# Implementation Issues of Cognitive Radio Techniques for Ka-band (17.7-19.7 GHZ) SatComs

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*Abstract*— **The usable satellite spectrum has become scarce due to continuously increasing demand for broadband multimedia, broadcast and interactive services. In this context, investigating efficient spectrum coexistence techniques is a crucial challenge in order to enhance the spectral efficiency of future satellite systems. Herein, we study a satellite-terrestrial coexistence scenario where a Fixed Satellite Service (FSS) downlink coexists with the Fixed Service (FS) point to point microwave links in the Ka-band (17.7-19.7 GHz). First, we identify various practical challenges and provide possible solutions in order to allow this coexistence. Then we propose four different sensing and avoidance schemes in order to protect FSS satellite terminals from the harmful FS interference. Further, we evaluate the performance of one of the proposed solutions in the considered scenario with the help of theoretical and numerical analysis. More specifically, we focus on harmful FS detection problem in order to guarantee the sufficient protection of FSS terminals. It is shown that the FS harmful interference can be reliably detected with the help of an additional dipole antenna and this solution further overcomes the noise uncertainty problem encountered while sensing with the satellite dish.**

***Index Terms*: Cognitive Radio, Satellite Communications, Spectrum Sensing, Interference Detection**

## I. INTRODUCTION

During the last decade, the demand for high speed wireless connections has been rapidly increasing due to the proliferation of broadband multimedia services. However, the usable wireless spectrum has become scarce due to spectrum segmentation and the dedicated frequency allocation of the standardized wireless systems. On the other hand, different spectrum occupancy measurement campaigns carried out at different parts of the world show that a significant amount of the wireless spectrum remains under-utilized in spatial and temporal domains [1]. Furthermore, the increased demand for consumer broadband over satellite has led to a number of high throughput Ka-band satellite systems and the exploitation of non-exclusive Ka-bands can further increase the overall system capacity. Although satellite systems have moved from a single beam platform to the multi-beam platform in order to enhance the system capacity, there is still a large gap to meet the spectral efficiency requirement for realizing the next generation Terabit satellites within the 2020 horizon [2]. This has motivated the concept of cognitive Satellite Communications (SatComs), which allows the coexistence of different satellite and terrestrial networks within the same spectrum in hybrid satellite-terrestrial and dual satellite coexistence scenarios [3–5]. In this context, we consider a hybrid satellite-terrestrial coexistence scenario in the Ka-band range 17.7-19.7 GHz band, used by fixed service point-to-point terrestrial microwave links.

Several Cognitive Radio (CR) techniques such as Spectrum Sensing (SS), underlay, overlay and database techniques have been proposed in the terrestrial paradigm [6]. However, the application of CR in the satellite paradigm is still in its infancy. Recently, there has been an increasing interest within the satellite research community in exploring suitable CR techniques for different scenarios. Examples include Co$^2$Sat (Cooperative and Cognitive Architectures for Satellite Networks) [3, 8], ACROSS (Applicability of CR to Satellite Systems) [9], CoRaSat (CR for SatComs) [4], etc. Existing literature related to the cognitive SatComs can be categorised into [7]: (i) hybrid satellite-terrestrial coexistence [3, 4, 9], and (ii) dual satellite coexistence scenario [8, 10, 11].

In this paper, we focus on one of the scenarios considered under the framework of European FP7 project CoRaSat [4]. This scenario (Fig. 1) deals with the coexistence of a Geostationary (GEO) Fixed Satellite Service (FSS) downlink with terrestrial Fixed Service (FS) links operating in the Ka band (17.7-19.7 GHZ). In the considered scenario, the incumbent (primary) and cognitive (secondary) links are FS link and FSS downlink, respectively. First, we identify various challenges and discuss several possible solutions for allowing this coexistence. And then we propose several sensing and avoidance schemes in order to separate the intended FSS signal from the interfering FS signal at the cognitive satellite terminal. The various schemes proposed in this paper are: (i) individual signal processing, (ii) joint signal processing, (iii) Rise over Thermal (RoT) measurement, and (iv) exploitation of pilot signals. Further, we discuss implementation aspects of these schemes from practical perspectives. Finally, we evaluate the performance of one of the considered solutions with the help of theoretical and numerical analysis.

The remainder of this paper is structured as follows. Section II describes the considered scenario in detail, and discusses important challenges and possible solutions. Section III proposes several sensing and avoidance techniques, and further discusses their implementation issues. Section IV evaluates the performance of one of the proposed solutions with the help of numerical results. Finally, Section V concludes the paper.

## II. SCENARIO AND PROBLEM DESCRIPTION

As mentioned before, we consider a spectral coexistence scenario of a GEO FSS satellite downlink and a terrestrial FS link both operating in the Ka-band ($17.7-19.7$ GHz) as shown in Fig. 1. In this scenario, the downlink interference from the cognitive satellite to the FS links is taken into account by system planning and can be kept below the defined regulatory limitations in terms of the maximum power flux-density (pfd) at the earth's surface [12]. However, the interference from FS transmitters to the cognitive satellite terminal needs to be taken into account in order to guarantee sufficient Quality of Service (QoS) of the cognitive users [4].

In star networks over the satellite (in DVB-S2 and DVB-SX standards), the link from a central hub station to the terminals employs Adaptive Coding and Modulation (ACM) in order to adapt the transmission modulation and coding to the terminal's Signal to Interference plus Noise Ratio (SINR) [13]. Depending on the link setup, the rain fading at the location of the FSS terminals may affect both the carrier as well as the FS interference level at the FSS receiver input with different magnitudes. We can define this margin as the amount the carrier power can be decreased (faded) to reach a specific threshold level of the used modulation and coding. This margin parameter is consequently systematically underestimated in case the interference could not be distinguished from the noise level at the FSS receiver input. This would be the case if we could not detect and estimate the interference received from the terrestrial FS links. The detection and estimation of the FS interference is however feasible in principle and investigated in the context of this paper. Within this work, we consider the problem of detecting the FS link interference presence at the FSS receiver input and compute the performance of a practical detector. The main principle of a sense and avoidance scheme considered in this paper is that the cognitive satellite terminal attempts to detect the harmful FS signal using different sensing techniques, and based on the result, it tries to avoid using active harmful FS carriers. In other words, the FSS terminal tries to avoid activity in the bands where the interference received from the FS transmitters exceeds a predetermined threshold.

The main challenges for implementing SS in the considered scenario are to detect the weak levels of the FS interference, and to define an appropriate sensing threshold in order to decide whether a harmful FS carrier is present or not. Since all the FS transmissions are not harmful to the FSS terminal, we define the harmful FS carrier as the active FS carrier which affects the normal operation of the FSS terminal by creating interference above its interference tolerance threshold. In the existing SS literature, the commonly used assumption is that all the cognitive users are silent during the period of sensing and the sensor receives only incumbent users' signal during the sensing interval. Unlike the above assumption, the FSS cognitive terminal under the considered scenario receives downlink transmission from its satellite beam as well as the FS transmission simultaneously. In this context, the main challenge is how to detect the presence of an incumbent signal from the received signal which can be a combination of the desired signal (FSS downlink signal), interference signal (transmit signal from the FS transmitter), and the receiver thermal noise.

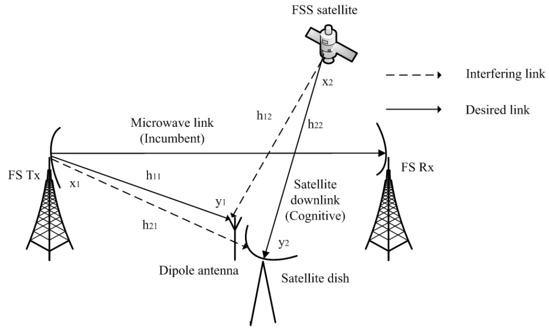

Fig. 1: Front end of satellite terminal with additional dipole antenna and corresponding desired/interfering links

To address the above issues, we can exploit the use of an additional Radio Frequency (RF) chain with a dipole antenna having a donut shaped gain pattern across the horizon in addition to the existing satellite dish antenna. The difference between two antennas is that the dish antenna used for receiving a satellite signal is directed towards the satellite and the additional dipole antenna can be dedicated for detecting the FS signal coming from the horizontal direction. Based on ITU-R S.456, the dish antenna receiving gain towards the horizon varies from 7 to $-6.6$ dB while considering GEO satellite terminals located in European continent with $10^\circ$ to $35^\circ$ elevation angles. Since a purely omnidirectional antenna is not practically realizable, we consider a half wave dipole antenna which has gain of 2.15 dB [14]. Other options can be (i) a rotating horn antenna, (ii) a Uniform Linear Array (ULA) with electronic steering, (iii) a 4/6 horn circular detector looking over the horizon, and (iv) several detectors on the back of the reflector. However, these options are quite costly in comparison to the inclusion of a dipole antenna.

In the above context, we assume that the cognitive satellite terminal is equipped with a dipole antenna, which is dedicated for the sensing purpose as depicted in Fig. 1. Let $x_1$(t) be the signal transmitted by the FS transmitter at time instant $t$ and $x_2$(t) be the signal transmitted by the FSS satellite. Further, let $h_{11}$ denote the channel gain from the FS transmitter towards the dipole antenna, $h_{21}$ be the channel gain from the FS transmitter towards the dish antenna, $h_{12}$ be the channel gain from the FSS satellite towards the dipole antenna and the $h_{22}$ as the channel gain from the FSS satellite towards the dish antenna. It can be noted that these channel gains depend on the gains of the transmit and receive antennas and the path loss of the corresponding link. It should be noted that from the view of detecting the harmful FS signal, Line of Sight (LoS) path between the FS transmitter and the dipole antenna is the worst-case and we do not consider the effects of rain fading and shadowing in this paper. Since these effects further reduce the interference level, the LoS model is the worst-case.

As depicted in Fig. 1, the dipole antenna receives two signals: one signal from the FS transmitter and another one from the FSS downlink transmission. Since the purpose of this antenna is to sense the FS transmission, the signal received from the FS transmitter is the desired one, and the signal received from the FSS transmission is the interfering one. Similarly, the satellite dish receives two signals: the desired signal from the FSS satellite and the interfering signal from the FS transmitter. In the aforementioned scenario, different individual or joint signal processing techniques can be applied in order to separate the intended signal from the FS interfering signal.

## III. APPLICABLE SENSING AND AVOIDANCE TECHNIQUES

### A. Individual Signal Processing

In this method, two RF chains of the cognitive satellite terminal process the received signals separately. The RF chain with the dipole antenna is responsible for sensing the presence of the FS signal. Basically, this process detects the power level received by the dipole antenna and applies the decision threshold in order to decide the presence or absence of the FS signal. Let $H_0$ denote the hypothesis for the absence of the FS harmful transmission and $H_1$ denote the hypothesis for the presence of the FS harmful transmission, then the binary hypothesis testing problem for detecting the presence of the FS signal can be written as

$$\begin{aligned} H_0 : y_1(n) &= h_{12}x_2(n) + z(n) \text{ FS absent} \\ H_1 : y_1(n) &= h_{11}x_1(n) + h_{12}x_2(n) + z(n) \text{ FS present}, \end{aligned} \quad (1)$$

where $z(n)$ is Additive White Gaussian Noise (AWGN) at the dipole receive chain. In order to test the above hypothesis, we need to find a decision statistic whose distribution sufficiently differs under the $H_0$ and the $H_1$ hypotheses. If the energy of the FSS received signal at the dipole antenna remains more or less the same and is known by performing link budget analysis, then the sensing threshold can be solely based on the distribution of the noise energy. Subsequently, the sensing threshold calculated from the distribution of the noise energy can be scaled based on the known value of the FSS received signal level. In the above hypothesis testing problem, if the hypothesis $H_0$ is satisfied, then it can be decided that the FS signal over a certain band is absent and then the FSS system can use this band in the secondary basis. Whereas, if the hypothesis $H_1$ is satisfied, the decision is the presence of the FS signal and the FSS transmission should be switched to another band. In case, other bands in the FS specific allocated band are not available or their quality is not better enough, the FSS transmission should be moved to the exclusive band. These decisions are to be taken centrally by the satellite network management system based on the feedback it receives by the terminals.

In the FS link detection problem considered in this paper, we treat the FSS signal as the noise. This is due to the fact that the FSS received signal at the dipole antenna is well below the harmful FS signal corresponding to the Interference to Noise ($I/N$) target of $-10$ dB as well as the noise level at the dipole antenna as verified by numerical analysis in Section IV. In this case, (1) reduces to the following conventional hypothesis testing problem

$$\begin{aligned} H_0 : y_1(n) &= z(n) \text{ FS absent} \\ H_1 : y_1(n) &= h_{11}x_1(n) + z(n) \text{ FS present}. \end{aligned} \quad (2)$$

In the following subsection, we apply an Energy Detection (ED) technique in order to solve the above binary hypothesis problem (2).

The sensing of the harmful FS transmission can be done either in the DVB-S2 receive chain or in the dipole chain. The main differences between these two approaches are: (i) sensing with the satellite dish requires to detect low Signal to Noise Ratio (SNR) i.e., $-10$ dB for $I/N$ target of $-10$ dB whereas the dipole antenna receives better SNR as illustrated in Section IV, (ii) sensing with the satellite dish requires the cancelation of the DVB-S2 signal before deciding the presence or absence of the FS signal whereas the DVB-S2 signal is negligible in comparison to the harmful FS interference while sensing with the dipole (illustrated in Section IV).

*1) ED based detection for dipole chain:* In this section, we provide theoretical expressions for probability of false alarm ($\mathcal{P}_f$) and probability of detection ($\mathcal{P}_d$) for the ED based sensing in the considered scenario. Let us consider that the transmitted FS signal $x(n)$ is an independent and identically distributed (i.i.d.) Gaussian random process with mean zero and variance $\mathbb{E}[x(n)]^2 = \sigma_x^2$ and the noise $z(n)$ is a Gaussian i.i.d. random process with zero mean and variance $\mathbb{E}[z(n)]^2 = \sigma_z^2$. Furthermore, we assume that the incumbent FS signal $x(n)$ is independent from the noise $z(n)$. Let $\tau$ be the sensing time and $N$ be the number of samples collected within this duration i.e., $N = \lceil \tau \rceil f_s$. The test statistic for the ED technique is given by $T = \frac{1}{N}\sum_{n=1}^{N}|y(n)|^2$. It can be noted that the test statistic $T$ is a random variable and under the $H_0$ hypothesis, for very large values of $N$, the Probability Density Function (PDF) of $T$ can be approximated by a Gaussian distribution with mean $\mu = \sigma_z^2$ and variance $\sigma_0^2 = \frac{1}{N}[\mathbb{E}[z(n)]^4 - \sigma_z^2]$ [15]. Using binary hypothesis testing, the expressions for $\mathcal{P}_f$ and $\mathcal{P}_d$ can be computed by

$$\begin{aligned} \mathcal{P}_f &= \Pr(T > \lambda_{th}|H_0), \\ \mathcal{P}_d &= \Pr(T > \lambda_{th}|H_1). \end{aligned} \quad (3)$$

where $\lambda_{th}$ is the sensing threshold. For Circularly Symmetric Complex Gaussian (CSCG) noise case, the expression for $\mathcal{P}_f$ can be written as [15]

$$\mathcal{P}_f(\lambda_{th}, \tau) = Q\left(\left(\frac{\lambda_{th}}{\sigma_z^2} - 1\right)\sqrt{\tau f_s}\right), \quad (4)$$

where $Q(.)$ is the complementary distribution function of the standard Gaussian random variable, given by $Q(x) = \frac{1}{\sqrt{2\pi}}\int_x^\infty \exp(\frac{-t^2}{2})dt$. Similarly, under the $H_1$ hypothesis, the expression for $\mathcal{P}_d$ is given by

$$\mathcal{P}_d(\lambda_{th},\tau) = Q\left(\left(\lambda_{th}/\sigma_z^2 - \gamma_{\mathrm{FS}} - 1\right)\sqrt{\frac{\tau f_s}{2\gamma_{\mathrm{FS}}+1}}\right), \quad (5)$$

where $\gamma_{FS}$ is the received SNR of the incumbent signal measured at the dipole chain, which can be written as $\gamma_{FS} = P_r/\sigma_z^2$, where $P_r$ is the received power at the dipole antenna, given by $P_r = P_t G_t(\theta) G_r \left(\frac{\lambda}{4\pi d}\right)^2$, where $P_t$ is the FS transmit power, $\theta$ is the offset angle (from the boresight direction) of the FS transmitting antenna in the direction of satellite terminal and $G_t(\theta)$ is the corresponding gain, $G_r$ is the fixed gain of the dipole antenna, $\lambda$ is the wavelength, $d$ is the distance between FS transmitter and the satellite terminal. It should be noted that we have used a free space path loss model in order to model the path loss of the link between the FS transmitter and dipole antenna. However, any practical path loss models can be easily applied under the considered framework.

Let $\bar{\mathcal{P}}_f$ be the target $\mathcal{P}_f$ and $\bar{\mathcal{P}}_d$ be the target $\mathcal{P}_d$. Then combining (4) and (5), $\mathcal{P}_d$ is related to $\bar{\mathcal{P}}_f$ as follows

$$\mathcal{P}_d = Q\left(\frac{1}{\sqrt{2\gamma_{\mathrm{FS}}+1}}(Q^{-1}(\bar{\mathcal{P}}_f) - \sqrt{\tau f_s}\gamma_{\mathrm{FS}})\right). \quad (6)$$

Using the above expressions, for a given pair of target false alarm and detection probabilities ($\bar{P}_f$,$\bar{P}_d$), the minimum number of samples required to achieve these targets can be determined using the following relation

$$N_{\min} = \frac{1}{\gamma_{FS}^2}[Q^{-1}(\bar{P}_f) - Q^{-1}(\bar{P}_d)\sqrt{2\gamma_{\mathrm{FS}}+1}]^2. \quad (7)$$

In the above analysis, it is assumed that the noise variance is perfectly known to the detector. However, in practice, the noise is neither perfectly Gaussian, perfectly white, nor perfectly stationary. Therefore, the noise variance in practice has to be estimated by using a proper noise calibration method. The noise calibration can be done either during the manufacturing process or by carrying out on-site Out of Bands (OoB) measurements. Another option for noise calibration is to use in-band measurements at the frequencies where the pilot is absent so that the noise statistics can be calibrated at the pilot frequencies [17]. Further, in the considered FS detection problem, the noise variance can also be estimated by carrying out sequential measurements over the band of interest if we know the spectrum grids used by the terrestrial links.

In [16], it has been shown that it's not possible to achieve the robust detection performance beyond a certain SNR value even by increasing the sensing duration in the presence of noise variance uncertainty. The distributional uncertainty of the noise can be represented with a interval $\sigma^2 \in [(1/\rho)\sigma_z^2, \rho\sigma_z^2]$, where $\sigma_z^2$ is the nominal noise power and the parameter $\rho > 1$ indicates the uncertainty level. Following the procedure in [16], to achieve target $\mathcal{P}_f$ and $\mathcal{P}_d$ robustly for the considered CSCG noise case, (4) and (5) in the presence of noise uncertainty can be written as

$$\mathcal{P}_f(\lambda_{th},\tau) = Q\left(\left(\frac{\lambda_{th}}{\rho\sigma_z^2} - 1\right)\sqrt{\tau f_s}\right). \quad (8)$$

$$\mathcal{P}_d(\lambda_{th},\tau) = Q\left(\left(\frac{\lambda_{th}}{\frac{1}{\rho}\sigma_z^2} - \gamma_{\mathrm{FS}} - 1\right)\sqrt{\frac{\tau f_s}{2\gamma_{\mathrm{FS}}+1}}\right). \quad (9)$$

The minimum number of samples required to achieve target $\bar{\mathcal{P}}_d$ and target $\bar{\mathcal{P}}_d$ in presence of noise variance uncertainty can be obtained after eliminating $\lambda_{th}$ from (8) and (9), given by

$$N_{\mathrm{min1}} = \frac{[Q^{-1}(\bar{P}_f) - Q^{-1}(\bar{P}_d)\sqrt{2\gamma_{\mathrm{FS}}+1}]^2}{[\gamma_{FS} - (\rho - \frac{1}{\rho})]^2}. \quad (10)$$

By assuming $2\gamma_{\mathrm{FS}} + 1 \approx 1$ for low SNR values in (10), it can be noted that $N \to \infty$ as $\gamma_{FS}$ decreases with the value of $\rho$. This particular value of SNR is called as SNR wall [16] and it reflects that the ED can not robustly detect the signal if $\gamma_{FS} \leq (\rho - \frac{1}{\rho})\sigma_z^2$. Furthermore, the value of SNR equal to $\frac{\rho^2-1}{\rho}$ is SNR wall of an energy detector. In Section IV, we provide numerical results on the performance of the ED technique for the considered FS signal detection problem.

*2) Cyclostationary Detection:* Ideally, the noise estimation can be perfect, however, in practice, accurate estimation of the noise variance is not possible, and this limits the performance of the ED at low SNRs. One of the strong techniques which is proposed in order to tackle the problem of noise uncertainty is Cyclostationary Detection (CD). The CD exploits the underlying cyclostationarity properties of the intended signal in order to identify this signal which is contaminated with noise or possibly other types of signal with different properties. Cyclostationarity means that the statistical properties of the signal such as the mean and autocorrelation are periodic over time [18]. Cyclostationarity may be caused by modulation or coding, or it may be intentionally produced to help channel estimation and equalization. Most of the wireless signals have cyclostationary properties. In our case, the cyclostationarity exists in the received FS signal due to employed linear modulation by the FS links. In the literature, plenty of techniques are developed to identify the linear modulation used in a signal based on cyclostationarity [19, 20]. We may use these techniques in order to see if a specific type of signal exists in the received samples at the dipole antenna. In case the exact modulation used in the FS link is known a priori, this information can be used to detect this specific modulation. Therefore, the underlying hypothesis testing problem becomes as follows

$$\begin{aligned} H_0 &: \mathcal{M} = 0, \\ H_1 &: \mathcal{M} = 1, \end{aligned} \quad (11)$$

where $\mathcal{M}$ denotes the existence of a specific modulation, with 0 and 1 indicating the respective absence or presence of the modulation, and thus the absence or presence of the FS link. It has been shown that CD has a much lower SNR wall than the ED, and particularly is reliable for low SNRs. However, note that we might end up detecting the FS link in a very low SNR which is not necessarily harmful to the FSS, and thus loose the opportunity of the carrier access. One possible solution for this issue is to first obtain a rough estimate of the FS SNR at the dipole antenna, and then perform CD if the

SNR is below a specific threshold. Such techniques known as two-stage SS [23] have been considered in the context of terrestrial CR which can be applied in this scenario as well.

### *B. Joint Signal processing*

This technique involves the joint processing on the signals received by the dipole and the dish antennas. For this purpose, suitable signal processing techniques such as receive beamforming can be investigated to remove the effect of FS cochannel interference on the desired FSS downlink signal. Depending on whether the knowledge of the Direction of Arrival (DoA) of FS transmitter is available or not, different techniques can be applied. The DoA information of the FSS satellite is available to the satellite terminal, and if the DoA information of the FS transmitter is also known, then angular beamforming approaches such as Linearly Constrained Minimum Variance (LCMV), and Minimum Variance Distortionless Response (MVDR) can be applied [21, 22]. If the DoA information of the FS transmitter is not available to the FSS terminal, purely SNR based techniques need to be investigated.

The signals $y_1 = h_{11}x_1 + h_{12}x_2 + z_1$ and $y_2 = h_{21}x_1 + h_{22}x_2 + z_2$ received by the dipole and the dish antenna can be written in the following joint form

$$\begin{bmatrix} y_1 \\ y_2 \end{bmatrix} = \begin{bmatrix} h_{11} & h_{12} \\ h_{21} & h_{22} \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} + \begin{bmatrix} z_1 \\ z_2 \end{bmatrix}. \qquad (12)$$

The above equation can also be written in the following form

$$\mathbf{y} = \mathbf{H}\mathbf{x} + \mathbf{z}. \qquad (13)$$

The objectives of the designed beamformer or receiving filter are to maximize the contribution of desired FSS signal i.e., $x_2$ and to minimize the contribution of the interfering FS signal i.e., $x_1$ in the total received signal. In this context, the research problem is the design of a suitable receive filter $\mathbf{W}$. The output of this filter can be written as $\mathbf{y_f} = \mathbf{W}\mathbf{y} = \mathbf{W}(\mathbf{H}\mathbf{x} + \mathbf{z})$.

Furthermore, dipole and directional antennas equipped in the FSS terminal receive two signals of different strengths. In this context, another issue is how to address the antenna generated power imbalance and the effect of it in designing the receive beamformer. If this power imbalance is too strong i.e., the off-diagonal components of the matrix $\mathbf{H}$ are very small, the best option is to go for individual signal processing instead of joint signal processing. The joint signal processing may not provide any additional benefit in this context. However, if any of the off-diagonal element of $\mathbf{H}$ is strong enough (usually $h_{21}$ in the above context), we can exploit the joint signal processing techniques in order to enhance the detection performance. Depending on the range of the power imbalance, different linear filters can be applied. The commonly used linear filters in the literature are (i) Zero Forcing (ZF), (ii) Matched Filter, and (iii) Minimum Mean Square Error (MMSE) filter [27]. All of these filters require the channel knowledge of all links. However, in practice, we only have the DVB-S2 link channel. If all the elements of $\mathbf{H}$ are equally strong, then the ZF filter can be applied. Actually this is not the practical case since off-diagonal elements are generally weaker than the diagonal components of $\mathbf{H}$. If both the diagonal components are weaker, the matched filter can be the optimal solution. Whereas, if one off-diagonal element is stronger in comparison to another off-diagonal element, which is most probably the case, then a MMSE filter can be the optimal solution. In the above context, it is an open research problem to analyze the effect of power imbalance on the performance of different filters.

### *C. Rise Over Thermal Measurement*

Rise of Thermal (RoT) can be an effective technique to define the sensing threshold. In the considered FSS-FS coexistence scenario, this metric specifies the ratio of interference received by the satellite dish to the receiver noise power $(I/N)$. In other words, this metric indicates how much is the level of the FS interference on top of the thermal noise level over the considered band of interest. Since the received power level and the thermal power floor vary with time, it's extremely important to measure the noise floor accurately. In wireless communication literature, RoT metric has been used as a measure of the cell load, which indicates the ratio between the total interference received at a radio station and the thermal noise [24].

Considering that the worst-case maximum allowable interference at the FSS terminal is 6 % above the noise floor [29], the decision on the presence or absence of the FS signal can be taken based on the measured value of the RoT. If the quality of the satellite link i.e., carrier to noise ratio (C/N) is known beforehand, then this threshold can be set higher in such a way that the desired SINR is maintained at the receiver. Therefore, the dynamic threshold assignment can be determined by employing the minimum required SINR at the FSS terminal, and the FSS link budget. In case, this information is not available, we can use a detector which can reliably detect the interference level of 6% above the noise floor. If the FS and the FSS links use different carrier bandwidths, the FSS satellite terminal can acquire the RoT value by carrying out sequential measurement of thermal noise over different sub-bands within the considered band of interest. However, the RoT measurement becomes difficult if the DVB-S2 signal is received at the same time.

### *D. Exploitation of Pilot Signal*

If we consider the frame structure of DVB-S2 standard, it employs pilot symbols in its transmission [28]. The knowledge of pilot symbols can be exploited as an additional information in order to sense the FS signal using joint processing. If the pilot signal is known to the terminal, it can be removed from the total received signal and the remaining signal can be used for detection of the FS signal. This can be done either in the signal level or in the power level. In the context of a terrestrial CR, several contributions have investigated the exploitation of pilot signals for SS purpose [25, 26]. The main principle used in these contributions is that the incumbent transmitter sends a pilot signal simultaneously with data, and the sensing receiver can perform its coherent processing assuming the perfect knowledge of the pilot signals. The same principle can be exploited while detecting satellite transmission with pilot signals. However, in the considered scenario, the objective is different since we are interested in detecting FS signal by assuming the perfect knowledge of the FSS pilot signals. In this case, the pilot signals are helpful in order to remove the part of the FSS signal from the combined received signal, which is the combination of the FSS signal, FS signal and the thermal noise. Subsequently, based on the remaining signal, a simple ED technique can be applied in order to decide the presence or absence of the FS signal. It should be noted that the sensing should be done during the period of FSS pilot transmission and a proper synchronization is necessary at the satellite terminal [28]. Furthermore, it remains an open challenge to exploit other pilot assisted sense and avoid schemes in the considered coexistence scenario.

While using the cancelation method for the DVB-S2 signal, we should be careful in canceling the proper signal energy from the total energy of the received signal. Since due to the variation in the propagation channel, the power level may vary over the time. The imperfect cancelation of DVB-S2 signal may cause degradation in the sensing performance. In this context, it's crucial to identify the effect of imperfect cancelation of DVB-S2 signal on the sensing performance.

## IV. NUMERICAL RESULTS

In this section, we provide sensing performance of the ED-based sensing and avoidance scheme in the considered scenario. It should be noted that the considered ED technique also works even if the received bandwidth of the FSS terminal (and detection bandwidth) is smaller than the FS link bandwidth, which can be the case for wideband FS links. While analyzing the detector sensitivity, we can use the worst-case condition considering the lowest possible Effective Isotropic Radiated Power (EIRP) of the FS transmitting antenna. Whereas, while analyzing the interference effect on the FSS terminal, we need to consider the highest possible EIRP value of the FS transmitter. In our results, we consider that the FSS signal received by a dipole antenna is well below the noise level at the dipole chain as well as the received harmful FS signal level corresponding to the $I/N$ target of $-10$ dB at the satellite dish. For example, using the link budget parameters specified in Table I, the harmful interference power threshold at the dipole chain is $-146.6$ dBW/MHz and the received FSS satellite signal level at the dipole chain corresponding to the maximum transmit power is $-151.8$ dBW/MHz which is 9.8 dB below the dipole chain noise level of $-142$ dBW/MHz and 5.2 dB below the harmful interference power threshold. It should be noted that this received FSS level further reduces when considering fading and atmospheric effects in the FSS downlink channel. From Table I, based on ITU-R F.758-5 and ITU-R F.699, the worst-case EIRP and the maximum possible EIRP for FS transmission are found to be $-44.79$ dBW and 36.29 dBW respectively.

TABLE I: Simulation and link budget parameters

| Parameter | Value |
|---|---|
| Carrier frequency | 18 GHz |
| *Parameters for FS Tx* | |
| Tx output range | -37 to -3.0 dBW (ITU-R F.758-5) |
| Feeder loss range | 0 to 2 dB (ITU-R F.758-5) |
| Antenna Radiation Pattern | ITU-R F.699-7 |
| Antenna diameter | 0.6 m |
| Lowest possible gain | -5.79 dBi |
| Lowest EIRP | -44.79 dBW |
| Maximum gain | 39.29 dBi |
| Maximum EIRP | 36.29 dBW |
| FS carrier Bandwidth | 5 MHz |
| *Parameters for dipole chain* | |
| Antenna type | Half wave dipole |
| Antenna Gain | 2.15 dB |
| Sampling Rate | 10 MHz |
| Rx Noise Temperature | 460 K |
| Noise power at dipole Rx | -142 dBW/MHz |
| *Parameters for DVB-S2 chain* | |
| FSS carrier BW | 27 MHz |
| FSS ES antenna | 42.1 dBi |
| Rx Noise temperature | 262 K |
| Noise power | -143.4 dBW/MHz |
| I/N target at dish | -10 dB |
| Interference Threshold | -153.4 dBW/MHz |
| Maximum rx antenna gain | 42.1 dBi |
| Antenna Radiation pattern | ITU-R S.456 |
| Antenna diameter | 0.75 m |
| FSS site height | 100 m |
| Terminal location | 49.68° N, 6.35° E |
| *Parameters for FSS satellite* | |
| GEO satellite location | 28.2° E |
| Satellite Altitude | 35786 km |
| Tx power @saturation | 80 W |
| Max. antenna gain | 50 dBi |
| Path loss to terminal | -208.67 dB |

Since we are interested in protecting the FSS terminal from the FS harmful interference, the hypothesis testing problem (2) while considering the $I/N$ threshold of $-10$ dB at the DVB-S2 receive chain can be written as

$$\begin{aligned} H_0 &: I \leq -10dB + N \text{ harmful FS absent}, \\ H_1 &: I > -10dB + N \text{ harmful FS present}, \end{aligned} \tag{14}$$

where $N$ denotes the receiver noise power in dBW over the considered bandwidth. In our detection problem, the FS interference level greater than $-10dB+N$ i.e., $I > -10dB+N$ should be successfully detected.

Figure 2 shows the performance of the ED-based sensing in the considered scenario in terms of Receiver Operating Characteristic (ROC) curves ($\tau = 2$ ms, $d = 1$ km). In this result, we have considered different lower values of EIRPs including the worst-case EIRP ($-45$ dBW). From the figure, it can be noted that the $P_d$ increases with the increase in the value of $P_f$ and better detection is achieved for higher values of FS EIRPs. The theoretical results plotted in Fig. 2 were obtained using (6). To evaluate the sensing performance with respect to the distance between FSS terminal and FS Tx, we plot $P_d$ versus distance between FS terminal and the FSS terminal in Fig. 3 with parameters ($\tau = 2$ ms, $P_f = 0.01$). From the figure, it can be noted that the value of $P_d$ decreases with the increase in the distance. Furthermore, the sensing performance increases with the increase in the value of FS EIRP. In order to evaluate the level of FS interference on the satellite terminal, we consider a Ka band FSS link with a satellite terminal situated in Betzdorf, Luxembourg (49.68° N, 6.35° E) communicating with the SES ASTRA 2D GEO satellite located at 28.2° E. The elevation angle of the considered terminal is found to be 29.36°. As stated earlier, we can follow the worst-case approach to find the offset angle of the FSS receiving antenna in the direction of the FS transmitter. For the elevation angle of 29.36° in the

TABLE II: Sensing time calculation for ED detector

| **Parameter** | **Value** |
|---|---|
| I/N target at the dish (FSS Rx LNB input) | -10 dB |
| FSS carrier bandwidth | 27 MHz |
| Rx noise temperature at the dish (FSS LNB I/P) | 262 K |
| Link noise contribution | 1 dB |
| Noise power (N) at the dish (LNB input) | -143.4 dBW/MHz |
| Interference threshold at the dish (LNB input) | -153.4 dBW/MHz |
| Received power threshold at dipole ($P_r$) | -146.6 dBW/MHz |
| Rx noise temperature at dipole (LNB input) | 460 K |
| FS carrier bandwidth | 5 MHz |
| Noise Power at dipole chain (LNB input) ($N_o$) | -142 dBW/MHz |
| $\gamma_{FS} = P_r/N_o$ threshold at dipole | $-4.59$ dB |
| Target probability of detection | 0.9 |
| Target probability of false alarm | 0.01 |
| Minimum number of samples $N_{\min}$ | $132.13 \approx 132$ |
| Sampling rate at dipole chain $f_s$ | 10 MHz |
| Sensing time $\tau = N_{\min}/fs$ | 0.0132 ms |

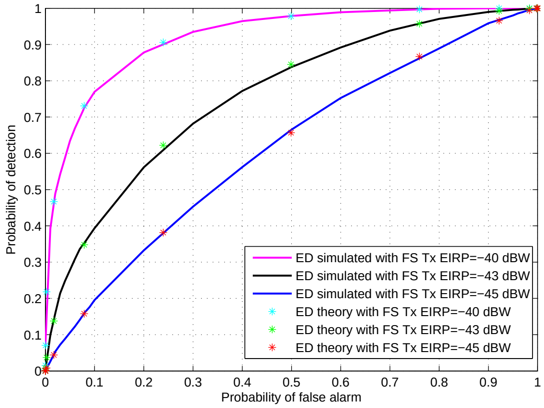

Fig. 2: Probability of detection versus probability of false alarm ($\tau = 2$ ms, $d = 1$ km)

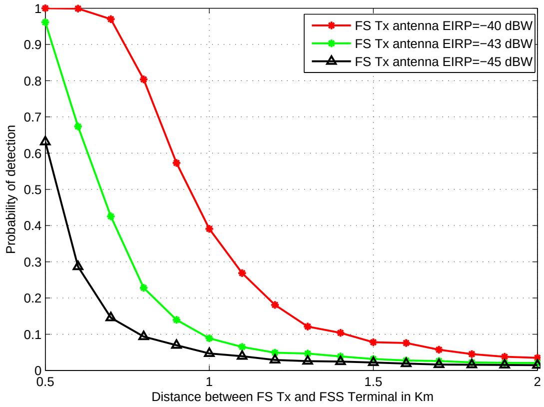

Fig. 3: Probability of detection versus distance between FS Tx and FSS terminal ($\tau = 2$ ms, $P_f = 0.01$)

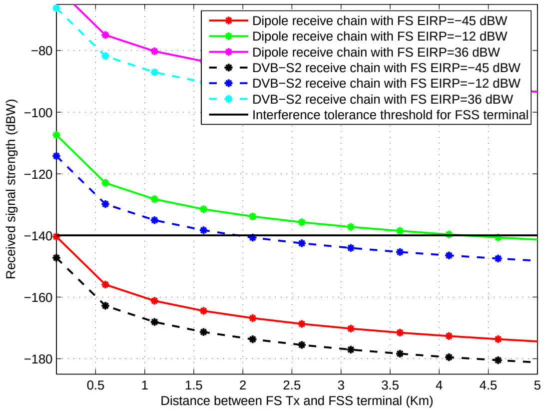

Fig. 4: Total signal strengths received by dipole and DVB-S2 chains for different EIRP values

considered use case, the gain of FSS receiving antenna in the direction of the FS transmission is equal to $-4.69$ dB, based on ITU-R S.456. The received power level detected by the dipole antenna can be converted to the interference strength received by the dish antenna in the following way. Interference level picked up by satellite dish antenna (dBW)=signal strength detected by the dipole antenna (dBW) $-2.15$ dB+Gain of the FSS antenna towards the FS transmitter (dB). Figure 4 depicts the signal strengths received by the dipole and satellite dish antennas for different values of FS transmit EIRP. From the figure, it can be noted that for the highest value of FS EIRP (36 dBW), the interference level picked up by the satellite dish antenna is well above the interference threshold and the use of shared spectrum band is not possible (even for very large separation distances) in this scenario. Furthermore, for the lowest EIRP value ($-45$ dBW), the interference level picked up by the satellite dish is well below the interference threshold and the sharing is feasible (even for very small separation distances). For the EIRP value of $-12$ dBW, it can be observed that the received interference level exceeds the interference threshold for separation distances less than 1 km. However, for the separation distances above 2 km, the received interference level is less than the interference threshold and frequency sharing between FSS downlink and FS link is possible. Therefore, it can be concluded that there exists a range of EIRP values of FS transmission for which frequency sharing is possible between FSS downlink and the FS link.

In Table II, we present calculations for obtaining sensing time for the ED technique considering the $I/N$ target of $-10$ dB at the DVB-S2 chain of the satellite terminal. It can be noted that the minimum number of samples required to satisfy the constraints of $P_f = 0.01$, $P_d = 0.9$ and $I/N$ target of -10 dB is around 5. Furthermore, considering the sampling rate of 10 MHz at the dipole chain, the sensing time comes to be 0.0132 ms as depicted in Table II. To analyze the effect of noise uncertainty in the considered problem, we consider the noise uncertainty range from 0 dB to 2 dB and evaluate the detection performance using the analysis presented in Section III-A. Figure 5 analyzes the sample complexity (in terms of $\log_{10}(N)$) of the ED technique with the noise uncertainty level for different $I/N$ target values at the DVB-S2 receive chain. Furthermore, we present the results of dipole sensing and dish sensing for the considered target values of $I/N$. From the figure, it can be noted that with dipole sensing, the number of samples for $I/N$ target values of $-10$ dB and $-6$ dB are practically feasible and there occurs no SNR wall problem for the considered noise uncertainty range. If we want to guarantee the $I/N = -12$ dB, the detector faces the SNR wall problem at 1.6 dB noise uncertainty value even with the dipole sensing. However, for the single interferer case, the $I/N$ value of $-10$ dB is quite practical and the dipole sensing provides the desired performance with realizable number of samples. Moreover, if we look at the dish sensing part, SNR wall problem occurs for all the $I/N$ target values within the considered noise uncertainty zone. From this result, it can

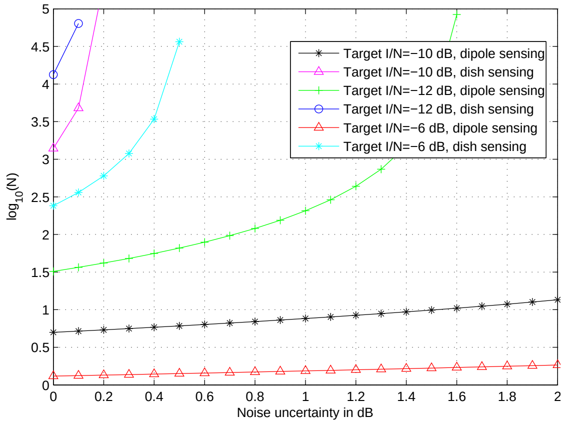

Fig. 5: Number of samples required versus noise uncertainty while using the ED technique (target $P_d = 0.9$, target $P_f = 0.01$)

be noted that the dipole sensing performs well in terms of sensing the FS signal while maintaining the desired $I/N$ target whereas the dish sensing fails within the considered noise uncertainty zone. Furthermore, in practice, another option to mitigate the harmful FS interference detection problem is to use other sensing antennas such as a higher gain antenna that has sufficient gain over the horizon to achieve a practical detection, for example a design with a ring of waveguide horns or a circular arrangement of dipoles in an array.

## V. CONCLUSION AND FUTURE WORK

The spectral coexistence of satellite and terrestrial networks enhances the overall spectral efficiency of the satellite systems by allowing them to use the terrestrial spectrum in the shared basis. In this paper, various sensing and avoidance schemes such as individual signal processing, joint signal processing, RoT measurement, and the exploitation of pilot signals have been proposed for allowing the coexistence of FSS downlink with the terrestrial FS links. The harmful FS signal detection problem has been studied using an energy detector with the help of an additional RF chain equipped with a dipole antenna. From the results, it can be concluded that the FS harmful interference can be reliably detected with the help of an additional dipole antenna equipped in the satellite terminal. Furthermore, it has been shown that this solution can overcome the noise uncertainty problem which arises while sensing with the satellite dish. In our future work, we plan to extend the current analysis to the scenario where multiple FS links coexist with the FSS downlink.

## ACKNOWLEDGEMENT

This work was partially supported by the EU FP7 project CoRaSat and by National Research Fund, Luxembourg under CORE projects CO$^2$SAT, SeMIGod and a PhD project (Reference 3069102).

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