On the Feasibility of Interference Estimation Techniques in Cognitive Satellite Environments with Impairments

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Abstract. The increasing demand of wider frequency bands in wireless communications has lead in the last years to the introduction of novel techniques allowing to exploit more efficiently the radio spectrum. In particular, spectrum sharing is considered one of the key technologies for future wireless systems. Cognitive radio is considered the most important technique for efficiently allowing the spectrum sharing among heterogeneous systems. If on one hand the cognitive radio techniques have been extensively assessed in terrestrial communications, they remain quite an unexplored area in Satellite Communications (SatComs). In this paper an Interference Estimation technique for SatComs aiming to reuse the spectrum resources primarily allocated to terrestrial communications is discussed. In particular, its assessment in a realistic scenario, where multiple impairments are considered, is discussed.

Keywords: Cognitive Radio · Satellite communications · Interference estimation · Spectrum sensing · Impairments

1 Introduction

Future satellite systems (2020–2025) are expected to exploit GEO satellites, with capacities ranging from hundreds of Gbps up to Tbps. This will be achieved by means of hundreds of spotbeams, via higher order frequency reuse. In fact, the limited amount of exclusive spectrum that can be accessed by the Fixed Satellite Service (FSS) limits the actual system capacity. Current 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 this context, access to additional frequency bands through frequency sharing for the user terminal frequency bands would provide additional capacity to

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further increase the capacity of the satellite system. Cognitive Radio (CR) techniques are seen as the most promising mean to tackle the spectrum scarcity problem [1]. 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 [2], while in SatCom their implementation and study is still in its infancy. SatComs represent a challenging application scenario for CRs, due to, *e.g.*, the geographically wide coverage of the spectrum allocation and the power imbalance among ground and user terminals [3].

In order to enable coexistence between primary and secondary systems, CR techniques can be employed in such scenarios [4]. In particular, spectrum awareness techniques allow the cognitive system to be aware of the primary system presence. The most common techniques that provide this kind of awareness, and that are often proposed also in terrestrial scenarios, are spectrum sensing [5] and databases [6].

These frequencies are defined as *non exclusive* since they are assigned to both services, with a primary use for feeder uplinks (BSS) or fixed services (FS). Aiming at reusing a wider spectrum portion by exploiting those bands in which weak incumbent signal levels may be present, FSS terminals that usually operate in the *exclusive* frequency bands can additionally use the *non exclusive* bands if room is found in order to get additional capacity. It is worthwhile noting that even bands in which incumbent signals are present might be exploited by the FSS, if a proper set of transmission parameters can be found to satisfy the target Quality of Service (QoS).

Rather than typical spectrum sensing techniques, which focus on discovering spectrum holes [5], in this paper the estimation of interfering levels is considered. In fact, while spectrum sensing is usually considered for its detection capabilities, our aim is to have a joint detection and estimation approach that allows to exploit also the underused spectrum intervals where the interference is not harmful.

To this aim, a proper interference estimation technique along the *non exclusive* spectrum should be employed allowing to identify which bands are available for transmission also allowing geographical reuse due to propagation terrain effects, geographical isolation and different direction of the links.

Among other interference estimators proposed in the literature [7], we rely on the Data Aided SNORE (DA-SNORE) algorithm [8] for estimating the signal to interference plus noise ratio (SINR) in each band. The effectiveness of the proposed technique has been described in [9] by assuming a satellite cognitive system based on the DVB-S2 [10] or DVB-S2x standards [11] for downlink transmission and the cognitive earth terminal, equipped with a receiving chain able to scan all the frequencies of interest with a sensing sub-bandwidth, able to perform the data aided estimation algorithm by means of pilot blocks.

In this paper, after recalling the most important characteristics of the SNORE based Interference Estimation algorithm [9], we will assess its performance in a realistic scenario. Indeed, a real cognitive radio SatCom scenario is characterized by presence of several impairments. To this aim, the robustness of the proposed technique in presence of the most typical impairments is evaluated.

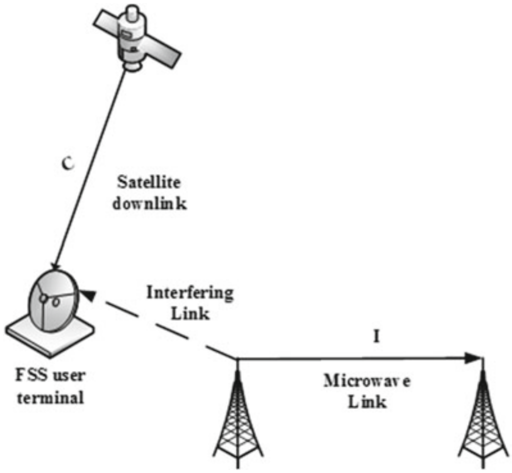

Fig. 1. Scenario representation

2 The Reference Scenario

A Ka-band FSS cognitive system, reusing for downlink transmission the frequency bands allocated to FS links (incumbent systems) as depicted in Fig. 1, is considered for performance assessments of the proposed technique. Since Radio Regulations define limits for emissions from FSS systems [12], it can be assumed that cognitive transmitters do not cause harmful interference towards FS links. Thus, the main focus is on allowing the cognitive system to operate in presence of interfering incumbent systems, as highlighted in Fig. 1. To this aim, the cognitive system shall be able to scan the non exclusive spectrum, estimate the interference levels, and identify the frequencies suitable for the transmission. Therefore, instead of typical cognitive sensing techniques, the system will rely on an estimation technique able to give an increased knowledge of the incumbent presence.

The SNORE based interference estimation algorithm has been proposed in [9]. For the sake of clarity, we summarize here the most important characteristics of the proposed algorithm by focusing more on the impairments in Sect. 3.

We assume that the receiver earth terminal of the cognitive system is equipped with a receiving chain able to scan all the frequencies of interest with a sensing sub-band, B_W, equal to 36 MHz, which is the typical bandwidth of DVB-S2 [10] and DVB-S2x [11] communications. Thus, the 400 MHz *non exclusive* spectrum portion is split into 11 sub-bands, and for each of these bands the DA-SNORE algorithm [8] is used in order to assess whether incumbents activities are present or not.

In the depicted scenario, we can represent the lowpass equivalent expression of the signal at the cognitive receiver denoted as $r(t)$ by

$$r(t) = \begin{cases} s(t) + \sum_k^{N_i} i_k(t) + n(t) & \text{with interferers} \\ s(t) + n(t) & \text{without interferers} \end{cases} \quad (1)$$

where: (i) $s(t) = \sqrt{P_0}v(t)\mathrm{e}^{j\phi_0}$ is the useful signal from the satellite; (ii) $i_k(t) = \sqrt{P_k}\iota_k(t)\mathrm{e}^{j(2\pi f_k t + \phi_k)}$ the k-th interferer, with $k = 1, \ldots, N_i$ and N_i denoting the number of the interferers; (iii) P_0, P_k, $k = 1, \ldots, N_i$, denote the received power on the useful and the k-th interfering links, respectively; (iv) ϕ_0, ϕ_k, $k = 1, \ldots, N_i$, denote the phase of the useful and k-th interfering signal, respectively. We can further assume $\phi_0 = 0$ without loss of generality; (v) f_k, $k = 1, \ldots, N_i$, is the frequency shift between the useful signal carrier ($f_0 = 0$ since we have lowpass equivalents) and the k-th interfering signal carrier; (vi) $v(t), \iota_k(t)$, with $k = 1, \ldots, N_i$, denote the lowpass complex signals of the cognitive and k-th interferering signals, respectively. We also assume that the interfering signals have white spectral density in their band, and can thus be modeled as a Gaussian random variable with variance $P_k, k = 1, \ldots, N_i$; and (vii) $n(t)$ the additive white Gaussian noise (AWGN) with zero mean and power spectral density N_0.

By exploiting the methodology introduced in [13], the explicit expressions highlighting the relationships between W, SINR, the estimation error variance σ_ϵ^2, and the Cramer-Rao bound (CRB) for the design of the proposed cognitive technique has been derived in [9].

It is worth to be noticed that in the SNORE estimator, the CRB normalized with respect to SINR^2 is defined as [13, Eq. (21)]:

$$\frac{CRB}{SINR^2} = \frac{4WN_s}{(2WN_s - 3)^2}\left(\frac{2}{SINR} + 1\right) \quad (2)$$

and the relationship between the error variance, σ_ϵ^2, and the SINR can be derived by taking into account the number of pilot blocks W that allow to reach the CRB (3) [13, Eq. (20)]:

$$\frac{\sigma_\epsilon^2}{SINR^2} = \frac{4\left(2W^2N_s^2\left(SINR + 2\right)\ SINR + WN_s\left(1 - 4SINR\right) - 1\right)}{\left(2WN_s - 3\right)^2\left(2WN_s - 5\right)} \quad (3)$$

2.1 The SNORE Based Interference Estimation

In order to cope with the problem of identifying which band gives best performance among those sensed in the *non-exclusive* spectrum, we propose to perform the scan operation periodically. In the depicted scenario, it is possible to sense with a very low duty cycle, in order to guarantee the desired capacity and satisfy QoS requirements without increasing the computational load on the cognitive system.

In [9] the authors highlighted that the estimation performance strongly depends on W, as the more pilots blocks are accumulated the lower the estimation error will be. On the other hand, increasing the number of pilot blocks to be accumulated also requires longer sensing periods.

A proper value of W for the design of the algorithm can be obtained according to the scenario we have to cope with and by exploiting (2) and (3). From (2), it is possible to derive W, as:

$$W = \frac{1}{N_s}\left(\frac{3}{2} + \frac{SINR^2}{CRB}\left(\frac{2}{SINR}+1\right)\left(\frac{1}{2}+\sqrt{1+\frac{6CRB}{SINR\,(2+SINR)}}\right)\right) \tag{4}$$

This closed-form expression provides the number of pilot blocks W as a function of the Cramer-Rao bound, the SINR, and the number of pilots per block N_s. The number of pilot blocks required to achieve a target error variance $\sigma_\epsilon^2|_t$ as a function of the SINR can be instead evaluated by solving the third degree equation:

$$W^3N_s^3 - \left(\frac{11}{2} + \frac{SINR}{\sigma_\epsilon^2}(SINR+2)\right)W^2N_s^2 + \left(\frac{39}{4} - \frac{1}{2\sigma_\epsilon^2} + 2\frac{SINR}{\sigma_\epsilon^2}\right)WN_s - \frac{45\sigma_\epsilon^2 - 4}{8\sigma_\epsilon^2} = 0 \tag{5}$$

that has been obtained from (3) after a few mathematical steps. The values of W obtained from (4) and (5) represent respectively the lower bound and the minimum number of W that achieve the target error variance. Hence, (4) and (5) give the description of how many pilots are needed to achieve a target estimation error as a function of SINR and can be used for the design of the proposed technique.

3 Interference Estimation Impairments

Even if the SNORE based interference estimation algorithm have promising performance [9] a proper calibration and performance assessment under realistic impairments should be performed. Thus, the proposed spectrum sensing technique based on measuring the SNIR requires a baseline calibration.

In the following we do not refer to any specific knowledge of the incumbent link for this sensing task. The spectrum sensing has to be performed during the first carrier lineup procedure of the terminal. The overall expected link performance is assumed known from planning and previous link budget exercises. This results in an expected signal to noise ratio that has to be met at the installation of the terminal.

During the terminal installation and after the antenna pointing task of the terminal installation, we have a basis of the two values for the expected and measured signal to noise ratio. A residual difference has to be correctly interpreted by the NCC. This difference is measured and expected SNIR may result from

Table 1. Potential perturbations contributing to an incorrect SNIR estimation

Potential contributing factor to measured SNIR delta perturbation	Estimated order of inaccuracy	Potential mitigation measure
Rainfade and atmospheric attenuation during terminal installation	Several dB in Ka-band	Use long term averaging and additional learning procedure in NCC
Inaccurate antenna pointing of the terminal	1 dB p-p	
Cross polarization interference	0.5 dB p-p	May be taken into account and neglected if under control
Bias in expected SNIR value resulting from margins at different levels	1 dB max peak	Reference terminals and an overall system learning of the expected SNIR is required
Interference from other satellite downlinks or adjacent beams of the same system	2 dB max peak	Requires a revised planning tool with potential reference terminals and measurements of expected levels
Interference from terrestrial contributions (scenario A / B) such as BSS feeder links or FS transmitters	Value to be estimated	N.A
Receiver gain variation	Long term variations (seasonal) 1–2 dB p-p	
LNB gain variation over temperature	1–2 dB typical	

different perturbations or inaccuracies in the overall system that needs to be addressed with the NCC integration of the spectrum sensing techniques. These include the aspects listed in Table 1.

The system spectrum sensing requires as a result a combination of planning tools, reference terminals and a system learning mechanism with a feedback to the terminal installation procedure. Additional mechanisms have to be defined in this context to address all possible sources of practical errors to devise a reliable detector for the terrestrial interference.

In this paper, we focus on the effect of perturbations and impairments that may occur in case the spectrum sensing technique proposed in [9], and previously described, is used. Earth terminals can be affected by typical issues that may arise also during set up procedure as:

- Pointing errors
- Fading uncertainties
- G/T and sat. gain uncertainties over coverage area

Impairments that affect the SINR estimation process during terminals installation and the sensing phase, are here introduced and summarized in Table 1. Further details can be found in [14,15]. Imperfect alignment of the transmitting and receiving antennas could cause pointing errors that are sources of additional losses. These losses are due to a reduction of the antenna gain with respect to its maximum and are function of the misalignment of the angle of reception θ_R, and can be evaluated as:

$$L_R = 12\left(\frac{\theta_R}{\theta_{3dB}}\right)^2 \quad [dB] \tag{6}$$

where θ_{3dB} is the 3 dB beamwidth angle between the direction in which the gain is maximum and that in which it is half of this latter value. Other losses of earth terminals, which are due to non idealities, are feeder losses L_{FRX} between the antenna and the receiver, and polarization mismatch losses L_{POL}.

Atmospheric events cause additional attenuation and variation with respect to the common free space loss propagation. Several effects are present but an overall contribution affecting the received power can be taken into account by adding to the free space loss attenuation A_{FS} the contribution A_P that includes all the atmospheric attenuation:

$$A_{TOT}[dB] = A_{FS}[dB] + A_P[dB]$$

These losses are significant above 10 GHz as in case of the Ka bands, which are used in the considered scenario. In such bands, tropospheric phenomena are the main contributions of the link availability and service quality degradation. These phenomena are (i) attenuation, (ii) scintillation, (iii) depolarization and (iv) increase of the antenna temperature in the receiving earth terminal. A more detailed description of these phenomena is included in [15, Chapter 3]. Link budget is affected by these contribution in many ways. In the downlink case, the carrier to noise ratio can be expressed as:

$$\left(\frac{C}{N_0}\right)_{DOWNLINK}[dB] = (1-\Delta_1)EIRP_{SAT} - A_{TOT} + (1-\Delta_2)\left(\frac{G}{T}\right)_{ES} - k_B \tag{7}$$

and can be rearranged in order to separate the ideal, or expected value $\left(\frac{C}{N_0}\right)_{FS}$ calculated in free space loss conditions, from contributions that cause its variation in the following way

$$\left(\frac{C}{N_0}\right)_{DOWNLINK}[dB] = \left(\frac{C}{N_0}\right)_{FS} - \Delta_1 EIRP_{SAT} - A_p - \Delta_2\left(\frac{G}{T}\right)_{ES} \tag{8}$$

where $EIRP_{SAT}$ is the satellite EIRP, $\left(\frac{G}{T}\right)_{ES}$the figure of merit of the earth terminal receiver and Δ_1 and Δ_2 a possible decrease of the satellite $EIRP_{SAT}$ and the figure of merit $\left(\frac{G}{T}\right)_{ES}$ respectively. In particular, the figure of merit G/T of the earth terminal at the receiver input, i.e., including also losses of the receiving chain, can be expressed as

$$\left(\frac{G}{T}\right)_{ES} = \frac{G_{R_{\max}}/L_R L_{FRX} L_{POL}}{T_{TOT}}[K^{-1}] \tag{9}$$

where T_{TOT} is the total downlink system noise temperature at the receiver input and it is function of the antenna temperature T_A, the feeder temperature T_F, and the effective input noise temperature of the receiver T_{eRX}

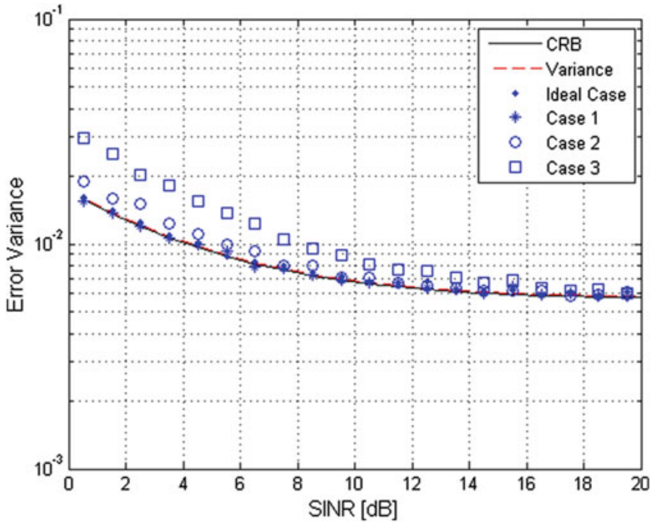

Fig. 2. Error variance as a function of the SNIR in presence of impairments

$$T_{TOT} = \frac{T_A}{L_{FRX}} + T_F\left(1 - \frac{1}{L_{FRX}}\right) + T_{eRX} \tag{10}$$

Temperature variations of the environment cause variation from the nominal value of $\left(\frac{G}{T}\right)_{ES}$ besides other impairments already been addressed as pointing errors. In particular, T_A and T_{eRX} are defined as

$$T_A = \frac{T_{SKY}}{A_p} + T_M\left(1 - \frac{1}{A_p}\right) + T_{GROUND}$$

$$T_{eRX} = (NF - 1)T_0$$

where in the former equation T_{SKY}, T_M, and T_{GROUND} are respectively the sky, the medium and the ground temperatures whereas in the latter equation the NF is the noise figure and T_0 the default noise temperature fixed at 290 K. Variations of these effects can be included in Δ_2.

4 Numerical Results

After having reviewed the impairments that may occur at the receiver during the estimation process, we performed computer simulations in order to verify the robustness of the proposed technique. System reference values taken into account for simulations are reported in Table 2.

As a first result, in Figs. 2 and 3 performance of the SNORE algorithm in presence of three specific impairments cases (Table 3), which have been selected among all the possible for their significance, are depicted.

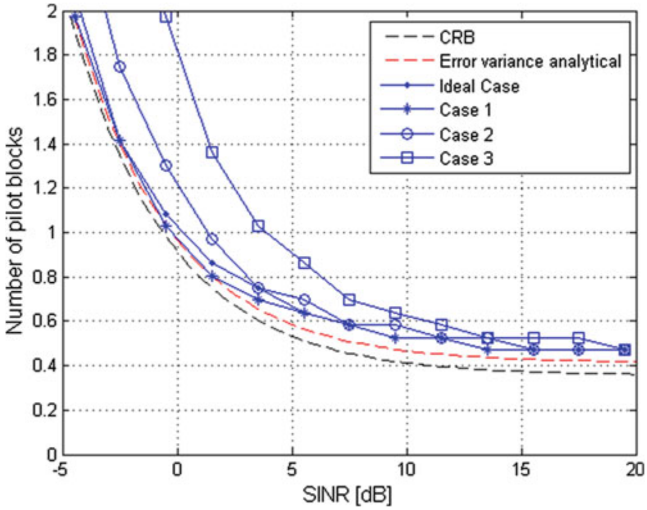

Fig. 3. Minimum number of pilot in presence of impairments

In particular, Fig. 2 shows the normalized error variance $\frac{\sigma^2}{SINR^2}$ as a function of the SINR when 5 pilot blocks of 36 symbols each are used for the estimation, whereas Fig. 3 describes the minimum required number of pilot blocks in order to achieve a target normalized error variance, i.e., $\frac{\sigma^2}{SINR^2}$, of 0.1 as a function of the SINR. In both figures, the solid line represents the Cramer Rao Bound, the dashed one the analytic value derived in [9], and the dots the simulated values under different impairments conditions. Under the ideal case the link budget is calculated without impairments and is considered as reference value, whereas in cases 1, 2, and 3 are introduced respectively the uncertainties shown in Table 3.

The SNORE based technique is also assessed in presence of impairments with respect to its applicability in a specific scenario. Both evaluations in frequency domain for a specific earth terminal and in geographic domain considering a wide region covered by the satellite beam pattern are performed by starting from reference results obtained on databases analysis [16].

The estimation capabilities of the terminal antenna under different impairments as listed in Table 3, are assessed. These simulations aimed at describing how accurate would be the estimation process for a fixed terminal antenna.

We consider a portion of spectrum wide 400 MHz from 18.4 GHz to 18.8 GHz, along which the estimation process is performed in carriers equal to 36 MHz. The FSS terminal is positioned in 47.5 N latitude and 19E longitude. The estimation process is performed under the different impairments listed in Table 3, accumulating 1 and 10 pilot blocks of 36 symbols, in Figs. 4 and 5.

As expected, in each band the SINR value estimated is lower than the real value due to impairments that cause additional losses. However, in case of high SINR values the estimated value even in presence of impairments can be considered reliable while, otherwise, to obtain the desired uncertainty target for lower values of the SINR, more pilot blocks have to be accumulated. In fact,

Table 2. System reference parameters for SNIR based sensing simulations

Parameter name	Value
Sky temperature (T_{SKY})	15 K
Ground temperature (T_{GROUND})	45 K
Temperature of the medium (T_M)	275 K
Downlink frequency	18.4 – 18.8 GHz
Satellite EIRP ($EIRP_{SAT}$)	50 – 70 dBW
Carrier bandwidth	36 MHz
Terminal efficiency	0.65
Terminal antenna diameter	0.6 meters
Figure of merit $(G/T)_{ES}$	34.9 dB/K
Additional $(G/T)_{ES}$ variation (Δ_2)	0 – 2 dB
Antenna gain (G_R)	50 62 dB
Polarization losses (L_{POL})	0 – 0.5 dB
Pointing losses (L_R)	0 – 1 dB
Feeder losses (L_{FRX})	0 dB
Terminal antenna temperature (T_A)	78 K
Effective noise temperature (T_{eRX})	262 K
Terminal component temperature (T_F)	290 K
Default temperature (T_0)	290 K
LNA Noise Factor (NF)	1.4 dB
QPSK symbols per pilot	36

considering bands 5 and 6, it can be noticed that in Fig. 4, i.e., in case of 1 pilot block is accumulated, the estimated SINR in presence of impairments is similar to the real value, whereas in Fig. 5, i.e., where 10 pilot blocks are considered, the estimation is more accurate. Thus, an inappropriate estimation of the SINR in presence of impairments causes a misunderstanding in detecting presence of impairments or interference due to incumbent users.

In addition to frequency analysis, geographic assessments are performed to evaluate the SINR estimation process within the beam coverage. Thus, the area from 47 N to 48N of latitude and from 19E to 20E of longitude is considered. Real SINR values that earth terminals experience within the coverage, are pre-

Table 3. The selected impairments cases

	Ideal case	Case 1	Case 2	Case 3
Polarization losses (L_{POL}) [dB]	0	0.5	0.5	0.5
Pointing losses (L_R) [dB]	0	1	1	1
Additional $(G/T)_{ES}$ variation (Δ_2) [dB]	0	2	2	2
Additional atmospheric attenuation (A_p) [dB]	0	0	5	10

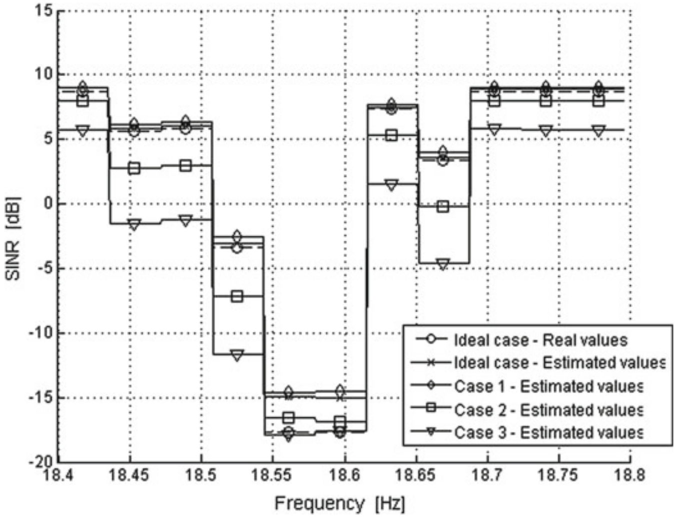

Fig. 4. Assessments on the frequency spectrum in presence of different impairments 1 pilot block

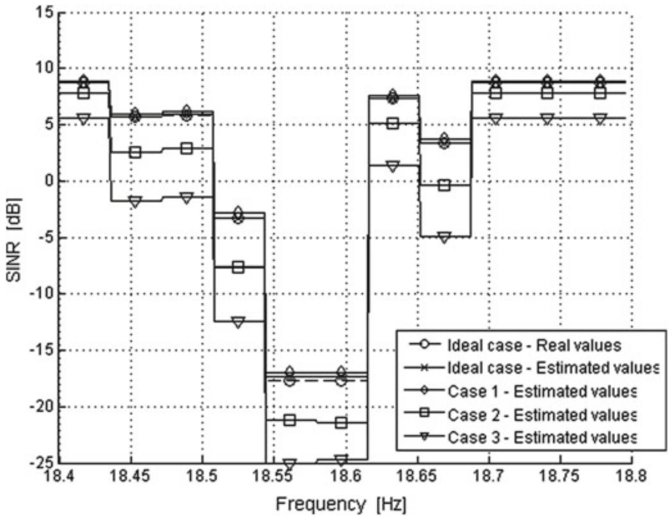

Fig. 5. Assessments on the frequency spectrum in presence of different impairments 10 pilot blocks

sented in Fig. 6. It can be noted the presence of a directive incumbent link and of some incumbent-free regions. Figure 7 shows the results for the cases listed in Table 3, when performing the estimation algorithm with 10 pilot blocks.

Results obtained from geographic simulations also confirm link budget losses due to presence of impairments and a more reliable estimation due to longer

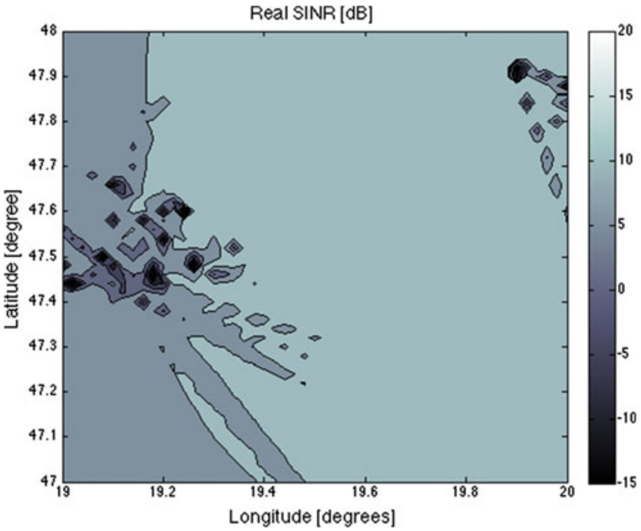

Fig. 6. Real SINR values along the selected geographic region

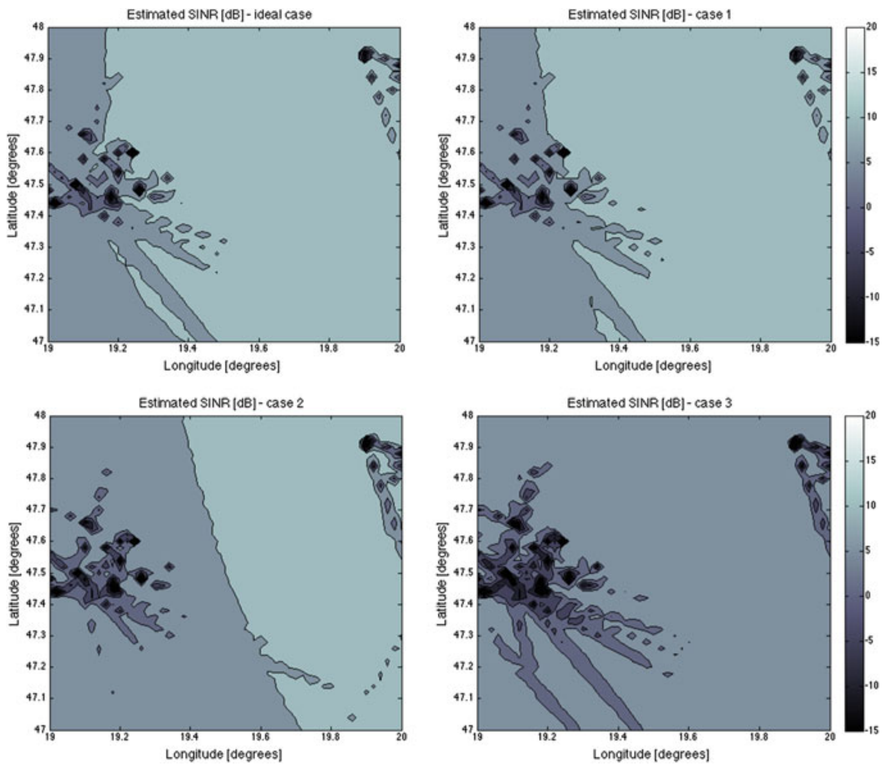

Fig. 7. Comparison between estimated values under different impairments conditions 10 pilot block

Table 4. Geographic assessments results

Case	1 pilot block	10 pilot blocks
Ideal case	0.48 %	0.19 %
Case 1	0.71 %	0.56 %
Case 2	2.42 %	2.46 %
Case 3	3.67 %	3.71 %

observation periods. Percentages of the SINR values estimated that differ from the real value more than $\frac{\sigma^2_{\epsilon|des}}{SINR^2} = 0.1$, where $\sigma^2_{\epsilon|des}$ is the difference between the real value and the estimated value under uncertainties conditions, are shown in Table 4, where the results with 1 pilot block are also reported. Results show that in both cases impairments lead to a degradation of the percentages of points correctly estimated. However, in presence of low impairments losses as for the Ideal case and Case 1, longer estimations provide more reliable estimations whereas in case of higher impairments losses the estimated values do not satisfy the target reliability even in case of longer sensing periods.

5 Conclusions

The success of spectrum sharing is mostly based on the effectiveness of cognitive radio techniques, and, among other components, on the spectrum sensing operations. In this paper, after introducing the SNORE based interference estimation technique, that results particularly effective for the selected heterogeneous terrestrial-satellite scenario, the presence if impairments is introduced. The numerical results shows that the proposed techniques is robust even in the case of communication impairments, resulting in a good candidate for the considered scenario.

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