Spectrum Awareness and Exploitation for Cognitive Radio Satellite Communications

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Abstract—**The Digital Agenda for Europe (DAE) sets forth ambitious requirements for broadband communications, in which Satellite Communications (SatCom) play a major role. In this context, spectrum sharing techniques offer unprecedented opportunities to increase capacity and reduce costs in order to allow SatCom to meet the DAE objectives. The EU FP7 Project CoRaSat is assessing Cognitive Radio (CR) techniques for Ka-band SatCom scenarios, showing that coexistence between Fixed Satellite Service (FSS) and Broadcasting Satellite System (BSS)/Fixed Service (FS) links would introduce significant benefits in non-exclusive frequency bands. In this paper, spectrum awareness and exploitation techniques are analyzed. Simulation results show that significant improvements can be obtained in both spectrum utilization (up to 2.4 GHz of additional spectrum) and available throughput (up to 600% increase).**

I. INTRODUCTION

The ever increasing demand of larger capacity for reliable broadband communications is a critical requirement to be met. In 2010, the European Commission (EC) defined the Digital Agenda for Europe (DAE), setting two challenging objectives for broadband communications: at least 30 Mbps shall be granted to all of the users and 100 Mbps to at least 50% of the households across Europe by 2020 [1]. Terrestrial communications alone cannot meet these requirements, particulary in remote and rural areas where their deployment would require too large investments. In this context, Satellite Communications (SatCom) are main actors in meeting the ambitious requirements set forth by EC. It has been recently shown in [2] that, in some regions, up to 50% of households will have satellite broadband access only.

Currently, High Throughput Satellites (HTS) in Ka-band and above have gained momentum to reduce the large cost per bit and allow Ka-band satellites to provide the required capacity. In particular, novel multi-beam Ka-band satellites are a promising solution that can significantly increase the overall system capacity, as SES-12 [3], Eutelsats KA-SAT [4], and ViaSat-1 [5]. These systems can provide up to 100 Gbps for each satellite. However, the limited amount of exclusive spectrum that can be accessed by the Fixed Satellite Service (FSS) limits the actual system capacity. Spectrum congestion is the main limiting factor in achieving the Digital Agenda requirements by 2020 [6]. For broadband satellites, it has been proposed to move feeder links up to Q/V bands, and focus is also on finding additional spectrum for the user link in Ka-band. ITU-R spectrum allocations specify that 19.7–20.2 GHz and 29.5–30 GHz bands are exclusive for downlink and uplink satellite systems, respectively, which allows uncoordinated FSS terminals. Other parts of the Ka-band are also allocated to FSS on a non-exclusive basis, as they are shared with Fixed Service (FS) and Broadcasting Satellite System (BSS) feeder links [7]. Within CEPT, ITU-R allocations are respected and expanded. In particular, Decision ECC/DEC/(05)08 [8] establishes that the band from 17.3 to 17.7 GHz is allocated without prejudice to the use by BSS feeder uplinks and no terrestrial service is allocated on an incumbent basis. Uncoordinated FSS earth stations are authorized in this band, as well. Moreover, Decision ERC/DEC/(00)07 [9] stipulates that, in the 17.7–19.7 GHz band, stations of the FSS can be deployed anywhere, but without right of protection from the interference generated by FS radio stations.

In such regulatory context, it is thus of paramount importance to identify advanced spectrum sharing techniques that allow to maximize spectrum utilization. Cognitive Radio (CR) techniques are considered as the most promising mean to tackle the spectrum scarcity problem [10]. They allow to efficiently share some portions of the spectrum while limiting harmful interference among different communication systems. CRs potential has already been demonstrated in wireless terrestrial services [11], while in SatCom their implementation and study is still in its infancy. SatComs represent a challenging application scenario for CRs, in particular due to the geographically wide coverage of the spectrum allocation and the power imbalance among ground and user terminals.

Within this context, the EU FP7 Project CoRaSat (COgnitive RAdio for SATellite Communications) aims at investigating the application of CR techniques to SatCom [12]. In particular, CR techniques have been designed and assessed for [12]–[19]:

- *Spectrum Awareness*, which aims at identifying bands that can be accessed on a shared basis and the related interference levels, which are needed to define the achievable Quality of Service (QoS);
- *Spectrum Exploitation*, which defines advanced cognitive techniques to exploit the bands identified by spectrum awareness mechanisms.

In this paper, we provide a description of the techniques adopted for both spectrum awareness and exploitation in two

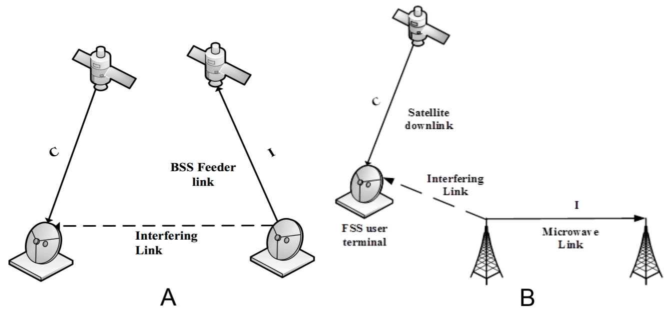


Fig. 1. Reference scenarios in Ka-band (C: cognitive link, I: incumbent link).

SatCom downlink Ka-band scenarios: scenario A in the 17.3–17.7 GHz band and scenario B in the 17.7–19.7 GHz band. In particular, for spectrum awareness, databases (DB) and interference estimation are analyzed. It will be shown that, in scenario A, 400 MHz can be exploited by FSS in the considered areas, thus providing a 80% increase for FSS systems, while, in scenario B, a large portion of the 2 GHz band can be used in most locations. As for spectrum exploitation, the utilization of the shared bands provides a gain in the achievable throughput up to 490%. Moreover, beamforming (BF) and carrier allocation (CA) techniques are implemented and it will be shown that further gains can be achieved, up to 30%.

This paper is organized as follows. In Section II, the reference scenarios are described. In Section III, spectrum awareness techniques are described and simulation results are provided. In Section IV, spectrum exploitation algorithms and the related simulation results are provided. Finally, Section V concludes this paper.

II. REFERENCE SCENARIOS

We focus on the following two downlink FSS scenarios in Ka-band [12]–[20] and shown in Fig. 1:

- *Scenario A*, 17.3–17.7 GHz: the BSS feeder links are incumbent links, but uncoordinated FSS links are also allowed;
- *Scenario B*, 17.7–19.7 GHz: the FS links are incumbent links, but uncoordinated FSS terminals can also be deployed without right of protection.

In both scenarios, interference generated from the cognitive FSS satellite towards the incumbent receiver is negligible: in Scenario A, since the FSS and BSS satellites occupy two separate orbital positions, interference is inherently avoided thanks to the actual antenna pointing. As for Scenario B, the incumbent system is a FS microwave link with highly directive antennas, which prevent the cognitive FSS satellite to generate harmful interference towards it. Moreover, Article S21 of the ITU Radio Regulations [7] defines the emission limits that shall be met by FSS systems up to 40 GHz, thus furtherly guaranteeing that BSS and FS incumbents are not interfered.

In these scenarios, coexistence between FSS downlinks and BSS/FS links is thus limited by the interference generated from the incumbent system towards the FSS terminal. In particular, a significant amount of aggregate interference may occur at a given FSS terminal due to the side-lobes of the receiving antenna pattern. CR techniques can thus be employed to foster the coexistence between FSS downlinks and BSS/FS.

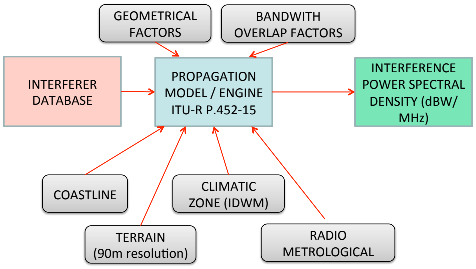


Fig. 2. Interference modelling engine in CoRaSat.

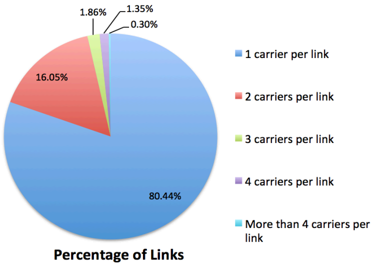


Fig. 3. Pie chart of FS carriers per link in UK.

III. SPECTRUM AWARENESS

Spectrum awareness techniques aim at identifying bands that are available for cognitive transmissions, and provide information on the interference level on these bands so as to define the achievable QoS. Spectrum databases and interference estimation are discussed and assessed in the following.

A. Database

A spectrum database includes operational characteristics and locations of the potential interferers. In particular, a database related to satellite terminals also needs to store information about the azimuth and elevation angles. This information can be exploited by means of accurate propagation and equipment models, as well as propagation path characteristics, and provide the interference levels at a given location (at the FSS terminal, specifically). Information on operational parameters and locations of BSS and FS systems are held by national administrations and are needed so as to implement a spectrum database in the proposed scenarios.

When such information is available, it can be processed by an interference modelling engine that provides the interference levels at each given location. In this paper, we consider the engine represented in Fig. 2. In particular, the ITU-R P.452-15 procedure is used, which describes how to evaluate the path loss between stations, also exploiting terrain databases [21]. This Recommendation includes all of the propagation effects present between 0.1 and 50 GHz, earth surface effetcs, terrain height, bandwidth overlapping, etc. The interference level that is provided as output of the proposed engine represents the long-term interference, *i.e.*, the interference that is 10 dB below the noise floor for at least 20% of the average year. The output interference level is then compared to interference threshold for FSS reception defined by ITU-R in Appendix 7 of the

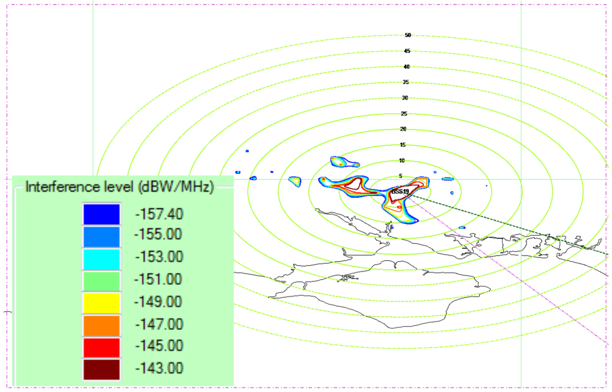


Fig. 4. Example of cognitive zones for Scenario A: FSS terminal pointing to a satellite at 53 degrees E longitude, BSS transmitting pointing to a satellite at 28.2 degrees E.

Radio Regulations, which is -154 dBW/MHz. This procedure is performed on a carrier-by-carrier basis for each location of the considered area. Once the interference is determined, the cognitive gateway can decide to assign a new carrier either in another part of the shared band or in the exclusive band.

UK made available a database for this study. In particular, for Scenario A, the database includes 442 carriers from 31 BSS uplink earth stations, transmitting from 8 locations towards 12 satellites. These carriers are allocated between 17.3 and 18.35 GHz, and 1 to 42 of them are assigned to each BSS earth station. Different stations may use different bandwidhts per carrier (26 MHz, 33 MHz, 36 MHz, or 66 MHz). The antenna patterns are defined in [22], [23]. As for scenario B, Ofcom UK provided a FS database in the 17.7–19.7 GHz band. It contains $12,712$ links with $15,970$ carriers. Fig. 3 shows the number of carriers per link from the UK FS database. It can be noticed that more than 80% of the links have one carrier, and actually more than 96% have up to 2 carriers. Moreover, analyzing the database, most of the carriers have a bandwidth ranging from 3.5 to 55 MHz. Thus, at a given location in the UK a very limited amount of the 2 GHz available spectrum is used by the FS, providing a significant opportunity for FSS.

The information stored in these databases has been processed by means of the proposed interference modelling engine. In particular, *cognitive zones* have been identified around the incumbent terminals. A cognitive zone is defined as the geographical area around an incumbent terminal where CR techniques should be employed to mitigate the interference to an acceptable level. As an example, Fig. 4 shows plots of the cognitive zones around a BSS station for scenario A. Based on the available databases, scenarios A and B have been analyzed as follows. In Scenario A, the band of interest has been split into ten 40 MHz sub-bands, and in each sub-band the area contours at different cognitive zone thresholds have been determined. An example is shown in Fig. 5 for the 17.3–17.34 GHz sub-band. Performing this analysis on all of the sub-bands, and comparing the interference levels with the ITU-R threshold at -154 dBW/MHz, it can be seen that less than 2% of the UK area is affected by BSS feeder links. Consequently, more than 98% of the UK can be used by FSS terminals without the need of any further action. This is a very significant result, as an additional 400 MHz band can be exploited by FSS, *i.e.*, an 80% increase with respect to the current exclusive band allocation.

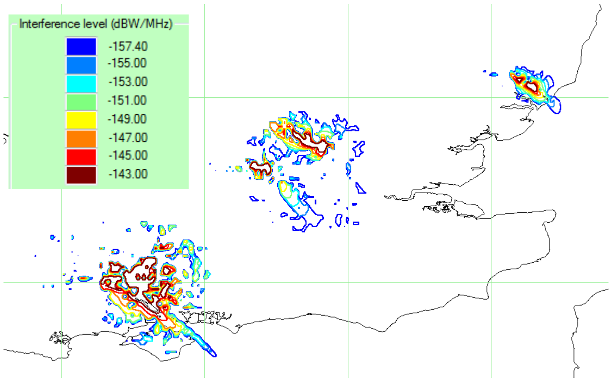


Fig. 5. Example of cognitive zones for the 17.3–17.34 GHz sub-band in Scenario A.

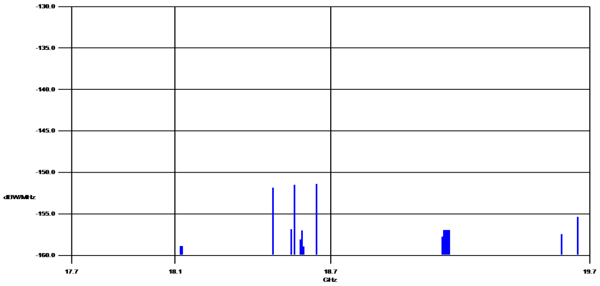


Fig. 6. Analysis of FS links at $(LAT = 52.5\text{deg.}, LON = 0.1\text{deg.})$ for Scenario B. FSS terminal pointing to a satellite at 53 degrees E longitude.

In Scenario B, due to the large number of carrier records, a similar approach is unfeasible. Thus, the spectrum analysis is performed at each location of the UK, instead of the whole UK area, so as to determine which carrier(s) can be used by a FSS terminal at a specific location. Fig. 6 shows the interfering Power Spectral Density (PSD) per MHz, from 17.7 to 19.7 GHz. It can be noticed that the number of interfering FS links is very low (less than 10), meaning that less than 0.1% of the overall FS links are interfering with a FSS terminal at the specific location. Thus, a large percentage of the 2 GHz band in Scenario B can be used by uncoordinated FSS terminals.

B. SINR estimation

A database approach, although very efficient, requires knwoledge on BSS and FS links, which might be confidential for some countries. Moreover, even in countries where such information is available, the database approach does not allow to adapt to short-term variations in spectrum occupancy. To cope with this, a Signal-to-Interference plus Noise Ratio (SINR) estimation algorithm has been proposed. Among different interference estimators available in the literature [24], we rely on the Data Aided SNORE (DA-SNORE) algorithm described in [25]. It is assumed that the cognitive Earth terminal is equipped with a receiving chain able to scan all frequencies of interest with a sensing sub-band equal to 36 MHz, which is the typical bandwidth of DVB-S2 and DVB-S2x standards [26], used by the cognitive satellite system. The algorithm, described in [16], is based on the knowledge of the pilot blocks of the DVB-S2 standard and the simulator block diagram is shown in Fig. 7. It is worthwhile highlighting that, as the pilot blocks are the

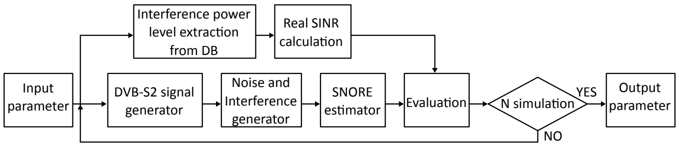


Fig. 7. Simulator block diagram.

TABLE I. THROUGHPUT PER BEAM [GBPS] FOR SCENARIOS A AND B.

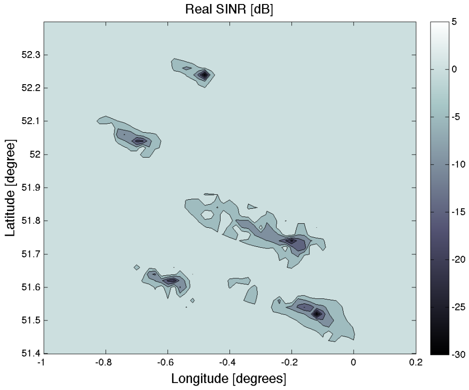
Case	Description	Scenario A	Scenario B
1a	exclusive band w/o CA	0.74	0.77
1b	exclusive band w/ CA	0.76	0.79
2a	exclusive+shared w/o interference w/o CA	1.84	3.8
2b	exclusive+shared w/o interference w/ CA	2.00	4.2
3a	exclusive+shared w/ CA	1.99	4.2
3b	exclusive+shared w/ CA+BF	2.13	5.24

same for both Scenario A and B, the algorithm can be applied with no modification to either of them. Focusing on Scenario A, the 400 MHz band is split into 11 sub-bands, and on each sub-band the DA-SNORE algorithm is applied to determine the interference level received from BSS feeder links. As the incumbent spectrum utilization is almost constant in time, the sensing operation can be performed with a relatively low duty cycle and when no data transmission is required, so as to lower the computational load. The information gathered during this *initial sensing phase* can then be reported to the Network Control Center (NCC), which allocates to each user the most reliable sub-band. Then, in order to control that the required QoS can still be met for the cognitive user, a *fast in-band sensing* can be performed during data transmission as well.

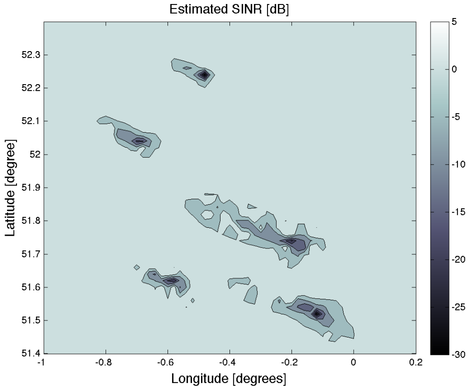
The performance of the SINR estimation algorithm has been compared to data extracted from databases. In particular, the potential geographical reuse factor of a specific carrier as a function of the relative location between interferer and interfered terminals has been performed. As an example, Fig. 8 provides the SINR values obtained from the database over a specific geographic area and compares them to the values estimated through the DA-SNORE algorithm. The estimated values excellently match the SINR values obtained from the database, and thus the DA-SNORE algorithm provides a valuable solution for spectrum awareness either to complement the information stored in databases or to provide the spectrum occupancy when databases are not available.

IV. SPECTRUM EXPLOITATION

The available resources identified by spectrum awareness have to be allocated among cognitive FSS terminals. Carrier allocation (CA) and beamforming (BF) techniques have been analyzed and implemented for spectrum exploitation [17], [18]. The CA module assigns carriers to each user based on two main objectives: i) maximizing the overall throughput; and ii) maximizing the availability. In the former case, the SINR of each user over each carrier is exploited to compute the achievable rate, and the Hungarian algorithm is used to maximize the system sum-rate. As for maximizing the availability, the minimum SINR demand is added as constraint to the previous problem. In order to furtherly enhance the system sum-rate, a BF algorithm has been implemented so as to increase the SINR values. In particular, both a Minimum Variance Distortionless Response (MVDR) and a Linearly Constrained Minimum Variance (LCMV) beamformers have been considered. The MVDR exploits spatial information to compute antenna weights by minimizing the variance subject to a constraint in the desired direction. The information required for this beamformer implementation is an array steering vector which depends on the Direction of Arrival (DoA) of the desired signal. The LCMV uses spatial information as well, and computes the weights by minimizing the variance subject to constraints in the desired and interfering directions. It is worthwhile highlighting that not all of the FSS terminals implement BF: in order to reduce the computational load, only those terminals experiencing a low SINR (namely, 4.71 dB) implement it so as to improve the performance.



(a) Database interference values.



(b) Estimated interference values.

Fig. 8. Geographic domain assessment: FSS terminal pointing to a satellite at 53 degrees E longitude.

Performance evaluation has been performed in three cases related to how the SINR and user rates were computed: 1) exclusive carriers only, with and without CA; 2) shared and exclusive carriers without BSS/FS interference; and 3) shared and exclusive carriers with BSS/FS interference. Table I shows the throughput per beam for scenarios A and B obtained in these cases, with or without CA and BF. In Scenario A, it can be noticed that, by employing CA, a significant portion of spectrum becomes available. This flexibility enhances the total per beam throughput by 162.6% in comparison to the per beam throughput achieved when using exclusive bands only. Moreover, the beamforming approach provides additional 7.39% gain in the per beam throughput over the case without BF [17]. The overall additional spectrum when using CA and BF, with respect to the exclusive band case, is equal to 180%. In Scenario B, it can be observed that exploiting the shared spectrum provides a 431.6% increase in the throughput per beam. In the shared plus exclusive case with interference, BF provides a further 24.7% increase in the throughput per beam with respect to the implementation of CA only. The overall additional spectrum when using CA and BF, with respect to the exclusive band case, is equal to 563.3% [18].

V. CONSIDERATIONS AND FUTURE WORK

In this paper, two downlink Ka-band scenarios have been analyzed for cognitive FSS systems, based on the outcomes of the EU FP7 Project CoRaSat. In particular, spectrum awareness and exploitation techniques have been described and significant simulation results have been provided. As for spectrum awareness, UK spectrum databases for BSS and FS systems have been used, and it has been shown that most of the 2.4 GHz in scenarios A and B are exploitable on a cognitive basis. Furthermore, a SINR estimation technique has been proposed to either complement databases in tracking fast variations in spectrum occupancy or to provide information for locations where databases are not available/accurate. Based on the spectrum awareness output, carrier allocation and beamforming techniques have been proposed to exploit the available opportunities. It has been shown that in scenario A, up to 180% increase in the overall throughput can be achieved, while in scenario B an increase up to $563,3\%$ can be obtained.

Based on the technical achievements described in this paper, the CoRaSat project has contributed in ETSI to a System Reference Document (SRdoc) that was submitted to the Technical Committee on EMC and Radio Spectrum Matters (TC-ERM) and then sent to CEPT FM44. A first version of this document was published by ETSI as TR 103 263 [27].

The CoRaSat project is now setting up the validation and demonstration of the techniques described in this paper. In particular, a testbed implementation of several selected test scenario is currently being defined, aiming at: i) validating the satellite terminal capabilities to adapt to changing interference environments and exploit non-exclusive frequency bands; and ii) assessing the achievable spectrum efficiency and QoS per cognitive user.

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