Extending the Usable Ka-Band Spectrum for FSS Satellite Systems by using a FS Database

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Abstract— **Broadband access by satellite in Ka-band will become constrained by spectrum availability. In this context, the European Union (EU) FP7 project CoRaSat is examining the possible spectrum extension opportunities that could be exploited by a database approach in Ka-band via the use of cognitive mechanisms. The database approach utilizing spectrum scenarios between Fixed Satellite Services (FSS), Fixed Services (FS) and Broadcast Satellite Service (BSS) feeder links are considered. Database statistics for several EU countries are also provided for database analysis. Interference in the downlink scenarios are evaluated by the database approach using real databases and propagation models. The importance of using correct terrain profiles and accurate propagation models are shown. For the case of BSS interference to the FSS downlink (17.3-17.7GHz) it is demonstrated that in the UK an area of less than 2% is adversely affected. FS interference into the FSS downlink 17.7-19.7GHz is shown for the UK to only affect a small percentage of the band at any location. Some initial preliminary findings when considering earth stations on moving platforms are also presented. It is concluded that by using a database approach to allocate frequencies it is possible to use most of the band across different locations for satellites services in the shared Ka-band.**

Keywords – Database approach; frequency sharing; propagation models; area analysis; spectrum analysis.

I. Introduction

In this paper we address the extension of spectrum for satellite systems in the Ka-band using a database approach [1].

The demand for higher rate and reliable broadband communications is accelerating all over the world. Within Europe the Digital Agenda sets a target for universal broadband coverage of at least 30 Mbps across the whole of Europe by 2020 and 100 Mbps to at least 50% of the households [2]. Fixed connections and cellular cannot alone meet this target, particularly in the rural and remote areas but also in some black spots across the coverage. In these latter regions satellite broadband delivery is the only practical answer as satellite will cover the whole territory. Some recent studies of the roll out of broadband have shown that up to 50% of households in some regions will only have satellite available as a means of accessing broadband and thus 5-10 million households are potential satellite customers [3]. Current Ku band satellites do not have the capacity to deliver such services at a cost per bit that makes a business case and thus, the satellite community has turned to High Throughput Satellites (HTS) operating at Ka-band and above. Examples of early HTS Ka-band satellites dedicated to such services are Eutelsat's KaSat [4] and VIASAT-1 [5]. These satellites employ multiple (around 100) beams using fourfold frequency reuse over the coverage area to achieve capacity of the order of 100 Gbps per satellite. The latter is limited by the exclusive spectrum available to satellite (FSS) of 500 MHz in both the up and downlinks and this limits the feasible user rates to 10-20 Mbps. Thus, looking ahead to the increased user demands we have to look to larger satellites (maybe up to a Terabit/s [6][7]) and to more spectrum. Moving up to Q/V bands has already been suggested for feeder links but for user terminals the additional expense is not considered desirable so we return to the problem of getting more usable spectrum at Ka band.

The Ka-band exclusive bands for satellite are 19.7 to 20.2 GHz in the downlink and 29.5 to 30 GHz on the uplink. In these bands FSS terminals can operate in an uncoordinated manner, which means that they do not have to apply for and be granted a license by the national regulators, provided they meet set performance characteristics. The issue in other parts of the Ka-band is that the spectrum is allocated, not just to FSS but also to fixed links (FS) and to BSS (uplinks for broadcast satellites) as well as mobile services (MS).

The International Telecommunications Union (ITU) has allocated this spectrum in three regions of the world as shown in Table I for Ka-band (Europe is Region 1). In these so called 'shared bands' the different services need to co-exist and this is usually done by the process of coordination. For example, a larger gateway or feeder link may use this band but is coordinated and then licensed to operate and receives protection from interference from other service users.

Within Europe, the European Conference of Postal and Telecommunications Administrations (CEPT) [8] have adopted decisions that expand those of the ITU and produce tighter regulation as follows;

- 17.3-17.7 GHz: the BSS feeder links are determined as the incumbent links but uncoordinated FSS links are also permitted in this band.
- 17.7-19.7 GHz: FS links are considered incumbent but FSS terminals may be deployed anywhere but without right of protection.
- 27.5-29.5 GHz: CEPT provide a segmentation of the band between FSS and FS portions as shown in Figure 1. Within each segment there is a specified incumbent but for instance FSS terminals can operate in FS portions provided they do not interfere with the incumbent FS.

The work reported in this paper has been conducted within the EU FP7 project CoRaSat [9][10][11][12] that examines ways in which FSS satellite terminals in the Ka-band can co-exist with FS and BSS links given the regulatory regime discussed above. Specifically, a database approach for such coexistence schemes is investigated and demonstrated to exploit the frequency sharing opportunities for uncoordinated FSS terminals and verify its applicability. The aim is to show that future satellite systems can access additional spectrum beyond the exclusive bands that is needed to deliver cost effective broadband services.

Section II presents scenarios addressed and an outline of the database approach. Section III presents the database analysis and Section IV the database analysis for the specific scenarios under consideration.

Section V presents the impact on regulations and standards whilst Section VI draws the major conclusions on the work.

II. Scenarios and Database Approach

We report for the first time in the literature that a full interference analysis has been performed for frequency sharing within the frequency bands presented in Section I. We aim to show how a database approach will allow sharing between the satellite and terrestrial services. Within the CoRaSat project three scenarios have been investigated that reflect the three spectrum components detailed in the previous section. In Figure 2 we illustrate the interference paths in these scenarios. Two of the scenarios are downlink for the FSS; scenario A, 17.3-17.7 GHz where the potential interference is from BSS uplinks and scenario B, 17.7-19.7 GHz where the potential interference is from incumbent FS transmitters. In both of these cases the FSS is permitted to operate but is not protected by the regulatory regime and thus it is important to ascertain the level of the interference and its effect on the FSS received signal. The third scenario C, is in the transmit band of the FSS from 27.5-29.5 GHz and the interference is from the FSS transmitting earth station into the FS receivers, which are protected. The latter is more critical in that we need to demonstrate that the FSS does not contravene interference limits imposed by the regulatory regime.

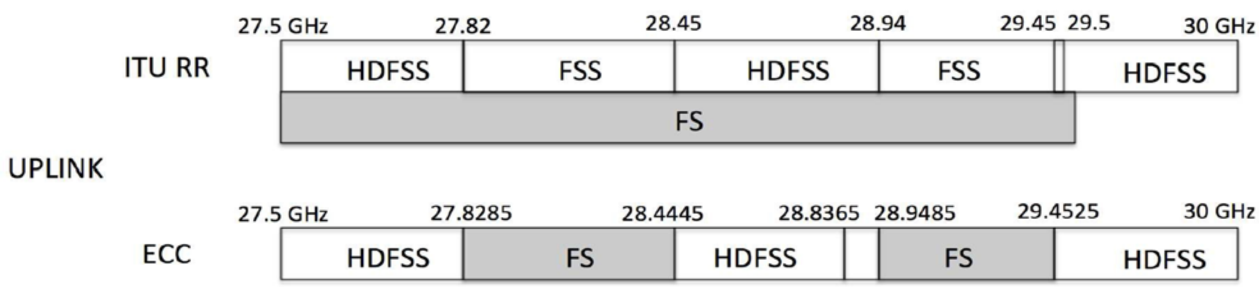


Figure 1. CEPT 27.5-29.5 GHz Segmentation

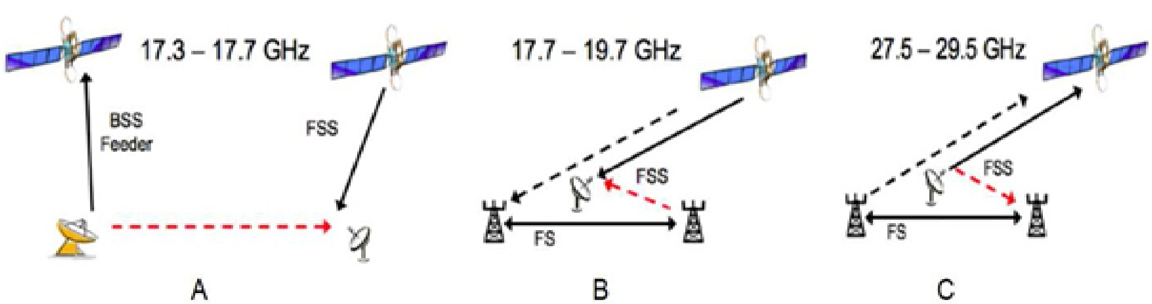


Figure 2. Scenarios in CoRaSat

The forward link, e.g., the downlink can be considered more important in that the ratio of downlink broadband to uplink broadband as operated via satellite is currently at around 6:1 and thus the acquisition of more spectrum here is key. In addition to this, operation in the downlink bands does not require regulatory changes but merely reassurance to the FSS users that the services need not be impaired.

The calculation of interference can be performed if one has obtained the corresponding accurate FS database, which includes the characteristics and locations of the potential interferers, then using this with equipment models, propagation models and the path details.

Similar ideas have been employed in Television White Space (TVWS) systems [13] to allow UHF frequencies to be used in the gaps between TV transmission regions. For scenario A the number of BSS uplinks in Europe is small and thus a database system is similar in magnitude to that of TVWS. However, for scenarios B and C the number of FS links runs into the tens of thousands and the database is much more complex. The data on the positions and the characteristics of the BSS and FS are generally held by national regulators and these need to be available for a database system to work.

The information from a real interferer database is interfaced to an interference modelling engine, which uses ITU-R Recommendation P.452-15 [14] procedures plus terrain and other databases. This is the latest version of this ITU Recommendation that contains a prediction method for the evaluation of path loss between stations. ITU-R P.452-15 includes all the propagation effects on the surface of the Earth at frequencies from 0.1 GHz to 50 GHz. In addition, other factors, which affect interference calculation, such as terrain height and bandwidth overlapping are also considered in the proposed database approach, which is illustrated in Figure 3. The typical interference threshold we determine is based on the long term interference, which can be expected to be present for at least 20% of the average year and it is set at 10 dB below the noise floor.

The interference thresholds for FSS reception and for FS reception are therefore -154 dBW/MHz and - 146 dBW/MHz, respectively as given in [15] and [16].

Having determined the interference level at the FSS (in scenarios A or B) it can be compared with the regulatory threshold. The action is then taken in the resource allocation at the gateway where a new carrier can be assigned either in another part of the 'shared band' where interference is acceptable or in the exclusive band. For scenario C the situation is different as the interference is caused by the FSS into the FS. Here the database is used to calculate the maximum permissible power that can be transmitted from the FSS in the vicinity in order to retain the threshold condition at the FS receivers. More details of the database approach are given in the following sections.

TABLE I. EXTRACT OF ITU TABLE OF FREQUENCY ALLOCATIONS

Frequency bands	ITU Region 1	ITU Region 2	ITU Region 3
17.3-17.7 GHz (Scenario A)	FSS (space-Earth) BSS (feeder links) Radiolocation	FSS (space-Earth) BSS (feeder links) Radiolocation	FSS (space-Earth) BSS (feeder links) Radiolocation
17.7-19.7 GHz (Scenario B)	FSS (space-Earth) BSS (feeder links 18.1 GHz) FS	FSS (space-Earth) FS	FSS (space-Earth) BSS (feeder links 18.1 GHz) FS
27.5-29.5 GHz (Scenario C)	FSS (Earth-space) FS MS (Mobile Services)	FSS (Earth-space) FS MS	FSS (Earth-space) FS MS

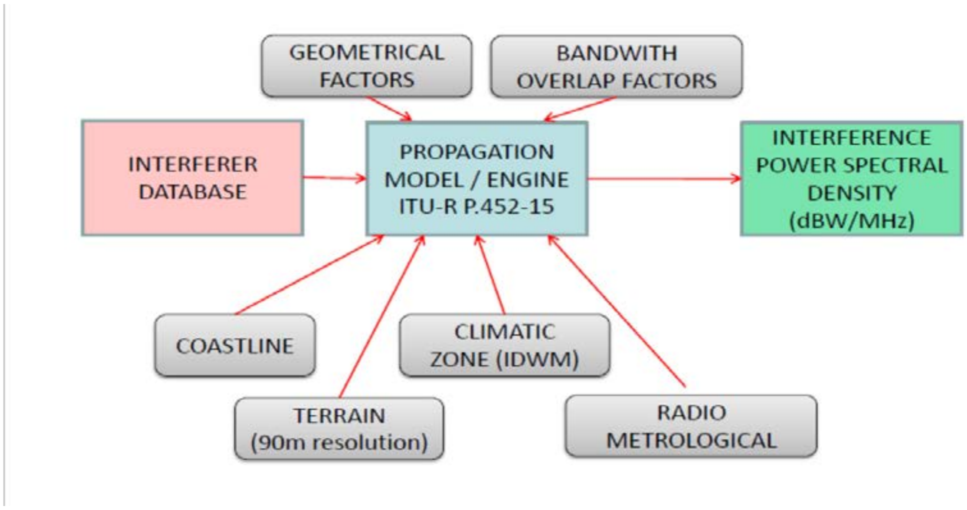
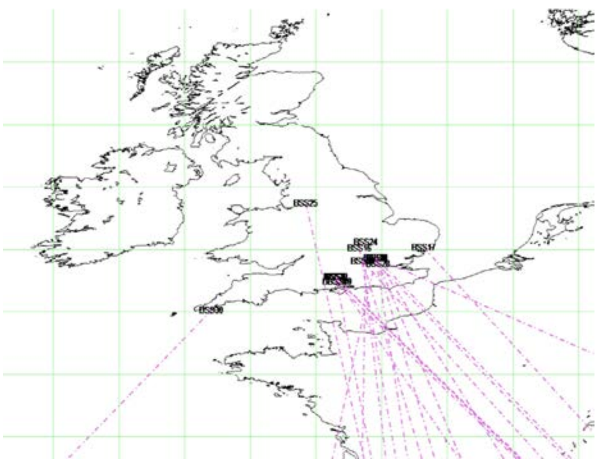
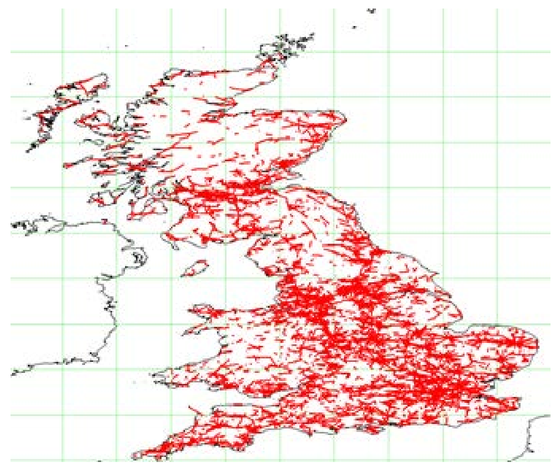


Figure 3. Interference modelling by ITU-R P.452-15



(a) Registered BSS feeder link stations in the UK.



(b) Registered FS links of the whole band in the UK

Figure 4. Registered BSS and FS links in the UK.

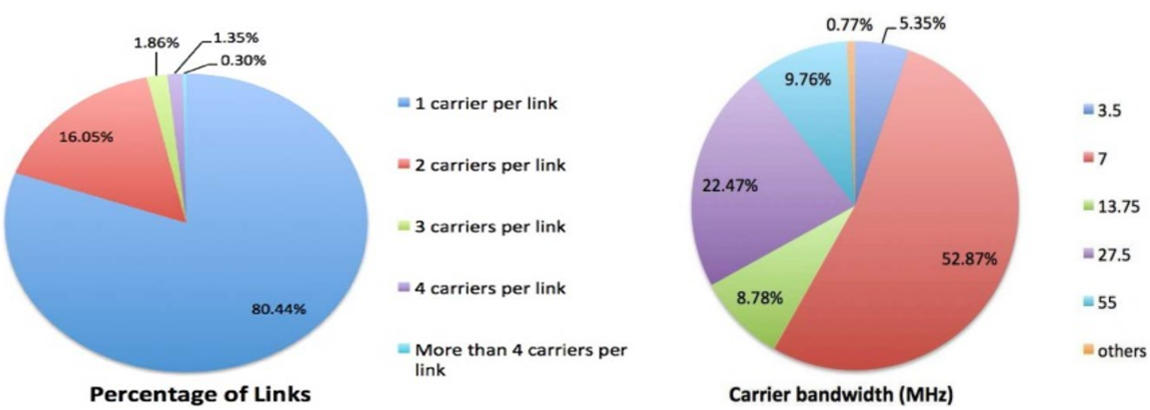


Figure 5. Pie chart of (a) UK FS carrier number of each link and (b) carrier bandwidths (MHz)

III. Database Analysis

The information in a database is normally listed on a carrier by carrier basis for a frequency band of interest. All carriers are usually detailed with their frequencies and channel bandwidths. When the database relates to satellite terminals the database should also contain details on the associated satellite in terms of satellite longitude and the earth stations azimuth and elevation angles. Polarization and antenna gain are also required along with the antenna radiation patterns as defined in ITU Recommendations for use in regulatory work or ETSI standards. In addition, transmission power and equivalent isotropic radiated power (EIRP) may also be included.

A UK BSS database made available for this study is used for scenario A and contains 442 carriers from a total of 31 BSS uplink earth stations at 8 physical sites, to 12 different satellites, which is shown as Figure 4(a). The locations of all these 31 BSS earth stations are marked with an indication of the direction of the beam to the satellite. The number of carriers of each BSS earth station ranges from 1 to 42. The carriers span the range 17.3 GHz to 18.35 GHz. The bandwidths of the carriers that belong to the same BSS earth station are the same while those that belong to different earth stations might be different and are typically 26 MHz, 33 MHz, 36 MHz or 66 MHz. The EIRP of these earth station antennas ranges from 69 dBW-84 dBW and all antenna radiation patterns are as defined in ITU-Recommendation S.465 [17] or S.580 [18].

FS databases at 18 GHz are required to evaluate scenario B. Again, an FS database was made available to this project (under the UK Freedom of Information Act). The database for the UK FS in the band 17.7 to 19.7 GHz is much larger than that for the UK BSS one and contains 12,712 links with 15,970 carriers recorded in the UK. A French database has also been examined at 18 GHz and is based on the latest ITU-R terrestrial services BR IFIC database [19], which contains 11,548 links with 17,384 carriers recorded. Figure 4(b) illustrates the FS links in the band 17.7 to 19.7 GHz in the UK and it can be seen that the FS links are much denser than for the BSS.

Figure 5 provides pie charts of numbers of carriers per link and carrier bandwidths based on the UK FS database in (a) and (b), respectively. It is indicated that more than 80% of links have only one carrier and more than 96% of links have up to 2 carriers. The majority of carriers have a bandwidth from 3.5 to 55 MHz. As a consequence, it can be deduced that at a particular location in the UK, little spectrum resource from the available 2 GHz band is used by the FS at a specific location. Thus, we are optimistic that spectrum available for FSS on a micro scale geographical basis is significant and can be exploited if the information of spectrum occupancy is known from the analysis of the database or is detectable by other mechanisms. A similar situation also exists for France.

We have implemented the ITU-R.P452-15 propagation and interference modelling to provide cognitive zones around incumbent terminals based on the available database. A cognitive zone here is defined as the geographical area around an incumbent user station where cognitive radio techniques such as spectrum sensing and beamforming should be employed to mitigate the interference to an acceptable level. In other words, the interference outside of this area is below the acceptable interference threshold thus, cognitive radio techniques are not necessary.

Figure 6 (a) and Figure 6 (b) show plots of cognitive zones around a BSS Station under scenario A case based on a free space loss model and the full ITU-R P.452-15 model, respectively. Similarly, Figure 6(c) and Figure 6(d) show plots of cognitive zones around a FS Station under scenario B case based on these two models. For the BSS cognitive zone the FSS terminal evaluated points to a satellite at 53 degrees E longitude and the BSS transmitting terminal points to a satellite at 28.2 degree while for the FS cognitive zone the FSS terminal is pointing to a satellite at 20 degrees E longitude and the FS transmitting terminal is pointing at a receive terminal on a bearing of 110 degrees East of True North (ETN). Clearly, for both cases the cognitive zones from the full model are much smaller and differently shaped than the ones under the free space model. On the average the areas are 9 times smaller at the -155 dBW/MHz and 3.5 times smaller at the -145 dBW/MHz thresholds. This is mainly because the diffraction effect based on the terrain data is considered in the full model while the free space loss model only includes line of sight propagation loss, which reflects the fact that the terrain databased diffraction effect is extremely significant in cognitive zone determination.

IV. Database Applications for the Scenarios

In this section we analyze for scenario A the areas that are affected by interference from BSS uplinks and for scenario B the availability of spectrum at FSS locations as a result of FS interference. Typical examples are provided to demonstrate the additional spectrum that could be available.

A. Scenario A: Area Analysis

Using the BSS database, area analysis for scenario A in the UK is provided to investigate how much area would be affected by interference from the BSS feeder links. The band of interest is split into 10 x 40 MHz sub-bands (SB1−SB10) and the analysis is then conducted in each sub-band to determine the area of the contours at different cognitive zone thresholds. These mirror the usual 40 MHz channel spacing adopted for BSS satellites. Area analysis is based on BSS database with the full ITU-R P.452-15 model employing the terrain and climatic zones and the FSS terminal evaluated points to a satellite at 53 degrees E longitude. The results are for long term interference (normally 20%), it being assumed that Adaptive Coding and Modulation (ACM) will mitigate short duration interference events including rain fades.

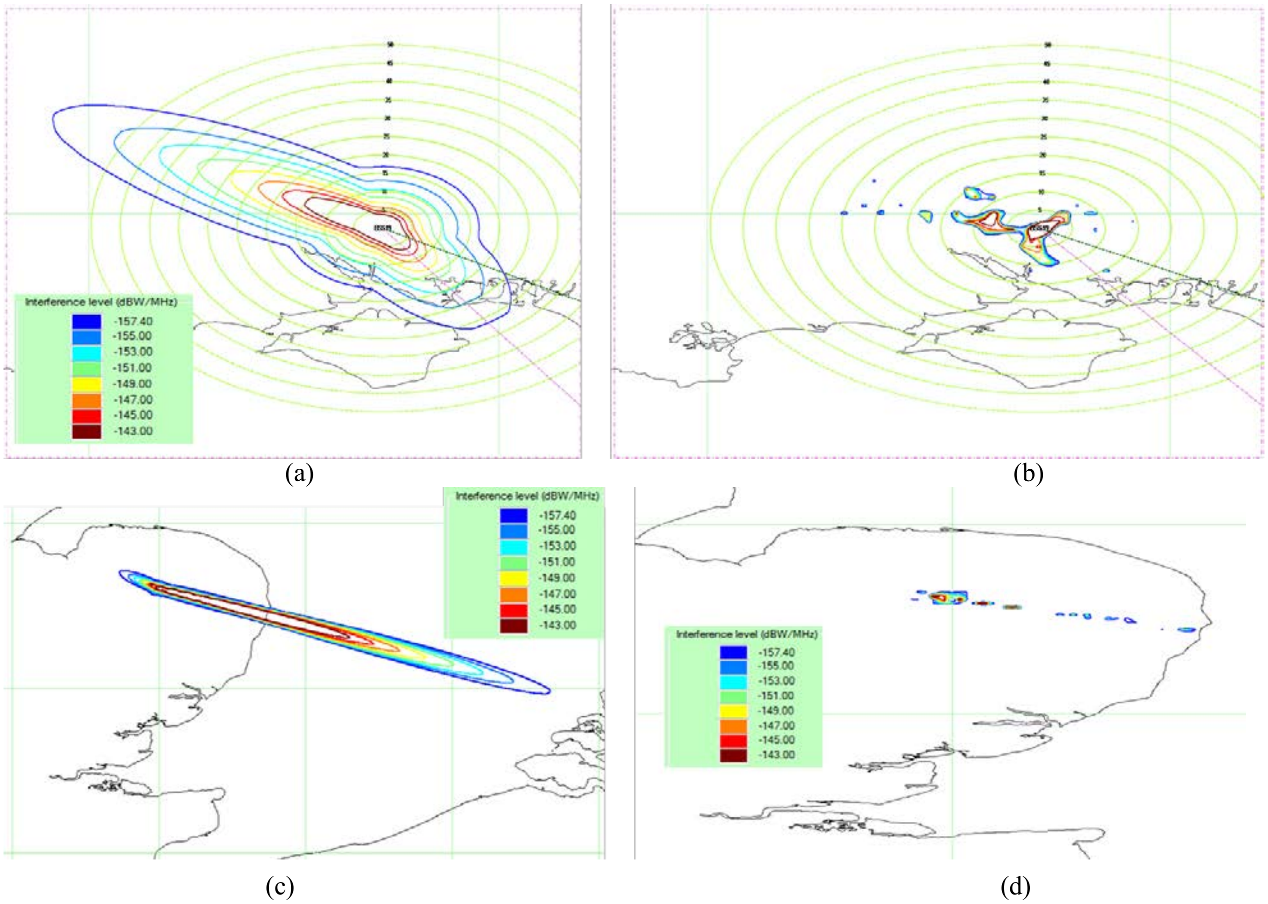


Figure 6. Example of cognitive zone for (a) BSS with free space loss model (b) BSS with full ITU model (c) FS with free space loss model (d) FS with full ITU model.

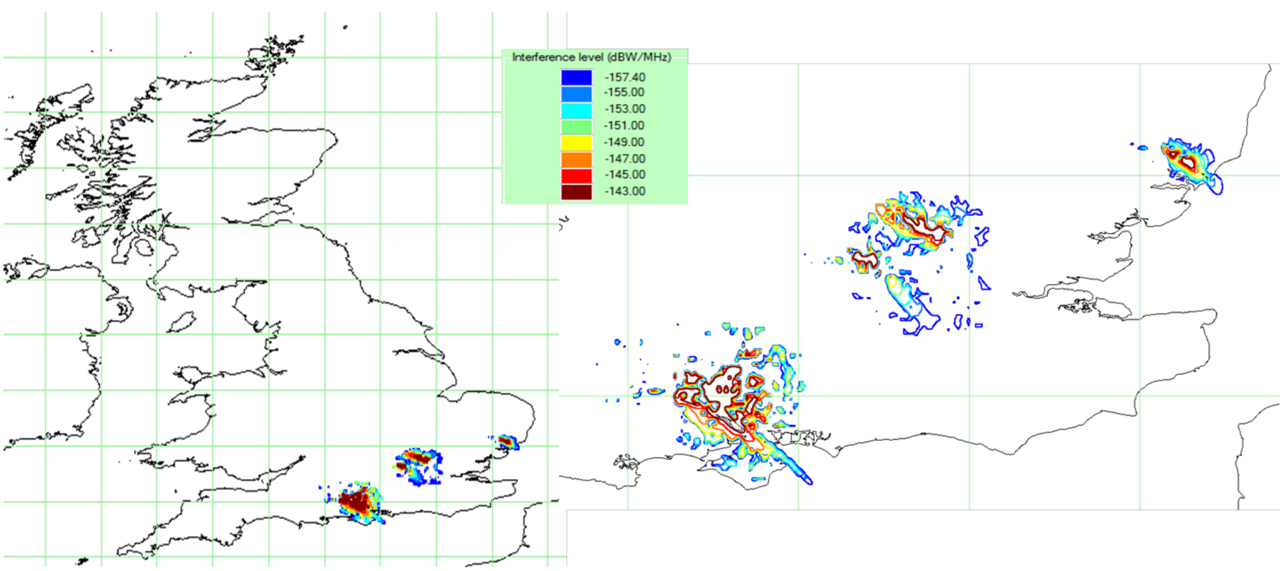


Figure 7. Example of cognitive zones for the sub-band 1 (17.3-17.34 GHz) based on full ITU model

One example of an affected area at different cognitive zone thresholds is shown in Figure 7, which represents SB1. Full data on the areas are given in the Table II. It can be seen that in general across the sub-bands at a -155 dBW/MHz threshold less than for 2% of the area of the UK is affected by BSS feeder links and thus more than 98% of the area of the UK can be used by an FSS terminal without the need for any further action. Some mitigation of excess interference may be required in these affected areas. Such mitigation could be achieved by suitable site shielding, beam-forming or reallocation to another frequency that is clear at the specific location. If such mitigation measures result in 10 dB suppression (a very conservative figure) then the remaining affected area would be of the order of 0.4% of the area of the UK. Re-farming the spectrum of such a small amount of traffic should not represent much of a challenge. This is very promising for future FSS deployment as the additional 400 MHz identified in scenario A (17.3-17.7 GHz) represents an 80% increase over the current exclusive band allocation (19.7-20.2 GHz).

Although we have presented results herein for an FSS terminal pointed at a specific orbit location we have examined a range of orbit locations from the UK and the results are very similar.

B. *Scenario B: Spectrum Analysis*

Unlike the situation in scenario A, the UK 18 GHz FS database comprises many more carrier records (15,036 records) over the 2 GHz band from 17.7 to 19.7 GHz. For scenario B we perform spectrum analysis for a particular location in the UK instead of geographical area analysis across the whole of the UK to determine what carrier(s) can be used by an FSS at a specific location. This information could then be integrated with a resource allocation algorithm in the satellite network to assign the carriers.

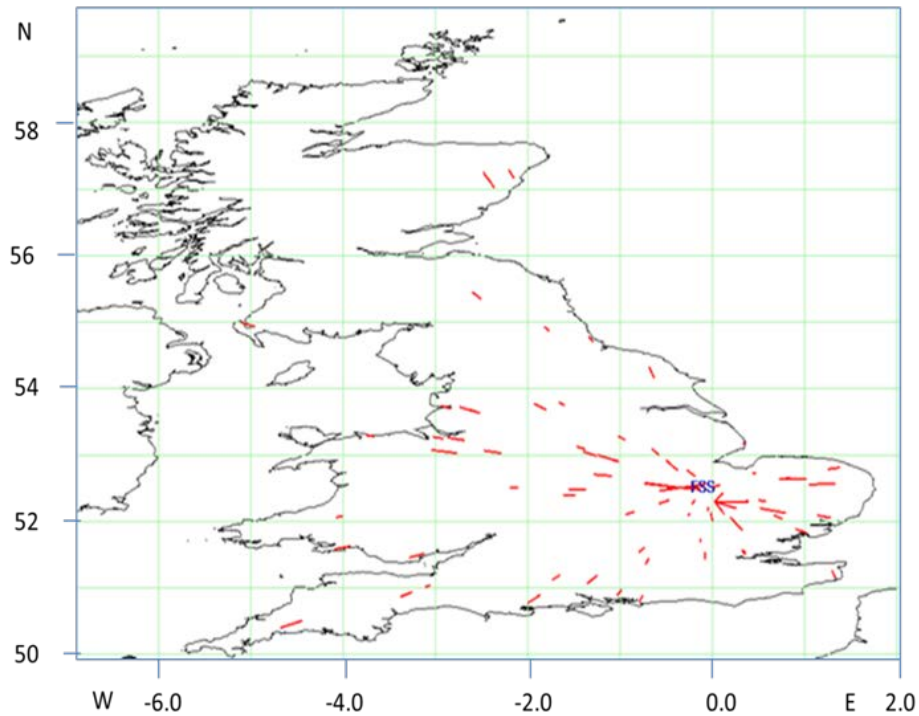
Spectrum analysis results for the UK FS links at 18GHz at a specified location (with latitude of 52.5 degrees and longitude of -0.1 degree) is shown here as an example. The analysis results of the location with both Line of Sight (LOS) and full model (ITU-R P.452-15) are shown as Figure 8 and Figure 9, respectively. The FSS terminal evaluated, points to the same satellite as the previous examples, which is located at 53 degrees E longitude. In each figure, a map of the links that exceed an interference level of -160 dBW/MHz is presented along with spectrum analysis as a plot of the interference power spectral density (PSD). Interference PSD is shown per MHz from 17.7 to 19.7 GHz. At this location, it can be seen that with the LOS model the interference from FS links can be much farther from the location of interest and these links are ones pointing directly at the location. There are only a few points with some angular offset and these are located very close so that interference is from their side lobes. From the interference PSD in Figure 8, it can be seen that there are significant white spaces in the plot and thus more than half of spectrum resource from 17.7 GHz to 19.7 GHz is available (with interference below the threshold) at this location for the LOS model. However, if the full terrain model is considered as in Figure 9, the number of interfering FS links dramatically decreases to less than ten, which means less than 0.1% of total FS links would cause problems at the location. Therefore, the majority of the 2 GHz band can be used by an uncoordinated FSS VSAT terminal site.

Complete maps of interference for locations in various European countries have been produced and these can be used as input to a resource allocation scheme that would then optimize the carrier allocation on the basis of the extra spectrum available. Examples for the UK and France are shown in Figure 10 and Figure 11 in terms of interfering spectrum occupied by the FS. It was noted that although the number of FS links in the database was large those that actually caused interference at a specific location and in a particular frequency band were quite small. It should also be noted that the available spectrum is not the same at each location and thus the database analysis can be used to optimize the carrier allocation as a function of FSS location.

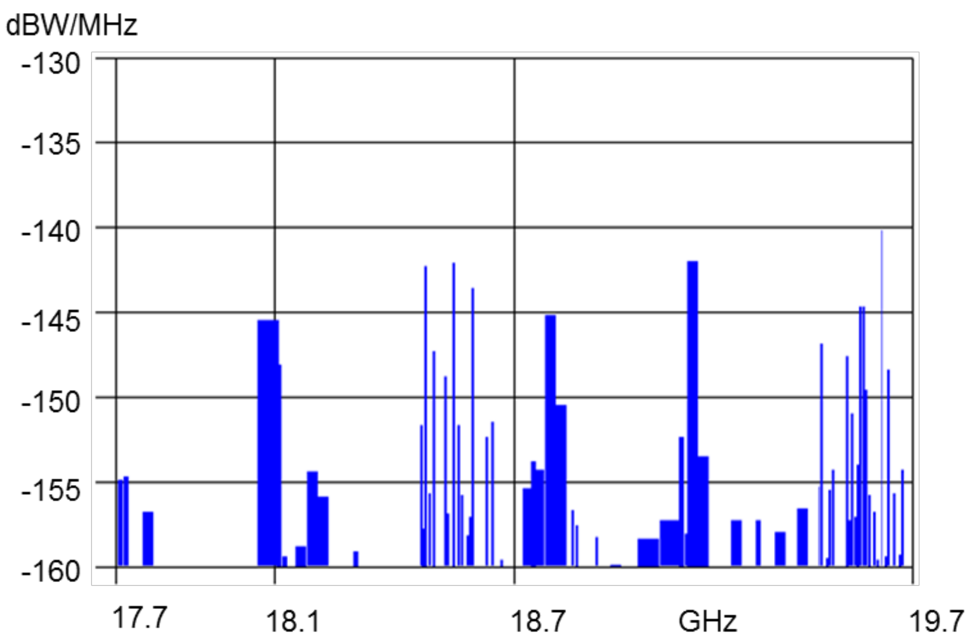
Calculations were also performed in order to assess the impact on a wider scale. In this case a range of FSS terminal locations from 8 degrees West to 2 degrees East at a longitude of 51.5 degrees North were used to assess the impact. In this case we present the number of FS links that would interfere (at -154 dBW/MHz interference threshold) for each location. The results are presented in Figure 12. It can be seen that the influence of the diffraction model is significant and for the more serious levels of interference the ratio of interfering links is of the order of 4.5:1.

TABLE II. AREA ANALYSIS (SQ. KM.) OF THE BAND 17.3-17.7 GHZ (BSS)

17.3−17.7GHz	**SB1**	**SB2**	**SB3**	**SB4**	**SB5**
−155 dBW/MHz	2, 420.9 (1.06%)	1, 692.4 (0.74%)	1, 692.4 (0.74%)	1, 683.3 (0.73%)	3, 570.9 (1.56%)
−145 dBW/MHz	683.0 (0.30%)	544.8 (0.24%)	544.8 (0.24%)	541.8 (0.24%)	926.0 (0.40%)
17.3−17.7GHz	**SB6**	**SB7**	**SB8**	**SB9**	**SB10**
−155 dBW/MHz	1, 683.3 (0.73%)	2, 411.0 (1.05%)	2, 535.6 (1.11%)	2, 367.6 (1.03%)	2, 936.4 (1.28%)
−145 dBW/MHz	541.8 (0.24%)	741.3 (0.32%)	774.2 (0.34%)	697.5 (0.30%)	928.6 (0.40%)

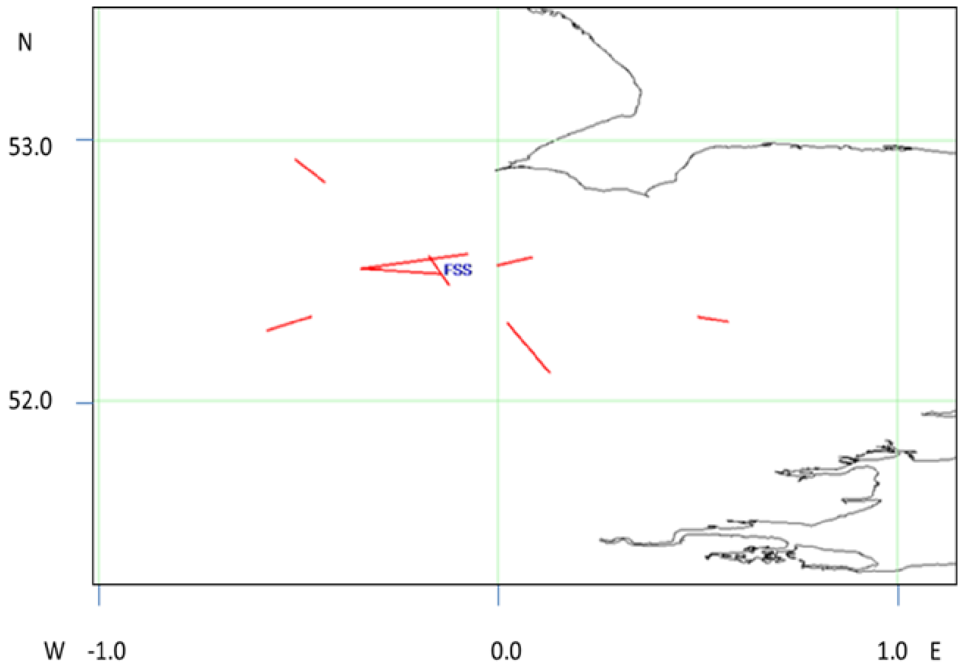


(a)

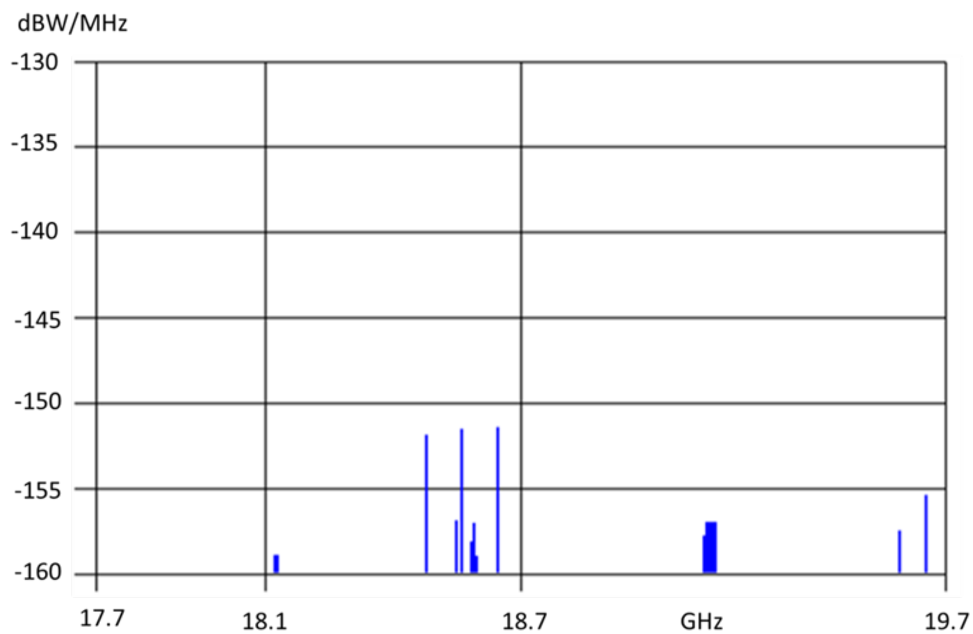


(b)

Figure 8. LOS result of all UK FS links, interfering to FSS terminal at latitude of 52.5 degs and longitude of -0.1 degs. (a) contributing links, (b) interference spectrum



(a)



(b)

Figure 9. Full ITU-R P452-15 result of all UK FS links, interfering to FSS terminal at latitude of 52.5 degs and longitude of -0.1 degs. (a) contributing links, (b) interference spectrum

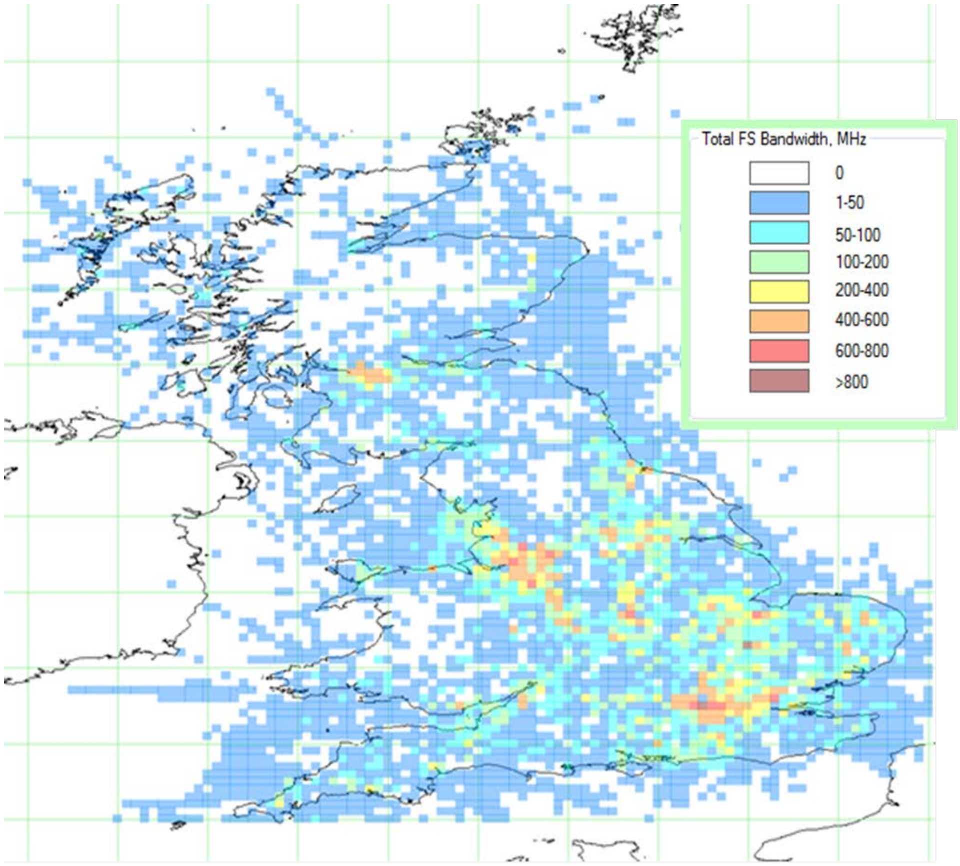


Figure 10. Interfering spectrum at -154 dBW/MHz for the UK

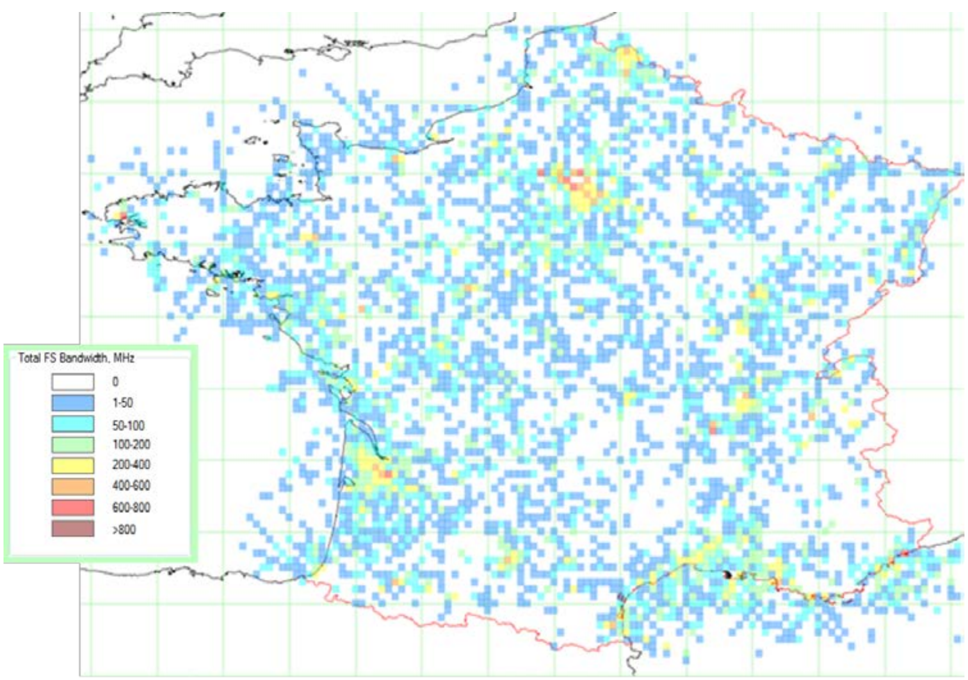


Figure 11. Interfering spectrum at -154 dBW/MHz for France

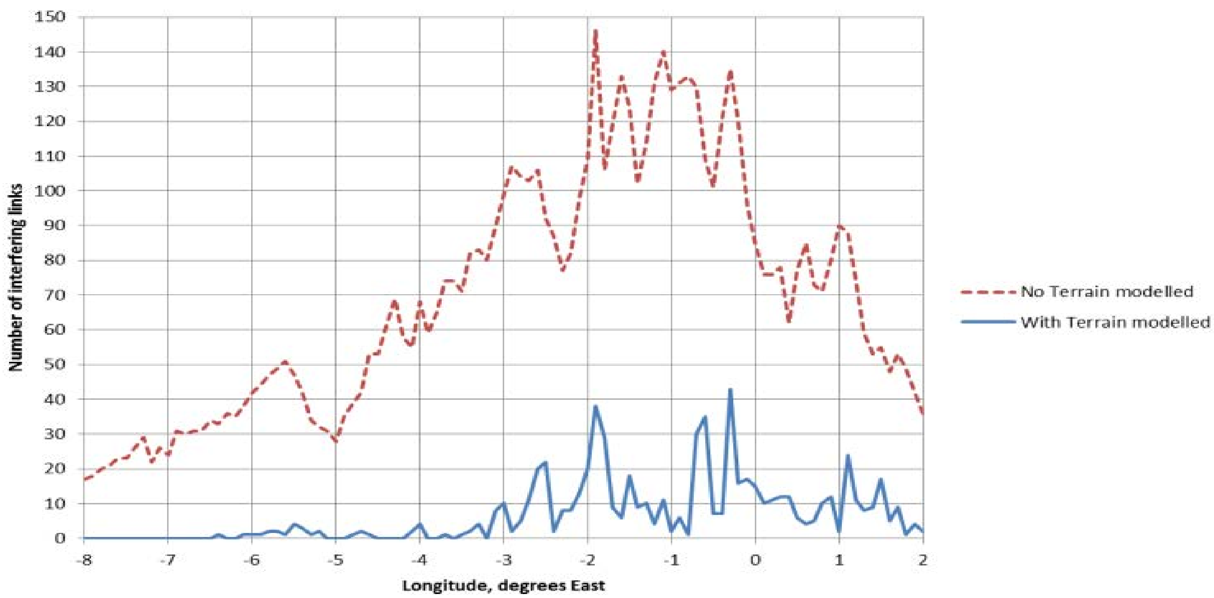


Figure 12. Number of links interfering (with and without terrain effects)

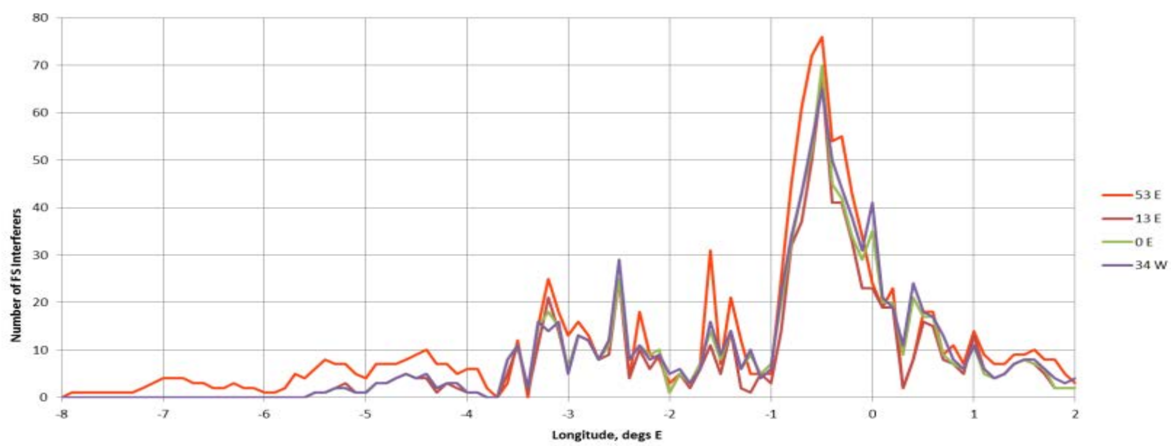


Figure 13. Number of FS interferers for different satellite locations (longitude)

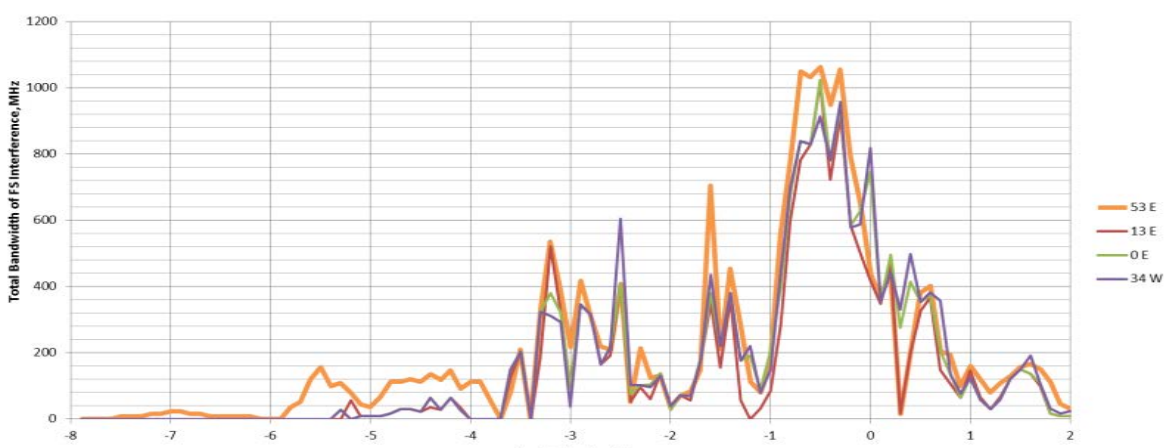


Figure 14. Total Bandwidth occupied by FS interferers for different satellite locations (longitude)

Impact of FSS Satellite Longitude

Calculations have been performed to assess the impact of the FSS antenna pointing to the satellite when the latter varies from 53E, 13E, 0E and 34W degrees longitude. Again, a range of FSS terminal locations from 8 degrees West to 2 degrees East at a longitude of 51.5 degrees North were used to assess the impact. Figure 13 shows the number of FS interferers for four different satellite locations (longitude). Figure 14 depicts the total bandwidth occupied by FS interferers for the same cases.

From these figures it can be seen that the assumption that the 53E longitude satellite represents the worst case scenario is validated.

Area Analysis of the FS interference

The ITU terrestrial services Radiocommunications Bureau (BR) International Frequency Information Circular (BRIFIC) provides us with databases to analyse the potential interference in the band of interest and from the results it is possible to get an increased insight into the situation. The analysis was conducted in UK, France, Poland, Hungary and Slovenia with the full diffraction model and statistics were derived from the results. To permit a fair comparison between the countries only the results for test point over land were included. The first set of statistics presented is the cummulative distribution function (CDF) of the number of interefering signals that exceed the -154 dBW/MHz threshold at each point. The resulting CDFs are presented in Figure 15.

A CDF was also produced for the total occupied bandwidth of the FS interferers at a point over the regions of interest. The resulting CDF is given in Figure 16.

NOTE: Also, in Figure 16, a second horizontal axis at the top indicates percentage of the total spectrum occupied by the FS.

The graphical results are also presented herein as tables.

Table III presents the CDF of number of FS links that interfer with a site in terms of the percentage of sites affected. Table IV presents the CDF of the total bandwidth of the interfering FS links that interfer with a site in MHz. Table V presents the same CDF but in terms of the percentage of the total bandwidth (17.7 – 19.7 GHz).

Maps of the total occupied bandwidth at locations within The UK and France were shown earlier in Figure 10 and Figure 11. These have also been produced at higher resolution for use as inputs to resource allocation software at the network gateway.

The results of the analysis for scenario B across various European countries is that there is over 90% of the 2GHz band between 17.7 and 19.7GHz available for most positions in the countries examined. The latter are considered to be typical and indeed represent the most dense distribution of FS in Europe. Thus, using a database or an interference map produced from the database to control the carrier allocations at the network gateway it should be possible to use this shared band spectrum for FSS down links.

Within the CoRaSat project there have been capacity gain calculations using a model multi beam satellite over Europe. These calculations are very dependent on the satellite characteristics and in particular on the satellite antenna C/I distribution across the beams. However, it was shown that in such a system using both the shared and exclusive bands a 400% increase in the forward capacity could be achieved [20].

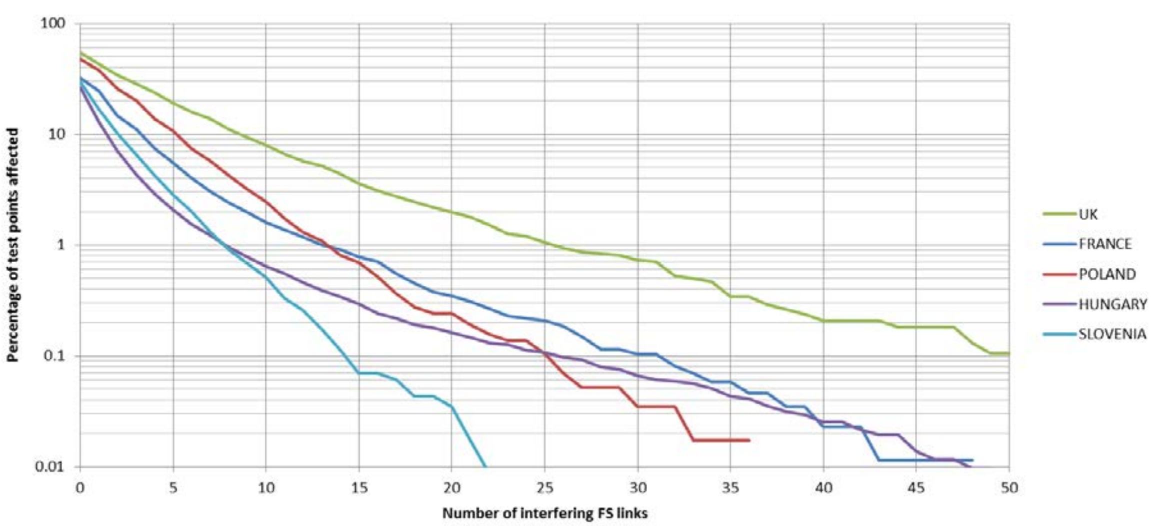


Figure 15. CDF of number of interferers at a test point (for -154 dBW/MHz threshold)

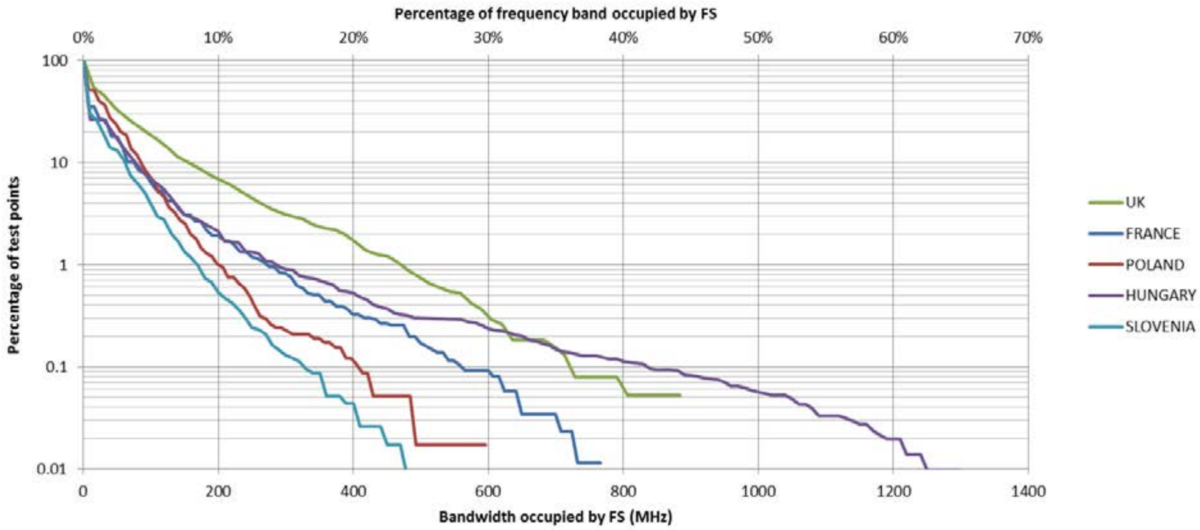


Figure 16. CDF of FS bandwidth occupied by interferers over the five regions (for -154 dBW/MHz threshold)

TABLE III. CDF OF NUMBER OF INTERFERES PER FSS SITE

% of sites	UK	FRANCE	POLAND	HUNGARY	SLOVENIA
>0	54%	31%	47%	26%	29%
10%	>9	>4	>5	>2	>2
1%	>25	>13	>13	>8	>8
0.1%	>50	>31	>25	>26	>13

TABLE IV. CDF OF TOTAL BANDWIDTH OF FS LINK INTERFERENCE PER FSS

% of	UK	FRANCE	POLAND	HUNGARY	SLOVENIA
sites	MHz	MHz	MHz	MHz	MHz
10%	139	58	80	45	50
1%	450	258	190	270	160
0.1%	700	550	400	820	405

TABLE V. CDF OF TOTAL BANDWIDTH OF FS LINK INTERFERENCE PER FSS SITE (% OF 17.7 – 19.7 GHZ)

% of sites	UK	FRANCE	POLAND	HUNGARY	SLOVENIA
10%	7%	3%	4%	2%	3%
1%	23%	13%	10%	14%	8%
0.1%	35%	28%	20%	41%	20%

C. Scenario C

Scenario C addresses the uplink from 27.5 to 29.5 GHz as shown in Figure 1. The ITU allows sharing across this band between FS and FSS but in Europe the CEPT have segmented the band between FS and HDFSS. For applications of HTS satellite systems designed for broadband internet access the uplink requirements are less than the down link. Current Ka-band systems in Europe are indicating an asymmetry of around 6:1. Thus, in Europe the availability of the two HDFSS bands may be adequate for early systems. However, in other regions of the world there could be a need to coexist in the uplink as well as the downlink.

In this case cognitive zones for scenario C are around FS stations and interference is from FSS terminals to FS links. This is a much more difficult case to address if we plan to use the whole of the shared band because we do not have access to adequate 28 GHz databases on which to operate. The techniques and software developed for scenario A and B can be used in a similar manner for scenario C if we have access to such a database. The results would be presented in a slightly different format as they would give the maximum allowable EIRP for the FSS at a given point. However, the HDFSS uplink band has been agreed for uncoordinated earth stations in all except 5 of the EU countries, therefore, perhaps the uplink increase in spectrum is not so urgent at this time. Some preliminary evaluation of scenario C was performed in [21] and the results of this indicated that only very close FS links (around 10km) would be affected and the density of FSS terminals would not cause a problem in the multi interference case. Some preliminary evaluations have also been done in the CoRaSat project using databases in Slovenia and Finland. These demonstrate that the reductions in FSS EIRP's are small and interference is not that much of a problem for the long term availability criteria. Thus, sharing of the uplink looks feasible but more evaluations are needed to be done for a wider selection of databases to confirm these results.

D. Earth Stations on Moving Platforms (ESOMPs)

More recently work has been focused upon Ka-band operation of ESOMPs in the shared bands.

The ESOMPs cases considered are as follows:

- Case 1: Aircraft- mounted ESOMP with downlink in the band 17.7-19.7 GHz and uplink in the band 27.5 to 30 GHz.
- Case 2: Ship-mounted ESOMP with downlink in the band 17.7-19.7 GHz and uplink in the band 27.5 to 30 GHz.

For Case 1 the situation is quite complex. The very directive nature of the FS antennas and the airborne antenna contribute very significantly to the level of interference and the number of significant interfering links, which vary quite rapidly as the aircraft travels along its flight path. Scenarios A, B and C can be considered for such cases where the FSS terminal is the ESOMPs terminal.

Analysis of Scenarios A and B for this case indicates that the above mentioned antenna effects will help reduce the cumulative interference levels to values that can be managed by appropriate mitigation techniques. An example of such analysis is given below.

For both cases, 1 and 2, for Scenario C we have limited our considerations to the case where in Europe the availability of the two HDFSS bands may be adequate for such systems and interference mitigation is not required. However, in other regions of the world this may not necessarily be the case. Work elsewhere has been addressing this matter in considerable detail [22], [23].

Case 1 Aeronautical ESOMP

The methodology adopted earlier using ITU-R P.452-15 can be extended to an aeronautical case by applying a number of critical modifications. These are:

1. Increase the height above mean sea level of the victim receiver so that it corresponds to the altitude of the aircraft;
2. Find the range from the FS transmitter to the aircraft for use in the calculations;
3. Find the azimuth and elevation angles of the aircraft as viewed from the FS transmitter;
4. Find the azimuth and elevation angles of the FS transmitter as viewed from the aircraft;
5. Using the above, determine the off-axis angle and thus gain of the FS transmitter antenna;
6. Using the above, determine the off-axis angle and thus gain of the aircraft receiving antenna;
7. Adopt the more complex ITU-R P.676-10 annex 1 model which is applicable to low elevation angles for calculating the gaseous losses;
8. Include the effect of aircraft fuselage attenuation;
9. Adjust the parameters to take account of the fact that the aircraft receive antenna diameter is 0.6 metres.

These modifications have been undertaken and wherever possible validated to be correct.

By way of an example we have performed calculations for an airborne ESOMP flying along the example path indicated in Figure 17 (a) and Figure 17 (b) at two different altitudes. The first altitude is 3.81 km (12,500 ft) and the second is for 11.88 km (39,000 ft), which is the average of the maximum altitude capability of known commercial airliners.

Figure 17 (b) has a background that is indicative of the general interference level in terms of bandwidth used by the FS but is indicative rather than being specific to ESOMPs.

The flight path is therefore over the more dense interference regions of the UK and typical of paths near Heathrow Airport. Detailed airborne ESOMP results are presented in Figure 17 (c), Figure 17 (d) and Figure 17 (e).

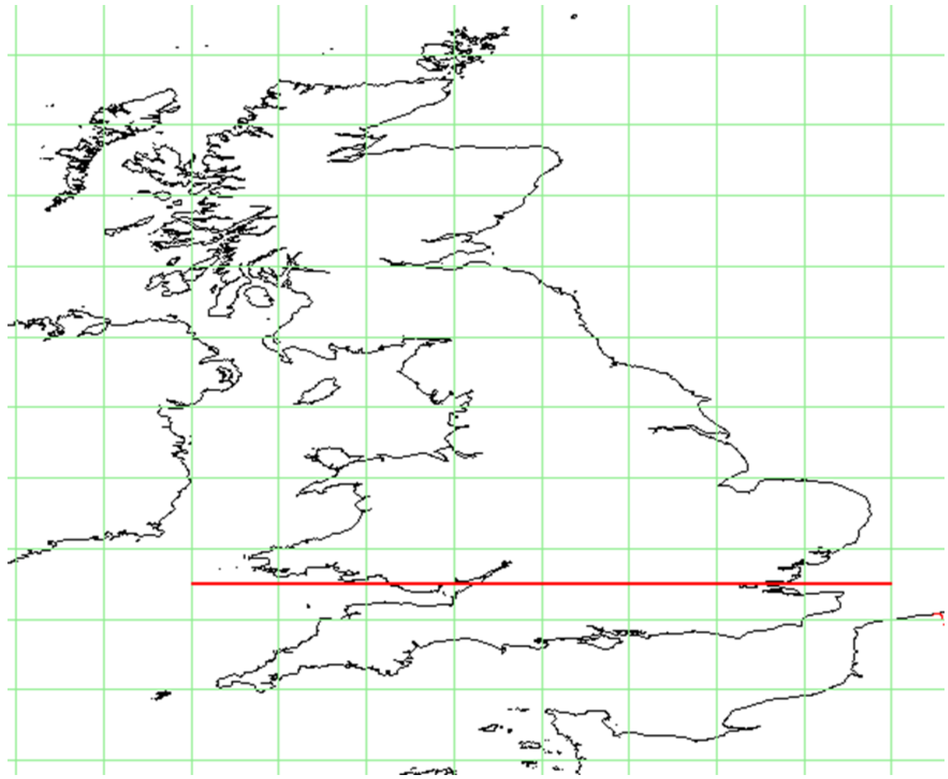


Figure 17. (a) ESOMP Flight Path

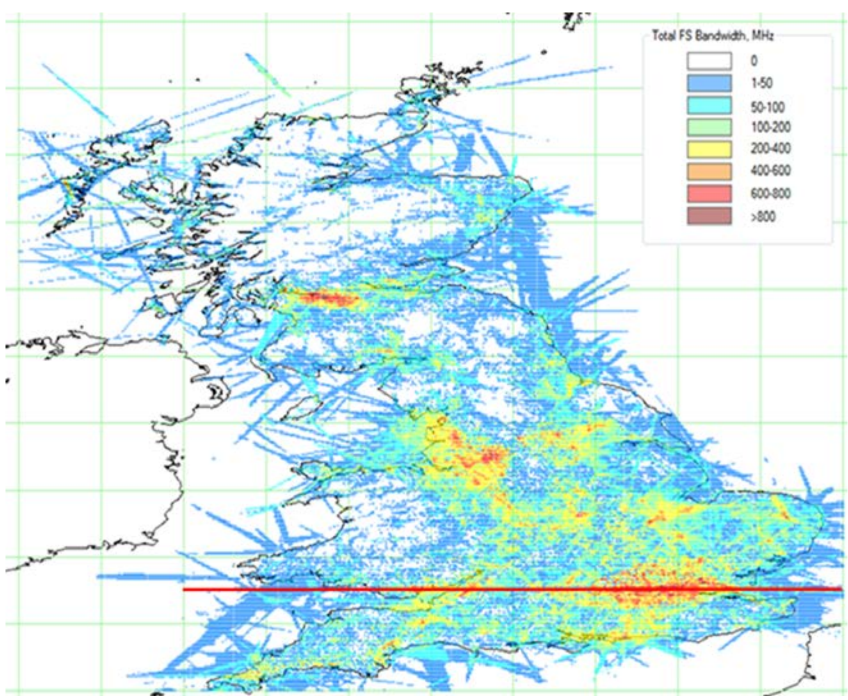


Figure 17. (b) Indicative Interference (FS BW used) around the flight path

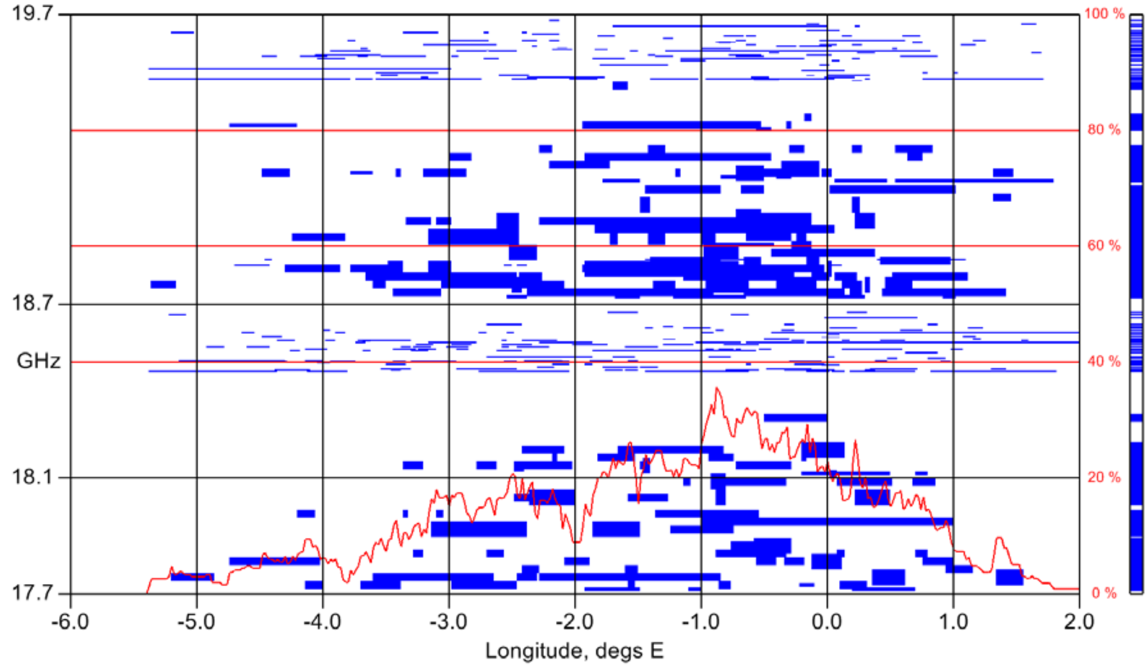


Figure 17. (c) ESOMP altitude 3.81 km (12,500 ft), threshold = -154.5 dBW/MHz

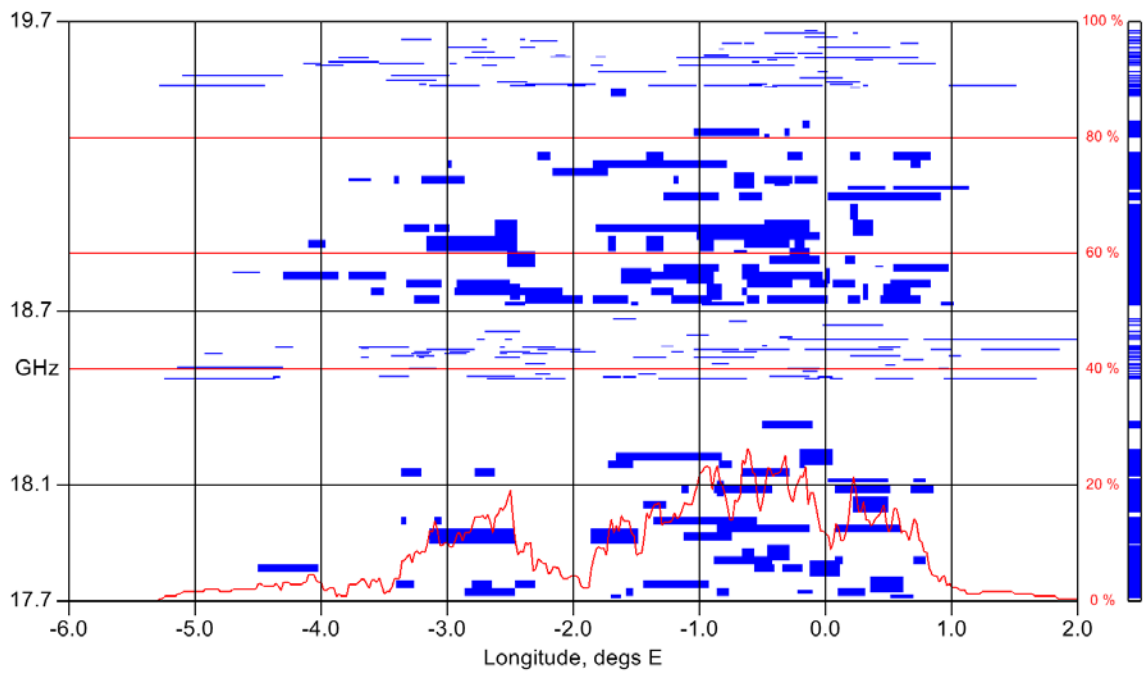


Figure 17. (d) ESOMP altitude 3.81 km (12,500 ft), threshold = -144.5 dBW/MHz

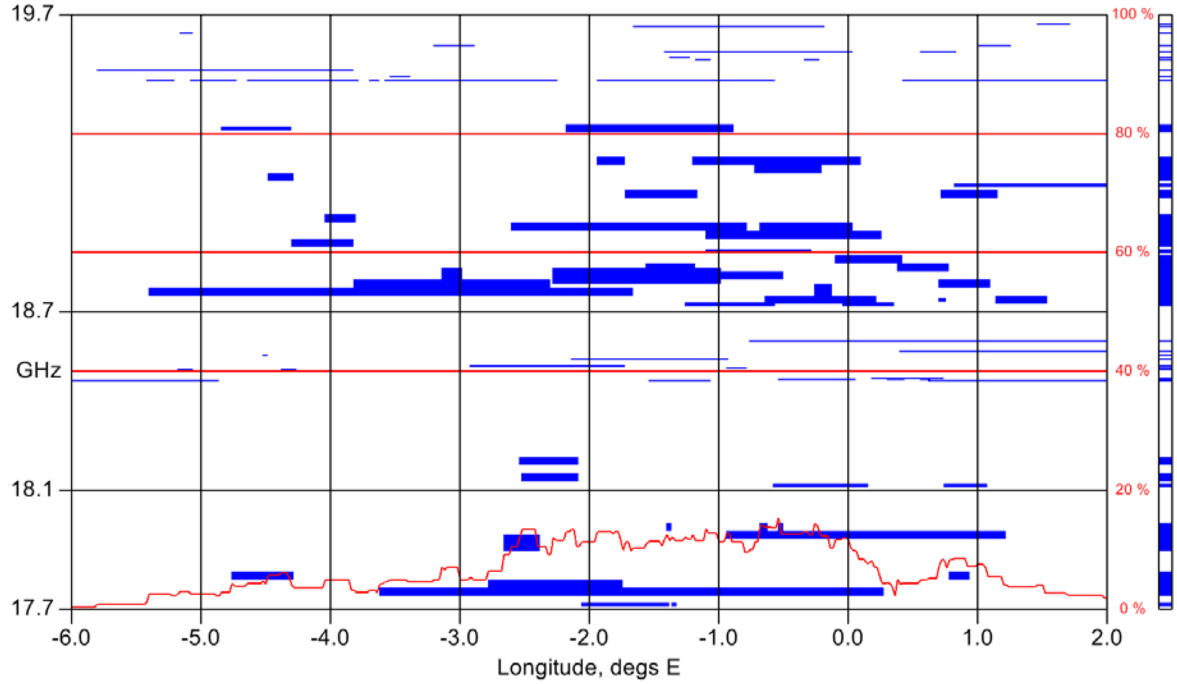


Figure 17. (e) ESOMP altitude 11.88 km (39,000 ft), threshold = -154.5 dBW/MHz

Figure 17 (c), Figure 17 (d) and Figure 17 (e) have several special features to note. Each interferer that exceeds the chosen threshold is shown as a blue band at the carrier frequency with its vertical extent indicating the carrier bandwidth. The length of the blue band indicates the longitude range (related to time) that the carrier remains an interferer. The narrow box on the right hand side of the figure indicates the composite amalgamation of all the interference entries. The red curve is associated with the scale on the right hand side of the figure and represents the percentage of the 2 GHz of available bandwidth that interference from the FS exceeds the given interference threshold.

Figure 17 (c) presents results for a low flying ESOMP at an altitude of 3.81 km (12,500 ft) with a threshold of -144.5 dBW/MHz. Figure 17 (d) is for the same case with a threshold of -144.5 dBW/MHz. Figure 17 (e) presents the results for an ESOMP flying at an altitude of altitude 11.88 km (39,000 ft) with a threshold of -154.5 dBW/MHz. It can be seen that the ESOMP experiences less FS interference at the higher altitudes and that some mitigation of the remaining interference should be possible with appropriate use of cognitive counter measures (especially interference aware radio resource management). There appears to be adequate bandwidth available for mitigating the FS interference, which in very encouraging.

Due to the movement of the terminal of interest causing a time variant element to the interference conditions the interference driven resource management mechanisms need to be much more dynamic than that required for the previously reported fixed location FSS cases.

Case 2 Maritime ESOMP

For case 2 when the ESOMP is maritime in nature then Scenarios A and B are simply extended in areas in the sea. In the case of Scenario B, with the ESOMPS ship operating in the 17.7 to 19.7 GHz band, example results are given for a ship sailing along the English Channel as depicted in Figure 18. Figure 19 presents the indicative interference field for total FS interfering bandwidth for a threshold of -154.5 dBW/MHz at any given point. The path of interest is shown in red and represents a journey of length 284 km.

In this example, it assumes that the ship is sailing in the interested path on the sea along the English Channel and that there are many UK based FS microwave stations on the land that may cause interference to the ship-borne ESOMP. Each FS link has its own frequency, bandwidth and the value of interference levels at each particular test point. The shipborne terminal is assumed to be pointing to a satellite located at 13 degrees East longitude with the ship receiving signals from the satellite. Antenna patterns, full terrain based propagation models and path losses were all taken into account for this calculation.

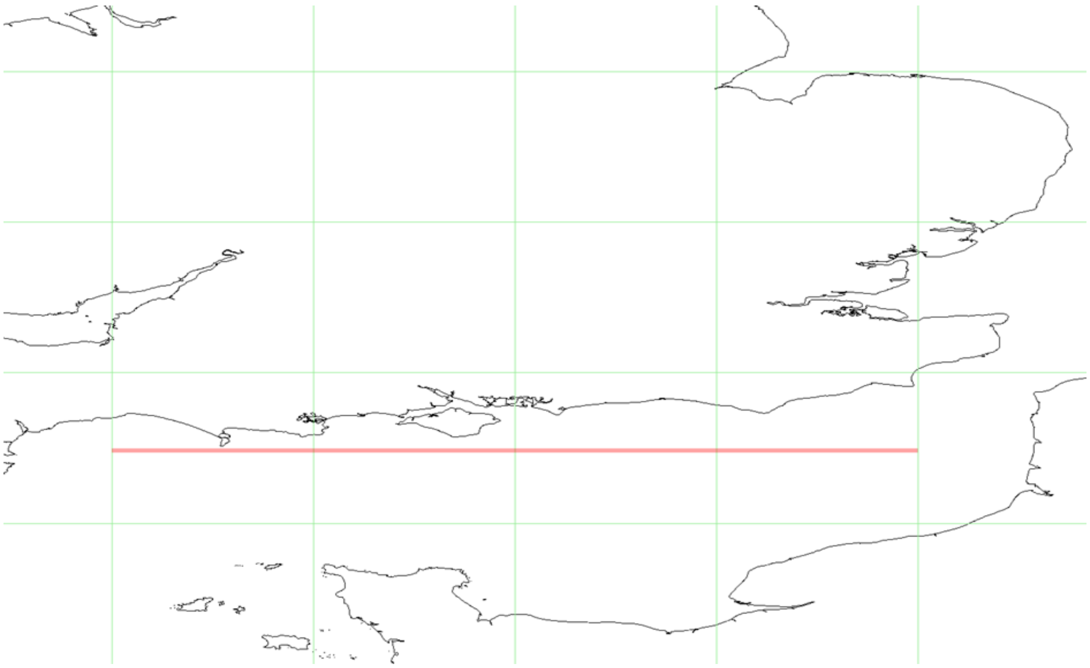


Figure 18. Example ESOMP vessel movement

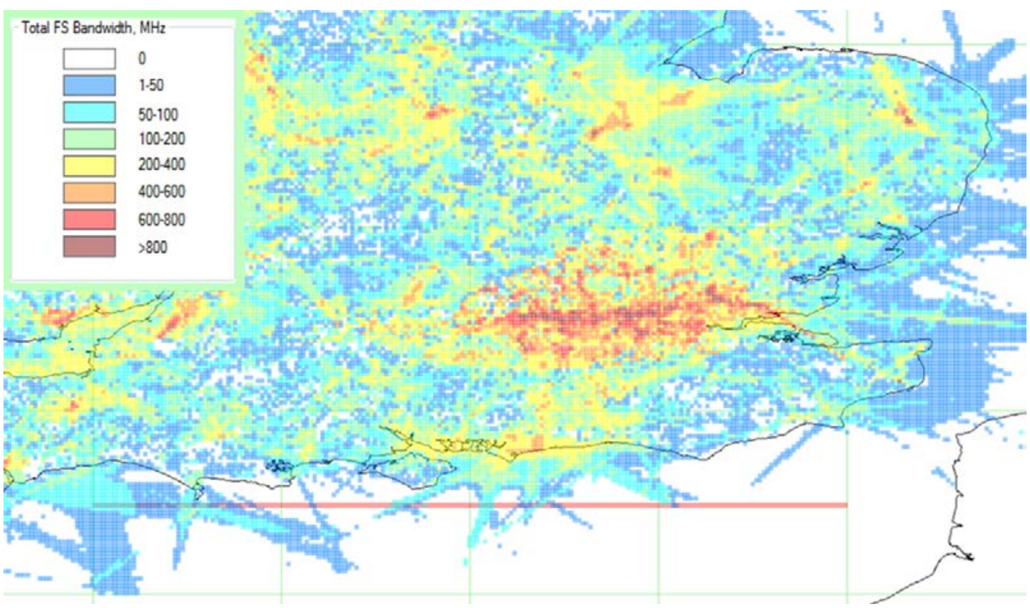


Figure 19. Indicative interference field for the maritime example

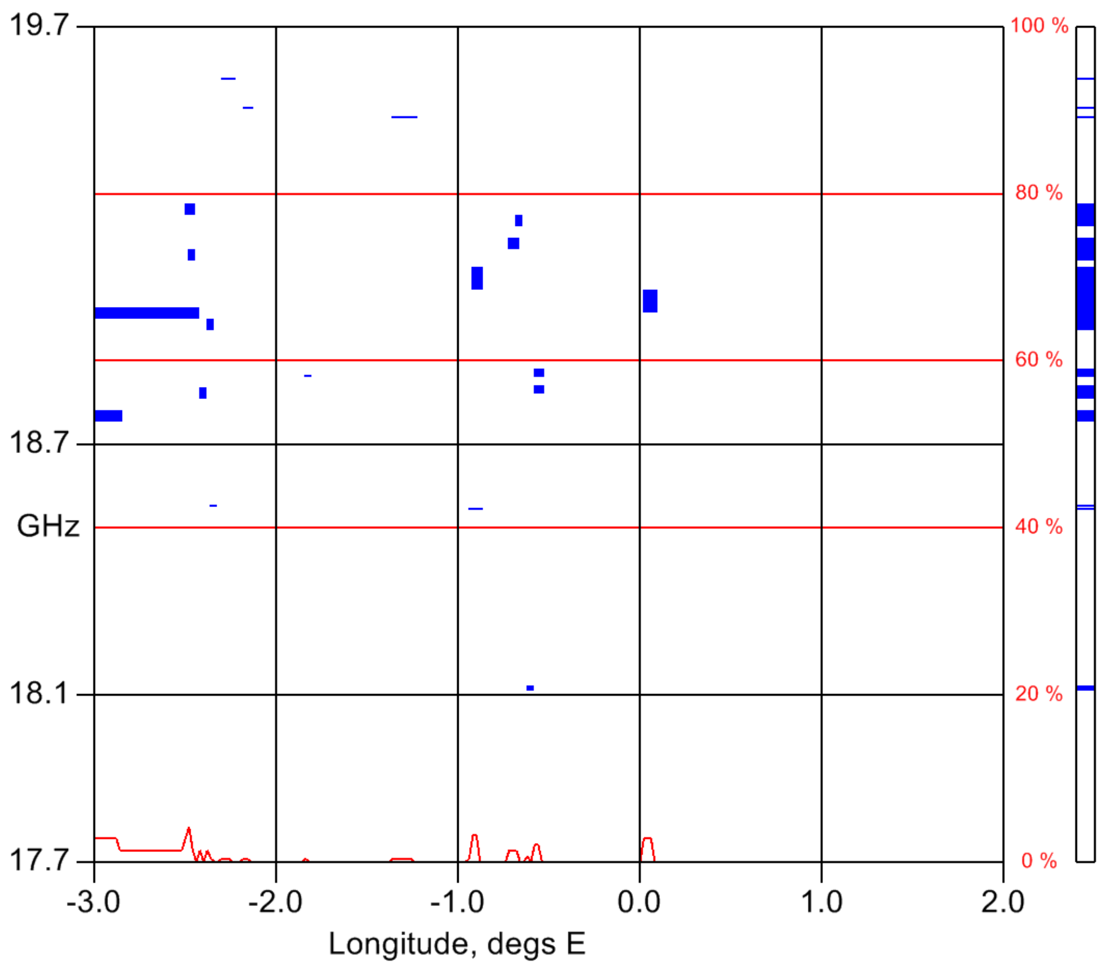


Figure 20. FS interference spectral plot along maritime path of interest (-155 dBW/MHz threshold)

The red line, associated with the right hand scale, in Figure 20 represents the percentage of the 2 GHz of available bandwidth that interference from the FS exceeds the given interference threshold along the example maritime path. It should be noted that such total bandwidth may be similar at different locations but be comprised of several carriers at quite different frequencies. Figure 20 indicates the spectral nature of the interfering carriers along the ships path. The presentation format is the same as that outlined for the Aeronautical ESOMP in Figure 17 (c), Figure 17 (d) and Figure 17 (e).

It can be seen that significant parts of the 17.7 to 19.7 GHz band are available for use with ESOMPs when the only mitigation approach required is spectrum management within the satellite resource allocation algorithms. The dynamic nature of the required interference driven resource management mechanism is not as fast or critical in the maritime case compared to the aeronautical one due to the lower speed of movement of the ESOMP.

ESOMP Summary

Example results for both shipborne and airborne operations have been presented indicating that with appropriate use of cognitive counter measures (especially interference aware radio resource management) there is adequate bandwidth available for mitigating the FS interference, which in very encouraging.

Due to the movement of the terminal of interest causing a time variant element to the interference conditions the interference driven resource management mechanisms need to be much more dynamic than that required for the previously reported FSS cases.

V. REGULATIONS AND STANDARDS

As has already been discussed in the paper, acceptance by the Regulatory regime is crucial in order to access the additional spectrum in the shared band. In parallel to the work being conducted in the CoRaSat project, work has been on going in the CEPT groups SE-40 and FM 44 on sharing in the band 17.7 to 19.7 GHz. Consultation documents have been issued in midyear 2015 by these committees. Some regulators have started to put their FS databases on the World Wide Web and it is hoped that more may follow. Others have been more reluctant to release information. SE-40 has been investigating software that could be made available to the national regulators so that they can interface with their databases and produce interference maps. The latter could then be made available to satellite operators and ground segment equipment providers to interface with resource allocation software at the gateways. Mechanisms are being sorted out amongst the regulators to allow the database systems with resource allocation to go ahead.

Within the standards arena a technical report based on the work of CoRaSat "ETSI .TR.103.263.v1.2- Electromagnetic compatibility and Radio spectrum Matters (ERM); System Reference document (SRdoc);Cognitive radio techniques for Satellite Communications operating in Ka-band" has already been published and is going through the updating process in 2015. Thus, manufacturers are engaged and buying into the use of systems as described in this paper.

With regard to ESOMPs, European Regulations are being put in place to permit the harmonized use, free circulation and exemption from individual licensing of ESOMPs within the frequency bands of interest [23].

VI. CONCLUSIONS

To meet future broadband access targets, in this paper we have described how the increased spectrum opportunities can be exploited by the proposed database approach together with interference mitigation techniques. We have demonstrated that in 17.3-17.7 GHz spectrum band 400 MHz of additional bandwidth is available across 98% of the UK, which houses the most dense BSS network in Europe, and similar results were obtained for Luxembourg. The evaluation needs to be repeated in other EU countries, but a similar if not better performance would be expected due to the lower density of BSS. If the FSS is required to be closer to a BSS, then cognitive means can be used to mitigate the interference.

We have also explored the availability of the 2 GHz of spectrum between 17.7 and 19.7 GHz (downlink) and the results have shown that the number of actual interfering FS links are limited due to terrain diffraction effects so that at a particular location substantial parts of the 17.7 to 19.7 GHz are available, but not the same frequencies at all locations. This indicates that a database interfaced with a resource allocation scheme could give access to the increased spectrum. This was demonstrated for the UK but needs to be validated in other European countries. In the case of the uplink 27.5-29.5 GHz The situation also looks very promising. Regulators and standards bodies are engaged with the sharing techniques and are now taking them forward to realization.

Our studies also indicate that the interference is also not too limiting for airborne and maritime ESOMPs operations in terms of interference from FS links into ESOMPs but a more dynamic interference aware resource management system will be required.

We would like to note that the work presented in this paper represents just part of the work conducted in the EU Project CoRaSat. In particular we note that other colleagues in the project have evaluated spectrum sensing using a novel SINR scheme, which can be used instead of a database or to augment its performance. In addition other colleagues have evaluated carrier resource allocation schemes to be used with databases. Finally, there has been a laboratory demonstration of all of these techniques, database, spectrum sensing and resource allocation with real satellite terminal equipment.

ACKNOWLEDGMENT

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