REPORT ITU-R SF.2046

Determination of the interference potential, and its possible reduction by mitigation techniques, between earth stations in the fixed-satellite service operating with non-geostationary satellites and stations in the fixed service in the 18/19 GHz band

(Questions ITU-R 237/4 and ITU-R 206/9)

(2004)

1 Introduction

Frequency bands have been allocated and identified for use by GSO and non-GSO FSS systems in bands shared on a primary basis with the FS. WRC-95/97 adopted a different set of provisions through No. 5.523A of the Radio Regulations (RR) to the non-GSO FSS utilizing the bands 18.8-19.3 GHz and 28.6-29.1 GHz from those provisions for non-GSO FSS utilizing bands outside these bands. This Report addresses only the 18.8-19.3 GHz band, which is referred to throughout as the 18/19 GHz band.

Sharing between the FSS and the FS should also take into consideration the impact of the proposed high-density deployment of both services, which requires special attention to the required separation distances. Such restrictions could impair the use of both services in the same areas, however, the sharing situation could be improved by the use of mitigation techniques.

2 Interference from an FS transmitter into a non-GSO FSS satellite earth station

The progressing deployment of FS stations or FSS earth stations may affect the future expansion of either service in the same frequency band. Accordingly, the FS station deployment patterns and the FSS earth station deployment patterns required for the introduction and growth of viable services have a major impact on the planning of band sharing. Studies to date are limited to the considered interference from FS transmitters into the LEOSAT-1 non-GSO FSS earth stations operating in the 18.8-19.3 GHz band.

2.1 Interference criteria and methodology

The interference calculations were performed by several administrations using FS parameters obtained from their administration databases.

Deterministic studies assume line-of-sight (LoS) transmission and were based on the use of a free-space loss plus atmospheric absorption propagation model. Some studies also took into account diffraction due to terrain and man-made obstacles.

The interference level into the earth station was calculated for each FS transmitter in the database and for all azimuths around each of these transmitters. The resulting exclusion zones were then superimposed graphically on maps of some major metropolitan areas. In all cases the minimum earth station antenna gain (backlobe) was used and the calculations were not dependent on anomalous propagation conditions, therefore, a long-term *I*/*N* criterion corresponding to 6% to 10% of the thermal noise level was used.

This criterion may require further study to take into account the effects of multiple FS transmitters simultaneously interfering into an non-GSO FSS user terminal receive bandwidth. In the case of LEOSAT-1, this would be the full 500 MHz receive bandwidth. When the non-GSO FSS user terminal receive bandwidth is reduced, the probability of having multiple FS transmitters interfering simultaneously is reduced.

Statistical studies evaluate, based on certain assumptions, the interfering power spectral density levels suffered by FSS receivers distributing these terminals in the satellite spot-beam with respect to assumed penetration rates in the different ground clutter classes. During the interference calculation procedure the FSS terminal location is selected randomly out of the predefined locations according to the penetration scenario with the following assumptions:

– the assigned frequency channel in the FSS downlink is randomly selected inside the FS frequency band with a bandwidth according to a randomly selected transmission capacity by combining the frequency channels for the FSS terminal under consideration (although this study assumes varying bandwidth such studies should be based on 500 MHz in the case of LEOSAT-1);

– the satellite responsible for communication with the FSS cell/spot-beam under consideration is determined by the criterion of the shortest distance;

– the antenna of the FSS terminal is placed on top of the buildings or above the vegetation.

The received power level from the serving satellite is calculated according to the elevation angle and the propagation conditions concerned. All FS transmitters within a distance of 60 km to the FSS receiver are selected in the affected frequency band. The resulting interference power density level is evaluated by aggregation of the signals of all FS transmitters considered.

The *C*/*I* ratio at the FSS receiver is calculated by comparing the interference power level with the received power level from the serving satellite. The interference level can also be referred to the receiver noise level, *N*. These interference levels are compared with a reference interference level of −145 dB(W/MHz) (i.e. −10 dB *I*/*N*). The cumulative distributions of the *C*/*I* ratios for standard propagation conditions (losses exceeded for less than 20% of time) as well as for rainy conditions (worst case: 0.001% of time) on the space-to-Earth path have been derived.

2.2 Possible application of a convolution process for assessing interference

One study presented a possible method for assessing interference from FS transmitters into non-GSO FSS earth station receivers, based on an application of a methodology similar to that of Recommendation ITU-R S.1323. The method accommodates the time-varying nature of the interference by convolving the probability density functions (pdf) of the rain degradation and the interference degradation, obtained through computer simulation, to generate the total degradation pdf.

3 Potential interference from point-to-point FS transmitters into non-GSO FSS earth station receivers without mitigation techniques

3.1 Interference without mitigation techniques

3.1.1 Deterministic studies

FS transmitters impose regions around themselves in which reliable operation of non-GSO user terminals may be precluded due to excessive interference. These blocked regions are referred to as "exclusion zones". A single point-to-point FS transmitter will (under clear sky, clear terrain conditions) impose a circular exclusion zone in the area immediately surrounding it (off-axis directions) and a elliptical exclusion zone extending a long distance along its on-axis direction of transmission.

3.1.1.1 Results using free-space loss calculations and no blockage

Figure 1 presents an example exclusion zone calculated using the parameters of a typical point-to-point FS transmitter with a 0.6 m parabolic dish. The boundary is based on a single-source, conservative long-term interference criterion of 6% of the non-GSO user terminal system noise (i.e. $I/N = -12.2$ dB) under clear sky, clear terrain conditions. Non-GSO user terminals would need to be kept outside of this contour in order to guarantee that interference levels from the FS transmitter would be acceptably low. It can be observed in the expanded view in Fig. 2 that the diameter of the exclusion zone around the terminal can be nearly 1 km and the length of the exclusion zone in the direction of transmission can be well over 45 km. However, this distance and the affected area would be reduced using a more appropriate long-term interference criterion of 10%.

FIGURE 1

Example exclusion zone for LEOSAT-1 standard terminals created by one typical FS transmitter using a 0.6 m diameter antenna (assuming 6% interference criterion unter free space loss propagation condition)

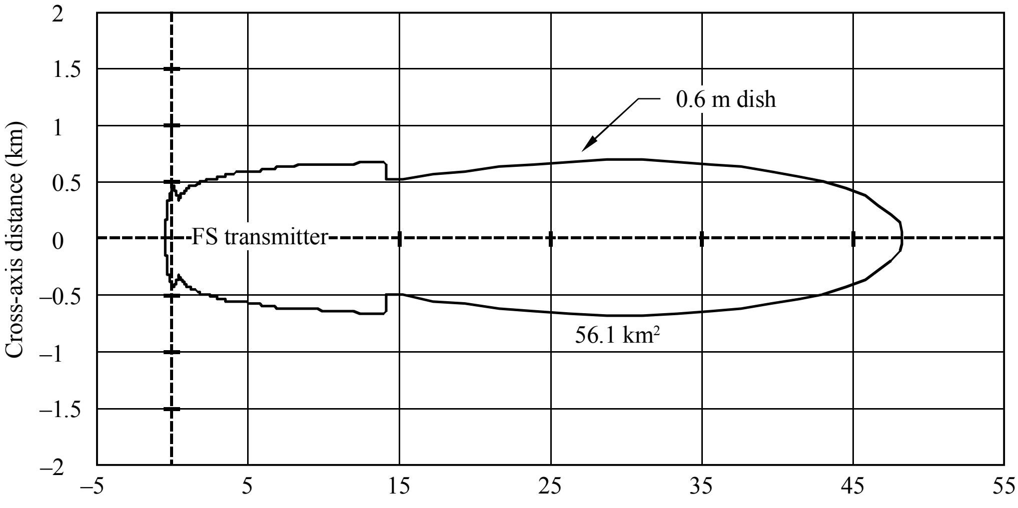

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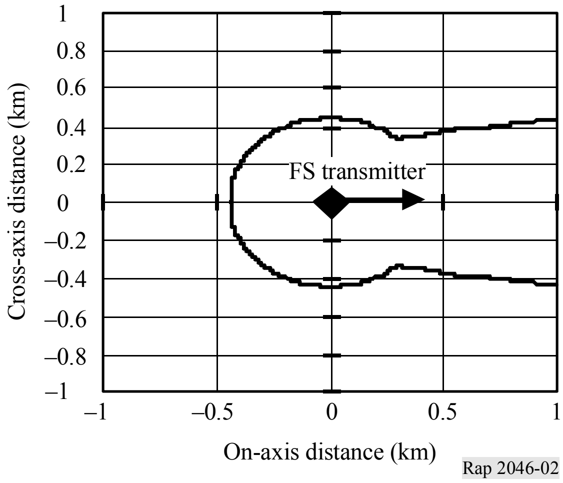
FIGURE 2

Expanded view of Fig. 1



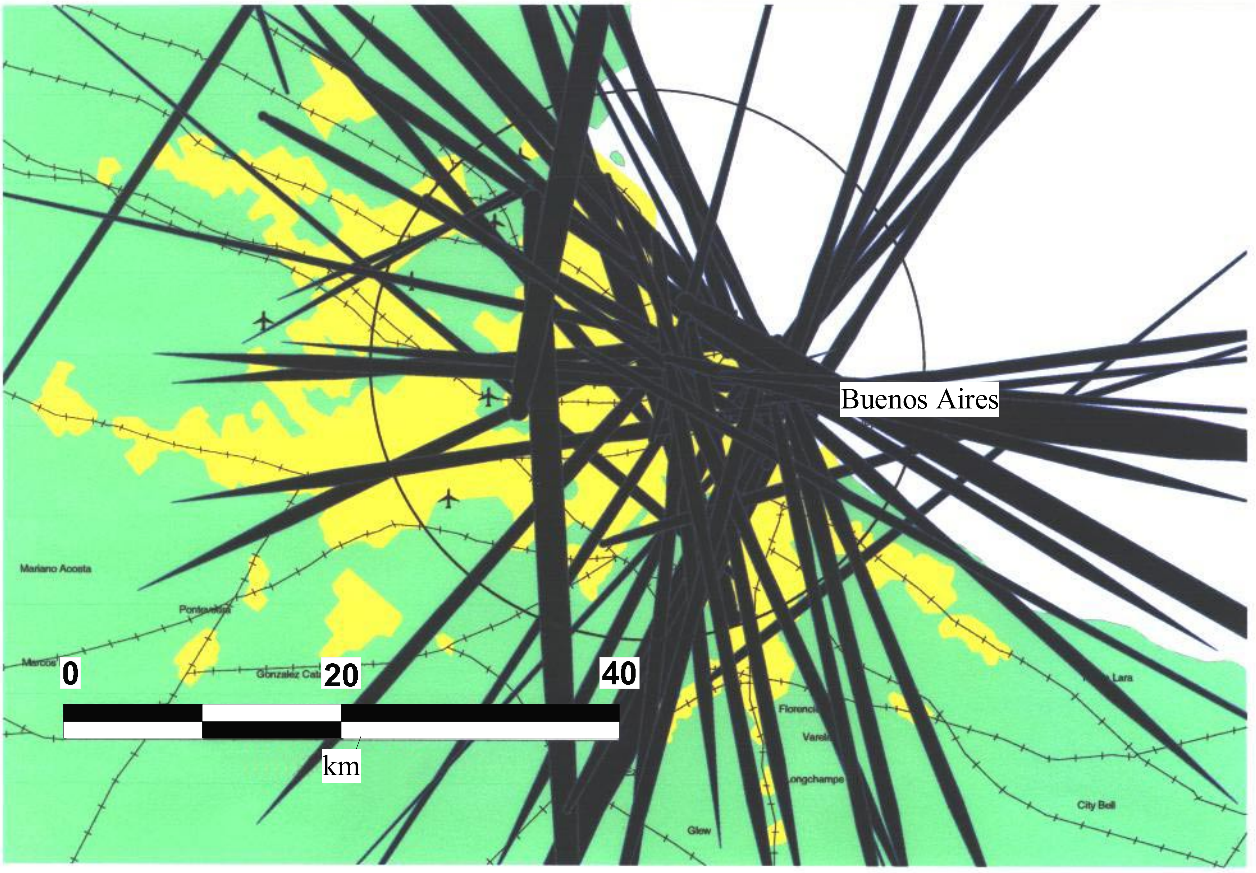
A study analysed the effects of interference from FS transmitters in Canada into a receiving non-GSO FSS earth station in the 18.8-19.3 GHz band. The calculations were performed using a database of FS parameters obtained from the Canadian licensing database and the resulting exclusion zones were then superimposed graphically on maps of some major metropolitan areas in Canada. The results of the deterministic interference calculations showed that the exclusion zone caused by the FS transmitters would be very long in the main direction of transmission, on the order of 40 to 80 km typically, but would be small in other directions well away from the FS main beam. In all cases, it was found that there was a significant area in each city where the non-GSO FSS terminal siting would be very difficult or perhaps even impossible. In fact, calculating the area of the exclusion zone within a 40-km diameter circle, representative of the metropolitan sites, indicated that areas of 35%, 48% and 47% would be unavailable for non-GSO FSS terminals in the three cases studied, in the absence of some blocking.

Another study analysed the interference that could be generated by typical FS transmitters into non-GSO FSS user terminals where they operate co-frequency and in close proximity, in the 18.8-19.3 GHz band. This analysis calculated these exclusion zones using the actual characteristics of the FS transmitters contained in a database of FS transmitters from Argentina.

Figure 3 shows the computed exclusion zones corresponding to each potentially interfering FS transmitter in the Buenos Aires urban region (assuming clear sky, flat and clear terrain conditions). The size variation between some exclusion zones is due to the differences in FS characteristics found in the database, such as transmitter power and antenna size. A circular region with a 40 km diameter was used as the reference area. In the high FS density urban region, 65% of the area would result in FSS terminals not meeting their performance objectives and would potentially be excluded from LEOSAT-1 service in the band 18.8-19.3 GHz.

FIGURE 3

Potential FSS earth station exclusion area in the Buenos Aires urban region due to 18.8-19.3 GHz FS terminal locations: composite exclusion zone 65% in reference 40 km circle



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The conclusion of this study is that, assuming free-space propagation and no blockage, deployment of FS stations in the band 18.8-19.3 GHz could significantly constrain the placement of non-GSO FSS user terminals. This is particularly true for areas that have a high density of FS stations. As FS deployment density increases, the placement of non-GSO FSS user terminals becomes more constrained.

3.1.1.2 Results using topographical data and building blockage environment

When topographical databases are used in the calculation of the exclusion zones, the area covered by exclusion zones can be significantly reduced. Table 1 compares the cases of two simulations where the exclusion zones correspond to areas where the long-term criterion ($I/N = -10$ dB) is not fulfilled and where:

- *Case 1:* the propagation model assumes that there are no terrain or man-made obstacles within the LoS around each FS and is based on the use of free space loss and atmospheric absorption.
- *Case 2:* the propagation model takes into account propagation loss and diffraction over terrain as well as man-made obstacles, using a topographical database (the non-GSO FSS receivers are placed 1 m above the building roofs).

TABLE 1

Comparison of exclusion areas with and without blockage

Simulation	Percentage of exclusion zone relatively to the global area (14 km × 14 km centred on Paris)
Case 1 (without taking into account any terrain or man-made obstacles)	20.6
Case 2 (taking into account terrain and man-made obstacles)	5.2

The studies have been made with a radio planning software which includes digital terrain modelling and ground occupancy layers (buildings, population, ...) and calculates the areas where the interference level into the ground stations receivers exceeds −97 dBm (10 dB below the receive system noise) from any of the fixed links.

The fixed links that have been taken into account in this study are those transmitting in the band 18.8-19.3 GHz and located in a square area of 14 km × 14 km around Paris (23 links).

3.1.2 Statistical studies

Two statistical studies have been carried out.

3.1.2.1 First statistical study

Statistical interference simulations between actual and planned FS links and non-GSO FSS user terminals at 18/19 GHz (LEO-SAT-1 system) in a 118 × 118 km square centred on Paris have been carried out.

The principle of the methodology used was to create, on a studied area, a hypothetical FSS user terminals network by a random deployment and then to calculate, for each user terminal, the aggregate interference from the existing FS microwave links in this area.

The FSS user terminals were implemented on the studied area according to penetration ratios (random stations/km^2) associated with each ground clutter class. The C/I required was assumed to be 20 dB.

This active satellite is chosen, at the beginning of the simulation, as the one with the higher elevation (closer satellite) and is kept as long as its elevation is higher than the minimum (40° for LEOSAT-1).

The interference simulations consist of interference calculations (C/I) for each user terminal, taking into account: the constellation geometry (elevation and azimuth); the Earth-to-space propagation conditions, according to Recommendation ITU-R P.618 (for this purpose, the rain attenuation and the scintillation attenuation are associated to a random percentage to provide, for each calculation, the space-to-Earth attenuation); the propagation loss according to Recommendation ITU-R P.452 (visibility, diffraction, tropospheric scattering, including all statistical factors); the characteristics of the microwave links (power, azimuth, antenna, …) and of the user terminal (receiver characteristics, antenna, …). Each C/I calculation is called a “sample” and, at the end of the simulation, the results are presented as a graph representing the C/I distribution.

Table 2 gives the results for a simulation with FSS terminal distribution in the dense urban zone.

TABLE 2

Results of the first statistical simulation

Simulation	Percentage of FSS user terminals for which C/I <20 dB
Urban areas	1.5

It was noted that a higher percentage of blocking would be indicated if this study were to take into account the 500 MHz downlink receiver bandwidth which is the normal bandwidth for LEOSAT-1.

3.1.2.2 Second statistical study

A particular study addressed the sharing between FS and FSS applications in the 18/19 GHz band taking into account heavy deployment of FS stations in a geographical area. The methodology applied differs from that of the previous study in that it includes the use of terrain and the use of the most common parameters and characteristics for the radio systems deployed in the 18/19 GHz band in the United Kingdom.

3.1.2.2.1 Approach

The study investigated the effects that FS links and receiving earth stations will have on each other when these are deployed in the same band and in the same geographical area.

The study looked into the reduction of FS links that can be deployed in a certain study area when HD-FSS receivers are present, but also investigated the possible reduction of suitable locations for the satellite receivers when the band is heavily used by FS links in a defined area.

This study used an approach that considered unequal deployments of FS links and satellite receivers, with larger number of satellite terminals than FS links in a 10 km × 10 km area in a suburban environment.

3.1.2.2.2 Parameters and characteristics of the simulated systems

FS link characteristics

In this study three FS systems have been modelled corresponding to 8 Mbit/s, 34 Mbit/s and 155 Mbit/s systems. The common FS parameters for the three systems are summarized in Table 3 and the specific ones to each system are shown in Table 4.

TABLE 3

FS common characteristics to the three simulated systems

Parameter	Value
Minimum required transmit power	Calculated
Tower location and antenna height	As in the tower's database
Transmitter antenna height	15 m
Antenna gain(1)	38.4 dBi
Antenna aperture size	0.6 m
Radiation pattern(1)	Compliant with Recommendation ITU-R F.699
Polarization	Vertical
Microwave interference prediction procedure	Recommendation ITU-R P.452
Atmospheric loss	Recommendation ITU-R P.676
Rain loss	Recommendation ITU-R P.530 (99.999% availability)

(1) Provided by manufacturer. It was acknowledged that in the United Kingdom many links in this band use antennas with 25-32 dBi gain.

TABLE 4

FS specific characteristics for the three simulated systems

Parameter/system	8 Mbit/s system	34 Mbit/s system	155 Mbit/s system
Path length	4 km-14 km	4 km-14 km	300 m-6 km
Channel spacing	10 MHz	27.5 MHz	55 MHz
Receiver IF bandwidth	7 MHz	18 MHz	55 MHz
Modulation	QPSK	QPSK	32-QAM
C/N threshold(1)	13.5 dB	13.5 dB	23.5 dB
Receiver threshold(2) (BER = 1×10^{-6})	–119.5 dBW	–105 dBW	–95 dBW

(1) ITU-R Handbook – Digital Radio-Relay Systems, Geneva 1996, pp.139-140, Table 4.2.2-1.

(2) Provided by manufacturer. It was acknowledged that in the United Kingdom many links in this band use antennas with 25-32 dBi gain.

Satellite parameters

The satellite parameters used to carry out the simulations are summarized in Table 5.

TABLE 5

FSS parameters

Parameter	Value
Downlink frequency range	18.8-19.3 GHz
Bandwidth	500 MHz
Antenna side-lobe gain	–3.2 dBi
System noise power	–117 dBW

3.1.2.2.3 Methodology

The study had two main parts:

In the first one, the study area was saturated with FS links and the results compared with the ones obtained if the same exercise is carried out in an area where a large deployment of receiving earth stations exists. In this way, it is possible to assess whether the spectral efficiency is maximized by a shared use of the spectrum by the two different services or by separating both services in frequency.

In the second part of the study, a large number of receiving earth stations are deployed over a saturated FS link scenario. Then, analysing the number of receiving earth stations that cannot be placed provides an indication of how much of the area would suffer an interference level that would be above the interference assessment criterion.

It must be noted that for the purpose of this study only five of the existing possible FS channels were used and that the term saturated relates to a saturation of these five channels and not the real saturation situation that will happen if all the FS channels are used. However, the *I*/*N* analysis is done on a per Hertz basis which is believed to be equivalent, for the *I*/*N* analysis, to make use of all the FS channels.

For both parts, a study area of 10 km × 10 km was used.

3.1.2.2.3.1 Deployment of FS links on top of a large deployment of receiving earth stations

In this first part of the study, the first step was to saturate the area of study in order to calculate how many FS links could be deployed in the area if no satellite receivers were present. The second step was to introduce a large number of receiving earth stations and determine how many FS links could be deployed in that case. Comparing the results for both exercises it can be seen whether, from the spectral efficiency point of view, it is better to have the FS and HD-FSS applications sharing the same spectrum in the same geographical area or whether it is better to employ band segmentation by allocating separate parts of the spectrum for each application.

Saturation of the study area

In this first phase, the user defines the rectangular area to be used and the appropriate radio systems characteristics and terrain data are loaded into the simulation input parameters. After this, the links start to be placed by selecting a random location and determining which of the towers in the study area are in LoS with the location chosen. There is then an attempt to place the link by calculating interference levels between all the radio systems in the area making use of Recommendation ITU-R P.452 for all the interference calculations. To do this the tool tries to place the link between the random location and the nearest LoS tower, the latter being at a distance of at least the minimum path length, in any of the available channels, while not exceeding the interference criterion with the previously inserted links. The interference criterion corresponds to an aggregate interference allowance *I*/*N* of –6 dB. If that process fails, the process is repeated with the next closest tower. A failure is considered, if after trying all the available channels for all the LoS towers, the link could not be placed and a new random location is chosen. The simulation is terminated, if after 20 consecutive attempts a link could not be placed in the network.

After this phase, the maximum number of FS links that can be deployed in the study area is obtained. This result will be compared with the number of links that can be deployed when satellite receivers are present.

Introduction of receiving earth stations and FS links

In order to compare the effect of the existence of receiving earth stations in an area of FS deployment, in the second phase of this part of the study, a large number of satellite receivers are introduced in the study area and then the tool introduces as many FS links as possible. In the link placement process, it is not only checked that the new link is not interfered with by the existing FS links but that the new link does not cause any interference to the previously introduced receiving earth stations and FS links. As in the previous case, the interference criterion corresponds to an aggregate interference allowance *I*/*N* of –6 dB.

This process is repeated for different numbers of introduced receiving earth stations in order to see the evolution of the number of FS links when the number of receiving earth stations increases.

3.1.2.2.3.2 Deployment of receiving earth stations on top of saturated FS link scenario

Although the maximum spectral efficiency may be obtained by forcing both applications, FS and HD-FSS, to share the same spectrum, this may lead to a percentage of the area where the level of interference, may be higher than the aggregate interference allowance of the receiving earth stations.

In this sense, the methodology described in this section aims to answer that aspect of the discussion and determine what proportional part of an hypothetical study area will not be suitable for HD-FSS receivers deployment due to interference from the FS links.

Generation of the FS links saturated area

In this step of the methodology, an FS link saturated area is generated in the same way as described in the previous methodology. However, this time the result of that generation will be saved and used to initialize a simulation where the receiving earth stations will be deployed on top of the FS link saturated area.

Introduction of receiving earth stations

After the saturated FS link area has been generated, the software tool introduces the receiving earth stations. In the satellite earth station receiver placement process, each of the receiving earth stations is introduced only if it is not interfered by any of the FS links. The insertion of new receiving earth stations continues until no more receiving earth station can be placed or the number of those inserted has reached a very high number.

3.1.2.2.4 Results

Following the two methodologies described in the previous sections, a set of simulations was carried out. The results of the simulations for different FS systems are summarized below.

3.1.2.2.4.1 Deployment of FS links on top of a large deployment of receiving earth stations

Number of 8 Mbit/s FS links that can be deployed in the presence of receiving earth stations

In the first phase of the simulation for this scenario, the maximum number of FS links that could be deployed in the study area was calculated. The exercise resulted in 216 FS links being deployed for the 10 km × 10 km area. When introducing receiving earth stations the number of FS links that could be deployed for progressively large numbers of receiving earth stations can be seen in Figure 4.

FIGURE 4

Number of 8 Mbit/s FS links that can be deployed in the presence of receiving earth stations

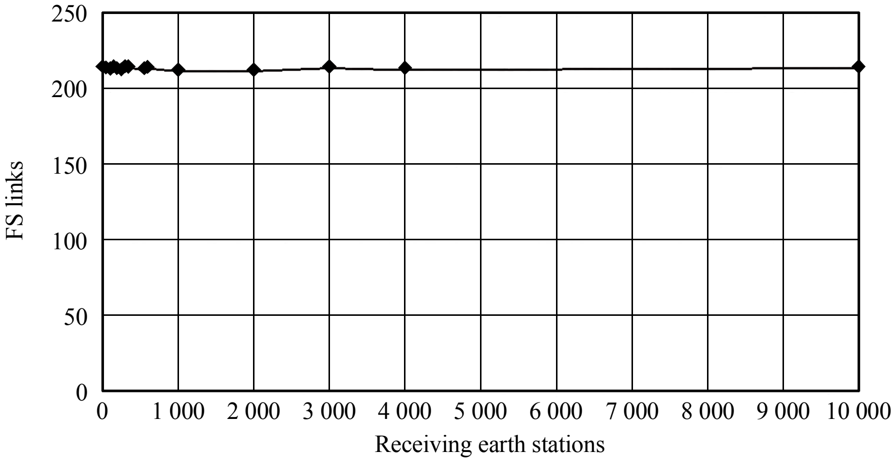

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Figure 4 indicates that the presence of satellite receivers even in very high concentrations (up to 100 satellite receivers/km^2) does not affect the possible deployment of 8 Mbit/s FS links, as the minimum differences between simulations are due to the random effect of choosing the FS link locations. Although even higher deployments of satellite receivers have not been simulated, due to the long processing time, the same results as the ones obtained for the HD-FSS deployments shown can be expected.

These results show that the effect that receiving earth stations have on 8 Mbit/s FS links as well as the one that 8 Mbit/s FS links have on the receiving earth stations is negligible.

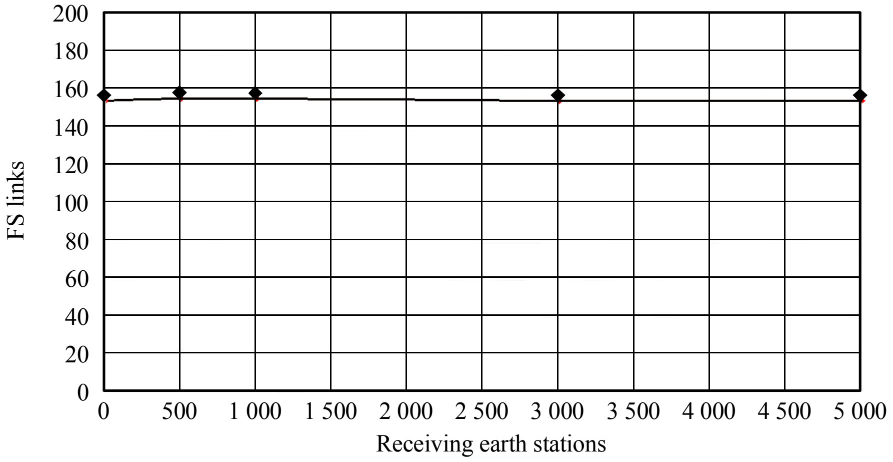
Hence, these results show that the most spectrally efficient way to allocate HD-FSS and FS applications (8 Mbit/s systems) in parts of the band 18/19 GHz would be to share the spectrum among both services.

Number of 34 Mbit/s FS links that can be deployed in the presence of receiving earth stations

Following the described methodology applied to the 8 Mbit/s case, a total of 156 FS links could be deployed in the study area if this would be free of receiving earth stations. Thus, the effect of introducing HD-FSS terminals can be seen in the graph in Fig. 5.

FIGURE 5

Number of 34 Mbit/s FS links that can be deployed in the presence of receiving earth stations



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As for the 8 Mbit/s case, the presence of satellite receivers in very high concentrations does not affect the possible deployment of 34 Mbit/s FS links. As already explained, the minimal differences between simulations are due primarily to the effect of randomness when choosing the FS links location.

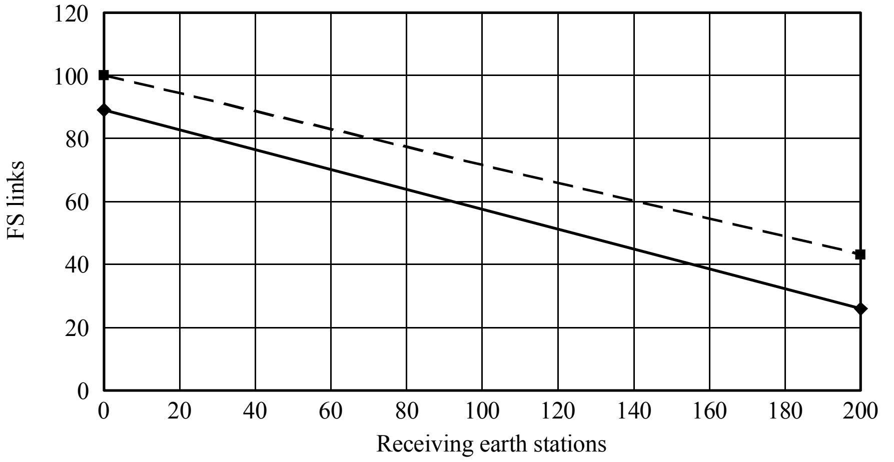
Hence, these results show that the most spectrally efficient way to allocate HD-FSS and FS applications (34 Mbit/s systems) in parts of the band 18/19 GHz would be to share the spectrum between both services.

Number of 155 Mbit/s FS links that can be deployed in the presence of receiving earth stations

For this case the number of FS links that could be deployed in the absence of receiving earth stations is 89 links and as can be seen in the solid line of Fig. 6, for this case, the presence of even a low number of receiving earth stations will cause a reduction in the number of FS links that could be deployed without causing unacceptable interference to the receiving earth stations.

FIGURE 6

Number of 155 Mbit/s FS links that can be deployed in the presence of receiving earth stations



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In order to improve the situation, automatic transmission power control (ATPC) as a mitigation technique was included in the simulations and then it can be seen, by the dashed line on Fig. 6, that although some improvement has been obtained, the presence of satellite receivers will still reduce the number of FS links that could be deployed without causing unacceptable interference to the receiving earth stations.

3.1.2.2.4.2 Deployment of receiving earth stations on top of saturated FS link scenario

Insertion of receiving earth stations over an 8 Mbit/s FS systems saturated area

The analysis of the total attempts to place a satellite receiver and the number of failed attempts shows that in this case only in a very low percentage of the total study area, 0.35%, would the interference limit for the receiving earth stations be exceeded.

This very small interference area would be negligible and therefore it would be possible to locate both FS and HD-FSS applications in the same geographical area.

Insertion of receiving earth stations over a 34 Mbit/s FS systems saturated area

In this case the analysis of the results shows that, of the total study area, 35.7% will experience interference above the limit acceptable by the HD-FSS receivers if no ATPC is implemented. However, when ATPC is implemented the interference area is reduced dramatically to 0.42% of the total.

Taking into account the significant reduction on the interference area when ATPC is implemented in order to mitigate the interference, it can be concluded that, for 34 Mbit/s system deployments, co-frequency sharing in the same geographical area is the best option for FS and HD-FSS applications deployment.

Insertion of receiving earth stations over a 155 Mbit/s FS systems saturated area

For this type of FS system, the results obtained show that when ATPC is not implemented 60.1% of the total study area will suffer an interference level above the interference criterion. However, if ATPC is implemented, the proportion of the interference area is reduced to 32.3%.

This, together with the improvement on the results obtained in the previous section when ATPC was applied, confirms that ATPC is a effective mitigation technique to improve the sharing conditions when HD-FSS and FS systems make use of the same spectrum in the same geographical area.

3.1.2.2.5 Conclusions of the second statistical simulation

In view of the results obtained, this study concluded that for large deployments of 8 Mbit/s, 34 Mbit/s and low-medium deployments of 155 Mbit/s FS systems a large number of HD-FSS earth stations can be deployed, in the same band within the 18/19 GHz frequency range and in the same geographical area, assuming that all stations are coordinated on a site by site basis. Moreover, the study shows that only in a very small percentage of the deployment area would the placement of an FSS earth station be precluded.

The results also have shown that for the considered FS systems, including 155 Mbit/s systems in high concentrations, the use of ATPC as a mitigation technique will significantly improve the sharing conditions.

3.2 Results without mitigation

The deterministic studies indicate that in the band 18.8-19.3 GHz, an FS transmitter could cause unacceptable interference to non-GSO FSS user terminals that are placed close to the FS station or in its main beam unless some mitigation is present to reduce the interference.

The results based on free space loss propagation but using different assumptions (as ground clutter, size and shape of the considered area) show that exclusion zones in urban areas (France, Canada and Argentina) can vary between 14% to 65% when mitigation techniques are not employed.

The studies showed that the higher the density of deployment of FS, the more restrictive becomes the placement of non-GSO FSS user terminals. Studies not taking account of any interference mitigation techniques nor consideration of blocking due to terrain and man made obstacles indicate that the percentage of area from which non-GSO FSS terminals could potentially be excluded can be quite large for areas with high FS deployment density.

Other deterministic studies showed that ground clutter and terrain variation can potentially reduce the areas of non-GSO FSS exclusion by a significant factor. For example, the above-mentioned study of a 14 km × 14 km area around Paris showed a reduction from 20.6% to 5.2% due to consideration of ground clutter. The study did not take into account reflections but also did not take into account any potential local site shielding effects and/or attenuation of reflections.

One statistical study lead to lower numbers of FSS user terminals suffering interference. About 1.5% (in the more realistic case where terminals are mainly distributed in dense urban zones) of these user receiving earth stations would suffer interference from the 23 actual links in Paris and 53 planned FS links in a cell of 118 × 118 km centred on Paris.

It was noted that increasing deployment of FS transmitters in 18.8-19.3 GHz will make it increasingly difficult to deploy non-GSO FSS user terminals in this band.

3.3 Results of measurements

To evaluate the effect of fixed links on the non-GSO FSS earth stations, a technical team carried out a group of measurements in different locations of Buenos Aires city. This had been the object of a theoretical study.

The measurements have been performed only inside the city limits, since it is the more congested area for fixed microwaves links. It does not include the surroundings (Greater Buenos Aires).

The measurements were carried out on building terraces of different heights distributed along Buenos Aires city, under good weather conditions and locating receiving stations in such way of obtaining clearance over elevation angles of 45°.

The procedure used consisted of finding measurable interference signals by rotating the antenna in all directions (360°), recording its frequency, azimuth and bandwidth. Then these values were compared with those coming from the theoretical calculations, which were carried out taking into account the database of the national regulator.

The results showed for each measurement the comparison between the measured interference signal and those calculated in each location.

– Eight out of the 14 (57%) measured locations had an interference signal that exceeded the interference criterion of –99.2 dBm (based on 6% of the noise of the FSS terminal). This value corresponds to the highest interference measurement in each location.

– The maximum interference signal for all measurements was below (between 4 and 15 dB) the calculated theoretical value.

– In four cases (28.5%) the maximum interference signal measured was due to reflections. This demonstrated that buildings can cause reflections as well as blockage.

– The interference is strongly dependent on the height at which the measurements are carried out. The measurements were performed in terraces between 3 m and 6 m over the street level, the interference detected were very low or null, even in those cases where a good clearance exists all around.

– The interference was also strongly dependent on the location of the station on the same terrace. A change in the position of the receiver can eliminate some interference, however it can make other interferers appear.

It can be concluded that:

Even though the number of places where the measurements were carried out may not be sufficient to verify the percentage of the exclusion zone, the tendency of percentage shows that the coexistence between FS and non-GSO FSS would not be feasible without methods of mitigation of interference in the studied urban area. It is not possible to make any direct comparison with the results of the statistical studies since the studied areas were completely different.

Moreover, a more comprehensive measurement campaign would be necessary to determine the actual interference environment in a specific urban area.

3.4 Conclusion based on the studies without mitigation techniques

Given the projected rapid growth of FS deployment, administrations should take into account these factors in the planning of their domestic spectrum decisions as early as practicable. Also, the FS and FSS communities should take these factors into account in the design of their systems.

In summary, the following points were retained:

- ubiquitous deployment of either or both services (FS and non-GSO FSS) in the same band and in the same geographical area may be difficult according to the systems considered unless mitigation techniques can be employed;
- administrations should take this into account in the planning of their domestic spectrum decisions.

4 An analysis of potential techniques proposed to facilitate sharing

Historically, the FSS and point-to-point FS systems have shared the same bands. Frequency coordination involved a relatively small number of terrestrial links and a relatively small number of large, expensive satellite earth stations. Coordination was not unduly burdensome for either service. Today, technological developments allow both satellite and terrestrial operators to provide service to a large number of end users.

This leads to the widespread deployment of both types of service in much higher number of terminals with the result that it could be difficult for either service to mitigate against so many interfering stations. As this deployment proceeds, the density of transceiver stations can quickly reach levels which would render co-frequency sharing unfeasible. It becomes impractical to coordinate the growing numbers of FS stations and satellite user terminals. The area of a region where terminals of both services may suffer interference becomes increasingly large.

To address this problem, some techniques have been proposed to facilitate use of the 18/19 GHz spectrum by FS transmitters and non-GSO FSS receiving terminals operating in the band 18.8-19.3 GHz. Section 4 summarizes the potential effectiveness of those proposed techniques and the feasibility of their implementation.

4.1 ATPC in FS systems

4.1.1 Potential effectiveness of the technique

The application of ATPC in the FS leads to a reduction of interference potential for FSS receivers due to the fact that maximum power of the FS transmitter is applied only in short periods of time. Under clear air propagation conditions, the theoretical benefit is estimated to be between 9 dB and 15 dB less power of the FS transmitter according to the ATPC range of the FS.

This technique could potentially reduce the size of the exclusion zones created by FS transmitters during clear-sky conditions, but would not sufficiently reduce the areas to permit ubiquitous deployment of non-GSO FSS user terminals. In cases where the FSS receiver is located away from the main FS pointing direction there can be instances where rain fading would impair the FS transmission so as to require additional power from the ATPC, but where such fading would not necessarily attenuate the signal path from the FS transmitter to the FSS user terminal. There are also opposite cases where the rain on only the interference path will decrease the interference level without inducing an increase of the FS emitted power.

In clear-sky conditions which represent long-term interference, ATPC has a straightforward benefit on the *I*/*N* level in the FSS receiver. In rain fading conditions, depending on the relative location of the FS transmitter, FSS station and rain zone, there can be some cases where the activation of the ATPC on the FS link can lead to an increase of the interference compared to the clear-sky conditions. But there can also be some cases where ATPC will not be activated while the rain will be located on the interfering path, decreasing then the level of interference into the FSS receiver. In principle, the main interference area of an FS link is reduced to a region along the ray of the transmitting antenna. Thus, it is considered that in most cases, the propagation conditions towards an interfered FSS station is quite similar to the conditions on the FS link. However, the interference levels under rain fade conditions will in any case be lower than the permanent interference level without ATPC.

One study providing simulations over the Paris metropolitan area shows the implementation of ATPC by the FS significantly decreases the exclusion zones around the FS transmitters (the study considered 23 FS links, which currently use 9 dB ATPC range). The results of this study for different ATPC ranges are summarized in Table 6.

TABLE 6

Effect of ATPC on exclusion areas

	No ATPC (%)	**9 dB ATPC range (%)**	**15 dB ATPC range (%)**
Percentage of exclusion zones in a 14 × 14 km area	5	2.3	1
Percentage of affected exclusion zones in dense urban zones	14	6.5	2.7

This study shows that the use of ATPC by the FS is a mitigation technique that reduces the size of exclusion zones around FS transmitters.

The benefits of this technique assume an ideal implementation of the ATPC tracking loop.

Some manufacturers have indicated that the ATPC response time is in the order of 20 ms and the slew rate is at least of 20 dB/s.

4.1.2 Feasibility of the technique

It was noted that implementing ATPC increases the equipment cost.

Due to the expense of implementing ATPC, it may not be practical for low-cost, ubiquitous FS terminal usage. However, many standards already (e.g. developed by the European Telecommunication Standardization Institute) implement, at least optionally, the ATPC. From 1 January 2003, ATPC is mandatory in this band in some European countries. Many manufacturers provide equipment having ATPC in this band. However, most FS systems currently deployed are not equipped with ATPC. An upgrade of existing hardware could be difficult.

Use of ATPC renders the FS links more susceptible to interference from FSS satellites and FS systems.

4.2 Dynamic channel assignment (DCA) in FSS systems

This technique has been studied as a possible mitigation technique, however, the studies concluded that while being theoretically feasible, implementation of DCA is not practicable for 18/19 GHz FSS networks planning ubiquitously-deployed earth stations.

4.3 Designation of separate spectrum for FS and non-GSO FSS

In view of the difficulties associated with co-frequency sharing between FS systems and non-GSO FSS user terminals planned for ubiquitous deployment in the same geographical area without the use of other mitigation techniques, the sections below investigate the potential effectiveness and feasibility of the designation of separate non-overlapping spectrum for the two different services in the 18/19 GHz band.

4.3.1 Potential effectiveness of this solution

On the point of view of interference avoidance, this solution is effective and allows the FS and the non-GSO FSS terminals to be ubiquitously deployed in a manner that avoids the burdens and constraints that one or both services would experience with co-frequency operation using interference mitigation techniques. Coordination would not be required between stations of the two services and the risk of interference would be avoided if there is no frequency overlap, therefore deployment of terminals in either service could be facilitated. This would avoid the administrative burden of effecting coordination. Designation of separate spectrum can allow effective use of spectrum, provide for high quality of service at low cost without regard to location, and provide flexibility for users of all systems in the affected services, especially in cases such as the 18.8-19.3 GHz band where ubiquitous deployment of terminals is planned. A drawback is that less bandwidth is available to both FS and FSS. In cases where ubiquitous deployment of FS and FSS terminals is not intended, however, designation of separate spectrum is a measure that may not be appropriate.

Consideration of designating separate spectrum to FS and non-GSO FSS should take into account the fact that the band 18.8-19.3 GHz (and the corresponding uplink band 28.6-29.1 GHz) is the only spectrum identified by the ITU that allows non-GSO FSS service link networks to operate without assuming the full burden of protecting the entire GSO arc.

4.3.2 Statistical analysis addressing the impact of this technique on the FS

A statistical study was performed to examine the relative merits of requiring HD-FSS user terminals to coordinate with FS terminals within a given country versus avoiding such national coordination by deploying FS in spectrum that is free of the burden of sharing with HD-FSS, and deploying HD-FSS in spectrum that is free of FS. The hypothetical question explored here is: "If national spectrum managers had 1 000 MHz of 18/19 GHz spectrum to be shared between FS and HD-FSS systems in their country, would greater overall spectral efficiencies be obtained by requiring the two types of systems to share across the entire 1 000 MHz or rather to provide 500 MHz to each type of system, free of the other type?"

4.3.2.1 Approach

The following algebraic reasoning was used to frame the basis of a simulation study:

1. If the FS had 1 000 MHz of HD-FSS-free spectrum, then the FS would have a saturated (i.e. maximum) utilization of $2Y$ links of a given bandwidth.

2. If the 1 000 MHz band were managed such that the FS operated in 500 MHz free of HD-FSS systems (and HD-FSS systems operated in the other 500 MHz free of FS systems), then the FS would be expected to have a saturated utilization of Y links of the same bandwidth as in 1.

3. However, if the FS and HD-FSS shared 1 000 MHz of spectrum on an equitable basis, the FS would have a utilization of $2Y\alpha$ where α is a factor that cannot be greater than one. If the value of α is less than 0.5, then the FS utilization would be less than Y and therefore, the FS would be better off operating with half as much spectrum that is free of systems of the other type. If the value of α is greater than 0.5, then an analysis of the HD-FSS utilization achieved would be required to determine the sharing method that would result in the most effective use of the 1 000 MHz.

4.3.2.2 Overview of simulation method

An estimate of the FS utilization factor, α, was obtained through Monte Carlo simulation as follows. First a simulation "pre-run" is performed to generate a precoordinated (intra-service), saturated FS deployment database. This is achieved by randomly locating co-frequency FS stations subject to the intra-service aggregate interference constraint (for both forward and return paths) until it becomes nearly impossible for the simulation to randomly place another FS station in the same geographical area (20 km diameter). The saturated environment is defined as the point where 10 000 trials have failed to successfully place an FS link at a random location with a random antenna main beam azimuth and a random link length, without violating the interference criteria of this station or other stations. The selected criteria are based on a single-entry I/N ratio of –10 dB and an aggregate I/N ratio of –6 dB (corresponding to a 1 dB degradation in margin). The result of these pre-runs is a set of saturated FS deployments to be used in the subsequent FS/HD-FSS simulation runs. The simulation procedure to create sample saturated FS environments was run 2 755 times resulting in an average station density of 49 per 20 km diameter region (0.156 stations/km^2).

Next, the FS/HD-FSS simulation tool is used to alternately place FS and HD-FSS terminals until the dual service environment reaches saturation. This process begins by randomly selecting one station from one of the FS pre-run databases to start a given Monte Carlo FS/HD-FSS run. Next an HD-FSS user terminal receiver location is randomly chosen and the interference that would be received by it from the FS transmitter is calculated. Assuming this interference is below the HD-FSS receiver interference criterion (aggregate $I/N < –9.1$ dB), the HD-FSS terminal is placed at this location and the simulation proceeds to the next step. If the interference threshold is exceeded, then the simulation randomly selects another location for the HD-FSS receiver until the interference is below the threshold.

At the next step of the run, another FS station is selected subject to the constraint that it not cause the aggregate interference criterion into any existing HD-FSS station to be exceeded. The simulation process proceeds in this manner randomly placing FS and HD-FSS stations alternately until the FS pre-run database is fully deployed or placing one more FS station is not possible. For each FS/HD-FSS Monte Carlo run, the value of α (FS utilization factor) is calculated. This procedure was repeated 549 times to determine a mean α.

However, it has been noted that this study has not made use of any type of topographical or building profile data or made any use of other mitigation techniques (e.g. site shielding) that will increase the density of deployment in both the FS-only and shared FS/HD-FSS calculations. Studies with mitigation techniques would be required to determine if the impact on the improvement in the FS utilization factor would be increased, decreased or left unchanged.

It was noted that:

– the study used Recommendation ITU-R S.465 for the FSS antenna patterns while it was suggested that the use of Recommendation ITU-R S.1428 could reduce the gain by 1.8 dB;

– the FS adjacent channel interference which may substantially impact the deployment of FS terminals for wide channels (e.g. 55 or 110 MHz), but it was pointed out that this would reduce the achievable deployment density in both the FS saturated (no HD-FSS) and shared environments. Further studies would be required to assess the relative reduction in the two cases;

– in the shared environment, when an FS link cannot be deployed due to interference into FSS terminals, no attempt was made to find another replacement link. However, it was argued that any new link could, in fact interfere into other FS links from the FS saturated environment and that with sufficient number of statistical trials the end results would converge to the same values. Further studies would be required to validate this statement.

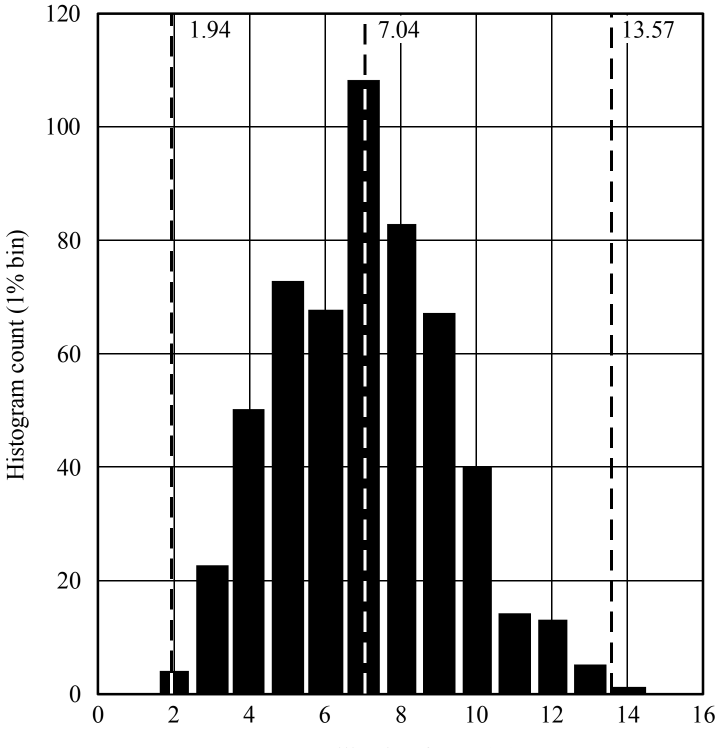
It was suggested that the overall spectrum efficiency including both types of systems should be assessed for this study.

4.3.2.3 Results

The results of the Monte Carlo runs (i.e. alternately placing FS and HD-FSS) are summarized in a histogram plot in Fig. 7. The height of each vertical bar in the Figure indicates the number of Monte Carlo runs that resulted in the corresponding FS utilization factor.

FIGURE 7

FS utilization results for 549 Monte Carlo runs
(simulating equal rate deployment with HD-FSS)



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These results indicate that on the average, the FS spectrum utilization achieved when the entire 1 000 MHz is shared equitably with HD-FSS is only 7%. (The highest FS utilization achieved with forced FS/HD-FSS sharing out of all Monte Carlo runs was less than 14% while the lowest was less than 2%.) On the other hand, if the spectrum managers were to take this same 1 000 MHz and give the FS access to 500 MHz free of HD-FSS, the FS spectrum utilization would be 50% of what it would be if the FS had access to the entire 1 000 MHz free of HD-FSS. This represents a better than seven-fold improvement (50% utilization vs. 7% utilization) for the FS on average with access to half the spectrum as compared to the case when that spectrum is free of HD-FSS. These results are shown in Table 7.

TABLE 7

Average FS utilization factors

	Average FS spectrum utilization factor, α (relative to that achieved with unconstrained access to 1 000 MHz)
Unconstrained FS access to 500 MHz (free of HD-FSS systems)	50%
FS required to share equitably with HD-FSS over 1 000 MHz	7%
Improvement in FS spectrum utilization factor with unconstrained access to 500 MHz vs. constrained access in 1 000 MHz	**7.10** (ratio of above results)

Previous studies which did not take into account mitigation techniques have shown that HD-FSS user terminals are not compatible with FS stations transmitting on the same frequencies in the same geographical area. Therefore, HD-FSS systems would be better off with access to 500 MHz free of FS versus being required to coordinate on a national basis with FS in 1 000 MHz. Furthermore, the results of the current simulation study show that the FS would also achieve much higher spectrum utilization with access to 500 MHz free of HD-FSS, versus shared access to 1 000 MHz. On the basis of these results, it can be concluded that for those countries desiring to benefit by HD-FSS systems, the better solution is to have portions of the 18/19 GHz band free of FS and other portions of the 18/19 GHz band free of HD-FSS systems instead of coordinating the two types of systems, if this is an option for the administration. However, it is noted that this study did not take into account actual propagation paths (with attenuation due to terrain and man made obstacles) that would have reduced the improvement shown in Table 7. Some administrations do not consider the frequency separation of FS and HD-FSS systems as an option.

4.3.3 Feasibility of this solution

The designation of separate spectrum of the 18/19 GHz band in order to give to the FSS on an exclusive basis the 18.8-19.3 GHz band leads to a minimum loss of spectrum of 25% for the FS as compared to the unconstrained use of the entire 2 GHz range (17.7-19.7 GHz) by this service. When considering duplex channel pairing, this loss could be as high as 50% unless a different FS channelization plan can be implemented in the corresponding duplex band. Unless a large number of units are deployed or many administrations adopt the new channelization plan, economies of scale will not be achieved. Designating separate spectrum for each service allows administrations not currently using this band to have unconstrained deployment of non-GSO FSS and FS.

For the countries where the FS is already deployed in this band, such as many European countries, the introduction of this technique would require removal or retuning of a very high number of links from the 18.8-19.3 GHz band and its paired band (representing half of the total band) which may not be feasible due to a lack of available spectrum in other bands and will have a huge financial impact. It has to be noted that if there is a need to move FS links to higher frequency bands (where propagation condition are substantially different (see § 4.3.4)), this could lead to different hop lengths and therefore the network structure would have to be completely redesigned.

The relocation or retuning costs of existing FS systems could be minimized by phasing out existing systems over a period, on a country by country basis, that is acceptable to both the FS and FSS.

The relocation or retuning costs of future FS systems could be minimized by:

– installing all new FS systems in accordance with a new channelization plan or in other bands while avoiding the band segment reserved for non-GSO FSS;

– using a new channelization plan;

– using the new channelization plan when upgrading existing systems with more spectrally efficient equipment.

4.3.4 Effect of rain on the choice of the bands for mobile networks FS infrastructure

A study on the impact of rain attenuation on the choice of the frequency bands to develop FS infrastructure networks has been carried out. Through the calculation of the margin at a given hop length, it showed that the 18/19 GHz band plays the role of the 23 GHz and 38 GHz bands for these infrastructure networks, in particular for mobile networks point-to-point FS infrastructure, in the geographical areas where the rain attenuation is high.

The calculation is based on the use of the Recommendations ITU-R P.530, with an availability of 99.99% minimum, and ITU-R P.676. The FS systems considered are point-to-point and their characteristics are taken from the Recommendation ITU-R F.758. In some cases, characteristics used by systems currently in operation (in Europe or in the French overseas departments) have been used.

The margin, M, is calculated as follow:

$$M = P_r - P_{r,min} = (G_e \cdot G_r \cdot P_e)/(L_T(p) \cdot FL) - P_{r,min}$$

where:

$P_{r,min}$: minimum level at the reception (usually for BER of 1×10^{-6})

$G = G_e = G_r$: antenna gain at the emission/reception.

P_e: input power at the emission

$L_T(p)$: total loss (rain at p%, gas, diffraction)

FL: feeder loss (total: at the emission and reception)

The result of a direct comparison between the available range of hop lengths, in the 18/19 GHz band in Zone Q, and the 23 GHz and 38 GHz bands in Zone E, is given in Fig. 8 using the characteristics in Table 8.

TABLE 8

Characteristics of FS systems in various frequency bands

Frequency (GHz)	18/19	23	38
FL (dB)	3	4	4
P_e (dBW)	–5	–5	–5
G (dBi)	45	46	46
$P_{r,min}$ (dBW)	–102.4	–108	–108

This theoretical study has been confirmed by the data provided by one operator which has deployed an FS infrastructure for mobile network in Metropolitan France and in French Oveseas Departments. As shown by Fig. 9, this operator does not use the 23 GHz and 38 GHz bands because of the rain attenuation. The highest frequency band is the 18/19 GHz band.

FIGURE 8

Comparison between the available range of hop lengths in the bands 18/19 GHz in Zone Q, 23 GHz and 38 GHz in Zone E

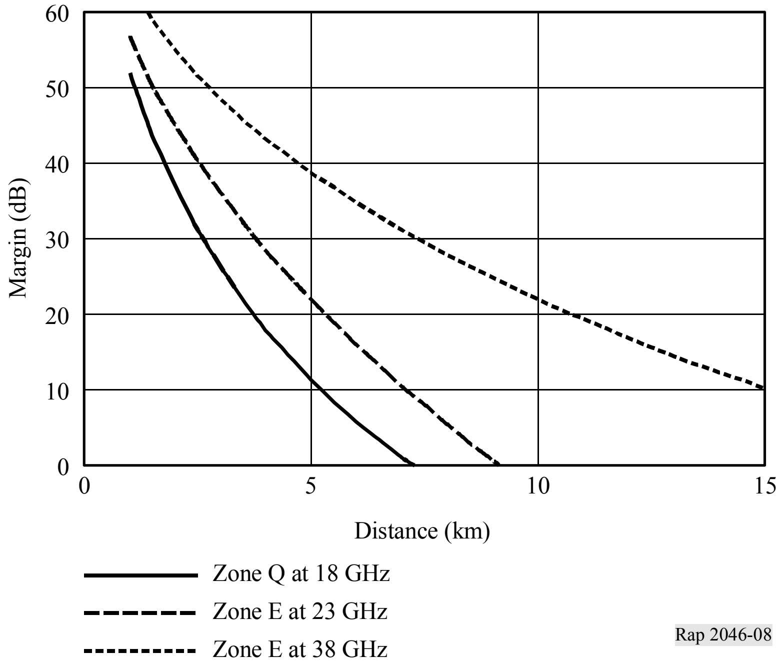

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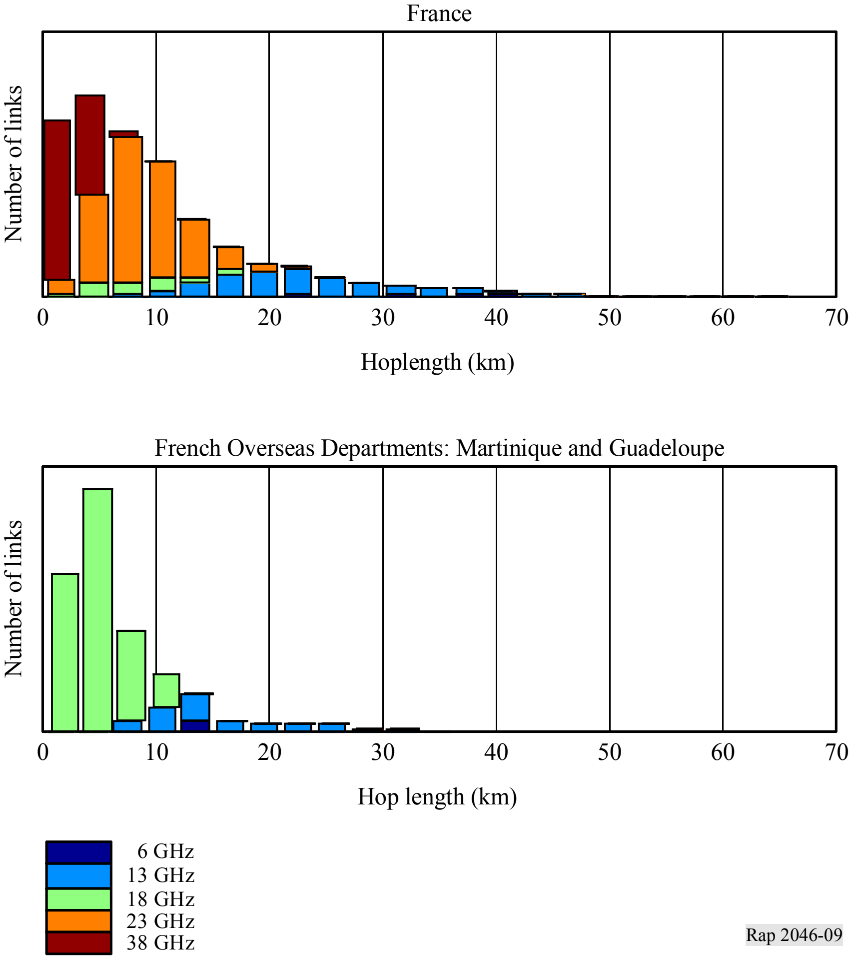
FIGURE 9

Distribution of the links for mobile networks infrastructure in the French metropolis and in the French Overseas Departments Martinique and Guadeloupe



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As a consequence, this study shows the risk of not allowing the FS to use the entire 17.7-19.7 GHz band in case of a segmentation of the latter.

4.4 Site shielding and positioning of the FSS station

As obstacles on the interference path from the FS transmitter into the FSS receiver can have a significant blocking effect of the interfering signal, several techniques can be used to improve sharing:

- Site shielding consists in intentionally placing the FSS receiver in locations where any potential interference from the FS would be blocked by the surrounding environment.
- Site positioning consists in finding the optimal location with respect to interference in the available area for the FSS station operation.

4.4.1 Potential effectiveness of the technique

Analysis of site shielding mitigation technique has indicated that non-GSO user terminal mounting positions that give significant isolation from the interfering FS signal result in unacceptably low visibility to the non-GSO satellites. Attempts to locate the non-GSO antenna receiver in positions with full satellite visibility result in no interference isolation or negligible attenuation. The conclusion of this analysis is that site shielding is not a viable mitigation technique to assure the coexistence of FS and non-GSO FSS in the 18.8-19.3 GHz band. The results of one measurement campaign have shown that interference is strongly dependent on the specific location of an FSS station on a terrace.

Regarding siting and positioning of FSS terminals, in cases where obstacles on the interference path from the FS transmitter into the FSS receiver can have a significant blocking effect of the main interfering signal and where the interference would come from diffraction and/or reflection, positioning of terminals can improve the situation. Therefore, in such a situation, the careful siting of an FSS station should be considered as a way to reduce the interference from the FS transmitter.

4.4.2 Feasibility of the technique

In some countries legislation poses many restrictions to the placement of antennas on the top of buildings. As an example, some legislation prohibits the placement of any equipment at all (even air conditioning devices) that extends more than 30 cm from the building facade. Obviously, this fact makes it very difficult to use the site shielding mitigation technique. Site shielding technologies that allow the FSS station to be completely blocked from any interference may be difficult to use due to technical constraints and municipal and/or land-use regulations.

Since positioning is optimized during the installation of the non-GSO FSS terminal, its effect requires a stable interference environment. In the situations where this technique would be feasible, the cost of installation may increase due to the need to analyse the interference environment. As it just consists in finding the optimal location regarding interference in the available area for the FSS station operation, it is a feasible technique, which would benefit the FSS.

4.5 High performance FS antennas

High performance FS antenna will have lower side-lobe and back-lobe gain.

4.5.1 Potential effectiveness of the technique

This technique could potentially reduce the width of the exclusion zones created by FS transmitters, but would not necessarily reduce their length, which is the most significant dimension of the typical exclusion zone. This would not likely result in a significant improvement in the ability to ubiquitously deploy non-GSO FSS user terminals, especially in areas where the density of deployment of FS stations is significant (e.g. urban areas) and where the exclusion zones of multiple transmitters overlap.

4.5.2 Feasibility of the technique

This technique is feasible but does not reduce the interference significantly.

4.6 High-gain FS antennas

4.6.1 Potential effectiveness of this solution

The employment of FS antennas with higher gain enables reduction of the output power of the FS transmitter, and thus reduces the area where FSS receivers might suffer interference. Doubling the antenna diameter of the transmitter and receiver of an FS link and, as a consequence, reducing the transmitter power in the way that the link performance does not change, will reduce the theoretical interference area by a factor of approximately eight.

4.6.2 Feasibility of this solution

This technique is feasible for new FS links, but the cost for existing FS links is significantly higher. Increasing the antenna size too much (e.g. diameter of 1.2 m) would hardly be possible due to limits in construction issues like wind load and weight of the antenna. Also, larger antennas receiving weaker signals would be more susceptible to interference from satellite transmitters.

4.7 Managing FS assignments in the band

The deployment of FS stations could be restricted in number, frequency band and/or geographic area in order to facilitate sharing with the FSS.

4.7.1 Potential effectiveness of this solution

Restricting the deployment of FS stations would certainly facilitate the introduction of FSS user terminals but would not relieve the burden of coordination.

4.7.2 Feasibility of this solution

Any restrictions on FS deployment may represent a corresponding cost.

4.8 Coordination between the FSS and the FS

This technique can be effective for large (gateway type) earth stations. Although quite feasible for large earth stations, coordination is not practicable for low-cost, ubiquitous user terminals. The cost and administrative burden of implementing coordination would be out of proportion to the low cost and ease of deployment of these small user terminals. In addition, if the user relocates there is no guarantee that a terminal that was previously coordinated would be able to continue operating interference-free at its new location.

4.9 FSS antenna patterns

The interference from an FS transmitter into an FSS receiving earth station will usually never lead to a main beam to main beam scenario. Thus, the performance of the FSS antenna beyond the main beam and first side lobes is of great importance for the interference situation. In principle, high gain FSS terminal antenna would lead to lower side lobe gains and in any case, FSS terminals should be designed considering the importance of the side lobe performance. However the cost of implementing high gain antenna in a user terminal can be expensive and may be counter to the objective of low-cost user terminals for ubiquitous non-GSO FSS applications.

4.10 Adaptive coding

This mitigation technique consists of increasing the redundancy of the information transmitted during a (small) percentage of time so as to compensate a reduction of the availability of the system due to the conjunction of an interference and a rain attenuation, the combined effect of which is higher than the addition of the margin for external interference, M_E, and rain margin, M_R.

Adaptive coding is a technique that can be used to combat time-varying degradations to link margin, e.g. fading. The interference from the FS into the FSS can be considered as constant over the time. In such a situation, the only variable effect over time is the rain attenuation. If the external interference degrades the system margin by M_E, a rain attenuation higher than M_R will lead to an unavailability of the service. If the level of interference exceeds the value M_E, the percentage of time of unavailability will increase since part of the rain margin will be used to compensate for this additional level of interference.

However, if the level of interference permanently exceeds $M_R + M_E$, use of adaptive coding could not prevent data rate reduction for 100% of time.

4.10.1 Impact of the reduction of the information data rate

Studies concerning the impact to FSS system performance of using adaptive coding to mitigate FS interference at 18/19 GHz have been performed and the quantification for the impact of FS interference for FSS systems using adaptive coding with various levels of fixed margin can be seen in the Table 9.

TABLE 9

Impact of FS interference on FSS average throughput and unavailability for FSS systems using adaptive coding (0.5 dB margin for FS interference)

Total degradation due to FS interference (dB)	**1 dB FSS fixed margin** **Average throughput 336.9 Mbit/s Unavailability 0.079%**		**3 dB FSS fixed margin** **Average throughput 338.3 Mbit/s Unavailability 0.042%**		**5.5 dB FSS fixed margin** **Average throughput 338.6 Mbit/s Unavailability 0.021%**	
	Percentage decrease in FSS throughput	**FSS unavailability(1) (%)**	**Percentage decrease in FSS throughput**	**FSS unavailability(1) (%)**	**Percentage decrease in FSS throughput**	**FSS unavailability(1) (%)**
0.5	0.0	0.079	0.0	0.042	0.0	0.021
1.0	0.4	0.087	0.0	0.046	0.0	0.024
1.5	1.8	0.097	0.1	0.049	0.0	0.026
2.0	12.4	0.109	0.1	0.054	0.0	0.027
2.5	21.8	0.122	0.3	0.059	0.0	0.029
3.0	30.3	0.158	0.7	0.071	0.1	0.031
3.5	37.9	0.181	1.9	0.078	0.1	0.036
4.0	44.6	0.210	12.5	0.086	0.1	0.039
4.5	50.6	0.293	22.0	0.107	0.2	0.046
5.0	56.0	0.458	30.4	0.121	0.3	0.050
5.5	60.8	0.556	38.0	0.156	0.6	0.059
6.0	65.1	0.777	44.7	0.179	1.8	0.065
6.5	69.0	1.390	50.7	0.244	12.4	0.079
7.0	73.3	5.012	56.1	0.453	21.9	0.097

(1) This FSS unavailability is computed relative to the case with 0.5 dB FS interference if the additional margin allowed by adaptive coding is used to increase the nominal availability.

As indicated in Table 9, the effect of a 0.5 dB degradation from FS interference (in excess to the 0.5 dB margin carried by the system for that purpose) will increase the unavailability of the FSS earth station by approximately 10% regardless of the FSS fixed margin. The Table also shows that if a 5.5 dB fixed margin is employed in addition to adaptive coding, the FSS system can accommodate up to a 6.5 dB long-term degradation due to FS interference before suffering a significant impact to average system throughput. However, it has to be noted that this same level of FS interference will increase the FSS unavailability (i.e. the unavailability that would result when the interference levels from FS is the 0.5 dB allocated value) for such a system from 0.021% to 0.097%.

Moreover, Table 9 shows the impact of degradation due to FS interference for an FSS system employing 1 dB or 3 dB of fixed margin in addition to adaptive coding. For an FSS system with 1 dB of fixed margin, a 1.5 dB increase in degradation due to FS interference will decrease the FSS average throughput by 12%. A 2.5 dB increase in degradation due to FS will reduce this throughput by 22% and a 5 dB increase in degradation due to FS interference will reduce the FSS average throughput by 61%. But it should be noted that this decrease allows the system to maintain the communication between the satellite and the earth station.

It should also be noted that for an FSS system a 1 dB fixed margin in conjunction with adaptive coding (allowing a reduction in data rate down to 25%) results in an availability value of 99.92% – a value well in line with many quoted FSS availability objectives. Every additional dB of fixed margin for an FSS system requires 25% more power from the satellite amplifiers, which can easily translate to similar figures for prime power and consequent launch weight and cost increases. However, a system that already has a large fade margin, would only need to take into account the additional costs of implementing an adaptive coding technique in its network. Realizing that many FSS systems intend to provide a global service and not just a local service, design objectives of such systems must on the one hand, take into account the impact that such an increase in fixed margin would have on total system cost, and on the other hand, weigh the increased opportunity to offer service to customers in areas where terrestrial services are heavily deployed, as well as the higher availability that would result for areas with little or no terrestrial deployment or in areas with higher rain rates. In other words, designing a large fixed margin into an FSS system in conjunction with adaptive coding results in the FSS system, which are over-designed for some regions of the world where FS deployment might not be too significant, in order to meet design objectives in some regions where there is significant FS deployment. However, it is expected that those FSS systems intended to serve all regions of the world will be designed to cope with situations where the level of rain attenuation is high in some areas and low in other. As a consequence, even assuming the absence of FS systems, those FSS systems have to be designed with sufficient fade margin.

4.10.2 Impact of the use of adaptive coding technique on potentially interfered FSS earth stations

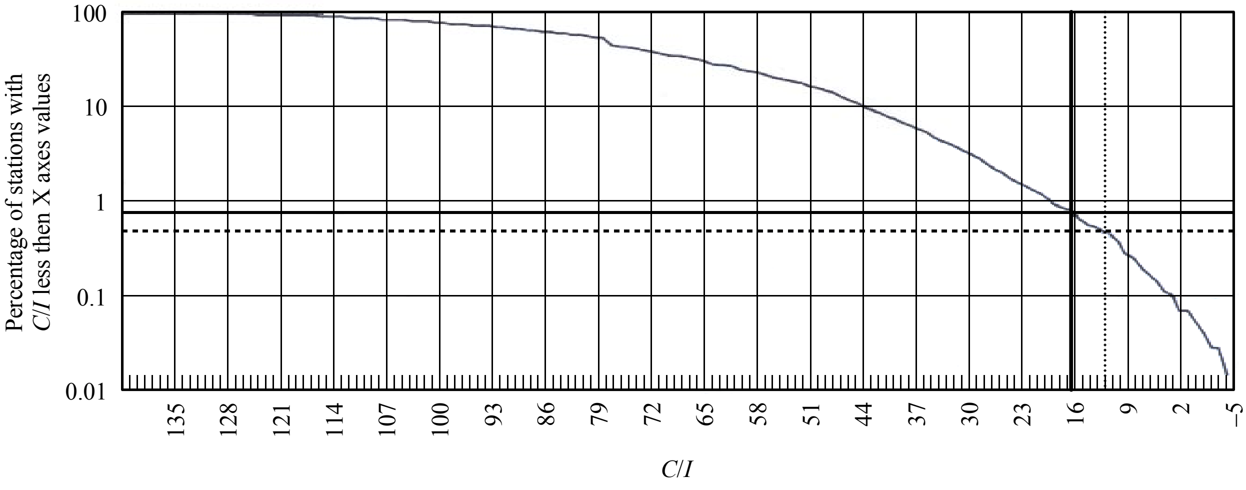
A study was carried out to quantify the improvement of the sharing between FS and FSS terminals when the FSS system uses adaptive coding as a mitigation technique. This study relied on two approaches, one based on statistical simulation and a second based on a deterministic calculation.

The statistical study relied on the same assumptions as those considered under § 3.1.2. It assumes a rain margin of 5.5 dB and an extra margin of 1 dB for the FSS downlink and considers two cases: for the first one, it is supposed that the adaptive coding can compensate for a degradation margin of 1 dB and for the second one, this value is of 3 dB. From these values, the C/I required for the FSS system has been recalculated from its initial value supposed to be of 20 dB. These values are respectively 16.4 dB and 12.2 dB.

Figure 10 shows, for one simulation, the percentage of stations for which the C/I is below the abscissa value.

FIGURE 10

Results of *C*/*I* calculations into non-GSO FSS earth stations



C/*I* = 16.4 dB (continuous line)
C/*I* = 12.2 dB (dotted line)

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Tables 10 and 11 summarize the percentage of stations with *C*/*I* < 16.4 dB or < 12.2 dB when adaptive coding is used for different simulations:

TABLE 10

Results for non-GSO FSS earth stations employing 1 dB margin

Percentage of stations with *C*/*I* < 16.4 dB when adaptive coding is used	Evolution of the number of stations below the required *C*/*I* with respect to the case without adaptive coding (%)
0.7	–44
0.8	–33

TABLE 11

Results for non-GSO FSS earth stations employing 3 dB margin

Percentage of stations with *C*/*I* < 12.2 dB when adaptive coding is used	Evolution of the number of stations below the required *C*/*I* with respect to the case without adaptive coding (%)
0.085	–93
0.5	–58

The effectiveness of adaptive coding on the FS/FSS sharing situation is significant since it allows a decrease by 33% to 93% the number of interfered stations, even when this number is already very low.

The deterministic study was based on the same assumptions than that one of § 3.1.1.1. As a consequence, a free space loss propagation model has been used together with the added gaseous attenuation. No terrain blocking was considered.

In these above-mentioned deterministic studies, a long-term interference allowance of 6% of the non-GSO user terminal system noise (i.e. *I*/*N* = –12.2 dB) under clear sky, clear terrain conditions was been considered. This corresponds to a maximum interference level in the FSS receiver of –99.2 dBm for a receiver noise of –87 dBm (assuming a 500 MHz bandwidth).

An *I*/*N* of –12.2 dB corresponds to a possible degradation margin of 0.25 dB to which (as explained above) is added the possible margin degradation authorized by the use of the adaptive coding. Table 12 gives the maximum interference value according to this added margin degradation.

TABLE 12

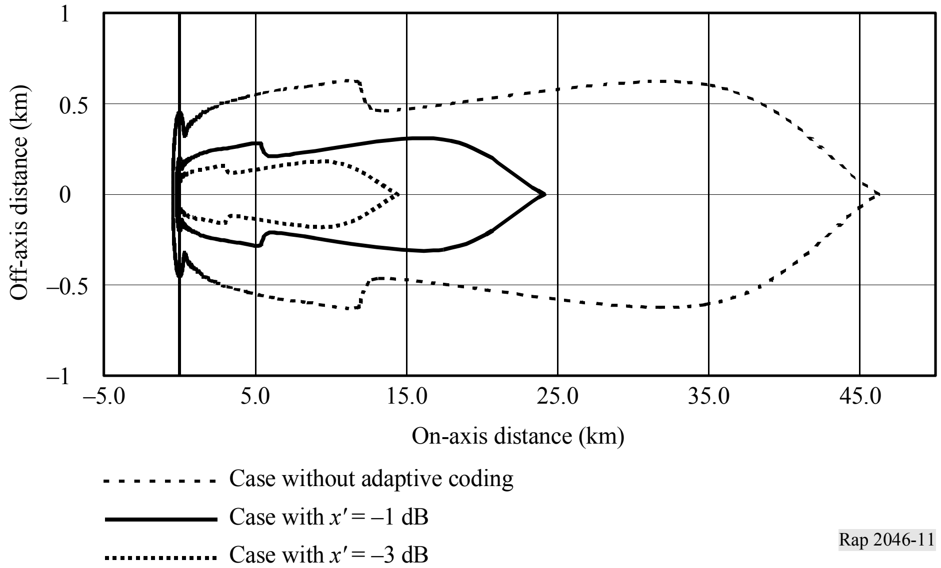
Maximum interference level at the FSS receiver

Added degradation margin (dB)	Total authorized degradation margin (dB)	Maximum interference level at the FSS receiver (dBm)
1	1.25	–91.77
3	3.25	–86.53

Figure 11 presents the results of the calculation for the three cases: without adaptive coding, and with, when the latter compensates an added degradation margin of 1 dB and 3 dB.

FIGURE 11

Areas where FSS receivers may suffer interference from FS in cases with and without adaptive coding



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When adaptive coding is used, the impact on the area where FSS earth station receivers may suffer interference is extremely significant. Not only the maximum distance in the FS main beam direction is reduced by 50% to 70% (24 km to 14 km) according to the compensated margin (1 dB or 3 dB), but the total area is obviously significantly decreased. It should also be noted that in the back lobe, the distance is reduced to less than 10 m to 20 m according to the considered case.

The deterministic studies gave results similar to those of the statistical one. The implementation of adaptive coding in the FSS downlink transmission is a very effective mitigation technique to reduce the risk of interference from FS transmitters to FSS receiving earth stations.

4.10.3 Implementation of adaptive coding

The implementation of adaptive coding in satellite systems is possible. This implementation can be done through the addition of a (new) level of coding associated with a mechanism of adaptation of this coding (e.g. through puncturing codes).

When the interference environment can be taken into consideration from the very beginning of the design of the FSS system, the choice of the adaptive codes can be optimized. It has been noted that by their very nature the use of Turbo Codes can significantly help in achieving this optimization, while minimizing the impact on the information rate.

From the information provided in § 4.10.1, it can be seen why an FSS operator might decide to employ only 1 dB of fixed margin even though a larger fixed margin would make the FSS earth terminals less susceptible to long-term interference from the FS and would allow it to offer service where it could not without this larger fixed margin to combat FS interference. Some administrations expressed the view that an FSS system employing adaptive coding and designed to operate in an environment shared with FS should not employ only 1 dB fixed margin.

4.10.4 Feasibility of the technique

The adoption of adaptive coding in satellite communications systems (e.g. USAMEO-1; DVB-RCS for which its use is foreseen in the implementation of return channel via satellite for narrow-band applications) indicates the viability of the implementation of these codes and may lead to a wider availability of the corresponding coder/decoders circuits.

In addition, Recommendation ITU-R S.1420 encourages, in the particular case of ATM transmissions, the use of forward error correction coding and adaptive regulation of the data rate so as to improve the quality of service of the transmission.

4.10.5 Conclusion on adaptive coding

Adaptive coding is a technique to combat time-varying degradation effects.

Even though for some interfering scenarios, the adaptive coding technique will not be able to overcome the sharing difficulties between FS and FSS systems, this technique still presents advantages and as a consequence, should be considered as a method for improving the sharing situation between FS terminals and FSS receiving earth stations.

It was noted that the use of adaptive coding cannot directly combat the reduction of link margin due to FS interference, but, at the expense of a reduction of data rate, it will be able to maintain the availability of the link, albeit at a degraded service.

4.11 Spread spectrum

The use of spread spectrum as a mitigation technique is based on the assumption that due to the frequency reuse characteristics of terrestrial infrastructure networks, it can be assumed that the potentially interfered earth stations receive interference simultaneously from a small number of FS transmitters (55 MHz, 27.5 MHz or 13.75 MHz bandwidth), resulting in most cases in a narrow-band interference with regard to the 500 MHz bandwidth used by the satellite broadband system.

Recommendation ITU-R SM.1055 provides examples of band sharing using the spread spectrum technique to provide increased resistance to certain types of interference.

In this context, three different spread spectrum techniques were studied: direct sequence (DS), multicarrier (MC) and frequency hopping (FH). It was noted that spread spectrum signals are associated with code division multiplexing (CDM) that as frequency division multiplexing (FDM) and time division multiplexing (TDM) are multiplexing techniques.

It has been noted that CDM techniques are generally more complex than FDM and TDM. However, CDM techniques have other advantages with respect to FDM and TDM. Compared to FDM, when using spread spectrum as a mitigation technique the satellite system does not need to know on which frequency the FS transmitter is locally transmitting.

4.11.1 Potential effectiveness of the technique

It was noted that the more FS links that are deployed, the more likely that spread spectrum techniques will not be able to overcome the sharing difficulties between FS and FSS systems, however, it is recognized that because of the intra service FS interference, the deployment of FS systems cannot increase indefinitely.

Spread spectrum can increase the interference margin by reducing the data rate (increasing the spreading factor without changing the allocated carrier bandwidth), which is the same that can be achieved by any other type of multiplexing (e.g. TDM) by reducing transmitted data rate while maintaining power levels to achieve higher margin. In both cases, the decrease in transmitted data rate results in additional fade margin on the FSS downlink. Allocating more fade margin to FS interference results in a greater proportion of the system unavailability being given to interference from this other service.

4.11.1.1 DS spread spectrum

DS spread spectrum can be defined as a signal structuring technique utilizing a digital code spreading having a chip rate $1/T_c$ much higher than the information signal bit rate $1/T_b$. Each information bit of the digital signal is transmitted as a pseudo-random sequence of chips, which produces a broad noise-like spectrum. The receiver correlates the RF input signal with a local copy of the spreading sequence to recover the narrow-band data information at a rate $1/T_b$.

When the interference is narrow-band, the cross correlation of the received signal with the replica of the spreading sequence reduces the level of the interference by spreading it across the frequency band occupied by the spread signal. Thus the interference is rendered equivalent to a lower-level noise with a relatively flat spectrum. Simultaneously, the cross correlation operation collapses the desired signal to the bandwidth occupied by the information signal prior to spreading.

The ratio of the total bandwidth W over the information bandwidth R ($W/R = T_b/T_c$) is the bandwidth expansion factor. As a good approximation, the improvement of the S/I power ratio is equal to the bandwidth expansion factor or the ratio between the bandwidth of the spread signal and the bandwidth of the interfering signal whichever is the smaller.

A certain level of flexibility in the user capacity can be obtained associating multiple orthogonal codes to the same user.

CDM systems employing direct sequence spread spectrum require some linearity on the power amplifier which translates either in a larger satellite amplifier or an increase in satellite output back-off affecting system performance.

4.11.1.2 Multicarrier spread spectrum

MC spread spectrum consists in taking M narrow-band waveforms, each on a different carrier frequency, and in assigning them all to one use, increasing the spread bandwidth by a factor of M. The receiver provides a correlator for each carrier, and the outputs of the correlators are combined to yield a processing gain comparable to that of a single carrier DS system. Similar to a conventional single carrier DS system, a multicarrier system has a narrow-band interference mitigation effect.

Rather than simply repeating the same data symbol on each of the M carriers, one can use a high-rate punctured convolutional code to match k input bits to n output bits (k close to n). The $n = M$ output bits are then modulated on the M carriers.

At the receiver level of the satellite user terminal, one or several of the M channels may be interfered. By using the redundancy in the transmitted data, the decoder in the satellite user terminal manages to fill the positions where such erasures occur and to recover the original information sequence. Such codes can be designed to correct one or several erasures, depending on the memory length of the code.

By a judicious choice of the high rate punctured convolutional code, it is thus possible to completely wipe out one (or several) of the M transmitted carrier(s). The interfered carriers, if any, can be different for each terminal within a spot beam.

It has been noted that the efficiency of this technique depends on the alignment of the M carriers to the frequency plan used by the terrestrial infrastructure networks. In the case of overlapping frequencies, two carriers (instead of one) may get interfered, however with lower power levels.

CDM systems employing multicarrier spread spectrum require some linearity on the power amplifier which translates either in a larger satellite amplifier or an increase in satellite output back-off affecting system performance.

4.11.1.3 Frequency hopping spread spectrum

FH spread spectrum can be defined as a signal structuring technique employing automatic switching of the transmitted frequency. Selection of the frequency to be transmitted is typically made in a pseudo-random manner from a set of frequencies covering a band wider than the information bandwidth. The intended receiver frequency-hops in synchronization with the transmitter in order to retrieve the desired information.

The frequency hopping spread spectrum technique improves the C/I requirements by creating diversity from interferers. The design C/I can be based on the average $(C/I)_{average}$ instead of the worst case. While some of the narrow-band channels are faded out or interfered, most frequencies are generally free from interference.

When the interfered frequencies are known to the satellite terminal, in a given geographical environment, then it may be possible that these frequencies can be avoided entirely in the hopping sequence. In some cases, for a given satellite terminal, this yields a shorter hopping sequence, but no loss in capacity.

4.11.2 Impact on the data rate

The instantaneous data rate to a user is reduced by the spreading factor. However, in the DS system, by dwelling longer at this user the average data rate can be maintained. Dwelling longer at a given user reduces the flexibility with which the system capacity can be used. This last effect can at least be mitigated by assigning multiple codes to the same user, keeping in mind that assigning multiple codes to the same user reduces the spreading factor.

In the MC system, the impact on the data rate is equivalent to the rate of the punctured convolutional code k/n. However, a TDM satellite system (point-and-shoot) using this technique in order to improve the sharing situation only has to reduce the data rate for the potentially interfered terminals.

Regardless of the type of spread spectrum multiplexing and satellite architecture, the peak data rate achieved by CDM when used as a mitigation technique against FS interference gets reduced. The data rate reduction required for spread spectrum is similar to the reduction in data rate that can be employed for other modulation techniques to increase the energy per bit and compensate for the FS interference. However, it has to be noted that the behaviour of frequency hopping spread spectrum in this context needs further study.

It has been shown that a satellite network employing direct sequence spread spectrum multiplexing does not provide any more interference protection than a system employing TDM using comparable data rate on the transponder, and this for either point-and-shoot satellite configurations or satellites employing fixed beams (satellite or Earth-fixed beams). In fact, in a study carried out using fixed beams, the TDM system was actually more robust to interference than the direct sequence spread spectrum system.

It must be pointed out that a spread spectrum signal could be dynamically adjusted in terms of spreading factor (and spreading gain) to accommodate each user's interference environment, but the same can be done with TDM access as long as adaptive data rate is provided to each user on a packet-by-packet or data transmission burst basis.

Moreover, for any given quality of service, the usage of N carriers with service rate R/N would provide an average traffic throughput lower than the traffic provided by a single larger carrier at a service rate R. This means that the use of any type of spread spectrum multiplexing as an FS mitigation technique leads inevitably to a loss of statistical multiplexing gain and therefore results in a loss in overall FSS satellite capacity.

4.11.3 Feasibility of the technique

It was noted that the various spread spectrum techniques can be more adapted to one or another satellite system architecture. Moreover, even though not widely used in satellite communications, these techniques have been developed for both terrestrial and satellite radiocommunication systems.

Regardless of the FSS architecture base line, when using direct sequence, multicarrier spread spectrum multiplexing or frequency hopping spread spectrum with multiple carriers to mitigate FS interference, the satellite amplifier would need to operate with an output back-off which increases with the number of carriers. The use of this back-off implies a reduction in amplifier power efficiency compared to a situation where the satellite payload is limited to a saturated single-carrier operation. This lowered power efficiency leads to an increase in required satellite amplifier power resulting in a larger satellite mass. It should however be noted that some FSS systems are designed to operate with FDM access using a set of carriers whose bandwidth ranges from less than 100 kHz to over 100 MHz. This implies that the satellite HPA will need to operate in its linear region in order for the FSS operator to be able to provide services involving multicarrier operation. Moreover the use of amplifier back-off in multicarrier operation is necessary in order to reduce the intermodulation products. In multicarrier operation, there is therefore a trade-off between the amplifier efficiency and the intermodulation products level. In the case of single-carrier operation, the entire amplifier power can be used.

While recognizing that this Report deals with the 18/19 GHz band, it was noted that there are some FSS systems that are designed in the 10-12 GHz range intending to use CDM techniques to provide service to a large number of earth stations in shared bands with terrestrial services. Given that design considerations and propagation conditions are different for the two frequency bands, implementation of CDM in the 12 GHz range might not be the same as CDM implementation in the 18/19 GHz band.

4.11.4 Conclusion on the use of spread spectrum as a mitigation technique

It is believed that, even though for some interfering scenarios spread spectrum technique will not be able to overcome the sharing difficulties between FS and FSS systems, this technique still presents advantages and as a consequence, should be considered so as to improve the sharing situation between FS terminals and FSS receiving earth stations.

It was noted that most proposed satellite systems in the band 18/19 GHz do not intend to use the spread spectrum technique but that, however, at least one system does.

4.12 Other mitigation techniques

The antenna type to be used. This is especially useful in the cases of interference for very close location (about 100 m). In some cases a difference of 10 dB can be reached, by means of the antenna characteristics, when there is sufficient angular separation between the pointing direction of the antenna of the FSS terminal and the location of the FS station.

From one contribution, it can be concluded that an appropriate location in the installation place can be considered as a mitigation technique. It can reduce the interference sensibly when being blocked by near obstructions.

4.13 Combination of different mitigation techniques

To the extent that techniques can feasibly be used to mitigate interference individually, their combined effect could improve the sharing situation relative to the methods taken individually.