Cognitive Zone for Broadband Satellite Communication in 17.3-17.7 GHz Band

Sina Maleki, Symeon Chatzinotas, Jens Krause, Konstantinos Liolis, and Björn Ottersten

Abstract—**Deploying high throughput satellite systems in Ka band to accommodate the ever increasing demand for high data rates hits a spectrum barrier. Cognitive spectrum utilization of the allocated frequency bands to other services is a potential solution. Designing a cognitive zone around incumbent broadcasting satellite service (BSS) feeder links beyond which the cognitive fixed satellite service (FSS) terminals can freely utilize the same frequency band is considered in this paper. In addition, we show that there is a rain rate called rain wall, above which cognitive downlink communications becomes infeasible.**

Keywords*—*Cognitive zone, satellite communications, cognitive radio, rain wall, Ka band.

I. Introduction

The limited exclusive bandwidth allocated to FSSs is not sufficient for the satellite operators to satisfy the increasing traffic demands. This problem has encouraged satellite actors to investigate the idea of dynamic or uncoordinated spectrum utilization employing cognitive radios in order to open up new spectrum opportunities [1]. Uncoordinated access refers to a type of co-spectrum access where the cognitive user can access the incumbent user's spectrum without prior coordination with the regulatory bodies and no right of interference protection, conditioned on not imposing harmful interference to the incumbent user. For an overview of the scenarios and techniques to enable cognitive satellite communications, we refer the readers to [1].

In this paper, we consider a scenario where a cognitive FSS terminal attempts to gain downlink access in the band 17.3-17.7 GHz. The incumbent users in this band are BSS feeder links which work in the uplink mode. As it is shown in Fig. 1, the incumbent geostationary (GEO) satellite receiver is sufficiently protected from the FSS GEO satellite because of the orbital separation. However, the FSS terminals may receive interference from the BSS feeder links. Based on the level of interference, we may determine specific cognitive zones beyond which the cognitive downlink terminal can be installed without receiving harmful interference from the BSS feeder link station, i.e. within the cognitive zone, the FSS terminal needs to employ cognitive mechanisms, e.g. spectrum sensing, in order to use the spectrum. Here, our goal is to determine the cognitive zone for the FSS terminal employing the information obtained from databases. We further distinguish between a blind cognitive zone which is determined solely based on the aggregated BSS interference level, and a link-based cognitive zone which takes the FSS link budget into account to attain a minimum rate. The link-based cognitive zone design which takes the impact of rain attenuation into account is the main contribution of this paper which shows that the size of the cognitive zone can be reduced significantly with respect to the blind cognitive zone when the link side knowledge is taken into account. Cognitive zone design has been recently addressed in [2] without considering the impact of key propagation phenomena, such as rain attenuation, and only for the blind scenario. In obtaining the cognitive zone, the cognitive terminal only relies on the database information and do not communicate the installation of the terminal to the regulators, and thus this is called the uncoordinated access. Based on the analytical results, we define a phenomenon called rain wall which shows that above a specific point rain rate, the cognitive downlink satellite service becomes unavailable. This is another contribution of this paper which determines a limiting factor of the link-based cognitive zone. Further, as mentioned before, this paper deals with the database-assisted uncoordinated access to the spectrum, the coordinated access through the regulatory radio planning is a well-established technique which is different from our approach.

The cognitive zone defined in this paper is different from the exclusive zone of the incumbent users in the terrestrial networks, e.g. in [3]. In the terrestrial networks, exclusive zone refers to a region around the incumbent user where the cognitive user activity results in harmful interference to the incumbent receiver. However, in our scenario the incumbent user is sufficiently protected and thus the cognitive zone is only determined to avoid the incumbent interference.

The idea of coexistence of satellite networks with other services is considered in a number of works recently. A cognitive satellite terrestrial scenario is considered in [4] where the authors investigate a cognitive uplink scenario in the presence of the terrestrial links. The work in [4] is different from our paper in some senses. First, we consider the cognitive downlink scenario while the uplink scenario is studied in [4]. Second, in [4], spectrum sensing is considered for all cases, while in this paper, we show that spectrum sensing is required only if we are within the cognitive zone.

The rest of the paper is organized as follows. The received interference from the incumbent BSS feeder links followed by analytical determination of the cognitive zone is presented in Section II. In Section III, we determine the blind and link-based cognitive zone for a case study in Luxembourg. Finally, we draw our conclusions in Section IV.

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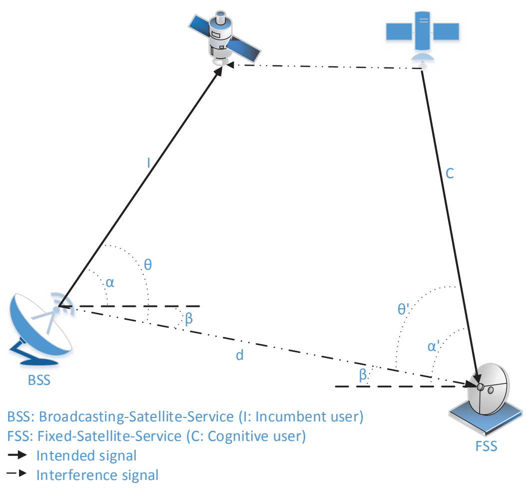

Fig. 1: Network model

II. Interference Model and Cognitive Zone

As mentioned before, in our scenario, the cognitive FSS terminal may receive interference from the BSS feeders. In practice, it is possible to receive interference over the same carrier from several BSS feeders pointing at different satellites. We denote by M, the total number of BSS feeders uplinking over the same carrier. Denoting I_{FSS} as the received BSS feeder links interference at the FSS terminal, P_{BSS} as the transmission power of the BSS feeder link, $G_{\text{BSS}}(\theta)$ as the BSS feeder link antenna gain at the off-axis angle of θ, $L(d)$ as the free space path-loss which depends on the distance d between the BSS feeder link and FSS terminals, R_{BF} as the rain loss over the interfering terrestrial path from the BSS feeders to the FSS terminal, and $G_{\text{FSS}}(\theta^{'})$ as the FSS antenna gain at the off-axis angle of $\theta^{'}$, the received BSS feeder links interference at the FSS antenna is obtained by

$$I_{\text{FSS}} = \sum_{i=1}^{M} P_{\text{BSS}_i} + G_{\text{BSS}}(\theta_i) - L(d_i) - R_{\text{BF}_i} + G_{\text{FSS}_i}(\theta_i^{'}) \text{ [dBW]}. \quad (1)$$

where subscript i denotes the i-th BSS feeder link. The angular configuration of the considered network model for one BSS feeder is shown in Fig. 1. Here, we model the path-loss as the free space path-loss model. However, in practice more accurate attenuation models can be considered, e.g. diffraction loss, atmospheric attenuation, clutter loss, etc. This leads to extra attenuation, and thus the free space path-loss model is the worst case scenario. Note that rain fading over this terrestrial path (R_{BF}) is another major fading source, which creates the so-called "Differential Rain Attenuation" due to the converging paths at the receiver [5], [6]. However, due to the fact that the calculation of rain fading over the interfering path requires the exact information over the whole path, and further rain fading is a short-term phenomenon and we are interested in designing a robust system for long-term, again we consider the worst case scenario and thus in this paper we put $R_{\text{BF}} = 0$. Here $L(d_i) = 20\log(d_i \text{ [m]}) + 20\log(f \text{ [Hz]}) - 147.55 \text{ [dB]}$, where f is the carrier frequency. Denoting α to be the BSS feeder link elevation angle, and β the angle between the over horizon projected main lobe of the BSS feeder link and the FSS terminal, θ is obtained by $\theta = \arccos\left[\cos(\alpha)cos(\beta)\right]$, where we neglect the BSS feeder link ground antenna height in calculating θ. Similarly, we can obtain $\theta^{'}$ by $\theta^{'} = \arccos\left[\cos(\alpha^{'})cos(\beta)\right]$, where $\alpha^{'}$ is the FSS terminal elevation angle, and again we neglect the height of the FSS antenna in calculating $\theta^{'}$.

Based on the BSS feeder links interference at the FSS terminal in (1), the cognitive zone can be determined by setting I_{FSS} to be greater than a specific threshold denoted by I_{T}, i.e. $I_{\text{FSS}} \geq I_{\text{T}}$. In case the interfering BSS feeders are co-located, the cognitive distance, defined as the distance to the source beyond which the cognitive terminal can freely perform downlink communication is obtained by $D_c = 10^{\frac{\sum_{i=1}^{M}\left[P_{\text{BSS}_i} + G_{\text{BSS}}(\theta_i) + G_{\text{FSS}}(\theta_i^{'}) - 20\log(f) + 147.55\right] - I_T}{20}} [m]$. where D_c denotes the cognitive distance. Again, we should note that this is the worst case cognitive distance. In the following subsections, we outline two approaches for determining the threshold I_{T}, a blind, and a link-based approach.

A. Blind Cognitive Zone

The most straightforward way of determining I_{T} is to look at the regulations regarding the frequency coordination among satellite terminals defined by ITU-R. ITU-R defines the maximum allowable interference for a long term (20% of the time), and a short term regime. In this paper, we consider the long term allowable interference threshold which is usually set 6 dB or 10 dB below the noise floor (borrowed from ITU-R F.758-5) depending on the requirements of the FSS terminal. We define the noise floor as $N = KTB$, where K is the Boltzmann constant, T is the thermal noise, and B is the bandwidth. However, since the FSS downlink transmission in this band does not interfere with the incumbent service, the FSS operators can be flexible in determining I_{T} according to their own limitations and service level agreements (SLAs).

B. Link-based Cognitive Zone

While the blind cognitive zone defines a robust approach in determining the cognitive zones considering a normal atmospheric condition, however it does not take the FSS link budget into account. This fact encourages us in finding a link-based technique to determine I_{T} based on the side link budget information of the FSS link. Denoting P_{FSS} as the received power at the FSS decoder, and $S_{\min}$ as the minimum required SINR margin at the FSS terminal, we have $P_{\text{FSS}}[\text{dBW}] - 10\log[10^{\frac{N\,[\text{dBW}]}{10}} + 10^{\frac{I_{\text{FSS}}\,[\text{dBW}]}{10}}] \geq S_{\min}$, and after some simplifications, we obtain

$$I_{\text{FSS}}[\text{dBW}] \leq 10\log[10^{\frac{P_{\text{FSS}}\,[\text{dBW}] - S_{\min}}{10}} - 10^{\frac{N\,[\text{dBW}]}{10}}]. \quad (2)$$

Therefore, the link-based interference threshold denoted by $I_{\text{T,D}}$ is defined as

$$I_{\text{T,D}}[\text{dBW}] = 10\log\left[10^{\frac{P_{\text{FSS}}[\text{dBW}]-S_{\min}}{10}} - 10^{\frac{N[\text{dBW}]}{10}}\right]. \quad (3)$$

Note that P_{FSS} can be obtained if the FSS GEO satellite equivalent isotropically radiated power (EIRP), and satellite to ground channel gain are known. Atmospheric phenomena (e.g. rain) may change the channel gain, and thus P_{FSS}. Denoting $\mathcal{E}$ as the GEO satellite EIRP, and AL as the atmospheric loss, P_{FSS} is obtained by $P_{\text{FSS}} = \mathcal{E} - L(d_{\text{GEO-FSS}}) - AL + G_{\text{FSS}}(0)$ [dBW], where AL consists of two components: a) a frequency dependent atmospheric absorption denoted by AGL, and b) an average rain attenuation component which is again dependent on the frequency as well as the point rain rate and the polarization. We denote the rain attenuation by RL, and following ITU-R P.618-11 define as follows

$$RL = kR^{a}\left(\frac{H_R[\text{km}] - H_{\text{FSS}}[\text{km}]}{\sin\alpha'}\right) [\text{dB}], \quad (4)$$

where R is the rain rate at a specific geographical location, and k and a are constants which depend on the frequency and polarization (the values can be found in ITU-R P.838-3, H_{FSS} is the height of the FSS antenna, and H_R is the rain height derived from ITU-R P.839-4 and for Lat $> 23°N$ equals to $5 - 0.075(\text{Lat}-23)$ km. Note that (4) does not take the randomness of the rain fading into account but provides reliable information to design the system for the long-term. Designing the cognitive system considering the short-term rain fading involves analysis of the spatial correlation between the rain attenuation over the space and multiple terrestrial paths. This analysis is important and delivers a dynamic version of the cognitive zone. However, it necessitates extra calculations which is beyond the scope of this paper and is considered as a topic for future work. From (2) and (4), we can see that for a given $S_{\min}$, there is a rain rate above which the cognitive downlink communication can not provide service availability. We call this phenomenon as rain wall. After some mathematical derivations, we obtain the following proposition which determines the rain wall for cognitive downlink satellite communications.

Proposition 1. Assuming $B = \mathcal{E} - L(d_{\text{GEO-FSS}}) - AGL + G_{\text{FSS}}(0) - S_{\min}$ [dBW], and denoting $\mathcal{R}_w$ as the rain wall, we have $\mathcal{R}_w = \left(\frac{B - 10\log[10^{\frac{I_{\text{FSS}}[\text{dBW}]}{10}} + 10^{\frac{N[\text{dBW}]}{10}}]}{kH}\right)^{1/a}$, where $H = \frac{H_R[\text{km}] - H_{\text{FSS}}[\text{km}]}{\sin\alpha'}$.

III. Case Study of a BSS Feeder Link in Luxembourg

In this section, we apply the cognitive zone to a real case study based on a BSS feeder link database obtained from the satellite operator SES in Luxembourg. The BSS feeder links are located in Betzdorf, Luxembourg. Note that due to confidentiality of the full database, without loss of generality, in this section, we determine the cognitive zone for one BSS feeder link. We consider a carrier frequency of $f = 17.7$ GHz. The transmission power of the BSS feeder link after waveguide loss of 2 dB is $P_{\text{BSS}} = 18.9$ dB. The lowest in-service BSS feeder link elevation angle in Betzdorf in 17.3-17.7 GHz is $28.22°$. Considering the latitude of Betzdorf (49.68°E), the maximum elevation angle for a GEO earth station is around $33°$. The maximum elevation angle for GEO terminals is $\alpha'_{\max} = 90° - \text{Lat} - \psi$, where Lat denotes the latitude of the FSS terminal, and ψ is apparent declination derived from $\arctan\left(\frac{-\sin(\text{Lat})}{6.61-\cos(\text{Lat})}\right)$ [8].The minimum elevation angle for GEO terminals is considered usually around $10°$ in order to tackle the geographical terrain effects. To calculate the gain of the BSS feeder link, we follow ITU-R S.580-6 and ITU-R S.465-6. Below is the detail of G_{BSS} and G_{FSS}

$$G_{\text{BSS}}(\alpha) = \begin{cases} 29 - 25\log(\alpha) \text{ [dBi]} & \text{for } \alpha \le 20° \\ -3.5 \text{ [dBi]} & \text{for } 20° < \alpha \le 26.3° \\ 32 - 25\log(\alpha) \text{ [dBi]} & \text{for } 26.3° < \alpha \le 48° \\ -10 \text{ [dBi]} & \text{for } 48° < \alpha \le 180° \end{cases}, \quad (5)$$

$$G_{\text{FSS}}(\alpha') = \begin{cases} 42.1 \text{ [dBi]} & \text{for } \alpha' \le 1° \\ 32 - 25\log(\alpha') \text{ [dBi]} & \text{for } 1° < \alpha' \le 48° \\ -10 \text{ [dBi]} & \text{for } 48° < \alpha' \le 180° \end{cases}. \quad (6)$$

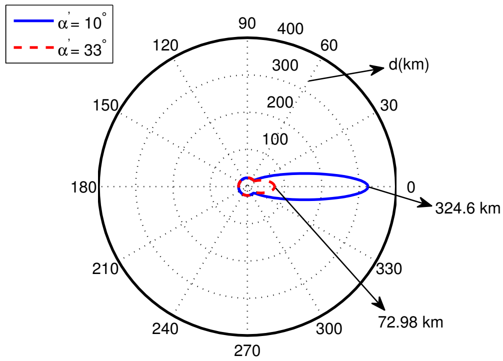

Fig. 2: Blind cognitive zone for $\alpha' = 10^o, 33°$, and $\alpha = 28.22°$, Betzdorf, $f = 17.7$ GHz, $I_{\text{T}} = -146$ dBW.

Fig. 2 depicts the cognitive zone for the BSS feeder link in Betzdorf with the mentioned parameters, and for the minimum and maximum elevation angles of the FSS terminal, i.e., $10°$ and $33°$, respectively. In this figure, $I_{\text{T}} = -146$ dBW which indicates an interference threshold of -10 dB below the noise floor of -136 dBW (with noise temperature of $290°$ K). We can see that for $|\beta| > 30°$, the FSS terminal can use this carrier, virtually everywhere without being concerned with the BSS feeder link interference. Here $|\cdot|$ denotes the absolute value. Note that $\beta = 0$ indicates that the two satellites are facing directly opposite each other. Since the satellite terminals in northern (southern) hemisphere look at the south (north), they can never directly face each other and further, the absolute value of the angle β is mostly larger than $30°$. This shows that a vast geographical area is available for cognitive downlink communications in this band without the need for extra efforts.

In order to see how the network link budget affects the

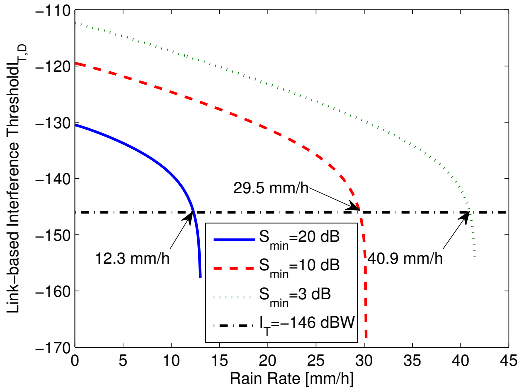

Fig. 3: Link-based interference threshold versus the rain rate, $\alpha = 28.22°$, $\alpha^{'} = 33°$, Betzdorf, $f = 17.7$ GHz.

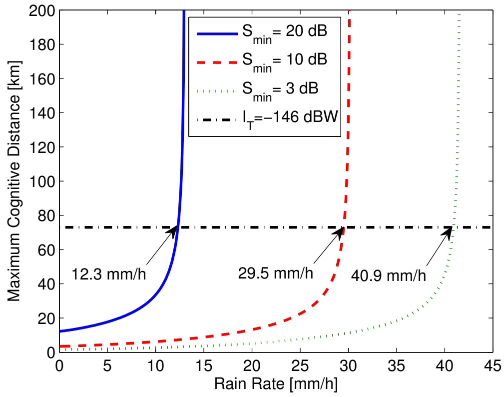

Fig. 4: Link-based maximum cognitive distance versus the rain rate, and $\alpha = 28.22°$, $\alpha^{'} = 33°$, Betzdorf, $f = 17.7$ GHz.

interference threshold, in Figures 3 and 4, the link-based interference threshold, and link-based maximum cognitive distance are depicted versus the rain rate. We consider a scenario where $\alpha = 28.22°$, $\alpha^{'} = 33°$, $f = 17.7$ GHz, the satellite EIRP= 58 dBW, $k = 0.071$ and $a = 1.1$ for horizontal polarization in this band, $d_{\text{GEO-FSS}} = 38000$ km, $H_{\text{FSS}} \sim 0$, $AGL = 0.5$ dB, and the BSS feeder link parameters are as in Fig. 2. The considered minimum SINRs are $S_{\min} = 20, 10, 3$ dB which corresponds to the modulation levels 32APSK, 16APSK, and QPSK, respectively [9].

In Fig. 3 , we can see that the stringent blind interference threshold equivalent to INR= -10 dB is a very conservative threshold for a large range of the rain rates even for very high minimum SINRs. For example for $S_{min} = 20$ dB in Betzdorf, the rain rate below which the link-based interference threshold is less than the blind interference threshold is 12.3 mm/h which is a very rare event in Luxembourg. This value for $S_{min} = 10$ dB which is yet considered as a very good SINR in satellite communications reaches to 29.5 mm/h which is even a more rare event. Further, we can see that the blind interference threshold fails in accommodating the service availability when the rain rate goes beyond a specific value. On the other hand, the link-based interference threshold can be adapted to this situation by changing the interference threshold to a lower value. In this figure, we can also see the rain wall above which the system can not provide the minimum SINR even for zero interference. As expected, the rain wall increases with reducing $S_{\min}$. The advantages of link-based interference threshold in reducing the maximum cognitive distance (achieved for $\beta = 0$) for a large margin of rain rates, with respect to the blind scenario, is also evident in Fig. 4. As in Fig. 3, we can notice the rain wall in Fig. 4 as well.

IV. Conclusion

Determining cognitive zones for broadband satellite communication in the band 17.3-17.7 GHz was investigated in this paper. We considered a blind and a link-based approach. It was shown that the link-based cognitive zone can provide higher service availability to more users with respect to the conservative blind cognitive zones. Further, we have shown that there is a rain wall above which cognitive satellite terminals can not deliver the requested data rates. With a case study based on the real data, it was shown that the rain wall is quite high which makes cognitive service unavailability a rare event in most of the places.

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