Resource Allocation for Cognitive Satellite Communications in Ka-band (17.7-19.7 GHz)

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***Abstract*—In this paper, we consider the problem of resource allocation in the context of cognitive Satellite Communications (SatCom). In particular, we focus on the cognitive downlink access by Geostationary (GEO) Fixed Satellite Service (FSS) terminals in the band 17.7-19.7 GHz, where the incumbent users are Fixed-Service (FS) microwave links. Assuming a multiple Low Noise Block Converter (LNB) satellite receiver at the cognitive FSS terminal-side, an efficient receive beamforming technique combined with carrier allocation is proposed in order to maximize the overall downlink throughput as well as to improve the beam availability. The proposed cognitive exploitation framework allows the flexibility of using non-exclusive spectrum for the FSS downlink system, thus improving the overall system throughput. More importantly, the proposed approach is validated with the help of numerical results considering realistic system parameters.**

Keywords*—*Cognitive SatCom, Carrier Allocation, Beamforming, Resource Allocation, Ka-band

I. Introduction

Satellite communications (SatCom) plays an important role in wireless communication field due to its inherent large coverage area, which makes it the most suitable access scheme to reach the remote areas, where terrestrial infrastructure is scarce and the deployment of wired and terrestrial wireless networks is not economically viable [1].

One of the fundamental challenges for SatCom is to improve the spectrum utilization efficiency. The ever-increasing demand for broadband data services together with the current regulation of the electromagnetic spectrum based on exclusive licensing of a particular band are rapidly consuming the limited amount of available frequency resources. Moreover, the traditional static spectrum allocation has been shown to be inefficient, with most of the allocated spectrum being underutilized [2]. These considerations suggest that a transition to a more intelligent and flexible spectrum management regime is indeed needed.

The challenging objectives of the future generation of satellites in terms of high-speed broadband access have motivated the concept of cognitive SatCom. While the application of Cognitive Radio (CR) in terrestrial scenarios has been widely considered [3], [4], its application in SatCom is still a rather unexplored area. Cognitive SatCom resolves the problem of limited spectral resources by enabling spectrum sharing between two satellite systems or between satellite and terrestrial systems [5], [6]. Recently, it has received interest in different research projects such as Co^{2}SAT (COoperative and COgnitive Architectures for Satellite Networks) [7], CoRaSat (COgnitive RAdio for SATellite communications) [8], [9], and SeMiGod (Spectrum Management and Interference Mitigation in Cognitive Radio Satellite Networks) [10]. Several scenarios enabling the cognitive SatCom have been discussed and analyzed based on market, business and technical feasibility within the ongoing CoRaSat project [8]. In this paper, we focus on one of the preselected scenarios in this project: a cognitive downlink access by Geostationary (GEO) Fixed Satellite Service (FSS) terminals in the band 17.7-19.7 GHz, where the incumbent users are Fixed-Service (FS) microwave links. The considered scenario is presented in Fig. 1. Unlike [11], we consider a free space propagation model between FS links and cognitive FSS terminals, which is the worst case from the interference analysis point of view.

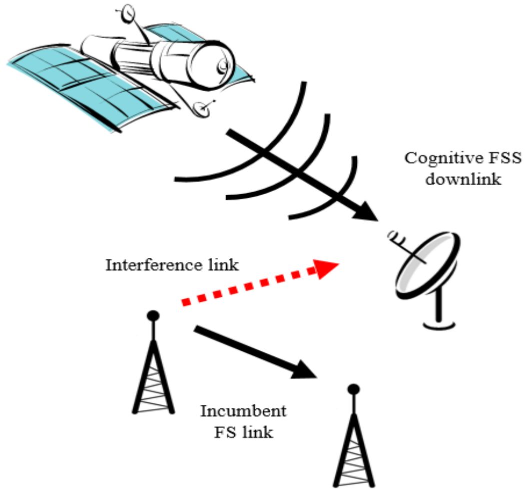

Fig. 1: Spectral coexistence of an FSS downlink with an FS link in the Ka-band (17.7-19.7 GHz)

Within Europe, the CEPT [12] has adopted the decision to allow uncoordinated FSS terminals to coexist with the FS links in the 17.7-19.7 GHz band but without the right of protection. In this uncoordinated scenario, the downlink interference from the cognitive satellite to the terrestrial FS receivers is negligible due to the limitation in the maximum Effective Isotropically

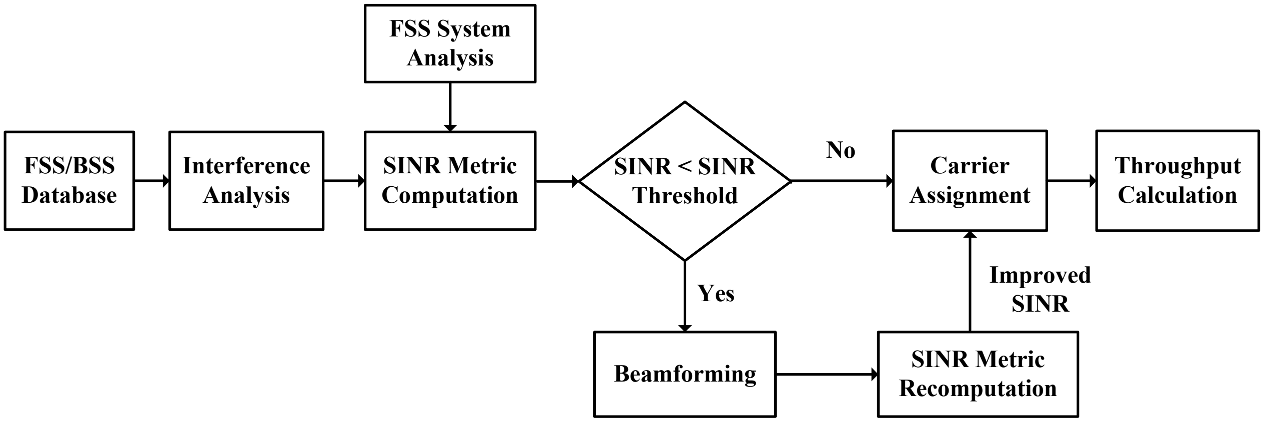

Fig. 2: Block diagram of the cognitive exploitation framework.

Radiated Power (EIRP) density of the current Ka band satellite systems. However, the interference from FS transmitters to the cognitive satellite terminal needs to be taken into account in order to improve the achievable rate of the cognitive users. This scenario has been studied in [13] from the perspective of harmful FS interference detection at the FSS terminal. In this paper, our focus is on how to optimally exploit the available spectrum so that the overall system throughput is maximized and the individual QoS requirement is satisfied.

Resource allocation in wireless networks has been an active research topic in the past several years [14]. However, the majority of the proposed techniques were originally introduced to work on cognitive and legacy terrestrial systems and a few were examined under the cognitive SatCom framework [10], [15]. In [10], a joint Beamforming (BF) and Carrier Allocation (CA) scheme has been applied for enabling the spectral coexistence of Broadcasting Satellite Services (BSS) feeder links and FS links in $17.3-18.1$ GHz. In this paper, we examine and evaluate the performance of BF and CA schemes in the spectral coexistence scenario of GEO FSS satellite system and the microwave FS links considering realistic system parameters.

The block diagram of the proposed cognitive exploitation framework is sketched in Fig. 2. First, the level of FS interference at the carrier level is determined based on the available information of FS databases. The locations of the FS transmitters are fixed along with the maximum transmission power of the FS transmitter, and thus a geolocation database approach provides a reliable solution to determine the interference level. Having determined the interference level and using the signal level obtained from the FSS system analysis, the Signal to Interference plus Noise Ratio (SINR) is computed for all the FSS terminals considering all the carrier frequencies. Subsequently, we apply BF only in the FSS terminals which suffer excessive interference. Next, the improved SINR is fed to the CA module in order to allocate the available spectrum resources by maximizing the overall throughput.

The remainder of this paper is structured as follows. Section II presents the interference analysis between the two systems under the considered scenario. The two exploitation mechanisms, namely BF and CA, are formalized mathematically in Section III and Section IV, respectively. Section V provides supporting results based on numerical data. Finally, conclusions are drawn in Section VI.

II. INTERFERENCE ANALYSIS

Let us assume a scenario with L FSS terminal users and N FS microwave stations. The aggregated interference from the N FS microwave stations received at the l-th FSS terminal for a particular carrier frequency f_m, $m = 1, \ldots, M$, is given by,

$$I_l(m) = \sum_{n=1}^{N} I_l(n, m), \tag{1}$$

where $I_l(n, m)$ denotes the interference level caused by a single n-th FS terminal at the m-th carrier under consideration. The latter can be written as,

$$I_l(n, m) = P_{\text{Tx}}^{FS}(n) \cdot G_{\text{Tx}}^{FS}(n, \theta_{n,l}) \cdot G_{\text{Rx}}^{\text{FSS}}(\theta_{l,n}) \cdot L(d_{n,l}, f_m), \tag{2}$$

where,

- $P_{\text{Tx}}^{FS}(n)$: Transmit power of the n-th FS station.
- $G_{\text{Tx}}^{FS}(n, \theta)$: Gain of the n-th FS transmitting antenna at an offset angle θ.
- $\theta_{i,j}$: Offset angle (from the boresight direction) of the i-th station in the direction of the j-th station.
- $G_{\text{Rx}}^{\text{FSS}}(\theta)$: Gain of the FSS terminal antenna at offset angle θ.
- $L(d, f) = \left(\frac{c}{4\pi df}\right)^2$: Free space path loss with d being the transmitter-receiver distance and f being the carrier frequency.
- $d_{i,j}$: Distance between the i-th transmitter and the j-th receiver.

The radiation patterns $G_{\text{Rx}}^{\text{FSS}}(\theta)$ and $G_{\text{Tx}}^{FS}(n, \theta)$ can be obtained from ITU-R S.465-6 and ITU-R F.1245-2, respectively. Unlike [11], we consider the worst case propagation model that would result from a line-of-sight path through free space, with no obstacles nearby to cause reflection or diffraction. In (2), we assume that the interfering signal falls within the victim bandwidth. If the spectra do not overlap completely, then a compensation factor of $B_{\text{overlap}}/B^{\text{FSS}}$ is applied, where B_{overlap} stands for the portion of the interfering signal spectral density within the receive modem filter bandwidth given by B^{FSS}.

The received signal level at an FSS terminal is determined by carrying out the analysis of the link between the FSS satellite and the concerned FSS terminal. Let $P_{\text{Tx}}^{\text{SAT}}$ denote the transmit power of the FSS satellite, then the received signal at the l-th FSS terminal is given by

$$P_{\text{Rx}}(l) = P_{\text{Tx}}^{\text{SAT}} \cdot G_{\text{Tx}}^{\text{SAT}}(l) \cdot G_{\text{Rx}}^{\text{FSS}}(0) \cdot L(D, f_m), \tag{3}$$

where $G_{\text{Tx}}^{\text{SAT}}(l)$ is the beam gain for the l-th FSS terminal user, $G_{\text{Rx}}^{\text{FSS}}(0)$ denotes the FSS terminal antenna gain in the boresight direction ($\theta = 0$) and D is the distance between the FSS terminal and the satellite. Without loss of generality, we assume the same distance for all FSS users equal i.e., $D = 35,786$ km.

Therefore, from (1) and (3), the FSS network controller can compute the SINR values per user and per carrier as follows,

$$\text{SINR}(m, l) = \frac{P_{\text{Rx}}(l)}{I_l(m) + I_{\text{co}} + N_0}, \tag{4}$$

where I_{co} is the cochannel interference caused due to signals transmitted in cochannel beams of a multi-beam satellite and $N_0 = kTB^{\text{FSS}}$ is the noise thermal power calculated over B^{FSS} with k being the Boltzmann's constant and T being the receiver noise temperature.

The complete interference analysis consists of the SINR values of each FSS terminal user at each available carrier frequencies. Thus, the individual SINR values can be stacked in matrix **SINR** $\in \mathbb{R}^{M \times L}$ as follows,

$$\textbf{SINR} = \begin{bmatrix} \text{SINR}(1,1) & \cdots & \text{SINR}(1,L) \\ \vdots & \ddots & \vdots \\ \text{SINR}(M,1) & \cdots & \text{SINR}(M,L) \end{bmatrix}, \tag{5}$$

where the rows indicate the carrier frequencies and the columns indicate the FSS terminal users.

Having determined the interference effect at the carrier level on each FSS terminal user, the next section is devoted to the BF design, whose objective is to maximize the SINR of the FSS terminals which suffer excessive interference. The resulting improved SINR will be used as an input parameter to the CA module, which is described in Section IV, in order to allocate the available spectrum resources.

III. BEAMFORMING STRATEGY

In this paper, a BF technique is used for interference management purpose. In particular, adaptive BF is applied at the FSS terminal in order to minimize the FS interference and to maximize the SINR of the desired FSS link. In this work, the Direction of Arrival (DoA) information of the FSS satellite is available to the satellite terminal and we assume that the DoA information of the interfering FS transmitters can be obtained with the help of the available database information. Subsequently, the beamformer can be designed to achieve the maximum reception in the desired direction while attenuating towards the interfering FS directions.

This section is divided into two parts. The first part concentrates on the BF weight design, whereas the second part introduces some discussion on the complexity issues of implementing BF in the considered coexistence scenario.

A. Beamforming Weight Design

BF methods have been widely considered in the existing terrestrial-based CR literature [16]. Recently, BF strategies have been addressed in the context of cognitive SatCom but mostly at the academic level [17], [18]. For the considered scenario in this paper, we apply the widely used Linearly Constrained Minimum Variance (LCMV) beamformer in which the design problem is to minimize the output variance of the beamformer by providing a unity response in the desired direction and the null responses in the interfering directions [19].

The receive LCMV beamformer $\mathbf{b} \in \mathbb{C}^{1 \times P}$, P being the number of Low Noise Block Downconverters (LNBs), is given by the solution of the following problem

$$\begin{aligned} \min_{\mathbf{b}} \quad & \mathbf{b}^H \hat{\mathbf{R}}_y \mathbf{b} \\ \text{s.t.} \quad & \mathbf{C}^H \mathbf{b} = \mathbf{g}, \end{aligned} \tag{6}$$

where $\mathbf{g} = [1 \;\; 0 \;\; \cdots \;\; 0]^T$ is the desired response vector, $\mathbf{C} = [\mathbf{s}_d \;\; \mathbf{s}_1 \;\; \cdots \;\; \mathbf{s}_{N_i - 1}]$ is the constraint matrix with $\mathbf{s}_i$, $i = 1, \ldots, N_i$, being the array response vectors towards the interfering FS stations, and $\mathbf{s}_d$ being the array response vector towards the desired direction. Further, the term $\hat{\mathbf{R}}_y$ is the sample covariance matrix of the received signal, given by; $\hat{\mathbf{R}}_y = \frac{1}{N_s} \sum_{k=1}^{N_s} \mathbf{y}(k)\mathbf{y}^H(k)$, where $\mathbf{y}(k)$ and N_s denote the received snapshot at the k-th time instant and the total number of available snapshots, respectively. In the above problem, the number of constraints must be smaller than the number of antenna elements ($N_i + 1 < P$), otherwise the problem becomes over-determined. The resulting beamformer is given by [19]

$$\mathbf{b} = \hat{\mathbf{R}}_y^{-1} \mathbf{C} \left(\mathbf{C}^H \hat{\mathbf{R}}_y^{-1} \mathbf{C} \right)^{-1} \mathbf{g}. \tag{7}$$

It is crucial that the set of interfering DoAs are precisely known, otherwise degrees of freedom are consumed without effectively removing the interference. To decrease the sensitivity to this mismatch, in practice, it is better to set the attenuation to some value greater than zero.

B. Discussion on complexity issues

In the considered receive BF problem, we assume the FSS terminal to be equipped with multiple LNB (MLNB) based Feed Array Reflector (FAR). This choice is motivated by the facts that the cost of a consumer grade single LNB is low and the compact design of MLNBs using dielectric feed elements is feasible. However, the number of LNBs should be kept low, e.g., 2-3 LNBs, due to cost, mechanical support and electromagnetic blockage issues [20]. It can be noted that in the presence of multiple harmful FS links, the considered scenario becomes overloaded since the FSS terminal usually has fewer LNBs than the received co-channel FS signals. To overcome this limitation, we include only the strongest FS interfering links to the BF design. Moreover, we consider implementation of the BF approach only in the FSS terminals whose SINR level is less than a specific threshold due to FS interference. In doing so, we avoid the significant overhead in terms of system complexity caused by implementing BF in all the FSS terminals. The SINR threshold which determines the application of BF can be set according to the MODCOD limit based on DVB-S2X specifications [21]. The proposed BF application in the scenario under consideration is detailed in Algorithm 1.

IV. CARRIER ALLOCATION

After applying BF, the improved SINR matrix, namely $\mathbf{SINR}_{BF}$, is used by the carrier allocation module to optimally allocate the carriers among the users by maximizing the total throughput. Let $a_{m,l} = \{0, 1\}$ be the (m, l)-th element of an $M \times L$ carrier assignment matrix $\mathbf{A}$ with 1 indicating that user l is assigned to carrier m. This way,

$$\mathbf{A} = \begin{bmatrix} a_{1,1} & \cdots & a_{1,L} \\ \vdots & \ddots & \vdots \\ a_{M,1} & \cdots & a_{M,L} \end{bmatrix}. \tag{8}$$

Our goal is determine the value of $a_{m,l}$ to be zero or one by maximizing the overall throughput of the system. This problem can be stated as follows

$$\begin{aligned} \max_{\mathbf{A}} \quad & \|\text{vec}(\mathbf{A} \odot \mathbf{R}(\mathbf{SINR}_{BF}))\|_{l_1} \\ \text{s.t.} \quad & \sum_{m=1}^{M} a_{m,l} = 1, \end{aligned} \tag{9}$$

where $\odot$ denotes the Hadamard product, vec$(\cdot)$ denotes the vectorization operator and $\|\cdot\|_{l_1}$ denotes the l_1-norm. Further, we denote by $\mathbf{R}(\mathbf{SINR}_{BF})$ the rate matrix with $r_{l,m}$, $l = 1, \ldots, L$, $m = 1, \ldots, M$, elements indicating the associated DVB-S2X rate [21]. To solve the problem in (9), we employ the widely used Hungarian algorithm [22].

Algorithm 1 Employed beamforming application

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Require: $\mathbf{SINR}$, SINR threshold ($\text{SINR}_{th}$), number of LNBs ($P$).
Initialize $\mathbf{SINR}_{BF}$.
for $m = 1 : 1 : M$ do
    for $l = 1 : 1 : L$ do
        if $\text{SINR}(m, l) < \text{SINR}_{th}$ then
            Identify the $P - 2$ FS stations that cause the strongest interference to the $l$-th user.
            Calculate the $P - 2$ offset angles of the $l$-th user towards the corresponding interfering FS station.
            Apply BF as described in Section III-A and update $\text{SINR}_{BF}(m, l)$ with the corresponding SINR value after BF.
        else
            $\text{SINR}_{BF}(m, l) = \text{SINR}(m, l)$
        end if
    end for
end for
return $\mathbf{SINR}_{BF}$
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V. NUMERICAL EVALUATION

In this section, we evaluate the performance of BF and CA approaches in the considered scenario.

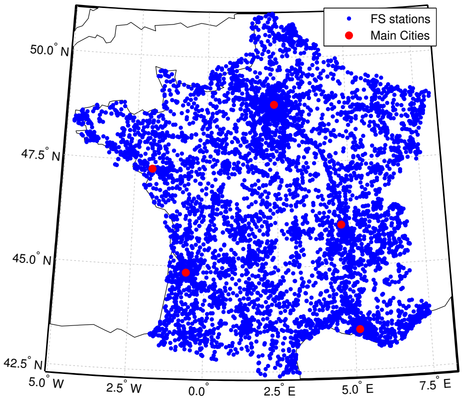


Fig. 3: FS distribution map for France.

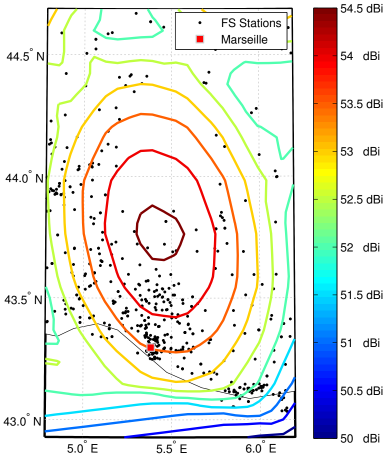


Fig. 4: Beam pattern of the FSS satellite over Marseille region.

A. Simulation Setup

The parameters related to FS microwave links are obtained from ITU-R BR International Frequency Information Circular (BR IFIC) database [23], which includes information listed on a station by station basis with the location of the antenna, maximum antenna gain, transmit power and channel bandwidth. In this section, we focus on the database related to France with more than 12,000 entries. The distribution map of FS links is illustrated in Fig. 3. The signal levels of the cognitive FSS system are accurately determined by considering a real FSS multibeam satellite system obtained from Thales Alenia Space (TAS), providing coverage over France. In particular, this paper focuses on a high density beam in terms of FS interfering links. The beam chosen is the one depicted in Fig. 4, which provides coverage over the region of Marseille. Similar results were obtained with a low density beam serving the area closer to Thiezac and thus not presented in this paper due to the lack of space.

The results shown in this section were obtained after 385 Monte Carlo runs, in which the locations of the FSS terminals were selected uniformly at random for each realization within the considered beam coverage according to the population density database produced by NASA Socioeconomic Data and

TABLE I: Simulation Parameters

Parameter	Value
Carrier bandwidth	36 MHz
Shared band	$17.7 - 19.7$ GHz (55 carriers)
Exclusive band	$19.7 - 20.2$ GHz (14 carriers)
Parameters for FSS system	
Satellite location	28.2°E
$P_{\text{Tx}}^{\text{SAT}}$	7 dBW
$G_{\text{Tx}}^{\text{SAT}}(l)$	Between 49.60 and 54.63 dBi
Co-channel margin	Between -7.37 and -14.16 dB
Reuse pattern	4 color (freq./pol.)
Channel	LoS channel (path loss and beamgain)
Satellite height	35,786 Km
FSS terminal antenna max. gain	42.1 dBi
FSS terminal antenna pattern	ITU-R S.465
Receiver noise temperature	262 K
Noise power	-128.86 dBW @ 36 MHz
Terminal height	2 m
Terminal altitude above the sea level	From terrain data available online
LNBs at the terminal	3
Parameters for FS system	From Database
Antenna pattern	ITU-R F.1245-2
Antenna gain	Between $5.3 - 41$ dBi
EIRP	Between $32.9 - 54.3$ dBW
Antenna height	Between $0 - 187$ m
Bandwidth	Between $13.7 - 55$ MHz

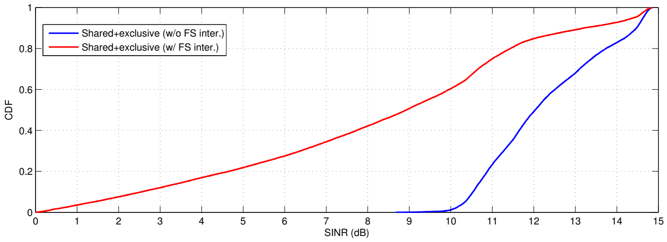


Fig. 5: CDF of SINR distribution

Applications Center (SEDAC) [24]. The considered system parameters are summarized in Table I.

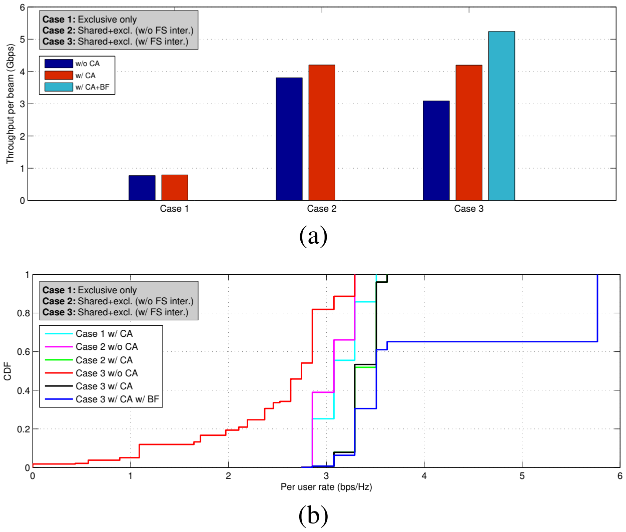
B. Numerical Results

In the considered system setup, 14 exclusive and 55 shared carriers should be optimally distributed among 69 cognitive FSS terminal users. In each realization, the SINR matrix described in Section II is obtained considering all the carrier-user combinations for both shared and exclusive cases. Clearly, in the latter, no interference is considered. The throughput evaluation is carried out for a single high density beam over the Marseille region depicted in Fig. 4. As mentioned in Section I, this paper presents the results for the spectral coexistence scenario of FSS downlink with the FS links. For the analysis in the uplink coexistence scenario, interested readers may refer to [25].

The effect of FS interference on the SINR of the FSS downlink system is depicted in Fig. 5 in terms of Cumulative Distribution Function (CDF). It can be observed that the SINR distribution degrades in the presence of FS interference. More specifically, only 1.2% of FSS terminals experience values of SINR below 10dB in an interference-free scenario, which increases up to 60% in the FSS-FS coexistence case. Next, we evaluate the benefits of BF and CA approaches in the considered coexistence scenario.

TABLE II: Throughput per beam

Case	Technique	Value (Gbps)
Case 1: Exclusive only	w/o CA	0.77
	w/ CA	0.79
Case 2: Shared+Excl. w/o FS inter.	w/o CA	3.80
	w/ CA	4.20
Case 3: Shared+Excl. w/ FS inter.	w/o CA	3.09
	w/ CA	4.20
	w/ CA+BF	5.24



(a)

(b)

Fig. 6: (a) Throughput per beam, and (b) Per user rate distribution.

For our analysis, we consider the following cases:

- **Case 1 - Exclusive only.** This denotes the conventional system without the use of cognitive SatCom.
- **Case 2 - Shared plus exclusive without FS interference.** This represents the scenario where the additional spectrum is allocated exclusively to FSS system. This case does not exist in practice but is considered for comparison purposes.
- **Case 3 - Shared plus exclusive with FS interference.** This depicts the scenario where FSS system share the band primarily allocated to the FS systems.

We present the per beam throughput comparison of the above cases in Fig. 6(a). The exact per beam throughput values depicted in Fig. 6(a) are given in Table II. The SINR threshold which determines the application of BF is considered to be $\text{SINR}_{th} = 9.71$ dB, which corresponds to the 16APSK 13/18 ModCod based on the DVB-S2X specifications [21]. As expected, the per beam throughput is improved when using the 2 GHz extra bandwidth. Even without considering any resource allocation strategy, the FSS system increases its overall throughput from 0.77 to 3.09 Gpbs by accommodating some FSS terminals in the shared band. Therefore, exploitation of spectrum opportunities in the cognitive SatCom resulted in an approximately 300% throughput improvement with respect to the conventional fixed spectrum allocation.

While the application of CA in the exclusive only case does not provide much benefit (2.6% improvement), its application in the shared plus exclusive bands provides a 35.9% improvement over the case without the CA in the presence of FS interference. Moreover, if we apply BF before performing the CA, this improvement goes up to 69.6%. It is worth mentioning that the case without CA allocates each available carrier to the worst user in terms of SINR, which clearly represents the worst CA case. The important point to note here is that the cognitive satellite system obtains significant profit by exploiting extra spectrum opportunities while using the proposed CA and BF techniques. In particular, the cognitive approach together with the cognitive spectrum management techniques provide an additional gain of 580.5% with respect to the exclusive only throughput, which is a considerable gain.

It may be an objective to have uniform service coverage resulting in a fair service offering for best effort traffic. The fairness is evaluated in Fig. 6(b) by means of the CDF curves of the per user rate for the considered scenarios in bps/Hz. The figure corroborates the observations of the previous results. It can be observed that by introducing CA the beam availability in the presence of the FS interference outperforms the availability that would be obtained in the absence of the FS interference without CA. Note that the minimum user rate in the cognitive scenario (Case 3) increases from 0 to 2.75 bps/Hz while employing the proposed cognitive spectrum management techniques. From the figure, it is evident that the users can achieve higher rates when CA and BF approaches are combined.

VI. CONCLUSION

In this paper, we proposed a novel spectrum exploitation framework for enabling the operation of cognitive FSS terminals in the band $17.7-19.7$ GHz in which the incumbent users are Fixed-Service (FS) microwave links. The presented numerical results showed that the beam throughput as well as the beam availability can be significantly improved with the proposed CA and BF techniques. More importantly, it has been shown that the cognitive approach together with the spectrum management techniques can provide 5 times higher throughput with respect to the exclusive only throughput.

ACKNOWLEDGMENT

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