KA-BAND SATELLITE TERRESTRIAL CO-EXISTENCE: A STATISTICAL MODELLING APPROACH

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Abstract

Cognitive radio (CR) is a potentially promising solution to the spectrum crunch problem that faces both future terrestrial and satellite systems. This paper discusses the applicability of CR in satellite/terrestrial spectrum sharing scenarios by modelling interference relations between these systems. It analyses the relative impact of several design parameters that can be tuned in order to reach a particular interference target. A realistic path loss model is considered and gain patterns of directional antennas are taken into account which are found to be efficient in minimising the interference. A generic model that is not restricted to particular systems is developed, and typical parameters are used to analyse the co-existence feasibility in a realistic sharing scenario. The results show that both satellite and terrestrial systems could potentially operate in the same band without degrading each other's performance if appropriate considerations are taken into account and an appropriate design of the interfering system is carried out.

1 Introduction

Nowadays, most of the allocated spectrum is inefficiently exploited by the licensed systems [1] and hence cognitive radio (CR) is becoming of increasing interest. CR is a smart radio that can gain knowledge of and adapt to its surrounding radio environment according to certain criteria and objectives. Dynamic spectrum access (DSA) is as a particular application of CR where terminals make use of CR techniques to access the spectrum dynamically, thus improving system performance and overall efficiency of spectrum utilisation. Depending on the spectrum sharing paradigm, DSA/CR allows secondary users (SU) to occupy either the same band as primary users (PU) or to transmit in portions left vacant by the PUs.

Interference relations between the PUs and the SUs are of great importance in analysing their co-existence feasibility. The authors of [2] analysed the interference generated by a terrestrial base station to a satellite terminal using free space propagation while [3] adopted a more realistic path loss model. Both [2] and [3] consider a single interferer without addressing the multiple interferers case. In contrast to satellite communications (SatComs) systems, most of the terrestrial work considers omnidirectional antennas and thus pointing directions of the antenna are ignored. Therefore, terrestrial models are not suitable for satellite/terrestrial frequency sharing scenarios and tailored models are required.

In this paper, we model the interference generated by a secondary (here named cognitive) satellite system to a primary (here named incumbent) terrestrial system in a realistic spectrum sharing scenario. We consider both single and multiple interferer scenarios whilst taking into account specific features of SatComs. The remainder of this paper is structured as follows: Section 2 describes the considered spectrum sharing scenario. In Section 3 we model the interference generated by a single interferer along with the path loss and gain patterns of directional antennas. Section 4 models the multiple interferers case and sets deployment constraints for the cognitive system based on the average aggregated interference and outage probability of the incumbent user (IU). Section 5 discusses numerical and simulation results obtained from the model while Section 6 concludes the paper.

2 Spectrum Sharing Scenario

Several satellite/terrestrial spectrum sharing scenarios have been identified in the FP7 European research project Cognitive Radio for Satellite communication (CoRaSat). The use of the terms primary and secondary may lead to some confusion since this terminology as used in the DSA/CR and ITU Radio Regulations (RR) contexts have slightly different meanings. In the DSA/CR context, a PU is the system that has priority to access the spectrum while a SU is a system that can access the spectrum when the PU is not making use of it and without causing interference to the PU. Whenever the PU accesses the spectrum and the operation of the SU would result in harmful interference, the SU must

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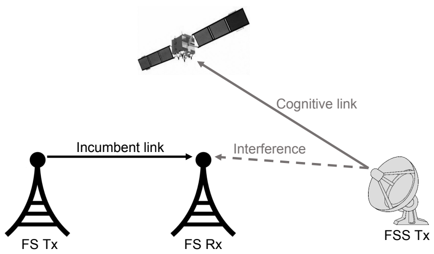


Figure 1: CoRaSat Ka-band uplink 27.5−29.5 GHz sharing scenario

vacate the spectrum. In the ITU RR parlance, PU (or IU) means the principal users in the bands. An IU can claim protection from harmful interference from any other systems that may be allowed to be present in the same spectrum. In this case secondary refers to the use of the band by other users who have to demonstrate non-interference with the IU. In some ITU bands, there is more than one primary listed e.g., fixed service (FS) and fixed satellite service (FSS). This is referred to as shared bands but really means that FS and FSS are both primary. In this paper, we follow the definitions used in the CoRaSat project i.e., we refer to the existing primary as IU and the new system as cognitive user (CU).

The CoRaSat project [4] identifies two Ka-band downlink scenarios (17.3−17.7 and 17.7−19.7 GHz) and one uplink scenario (27.5−29.5 GHz). The ITU allocations within these bands have an exclusive satellite portion but the remainder is shared between FS and FSS. However, CEPT definitions in Europe segment the band between FS and FSS and hence with current regulatory rules sharing could require a change to regulations. There are many FS links operating in this band, thus we consider the FSS terminals as the new or CU entrants with the FS links as the IU. Hence there are two downlinks in which the interference is from the terrestrial FS transmitter (Tx) into the satellite FSS receiver (Rx) and one uplink in which the interference is from the satellite FSS Tx into the terrestrial FS Rx. The CoRaSat project addresses all three scenarios but herein we just report on the uplink scenario as shown in Fig. 1.

3 Single Interferer Model

Satisfying quality of service (QoS) requirements of the incumbent FS system requires guaranteeing interference I to the IU less than a tolerable level I_{thr}. i.e.,

$$\text{Protection condition:} \quad I \leq I_{thr} \tag{1}$$

We consider only the long term interference which is usually taken as 6 or 10 dB below the Rx noise [5]. Several parameters can affect I such as the power supplied to FSS Tx antenna P_s, the path loss $PL(r)$ and antenna gain pattern of the FSS Tx towards the FS Rx $G_s(x_s)$ and vice versa $G_t(x_t)$.

$$I = P_s + G_s(x_s) - PL(r) + G_t(x_t) \qquad \text{[dBW]} \tag{2}$$

where r is the distance between the FSS Tx and the FS Rx, x_s is the off-boresight angle of the FSS Tx towards the FS Rx while x_t is the off-boresight angle of the FS Rx towards the FSS Tx. Throughout this section, the components of (2) are expressed in dB unless otherwise stated. Substituting (2) into (1) and rearranging the equation gives a higher bound for P_s whilst satisfying the protection condition of (1).

$$P_s \leq I_{thr} + PL(r) - G_s(x_s) - G_t(x_t) \qquad \text{[dBW]} \tag{3}$$

Terrestrial loss mechanisms have been identified in ITU-R P.452 [6] such diffraction loss L_d, clutter loss A_h and gaseous attenuations A_g in addition to other mechanisms applicable to over water and trans-horizon paths. Rain attenuation is another loss mechanism that enhances the FS Rx protection and provides additional room for increasing P_s. Nonetheless, rain is an occasional event and the interference power level at the FS Rx cannot be computed under the assumption that rain is present, since the interference threshold might be exceeded when rain is not present. Equation 4 gives the considered path loss model with f being the frequency of the FSS Tx signal in GHz and r in km [3], [6].

$$PL(r) = 92.5 + 20\,\log(f) + 20\,\log(r) + L_d + A_g + A_h \tag{4}$$

Diffraction loss is the dominant loss component under normal conditions beyond line of sight [6]. A full propagation model as defined in [6] is extremely complex. Thus herein we investigate an approximate model with sufficient accuracy to allow initial evaluation of the path loss. A single knife-edged obstacle at the middle of the distance between the FSS Tx and the FS Rx is assumed and L_d is estimated as [7]:

$$L_d = 6.9 + 20\,\log\left(\sqrt{(v-0.1)^2+1} + v - 0.1\right) \tag{5}$$

L_d is approximated by 0 for $v \leq -0.78$. The latter is a dimensionless parameter that has several forms depending on the available information. For the mid-point obstacle assumption, v can be written as:

$$v = \theta \cdot \sqrt{\frac{r \cdot 10^3}{2 \cdot \lambda}} \quad (6)$$

where λ is the wavelength of the FSS Tx signal in meters and θ is the diffraction angle in radians. On the other hand, the local ground clutter provides shielding protection that reduces I and allows increasing P_s safely. This loss is height dependent and it is modelled in [6] as a height gain function given by:

$$A_h = 10.25\,\mathrm{e}^{-d_k}\ (0.25 + 0.375\ (1 + \tanh(7.5\,[f - 0.5]))) \left(1 - \tanh\left(6\ \left[\frac{h}{h_a} - 0.625\right]\right)\right) - 0.33 \quad (7)$$

where d_k is the distance, in kilometres, from the nominal clutter point to the antenna, h is the antenna height above the local ground level in meters and h_a is the nominal clutter height above the local ground level in meters. We follow [3] and consider the worst case clutter category that provides the least loss (i.e., sparse houses, high crop fields and irregularly spaced sparse trees with $d_k = 0.1$ km and $h_a = 4$ m). On the other hand, the gaseous attenuation consists of dry air attenuation γ_0 and water vapour attenuation γ_w. ITU-R P.676 [8] provides a straightforward model to estimate this attenuation. With a default water vapour density of 7.5 $\mathrm{g/m}^3$ [6], Europe atmosphere profile, 28.5 GHz frequency and FS Rx height of 20 m [9], $A_g \approx 0.107 \cdot r$.

SatComs and point-to-point FS systems use highly directional antennas, thus pointing directions of such antennas should be taken into account to accurately estimate I and P_s. Gain patterns of these antennas depend on the off-boresight angles which can be estimated by [6]. This model requires knowledge of station location and considers the true north as a reference for azimuth angles. We consider the azimuth of each station w.r.t. the other station's location by slightly modifying the model without affecting the resultant off-boresight angles. Following the derivations in [6], x_s and x_t are given by:

$$x_s = \arccos\left(\cos(\varepsilon_s)\cos(\varepsilon_{ps})\cos(\alpha) + \sin(\varepsilon_s)\sin(\varepsilon_{ps})\right) \quad (8)$$

$$x_t = \arccos\left(\cos(\varepsilon_t)\cos(\varepsilon_{pt})\cos(\beta) + \sin(\varepsilon_t)\sin(\varepsilon_{pt})\right) \quad (9)$$

where α (β) is the azimuth of the FSS Tx (FS Rx) w.r.t. the FS Rx (FSS Tx) considered to be positive for clockwise bearing and negative for counter clockwise bearing. ε_s and ε_t are the elevation angles of the FSS Tx and the FS Rx respectively. ε_{ps} and ε_{pt} are the elevation angles of the radio path at the FSS Tx and the FS Rx, respectively.

ITU-R S.465 [10] provides an expression for gain pattern of FSS Earth stations that is based on actual measurements. It assumes rotationally symmetric antennas and provides the pattern for $x_s \geq 1^\circ$ (and similarly for $x_s \leq -1^\circ$ given the symmetrical property of the antenna). Hence the off-boresight gain of the range $-1^\circ < x_s < 1^\circ$ will be approximated by the boresight gain of the FSS Tx (G_{sm}):

$$G_s(x_s) = \begin{cases} G_{sm} & ,\ 0^\circ \leq x_s < 1^\circ \quad \text{or} \ -1^\circ < x_s \leq 0^\circ \\ 32 - 25\,\log(|x_s|) & ,\ 1^\circ \leq x_s < 48^\circ \quad \text{or} \ -48^\circ < x_s \leq -1^\circ \\ -10 & ,\ 48^\circ \leq x_s \leq 180^\circ \quad \text{or} \ -180^\circ \leq x_s \leq -48^\circ \end{cases} \quad (10)$$

On the other hand, ITU-R F.699 [11] provides a reference radiation pattern for FS antennas used in fixed wireless systems. To determine the appropriate pattern, a diameter of 0.3 m is assumed (diameter of typical commercial FS antennas, see for example the model THP 03 275 S [12]). Based on this consideration, the reference pattern for rotationally symmetric FS antennas is given by [11]:

$$G_t(x_t) = \begin{cases} G_{tm} - 25 \cdot 10^{-3}\left(\frac{D}{\lambda}x_t\right)^2 & ,\ 0^\circ \leq x_t < x_{tm} \quad \text{or} \ -x_{tm} < x_t \leq 0^\circ \\ G_1 & ,\ x_{tm} \leq x_t < x_{td} \quad \text{or} \ -x_{td} < x_t \leq -x_{tm} \\ 52 - 10\,\log\left(\frac{D}{\lambda}\right) - 25\,\log(|x_t|) & ,\ x_{td} \leq x_t < 48^\circ \quad \text{or} \ -48^\circ < x_t \leq -x_{td} \\ 10 - 10\,\log\left(\frac{D}{\lambda}\right) & ,\ 48^\circ \leq x_t \leq 180^\circ \quad \text{or} \ -180^\circ \leq x_t \leq -48^\circ \end{cases} \quad (11)$$

with: $x_{tm} = \frac{20\,\lambda}{D}\sqrt{G_{tm} - G_1}$, $G_1 = 2 + 15\,\log\left(\frac{D}{\lambda}\right)$ and $x_{td} = 100\,\frac{\lambda}{D}$ where G_{tm} and D are the maximum gain (in dB) and the diameter (in m), respectively, of the FS Rx antenna.

4 Multiple Interferers Model

In this section, we model the average aggregated interference from multiple FSS Txs that are randomly distributed around the FS Rx. A statistical modelling approach is adopted to avoid considering the parameters associated with each terminal. An exclusion region around the FS Rx with radius r_{min} is enforced because it is not expected that the FSS Tx and the FS Rx will be located at the same point. Notice that this region should not be confused with the so-called cognitive or protection areas.

4.1 Average aggregated interference

A simple way to characterise the interference from a heterogeneous set of interfering transmitters is to assume that there is a constant and uniform density of FSS Txs power per unit of area: $D_p = \frac{P}{A}$ which represents the density of the total power supplied to all FSS Txs antennas P in an area A. This density does not take into account the particular details of each FSS Tx, but rather the aggregated levels in a statistical manner. The interference density at the FS Rx (I_D) can then be expressed as:

$$I_D = D_p \cdot G_s^l(x_s) \cdot PL^l(r) \cdot G_t^l(x_t) \tag{12}$$

where the superscript l means the linear form of the function (e.g., $PL^l(r) = 10^{\frac{PL(r)}{10}}$). Initially, we assume that the interference component from each FSS Tx is constant, i.e., x_s is constant. At a later stage, this assumption will be relaxed to compute the real interference. The aggregated interference $I_t(x_s)$ for a particular value of x_s can be computed by integrating I_D in polar coordinates. However, point-to-point FS stations usually have less than 10° elevation angle [9], while ε_{pt} is used as a correction for heights difference and it has a negligible value ($\approx 0°$). Recalling (9), the FS Rx off-boresight angle simplifies to $x_t \approx \beta$, i.e., x_t can be approximated by the relative azimuth of the FS Rx w.r.t. the FSS Tx and can be used as the radial coordinate. As a result, $I_t(x_s)$ can be written as:

$$I_t(x_s) = 2\, D_p\, G_s^l(x_s) \int_0^{180} G_t^l(x_t) \left[\int_{r_{min}}^{\infty} PL^l(r)\, r\, \mathrm{d}r \right] \mathrm{d}x_t = D_p \cdot G_s^l(x_s) \cdot C \cdot T \tag{13}$$

$$C = \int_{r_{min}}^{\infty} PL^l(r) \cdot r\, \mathrm{d}r \quad , \quad T = 2 \int_0^{180} G_t^l(x_t)\, \mathrm{d}x_t \tag{14}$$

In order to solve the integral for C, an approximation to the diffraction loss is developed by curve fitting procedures. The approximated form is given by:

$$L_d^l \approx (v + 1.62)^{3.39} \tag{15}$$

Comparing (5) and (15) by using several values of v indicates that the approximated formula of (15) gives results similar to the ITU-R P.526 model with a maximum error of 1−2 dB. Section 3 shows that for the Europe's atmosphere profile and frequency range 27.5−29.5 GHz, $A_g \approx 0.107$ dB/km which is negligible compared with other loss's terms and can be ignored. On the other hand, the clutter loss has a constant value that depends only on the clutter category [6]. The considered category gives a clutter loss $A_h = 14.83$ dB. Applying these values along with (15) to the linear form of (4) and following the mathematical details, C can be computed as:

$$C \approx \frac{3.3 \cdot 10^{-15} \cdot \lambda^{3.7} \cdot {}_2\mathrm{F}_1 \left[3.39,\ 3.39;\ 4.39;\ -\frac{7.2 \cdot 10^{-2}}{\theta} \sqrt{\frac{\lambda}{r_{min}}} \right]}{\theta^{3.39} \cdot (r_{min})^{1.7}} \tag{16}$$

where ${}_2\mathrm{F}_1[a, b; c; d]$ is the Gauss hypergeometric function. Similarly, T can be calculated by substituting the linear form of (11) into (14) and solving the integration:

$$T = \frac{2 \cdot \lambda}{D} \left[37 \cdot G_{tm}^l \cdot \mathrm{erf}\left(\frac{0.024 \cdot D \cdot x_{tm}}{\lambda} \right) + G_1^l \left(100 - \frac{D \cdot x_{tm}}{\lambda} \right) + 106 \left(\frac{D}{\lambda} \right)^{1.5} + 1002.3 \right] \tag{17}$$

The interference modelled so far assumes x_s is constant. The next step is to relax this assumption to obtain the real interference. Equations (8) and (10) indicate that x_s is a function of antennas orientation as well as stations location. Thus, x_s can take any arbitrary value in the range $[-180°, 180°]$ even if the azimuth and the elevation angles are constant (e.g., specific region and satellite slot). In other words, the same FSS Tx will have a small (large) x_s value when it is located in front of (behind) the FS Rx antenna. Hence the parameter x_s can be modelled as a random variable uniformly distributed in this interval with a probability density function (pdf) given by:

$$f_X(x_s) = \begin{cases} \frac{1}{360} & , \ -180° \leq x_s \leq 180° \\ 0 & , \ \text{otherwise} \end{cases} \tag{18}$$

The average aggregated interference I_{avg} can now be calculated by averaging $I_t(x_s)$ over all the possible values of x_s:

$$I_{avg} = \int_{-180}^{180} I_t(x_s) \cdot f_X(x_s)\, \mathrm{d}x_s = 5.6 \cdot 10^{-3} \cdot R \cdot \left(G^l_{sm} + 1066.62\right) \quad \text{[watt]} \tag{19}$$

where $R = D_p \cdot C \cdot T$. Equation 19 can be used as a design tool to impose limits on the FSS system density so that the total average aggregated interference does not exceed I_{thr}. Given the protection condition of (1) and the definition of the power density $D_p = \frac{P}{A} = D_N \cdot P^l_s$ where D_N is the FSS Txs density (i.e., Tx per unit of area), the maximum allowed density of the FSS Txs can be formulated as:

$$D_N = \frac{18 \cdot 10^7 \cdot I^l_{thr}}{P^l_s \cdot C \cdot T \cdot \left(G^l_{sm} + 1066.62\right)} \qquad [\mathrm{Tx/km}^2] \tag{20}$$

4.2 FS Rx outage probability

Imposing constraints on the cognitive system based on average levels of interference may not always provide an acceptable level of protection to the IU since the instantaneous aggregated interference may sometimes exceed the average level and thus the required protection threshold. A more convenient design approach is to impose limits on D_N based on outage probability of the incumbent system $\mathbb{P}_o$. The latter can be defined as the probability that the aggregated interference is higher than I_{thr}, i.e.,

$$\mathbb{P}_o = \mathrm{Pr}\left(I_t > I^l_{thr}\right) = \int_{I^l_{thr}}^{\infty} f_Y(I_t)\, \mathrm{d}I_t \tag{21}$$

where Pr(z) means the probability of z and $f_Y(I_t)$ is the pdf of I_t. Substituting the linear form of (10) into (13) gives:

$$I_t = \begin{cases} G^l_{sm} \cdot R & , \ 0^\circ \le x_s < 1^\circ \quad \text{or } -1^\circ < x_s \le 0^\circ \\ 1585 \cdot |x_s|^{-2.5} \cdot R & , \ 1^\circ \le x_s < 48^\circ \quad \text{or } -48^\circ < x_s \le -1^\circ \\ 0.1 \cdot R & , \ 48^\circ \le x_s \le 180^\circ \quad \text{or } -180^\circ \le x_s \le -48^\circ \end{cases} \tag{22}$$

Notice that the notation $I_t(x_s)$ is replaced with I_t to simplify the expression. However I_t is still a function of x_s. Obtaining the distribution of I_t from the distribution of x_s is not a straightforward process because the transformation function (i.e., I_t) is not a monotone function. Hence, the calculation of $f_Y(I_t)$ is divided into three parts according to the function trend of (22):

$$\mathrm{Pr}\left(I_t = G^l_{sm} \cdot R\right) = \mathrm{Pr}\left(-1^\circ < x_s < 1^\circ\right) \approx 6 \cdot 10^{-3} \tag{23}$$

$$\mathrm{Pr}\left(I_t = 0.1 \cdot R\right) = \mathrm{Pr}\left(-180^\circ \le x_s \le -48^\circ\right) + \mathrm{Pr}\left(48^\circ \le x_s \le 180^\circ\right) = 0.733 \tag{24}$$

It can be noticed that I_t is a monotonic decreasing function in the range $-48^\circ < x_s \le -1^\circ$ and the range $1^\circ \le x_s < 48^\circ$. Thus the pdf of I_t in this range can be calculated by transforming $f_X(x_s)$ with the transformation function I_t, i.e.,

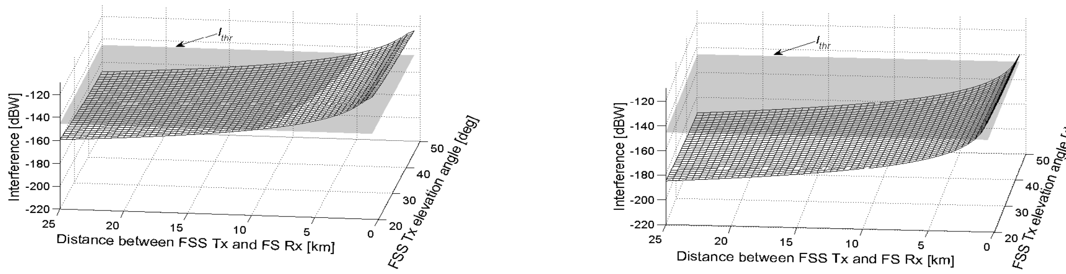
$$\mathrm{Pr}\left(I_t = 1585 \cdot |x_s|^{-2.5} \cdot R\right) = 2 \cdot f_X(x_s) \cdot \left|\frac{\mathrm{d}x_s}{\mathrm{d}I_t}\right| = 42 \cdot 10^{-3} \cdot R^{\frac{2}{5}} \cdot I_t^{-\frac{7}{5}} \tag{25}$$

Combining (23), (24) and (25) gives the pdf of the aggregated interference $f_Y(I_t)$ which can be used to calculate the outage probability as defined in (21).

$$f_Y(I_t) = \begin{cases} 0.733 & , \ I_t = 0.1 \cdot R \\ 42 \cdot 10^{-3} \cdot R^{\frac{2}{5}} \cdot I_t^{-\frac{7}{5}} & , \ 0.1 \cdot R < I_t \le 1585 \cdot R \\ 6 \cdot 10^{-3} & , \ I_t = G^l_{sm} \cdot R \\ 0 & , \ \text{otherwise} \end{cases} \tag{26}$$

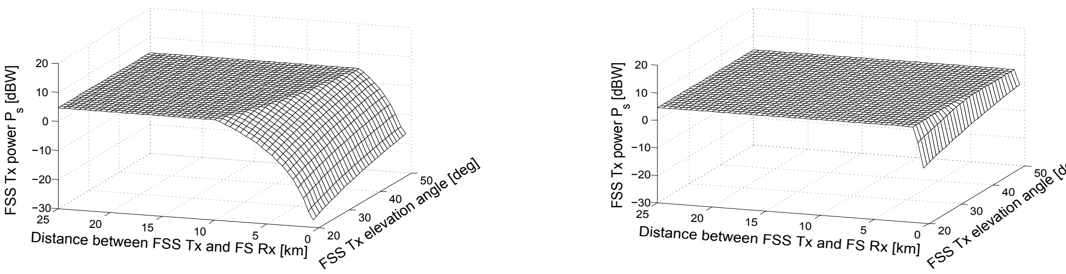
$$\mathbb{P}_o = \left(0.106 \cdot \left(\left(\frac{R}{M}\right)^{\frac{2}{5}} - 0.052\right)\right) + 6 \cdot 10^{-3} \quad , \quad M = \min\left(I^l_{thr}, 1585 \cdot R\right) \tag{27}$$

It is worth mentioning that (27) is applicable to $0.1 \cdot R \le I^l_{thr} \le G^l_{sm} \cdot R$ only. For smaller and larger values of I^l_{thr}, $\mathbb{P}_o = 1$ and 0 respectively. Finally, the maximum allowed density for the cognitive FSS system



(a) $\alpha = 0^\circ$, $\beta = 0^\circ$ (b) $\alpha = -10^\circ$, $\beta = 10^\circ$

Figure 2: Interference received by the FS Rx from FSS Tx transmits at its nominal non-controlled power



(a) $\alpha = 0^\circ$, $\beta = 0^\circ$ (b) $\alpha = -10^\circ$, $\beta = 10^\circ$

Figure 3: Power supplied to FSS Tx antenna P_s after applying the power limit of (3)

can be determined by substituting $M = I^l_{thr}$ into (27) and solving the equation for D_N. However, the special case of $\mathbb{P}_o = 0$ implies that $I^l_{thr} \geq G^l_{sm} \cdot R$. In this case, the maximum allowed density can be calculated by solving this inequality for D_N.

$$D_N = \begin{cases} \frac{I^l_{thr} \cdot 10^6}{C \cdot T \cdot P^l_s \cdot G^l_{sm}} & , \ \mathbb{P}_o = 0 \\ \frac{2.73 \cdot 10^8 \cdot I^l_{thr} \cdot \mathbb{P}_o^{\frac{5}{2}}}{C \cdot T \cdot P^l_s} & , \ 0 < \mathbb{P}_o \leq 1 \end{cases} \tag{28}$$

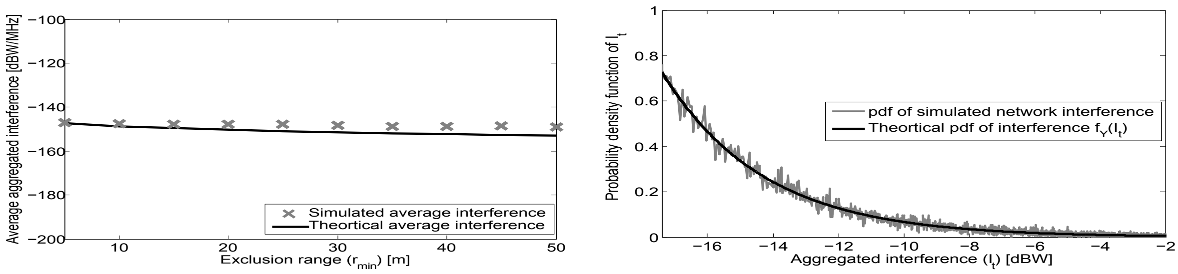
5 Numerical and Simulation Results

5.1 Single interferer model

Fig. 2 shows a 3D diagram of interference power that would be received by an incumbent FS Rx with a 20 m height, $\varepsilon_t = 0^\circ$ and $I_{thr} = –146$ dBW/MHz [5], [9] from a FSS Tx with a 2 m height and maximum EIRP of 55 dBW [13] (i.e., $P_s = 4.7$ dBW/MHz for a terminal with 45.5 dB antenna gain and 3 MHz bandwidth) for the commonly used satellite elevation angles in Europe $20^\circ - 50^\circ$ [3] before restricting the FSS Tx power. Note that the single interferer derivation is based only on power and thus a mapping to power density needs to be made. Here we assume a transmit and receive bandwidths of 1 MHz. For other transmit and receive bandwidths a mapping can be made.

It can be seen that changing the FSS Tx and the FS Rx pointing directions changes the received interference significantly. With a constant $P_s = 4.7$ dBW/MHz and 0° relative azimuth angles, the FS Rx will suffer from harmful interference in distances less than 10 km as indicated by Fig. 2a. Hence DSA/CR techniques such as the power limit of (3) are needed in the high interference region. Rotating the FSS Tx antenna by -10° (anti-clockwise) w.r.t. the FS Rx, and FS Rx antenna by 10° (clockwise) w.r.t. the FSS Tx in the horizontal plane (Fig. 2b), reduces the interference to acceptable levels except for distances less than 2 km. Therefore, the antenna pointing angle is an important design parameter that can be exploited to effectively control the interference generated on the incumbent system.

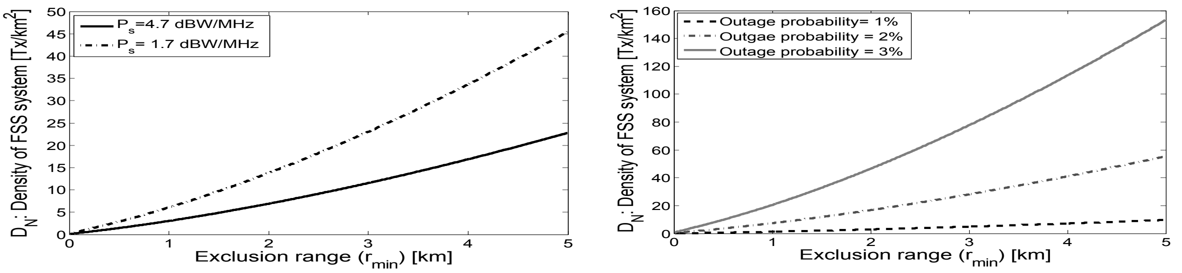
Fig. 3 shows the FSS Tx power after applying the power limit of (3). As can be seen, in the low interference region the FSS Tx transmits with its nominal power. However, the FSS Tx reduces its power in the high interference region to reduce the interference to the tolerable level by the FS Rx with a proportional relationship between the distance, the elevation angle and the power limit. In other words, the FSS Tx determines if its nominal power would generate harmful interference to the incumbent Rx according to location information, gain patterns and path loss model awareness. If the interference is below the FS Rx tolerable level, the FSS Tx does not change its nominal power, otherwise the FSS Tx reduces its power to a level that ensures non-harmful interference at the FS Rx input. It is worth mentioning that



(a) Average aggregated interference

(b) pdf of the aggregated interference

Figure 4: Multiple interferes model validation by means of simulation



(a) Based on the average aggregated interference

(b) Based on the outage probability. $P_s = 4.7$ dBW/MHz

Figure 5: Maximum allowed density of the cognitive FSS system

the additional loss mechanisms increase the total path loss by roughly 40 dB as compared with the free space model. This provides additional protection to the FS Rx and allows the cognitive FSS Tx to increase its power w.r.t. the power limit that would be predicted if only the free space model is considered. This result highlights the importance of using realistic models as the one developed in this paper.

5.2 Multiple interferes model

A simulator has been developed to validate the theoretical expressions of the multiple interferers model. FSS Txs are randomly distributed in a circular area centred at the FS Rx with inner radius r_{min} and outer radius of 350 km. Unless otherwise stated, the typical FSS Tx and FS Rx parameters mentioned in Section 5.1 are used. As can be seen in Fig. 4a, the average values predicted by the theoretical model are similar to the results obtained by means of simulations, with a maximum relative error of 2.6% w.r.t. the simulation value. This indicates that the theoretical expression of I_{avg} is accurate enough and can be reliably used to approximate the average interference of practical networks. In addition, the comparisons of Fig. 4b show the accuracy of the theoretically derived distribution of the aggregated interference. This validation indicates that $f_Y(I_t)$ can be reliably used to calculate $\mathbb{P}_o$ as well as the maximum density.

Fig. 5a gives the maximum allowed D_N for a given r_{min} value whist ensuring $I_{avg} \leq -146$ dBW/MHz. With 340 m exclusion range and constant P_s of 4.7 dBW/MHz, only one FSS $\mathrm{Tx/km^2}$ is allowed to transmit. Doubling r_{min} allows increasing D_N to 2 without violating the protection condition. Increasing r_{min} to 5 km allows density up to 22 FSS $\mathrm{Tx/km^2}$ without degrading the FS Rx performance. As a result, a more dense deployment of the FSS Txs can be achieved by imposing a more strict r_{min} value. However, the price to pay is reducing the deployment area of the cognitive system. As can be seen in Fig. 5a, P_s plays an important role with r_{min} in determining the allowed density of the cognitive FSS system. Halving P_s (from 4.7 to 1.7 dBW/MHz) doubles the allowed density for the same r_{min} value. In other words, decreasing P_s allows decreasing r_{min} (and hence increasing the FSS deployment area) without reducing the deployment density.

Fig. 5b gives the maximum allowed density of the cognitive FSS system according to the targeted FS Rx outage probability. It can be observed that a small increase in $\mathbb{P}_o$ allows significant increase in D_N. With a constant $P_s = 4.7$ dBW/MHz and $r_{min} = 1$ km, only 1.3 FSS Tx/km^2 are allowed to guarantee 1% FS Rx outage probability. On the other hand, a tolerable outage probability of 3% allows up to 20.5 FSS Tx/km^2. It can be noticed that a CUs density of 20 FSS Tx/km^2 can be achieved with an outage probability of 3% and exclusion region of 0.9 km. Reducing $\mathbb{P}_o$ to 2% requires increasing r_{min} to 2.3 km in order to achieve the same density. Thus, with a price of reducing the cognitive system deployment area, the trade-off in achieving the IUs and CUs requirements can be overcome by reducing $\mathbb{P}_o$ (which enhances the IU performance) and increasing r_{min} (which increases the CUs density).

6 Conclusion

In this paper, we have modelled the interference between cognitive Ka-band FSS satellite user terminals and incumbent FS radio links. The developed models consider single and multiple interferers scenarios and incorporate gain patterns of directional antennas as well as simplified ITU radio propagation models. The FSS uplink band $27.5 - 29.5$ GHz has been considered which can in principle be shared by the systems. Preliminary results indicate that satellite/terrestrial coexistence in the same frequency band may be feasible under appropriate operation conditions. For a single interferer scenario and equal bandwidths of 1 MHz, protection areas of less than 10 km could apply, outside of which sharing may pertain. Inside such areas CR techniques could be used to permit sharing. The results of the multiple interferers scenario show the trade-off between deployment area and deployment density of the cognitive system as well as the power/deployment density trade-off. The modelling adopted herein could be applied also to the downlink scenarios, and these aspects are being studied in the CoRaSat project.

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