R M.2109, may be considered, both indoor and outdoor, to provide local coverage in some part of the frequency band under consideration. Using such low/medium power stations, noting also the propagation attenuation through building structures in case of indoor deployment, enhances the possibility of sharing between these mobile networks and FSS receiving earth stations. In this sense, the implementation of such low/medium power networks[5] may be considered to meet vertical needs for local coverage and may be used to act as a potential buffer between bands that are used by receiving earth station of the FSS and IMT. It should be noted that with low/medium power implementations, there may be associated limitations to the IMT performance, and a greater number of base stations required for an equivalent coverage with a standard power IMT network.

[5] Standard power IMT base station may also be used to satisfy needs for local coverage in areas where the corresponding frequencies are not being used by FSS receiving earth stations. These cases should not be generalized.

6.6 Unwanted emissions of IMT transmitting stations

IMT stations are designed based on international standards where the unwanted emission levels are defined. To further reduce the unwanted emissions of IMT stations falling in the receiving band of the earth station, additional filtering requirements could be considered at the output of the IMT base station transmitters. This would be applicable for non-AAS deployment and such additional filtering could be based on the result of the coordination process between FSS earth station and IMT operators. It should also be noted that there will be cost implications for this additional filtering requirement.

It should be noted that this technique would not help mitigate the effect of LNB overdrive or emissions of IMT stations operating in overlapping bands with the FSS receiver.

7 Mitigation measures applicable to both the IMT and FSS earth station side

7.1 Additional considerations in adjacent band operations: Inter-service frequency separation

Inter-service frequency separation is the separation between the nominal edges of the operating band of one service and the nominal start of band of the service in the immediately adjacent spectrum allocation. This dedicated portion of the spectrum, also referred to as a guardband, may act as a buffer to help limit interference between two adjacent services. If a guardband is deemed necessary it can be applied within the FSS assignment, IMT assignment or shared between the assignments.

Guardbands should be minimised as much as possible to avoid unused spectrum. In the case of FSS and IMT deployments in adjacent band scenarios, the frequency separation can facilitate coexistence between the two deployments.

The frequency separation between the operations of IMT and FSS services has thus two objectives:

i) On the one hand, it ensures that in the band assigned to the FSS, the emissions of IMT stations reach the lowest levels of unwanted emissions (spurious levels). The size of the frequency separation must then consider the characteristics of the emission profile of the IMT stations in the adjacent band.

ii) On the other hand, when RF filters are used as a technique to protect the LNB of an FSS earth station, the frequency separation ensures that the emissions in the transition regions of the filter decrease monotonically with increasing frequency. Otherwise, the RF filter will not be effective in its main task of mitigating interference. Without a frequency separation, even in the presence of RF filters, a portion of the IMT signals could potentially reach the LNB input, and may result in degrading (up to a complete loss of) the FSS signal.

Therefore, the magnitude of the frequency separation should consider:

i) the emission profile of the IMT service (described in the form of a spectrum emission mask or SEM);

ii) the RF frequency response of the earth station receive chain. This can be modified by means of filtering in the RF section (see § 5.2.1.1); and

iii) the value of the protection criterion for FSS service compatibility (usually in the form of an I/N ratio in dB).

Frequency separation is helpful even in cases where the mitigation techniques of physical separation have been deployed.

7.2 Distance based mitigation: the concept of exclusion and restriction zones

Distance-based mitigation techniques can be deployed to facilitate coexistence, albeit impacting the deployment of FSS and IMT stations. The mitigation techniques applicable on both FSS ES and IMT sides presented in §§ 5 and 6, respectively, can be applied in order to reduce the required separation distances on a case-by-case basis. The mitigation techniques can be combined with coordination procedures to assess the relative reduction of separation distance while mitigating potential impact on the FSS system performances.

7.2.1 General principles affecting the size and shape of the zones

Distance-based mitigation can be defined with different approaches which broadly fall in three categories (see for example Recommendation ITU-R F.1766):

– Distance-based zones: the simplest method used to define the areas considers a fixed distance around the reference location. The area enclosed by the resulting circle represents the area within which transmission could be subject to technical or regulatory control. This approach can lead to large zones as there are often worst-case azimuths for which large separation distances are required.

– Propagation loss-limited zones: in this case, the separation distances per azimuth value around the reference location are defined based upon computing a minimum required propagation loss, such that it varies depending upon azimuth. The resulting contours include a degree of propagation loss by taking account of the different characteristics of radiowave propagation over land and sea. This approach can be extended to use the local terrain and a detailed propagation model such as that described in Recommendation ITU-R P.452, including time-varying effects evaluated by a given percentage of time for which the calculated propagation loss is not exceeded. The resulting shape is expressed usually in terms of coordinates of the vertices of the enclosing polygon.

– Demographic-based zones: these zones are built based on population density in an area such as a census block or other administrative subdivision. The technical conditions of the incoming service are adjusted so that the percentage of people that would be impaired in the area under analysis is kept under a specified threshold. This type of area is more applicable to analyses where the incumbent service is point to area and may not be common for determining coexistence conditions between two services, one being a point-to-area service and the other a point-to-point service.

7.2.2 Definition of exclusion zone

An exclusion zone (EZ) is the name given to a geographical area within which the operations of stations part of a service are not authorised.

EZs can be defined using the principles described in the previous section.

When constructing exclusion zones (e.g. defining area and shape) it is necessary to consider the desensitisation and blocking of the FSS receivers caused by the in-band signals from the IMT stations in the frequency band 3 400 to 3 600 MHz, the actual terrain and clutter around the earth stations, and potential deployment of IMT base stations over time.

Examples of exclusion zones

Various administrations have defined exclusion zones around designated FSS earth stations which serve a specific purpose such as telemetry monitoring and commanding (TT&C) of the space stations. At the time of the development of this Report some examples include the restriction zones defined in

Hong Kong around Tai Po Industrial Estate and Stanley[6], the exclusion zones defined by IMDA in Singapore around the earth stations in Bukit Timah and Seletar[7] and certain zones in Australia.

It is important to note that, while effective by design, exclusion zones reduce the ability of a mobile operator to provide services to all users regardless of location. Exclusion zones may also result in business impact, especially in cases where exclusion zones are large in area, potentially occupying a substantial part of the country. This may occur where the predominant terrain features of the deployment area analysed could be classified as flats, plains or with very low hills, with low clutter and vegetation cover.

7.2.3 Definition of restriction zone

Restriction zones are those areas within which transmissions from the interfering service are allowed subject to technical conditions which may be more stringent than those defined for unrestricted areas. For instance, base stations of the mobile service or IMT base stations could be allowed operations subject to reduced e.i.r.p. levels, certain limits on tilt angles, or to the use of filters to control the levels associated to IMT out of band emissions.

The restriction zone is defined following similar principles as those described to construct exclusion zones, that is, considering a maximum level of acceptable interfering signal, and by using propagation methods that consider surrounding terrain and clutter to determine the losses for each azimuth considered around the reference location

Examples of restriction zones

Restriction zones may be known by other names such as ‘precautionary zones’ or ‘protection zones’. As example, restriction zones have been defined in Singapore[8] in certain areas where there is a high density of FSS earth stations.

8 Unwanted emission limits: determining the total power in a frequency range

8.1 Definition of a spectrum emission mask

A spectrum emission mask (SEM) specifies power levels over portions of the spectrum intended to be used by a service, and over portions of the spectrum adjacent to the intended block. The SEM can contain specifications that can help prevent harmful interference into other systems. It is expected that emissions from all transmitters operating within the licensed block must comply with the prescribed SEM. SEM are defined for the purposes of national use, and may differ between neighbouring countries. SEM may also be known as Block Edge Masks (BEM) to certain administrations. SEM have been used, for example, in the development of ITU-R studies such as Study #A in Attachment 1 to Annex B to Report ITU-R S.2199.

As noted, an SEM is expressed as power versus frequency. It specifies permitted power levels both over the block of spectrum of interest (referred to as in-block) and outside the assigned block (referred

---

[6] Annex B in https://www.coms-auth.hk/filemanager/statement/en/upload/441/ca_statements20180328_en.pdf.

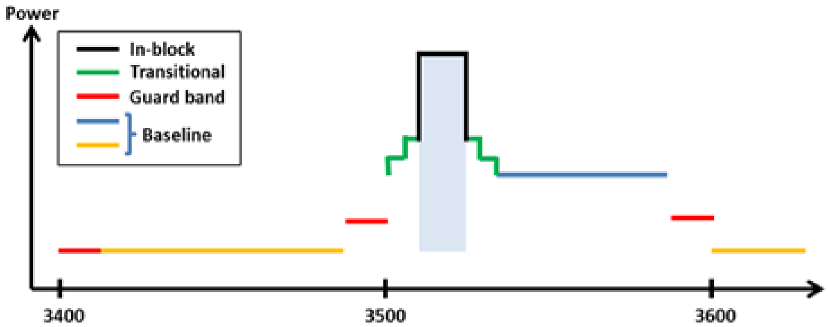
[7] Annex B1 in https://www.imda.gov.sg/-/media/Imda/Files/Regulation-Licensing-and-Consultations/Consultations/Consultation-Papers/Second-Public-Consultation-on-5G-Mobile-Services-and-Networks/5G-Second-Consultation-Decision.pdf.

[8] https://www.imda.gov.sg/-/media/Imda/Files/Regulation-Licensing-and-Consultations/Consultations/Consultation-Papers/Second-Public-Consultation-on-5G-Mobile-Services-and-Networks/5G-Second-Consultation-Decision.pdf.

to as out-of-block) including transitional levels to facilitate coexistence with the same or with other services sharing the frequency range and potentially additional baseline levels for emissions extending beyond the edge of the mask [22], [24], which are used for sharing with other services outside the frequency range covered by the assignment. Minimum or baseline levels may be defined taking into consideration the conditions set for coexistence between the service in-block and the service in adjacent bands. To illustrate its typical components, Fig. 24 presents an example of a SEM.

FIGURE 24

Schematic of a spectrum emission mask (SEM). Source [25]



8.2 Examples of spectrum emission masks

As a result of national processes to allocate spectrum in the frequency range 3 400-3 600 MHz to IMT services, and to suit different national interests and priorities, different SEMs have been developed. Figure 25 presents a few examples, for illustrative purposes only, with their associated technical parameters described in Tables 6 to 10.

FIGURE 25

Some examples of spectrum emission masks for IMT emissions

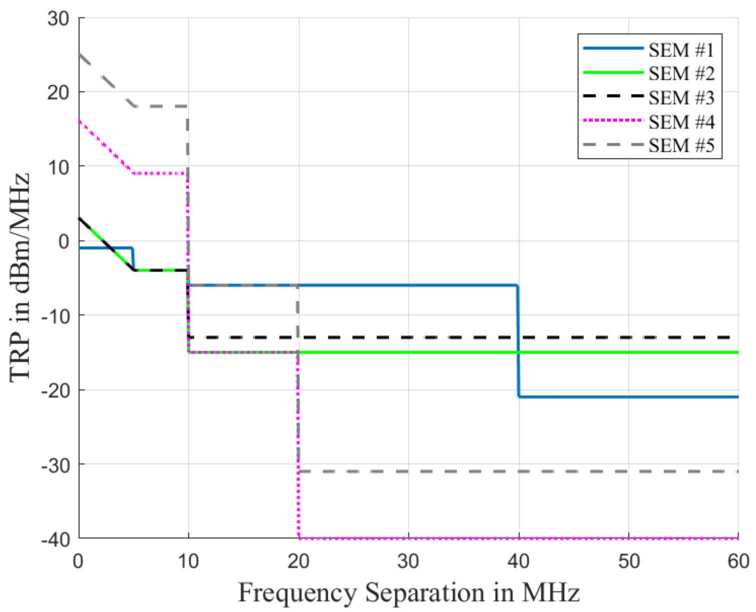


TABLE 6

Example SEM No. 1

Frequency offset of measurement, Δ*f* (MHz)	***TRP* (dBm)**	**Measurement bandwidth**
0 MHz ≤ Δ*f* < 5 MHz	−11	100 kHz
5 MHz ≤ Δ*f* < 10 MHz	−14	100 kHz
10 MHz ≤ Δ*f* < 40 MHz	−6	1 MHz
40 MHz ≤ Δ*f*	−21	1 MHz

TABLE 7

Example SEM No. 2

Frequency offset of measurement, Δ*f* (MHz)	***TRP* (dBm)**	**Measurement bandwidth**
0 MHz ≤ Δ*f* < 5 MHz	$-7-\frac{7}{5}(\Delta f-0.05)$	100 kHz
5 MHz ≤ Δ*f* < 10 MHz	−14	100 kHz
10 MHz ≤ Δ*f*	−15	1 MHz

TABLE 8

Example SEM No. 3

Frequency offset of measurement, Δ*f* (MHz)	***TRP* (dBm)**	**Measurement bandwidth**
0 MHz ≤ Δ*f* < 5 MHz	$-7-\frac{7}{5}(\Delta f-0.05)$	100 kHz
5 MHz ≤ Δ*f* < 10 MHz	−14	100 kHz
10 MHz ≤ Δ*f*	−13	1 MHz

TABLE 9

Example SEM No. 4

Frequency offset of measurement, Δ*f* (MHz)	***TRP* (dBm)**	**Measurement bandwidth**
0 MHz ≤ Δ*f* < 5 MHz	$-7-\frac{7}{5}(\Delta f-0.05)$	100 kHz
5 MHz ≤ Δ*f* < 10 MHz	−14	100 kHz
10 MHz ≤ Δ*f* < 20 MHz	−15	1 MHz
20 MHz ≤ Δ*f*	−40	1 MHz

TABLE 10

Example SEM No. 5

Frequency offset of measurement, Δf (MHz)	*TRP* (dBm)	Measurement bandwidth
0 MHz ≤ Δf < 5 MHz	$2 - \frac{7}{5}(\Delta f - 0.05)$	100 kHz
5 MHz ≤ Δf <10 MHz	−5	100 kHz
10 MHz ≤ Δf < 20 MHz	−6	1 MHz
20 MHz ≤ Δf	−31	1 MHz

8.3 Procedure to determine the total unwanted emission power expected within a frequency range covered by a spectrum emission mask

As discussed, since the SEM defines the levels of radiated power in blocks adjacent to the in-band IMT emissions, they can be used to determine the maximum levels of unwanted signals that could be present in the operating band of an FSS earth station.

The total radiated power over a specific frequency range can be computed as follows:

$$TRP_{tot}(f_1, f_2) = \int_{f_1}^{f_2} TRP_{BEM}(f)df \tag{16}$$

with:

$TRP_{tot}(f_1, f_2)$: the aggregated total radiated power within the frequency range $[f_1, f_2]$ which can be expressed in dBm

$TRP_{BEM}(f)$: the TRP density in dBm/Hz at a given frequency, f.

The aggregated total radiated power can then be used to calculate the interference into a specific FSS ES:

$$I_{IMT\rightarrow FSS}(f_1, f_2, d) = TRP_{tot}(f_1, f_2) + G_{tx_{IMT\rightarrow FSS}} + G_{rx_{FSS\rightarrow IMT}} - PL(d) \tag{17}$$

where:

$I_{IMT\rightarrow FSS}(f_1, f_2, d)$: unwanted emission generated by an IMT station received at an FSS ES separated by a distance d in the frequency range $[f_1, f_2]$. This interference is expressed in dBW or dBm

$G_{tx_{IMT\rightarrow FSS}}$: IMT transmitter gain towards the FSS ES receiver in dBi. This gain is dependent on the off-axis angle in both azimuth and elevation between the IMT beam pointing and the direction at which the FSS ES is seen

$G_{rx_{FSS\rightarrow IMT}}$: FSS ES receiver gain in the direction of the IMT transmitter in dBi. The FSS ES gain is dependent on the off-axis angle between the FSS ES pointing and the direction at which the IMT station is seen

$PL(d)$: propagation loss between the IMT transmitter and FSS ES receiver in dB.

8.3.1 Total power at the input of the FSS earth station, calculation example

In order to illustrate the above procedure, a calculation example for the total power falling within the frequency range 3 550-3 600 MHz produced by an IMT BS operating in 3 400-3 500 MHz adhering to a sample SEM profile #3 is presented. SEM #3 is reproduced in TABLE 11 for convenience.

TABLE 11

Example SEM No. 3

Frequency offset of measurement, Δ*f* (MHz)	***TRP* (dBm)**	**Measurement bandwidth**
0 MHz ≤ Δ*f* < 5 MHz	$-7-\frac{7}{5}(\Delta f-0.05)$	100 kHz
5 MHz ≤ Δ*f* < 10 MHz	−14	100 kHz
10 MHz ≤ Δ*f*	−13	1 MHz

Since the frequency range considered is 3 550-3 600 MHz, the signals lie in 50 MHz ≤ Δ*f* ≤ 100 MHz. Therefore, $TRP_{SEM}(f)$ = −13 dBm/MHz with f in the range [3 550 MHz, 3 600 MHz].

Applying equations (13) and (14) with f_1 = 3 550 MHz and f_2 = 3 600 MHz is obtained:

$$TRP_{tot}(3\,550\text{ MHz}, 3\,600\text{ MHz}) = \int_{3\,550}^{3\,600} TRP_{BEM}(f)df \qquad (18)$$

$TRP_{BEM}(f)$ is a constant over the specified frequency range of interest, the total power falling in the band 3 550-3 600 MHz is obtained as follows:

$$TRP_{tot}(3\,550\text{ MHz}, 3\,600\text{ MHz}) = -13 + 10\log_{10}(3\,600 - 3\,550) \qquad (19)$$

$$TRP_{tot}(3\,550\text{ MHz}, 3\,600\text{ MHz}) = 4\text{ dBm} \qquad (20)$$

The value of TRP_{tot} in equation (20) can then be used to determine the power received in this portion of the spectrum by the FSS ES.

8.3.2 Use of an SEM for the determination of effective rejection and as aid to the development of an RF filter specification

The SEM can also be useful as part of the development of specifications for required rejection of an RF filter. The concept of effective rejection discussed in § 5.2.1.2 is illustrated below with the use of a sample SEM applicable in the frequency range 3 400-4 800 MHz. One possible approach to the development of a filter specification is to iterate over the values of the required rejection within each spectrum portion until a satisfactory compromise between filter expected complexity and total effective rejection is achieved, before moving to prototyping.

TABLE 12

Illustration of the use of an SEM to determine filter effective rejection. The desired rejection values are provided as an illustration for the calculation procedure

E.i.r.p. density within spectrum portion (dBm/5 MHz)	**Designator**	**Lower limit (MHz)**	**Upper limit (MHz)**	**Desired rejection within portion (dB)**	**Pin (dBm)**	**Pout (dBm)**
68.0	IMT Assigned band	3 400	3 600	−45.0	84.0	39.0
21.0	Transitional block 1	3 600	3 605	−22.0	21.0	−1.0
15.0	Transitional block 2	3 605	3 610	−22.3	15.0	−7.3
13.0	Transitional block 3	3 610	3 625	−1.0	17.8	16.8
−2.0	Out-of-band Region 1	3 625	3 700	−0.5	9.8	9.3

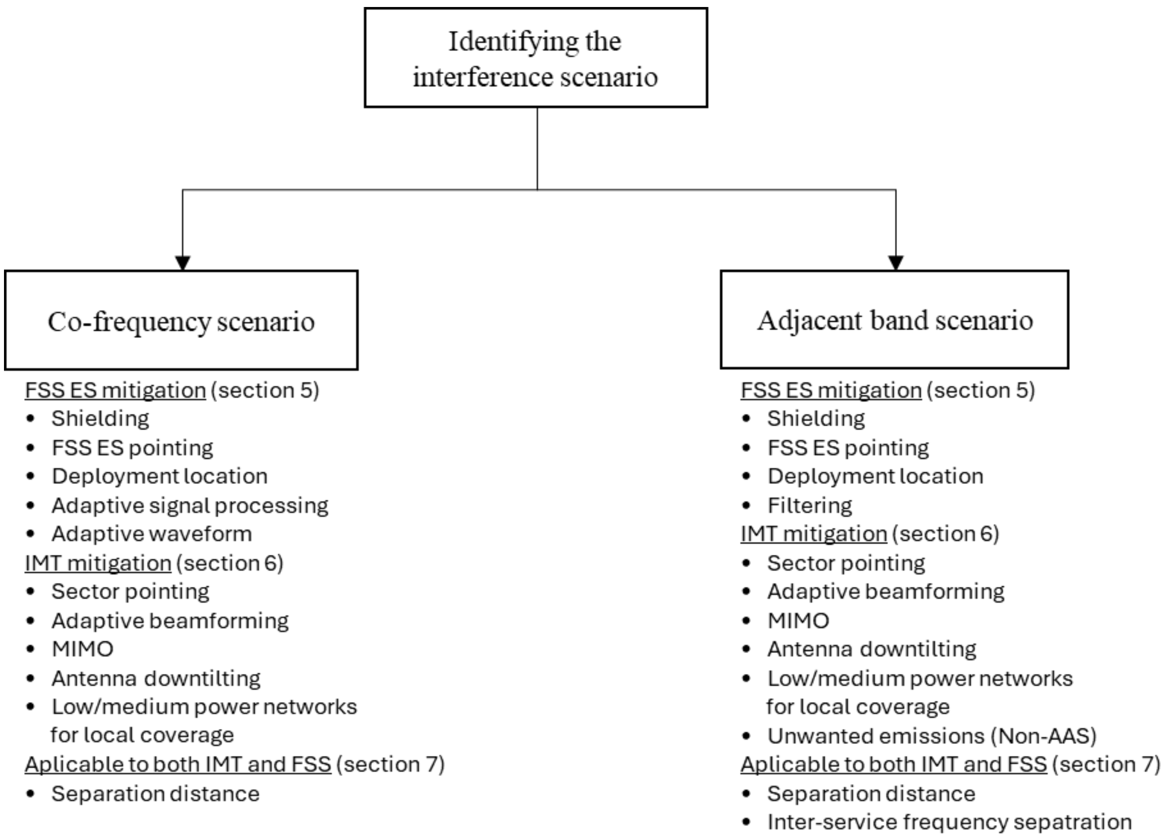
TABLE 12 (*end*)

E.i.r.p. density within spectrum portion (dBm/5 MHz)	**Designator**	**Lower limit (MHz)**	**Upper limit (MHz)**	**Desired rejection within portion (dB)**	**Pin (dBm)**	**Pout (dBm)**
−2.0	Out of band Region 2	3 700	4 200	−0.5	18.0	17.5
−2.0	Spurious region	4 200	4 800	−55.0	18.8	−36.2
Effective rejection in 3 400-3 600				−45.00	dB	
Effective rejection up to end of transitional sections				−44.99	dB	
Effective rejection within filter PB (3.625-4.2 GHz)				−0.50	dB	

9 Summary

This Report describes the different mitigation measures that improve sharing between by IMT transmitters and FSS ES receivers and contains a number of example mitigation techniques that are applicable to both the IMT and FSS stations (section 7), the FSS earth stations (section 5) and the IMT transmitters (section 6) in the frequency band 3 400-3 600 MHz.

The following Figure attempts to summarise the mitigation techniques applicable to the FSS earth station, according to the spectrum coexistence scenario under review by the administrations.



Based on the contents presented in this Report, administrations may find the following considerations useful:

1) Involvement from the communications ecosystem stakeholders is crucial throughout the process of selecting the frequencies to allocate, establishing the technical conditions, and finally defining the mitigation techniques to deploy. The stakeholders can be involved in the process by participating in public consultations.

2) In order to inform the regulatory agency in charge of analysing the frequency allocation procedures, knowledge of the locations of the FSS earth stations using the frequency band 3 400-3 600 is important. A mechanism used to obtain information about the earth stations is to invite the users of the FSS service to register the earth stations, and as part of the registration to provide geographical and radio frequency information such as coordinates and altitude, capabilities of the earth station in terms of frequency (frequency ranges of operation and frequency agility), antenna diameter and applicable radiation pattern envelopes (e.g. Recommendation ITU-R S.580, Recommendation ITU-R S.465 or other applicable gain envelopes).

3) An understanding of the technical specification of the IMT (where available) can be useful. The IMT specifications such as information contained in an SEM can be used to determine the amount of power expected from IMT base stations and can be used to estimate potential impact to neighbouring receiving earth stations.

4) Conversely, understanding the expected power levels of the receive chain of satellite earth stations and the limits applicable to the operations of the low noise amplifiers used by the earth stations will inform regulators during the SEM development process.

5) Radio frequency filters are a useful mitigation technique, and the design of the specification of the RF filters benefits from information such as the SEM and the proposed frequency allocations. Parameters such as required filter rejection, maximum insertion loss, selectivity and width of the transition region can be derived from the information contained in the SEM. Conversely, defining criteria for the filter response can also be used as an input for the development of a SEM.

6) The design of a filter response and a SEM is a process which benefits from constructive feedback from all stakeholders, and involvement from the stakeholders in the design of the technical conditions via a mechanism such as public consultations is valuable.

7) The establishment of frequency separation between services can contribute to facilitate the coexistence in adjacent band sharing scenarios. The design of an optimal frequency separation should consider, in addition to the national regulatory interests of optimising spectrum use, technical aspects such as:

   i) the desired width of the transition bands in the filter response and the desired selectivity;

   ii) the levels defined in the SEM for out of band and spurious domains;

   iii) based on the available information on FSS earth station locations, the expected separation distances between FSS deployments and IMT deployments. Establishing a database of earth station locations can be beneficial in this respect as well.

8) In certain cases, such as those associated with mission-critical FSS earth stations (e.g. stations dedicated to telemetry and command of space stations or supporting national strategic interests), Administrations may wish to analyse with additional detail some distance-based mitigations. Conscious use of distance-based mitigations can facilitate protection for both co-frequency as well as adjacent band scenarios.

References

[1] de Villiers, D.I.L. and R. Lehmensiek, *Rapid Calculation of Antenna Noise Temperature in Offset Gregorian Reflector Systems*. IEEE Transactions on Antennas and Propagation, Vol. 63, No. 4, April 2015.

[2] CPII communications. 1.8 m RD Rugged Deploy Antenna. https://www.cpii.com/docs/datasheets/612/1.8M%20RUGGED%20DEPLOY%20ANTENNA%201188%20Final%20092320.pdf. Last accessed: March 2023.

[3] CPII communications. 2.4 Meter Rx/Tx High Wind Antenna. Series 2244. Available online: https://www.cpii.com/docs/datasheets/713/2.4M%20C%20Ku%20Band%20Antenna%20High%20Wind%20RXTX%20%202244%20%20Final%20%20091720.pdf. Last accessed: March 2023.

[4] CPII communications. *3.8 meter Tx/Rx VSAT antenna*. Series 1385. Available online: https://www.cpii.com/docs/datasheets/728/3.8M%20C%20KU%20XBAND%20TXRX%20VSAT%20Antenna%20Series%201385_02.2021.pdf. Last accessed: March 2023.

[5] Recommendation ITU-R S.733-2, "Determination of the G/T ratio for earth stations operating in the fixed-satellite service". Geneva, 2000.

[6] ECC Report 340, "Receiver selectivity performance of satellite Earth stations in the band 3 800-4 200 MHz". Online: https://docdb.cept.org/download/4019. Last accessed: April 2023.

[7] ITU-R Handbook on satellite communications, 3rd Ed. Geneva, 2002.

[8] Wait, D. F., "Precision Measurement of Antenna System Noise Using Radio Stars", in IEEE Transactions on Instrumentation and Measurement, vol. 32, no. 1, pp. 110-116, March 1983, doi: 10.1109/TIM.1983.4315019.

[9] Ippolito, L.J. Satellite Communications Systems Engineering: Atmospheric Effects, Satellite Link Design and System Performance. Second Edition. Wiley.

[10] Allnut, J.E., *Satellite-to-Ground Radiowave Propagation*, 2nd. Ed. IET Electromagnetic Waves Series. 2011.

[11] Meyer, R. G. and A. K. Wong, "Blocking and desensitization in RF amplifiers", in *IEEE Journal of Solid-State Circuits*, vol. 30, no. 8, pp. 944-946, Aug. 1995, doi: 10.1109/4.400438.

[12] Recommendation ITU-R S.1541-6, "Unwanted emissions in the out-of-band domain", Geneva, 2015.

[13] Alejos, Ana V., García Sánchez, M. and Iñigo Cuiñas. *Measurement and Analysis of Propagation Mechanisms at 40 GHz: Viability of Site Shielding Forced by Obstacles*. IEEE Transactions On Vehicular Technology, Vol. 57, No. 6, November 2008.

[14] Scheeren, P. M. J., "Interference-reduction techniques for earth stations, and the specific problem of near-field site shielding against terrestrial interference", IEE Colloquium on Radio Frequency Co-Channel Interference Measurements and Modelling at 1-30 GHz, 1988, pp. 6/1-6/4.

[15] International Radio Consultative Committee Report CCIR 390-6. Earth-station antennas for the fixed-satellite service. Geneva, 1990.

[16] S. A. Bokhari, M. Keer and F. E. Gardiol, "Site shielding of earth-station antennas", in IEEE Antennas and Propagation Magazine, vol. 37, no. 1, pp. 7-24, Feb. 1995, doi: 10.1109/74.370577.

[17] Ruze, J, Shefiman, F.I., and D. A. Cahlander, "Radar ground clutter shields", Proceedings of the IEEE, 54, 1966, pp. 1171-1183.

[18] Report ITU-R S.2150, "An interference reduction technique by adaptive-array earth station antennas for sharing between the fixed-satellite service and fixed/mobile services". Geneva, 2009.

[19] Ellingson, S. *Radio systems Engineering*, Ed. Cambridge Press. 2016.

[20] T. Djerafi, K. Wu and D. Deslandes, "A Temperature-Compensation Technique for Substrate Integrated Waveguide Cavities and Filters", in IEEE Transactions on Microwave Theory and Techniques, vol. 60, no. 8, pp. 2448-2455, Aug. 2012, doi: 10.1109/TMTT.2012.2201741.

[21] Keats, B. Bimetal Temperature Compensation for Waveguide Microwave Filters. PhD thesis, University of Waterloo, 2007. Online: https://uwspace.uwaterloo.ca/handle/10012/3529?show=full. Last accessed: July 2022.

[22] Technical Report ETSI 103 139 v1.1.1, "Mobile Specification Group (MSG); Assessment of IMT Base Station (BS) emissions in relation to Block Edge Masks (BEM)". 2013.

[23] European Commission. Radio Spectrum Committee, *Technical conditions regarding spectrum harmonisation for terrestrial wireless systems in the 3400-3800 MHz frequency band*. Online: https://circabc.europa.eu/sd/a/500f0fc5-3adc-4669-a793-dfc8c1cf9534/RSCOM13-69%20CEPT%20Report%2049%20on%203.6%20GHz%20band.pdf. Last accessed: July 2022.

[24] Forde, T. K., Doyle, L. E. and B. Ozgul, "Dynamic Block-Edge Masks (BEMs) for Dynamic Spectrum Emission Masks (SEMs)", 2010 IEEE Symposium on New Frontiers in Dynamic Spectrum (DySPAN), 2010, pp. 1-10, doi: 10.1109/DYSPAN.2010.5457918.