On the Feasibility of a Secondary Service Transmission Over an Existent Satellite Infrastructure

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Résumé – Dans cet papier, nous présentons un cas d'utilisation réaliste afin d'étudier la faisabilité de la transmission d'un service secondaire en utilisant une infrastructure de satellite déjà existante. En utilisant des techniques de radio cognitives de type overlay, nous obtenons un débit supérieur à 16 kbps pour un service secondaire, ce qui convient aux applications M2M, tout en conservant pour les mêmes performances du service primaire qu'en absence d'interférence.

Abstract – In this paper, we present a realistic use case in order to investigate the feasibility of a secondary service transmission over an existent satellite infrastructure. As a result, by using overlay cognitive radio techniques, we reach a data rate greater than 16 kbps for the secondary service, which is suitable for M2M applications, while the primary service maintains the same performance as in absence of interference.

1 Introduction

Despite of the continuous technological developments in terrestrial networks, the satellite communications systems play a key role in the modern telecommunications world. This affirmation can be sustained especially today, since the demand for the rising new services has experienced a significant growth, supported by the unique characteristics such as multicast and broadcasting capabilities, mobility aspects, global reach, besides the ability to cover and connect green space and hostile environments [1]. As a typical example of these application, we could point out the use of satellite for machine-to-machine (M2M) applications, providing to the end-users connectivity anytime, anywhere, for any media and device.

As a counterpoint, to meet these increasingly challenging requirements and to keep the competitiveness facing the terrestrial technologies, the satellite segment needs to push the boundaries in the direction to more and more efficient technical solutions. In this sense, the search for power and bandwidth efficiency as well as the actual trend to low complexity systems are of the upmost importance. It is within this framework that the terrestrial cognitive radio techniques have also attracted the attention for satellites application. Supported by the recent developments in the space qualified Software Defined Radios (SDR), and also by the maturity of concepts such as flexible and hosted payloads, these techniques has becomes feasible and some relevant contributions were developed, resulting in a smart spectrum management.

In a nutshell, the cognitive user (CU), unlicensed for operate in a specific spectrum band, senses the environment around it and is able to adapt its transmission as a function of the interference, by adjusting the frequencies, waveforms and protocols in order to access the licensed primary user (PU) spectrum efficiently. Without going into further details, three paradigms classifies the CU operation : (i) interweave, where the CU transmits opportunistically into the spaces not allocated by the PU ; (ii) underlay, where the CU adjusts its parameters according to the PU signal characteristics in order to transmits simultaneously, however respecting an interference threshold ; and (iii) overlay, where the CU has the noncausal knowledge about the PU signal and message and, by using the superposition and dirty paper coding (DPC) techniques, is able to transmits its signal simultaneously with PU at the same frequency, time and polarization, without power limitation and mitigating both links interference.

The main reason to propose the overlay paradigm for satellite communications lies in the feasibility of transmitting both unlicensed and licensed services simultaneously towards its respective terminals. We emphasizes that, due to priority among users, the superposition coding strategies is required, unlike the solutions adopted for the broadcast channel. In practice, this method enables the addition of a secondary service taking advantage of the legacy and the infrastructure of the primary service, instead of using a dedicated satellite or constellation to provide this specific service.

This paper presents a practical scenario considering the techniques previously exposed in the recent publications [2] and [3], which concerns a design of overlay paradigm transmission for satellite communication systems. By using the concepts and the framework well characterized by these references, the present work acts as a complement in relation to the previously ones, focusing at the application and in the feasibility for a low data rate secondary service transmission. Also, a practical use case is evaluated, which uses Commercially available Off-The-Shelf (COTS) parts [4] and realistic link budget parameters.

This approach could be seen as part of the "preliminary phase" of an engineering process plan.

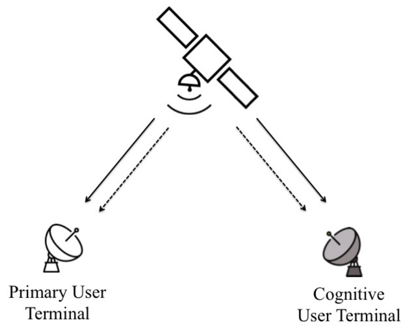

FIGURE 1 – Satellite Scenario

2 Overlay Model Description

An example of scenario where the overlay technique might be applied to satellite communication is illustrated in the Fig.1. In this case, the LEO/MEO satellite provides two different services towards different terminals, where the PU is the licensed one and takes priority over the CU. It is worth noting that others scenarios could be applied such as, for instance, a GEO multibeam satellite which transmits also both licensed and unlicensed services. In this last case, because of the frequency reuse, the interference among adjacent beams shall be resolved.

In both scenarios, the interference model with side information, presented in Fig.2, can be applied. As the signals are onboard the satellite, we assumed that the cognitive encoder has full and noncausal knowledge about the PU signal and message, as represented by the dashed arrow. In this sense, the encoded cognitive signal X_c^n is function of both primary and cognitive messages m_p and m_c, respectively, whereas the PU encoding strategy remains the same.

The cognitive channel gains are considered real and defined by the direct paths ($\mid h_{pp} \mid$ and $\mid h_{cc} \mid$), and the interfering paths ($\mid h_{pc} \mid$ and $\mid h_{cp} \mid$). The following pair of equations describes the channel :

$$Y_p^n = \mid h_{pp} \mid X_p^n + \mid h_{pc} \mid X_c^n + Z_p^n \tag{1}$$

$$Y_s^n = \mid h_{cc} \mid X_c^n + \mid h_{cp} \mid X_p^n + Z_s^n, \tag{2}$$

Finally, based upon the fact that the terminals are located in different sites, the noise component Z_p^n is assumed as $\mathcal{N}(0, N_p)$ and Z_s^n as $\mathcal{N}(0, N_s)$. Also, the power constraints to be satisfied are $E[|X_p^n|^2] = P_p$ and $E[|X_c^n|^2] \leq P_c$, respectively.

3 Enabling Techniques

3.1 Superposition Strategy

The purpose of the superposition technique is to ensure that the signal-to-noise ratio (SNR) at the PU receiver is not decreased in the presence of interference . To accomplish this goal, the CU shares part of its power to relay PU. Based on that operation, the CU transmitted signal is given by :

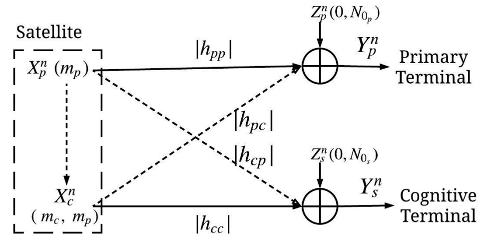

FIGURE 2 – Overlay Model

$$X_c^n = \hat{X}_c^n + \sqrt{\alpha \frac{P_c}{P_p}} X_p^n, \tag{3}$$

where $\alpha \in \ [0, 1]$ is the shared fraction of power P_c.

Under the assumption that both components are statistically independents, the new power constraint $E[|\hat{X}_c^n|^2] \leq (1 - \alpha) P_c$ is defined. By this way, the signal-to-interference-plus-noise ratio (SINR) at the primary receiver should reach the following equality :

$$SINR_P = \frac{E\left[\|(\mid h_{pp} \mid + \mid h_{pc} \mid \sqrt{\alpha \frac{P_c}{P_p}}) X_p^n \|^2 \right]}{E[\| \mid h_{pc} \mid \hat{X}_c^n \|^2] + E[\| Z_p^n \|^2]} = \frac{\|h_{pp}\|^2 P_p}{N_p} \tag{4}$$

The superposition factor $\alpha \in \ [0, 1]$ that guarantees (4), for interference condition ($\mid h_{pc} \mid > 0$), is given by :

$$\alpha = \left(\frac{\mid h_{pp} \mid \sqrt{P_p} \left(\sqrt{N_p^2 + \|h_{pc}\|^2 P_c (N_p + \|h_{pp}\|^2 P_p)} - N_p \right)}{\mid h_{pc} \mid \sqrt{P_c} (N_p + \|h_{pp}\|^2 P_p)} \right)^2 \tag{5}$$

3.2 Dirty Paper Coding

Once the superposition is computed and the CU signal is partially shared to relay the PU signal, the next step is to design $\hat{X}_c^n$ efficiently, in such way to minimize the PU interference. The optimal strategy uses the theoretical results presented by Costa [5]. Without further details, in theory, on the assumption that the interference is noncausally known at transmitter, a transmitter-based interference presubtraction can be implemented, without any power increase, reaching the AWGN capacity.

By rearranging the Eq.2 and considering the superposition results, we have :

$$Y_s^n = \mid h_{cc} \mid \hat{X}_c^n + \underbrace{\left(\mid h_{cp} \mid + \mid h_{cc} \mid \sqrt{\alpha \frac{P_c}{P_p}} \right) X_p^n}_{S^n} + Z_s^n, \tag{6}$$

where the interference is defined by S^n. In addition, in order to simplify the notation through this paper, the Eq.6 is normalized by the direct path attenuation factor$\mid h_{cc} \mid$.

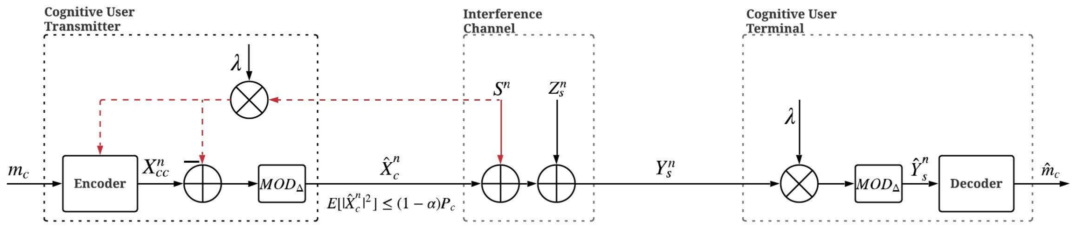

FIGURE 3 – Proposed DPC Encoder

The Fig.3 presents the diagram of the DPC encoder. The partial interference pre-subtraction (PIP) is implemented. In this way, the signal $\hat{X}_c^n$ is designed as :

$$\hat{X}_c^n = \Big[X_{cc}^n - \lambda S^n \Big] MOD_\Delta \ , \tag{7}$$

where X_{cc}^n is the coded signal and the factor λ, to be properly chosen, controls the fractioned interference to be presubtracted. Also, MOD_Δ is the complex-valued modulo operation. The amplitude is defined by $\Delta = \sqrt{M} d_{min}$, where M is the number of points of expanded square QAM constellation and d_{min} the minimum intersymbol distance.

In this work, the called trellis-shaped based DPC encoder was implemented, using a 16-QAM expanded constellation at the transmission rate is $R_{cu} = 2$ bits/symbol. The modulo operation presubtracts the interference while assuring a low increasing power, however, causing some distortion. The detailed analyses and characterization of this encoder can be find in [2].

The receiver operation, considering the elements presented in the last section, is illustrated by Fig.3. At the decoder input, the signal is given by :

$$\hat{Y}_s^n = \Big[(\hat{X}_c^n + S^n + Z^n)\lambda \Big] MOD_\Delta \tag{8}$$

Finally, the value of λ used in practice in order to minimize the equivalent noise for DPC systems is defined by [5] :

$$\lambda = \frac{(1-\alpha)P_c}{(1-\alpha)P_c + E[|Z_s^n|^2]}. \tag{9}$$

3.3 Practical System Analysis

Concerning the CU transmission, it could be design by implementing a particular and independent transmission chain and antenna or by sharing the same antenna with PU. It is noticed that the transmission of both signals into the same power amplifier should be avoid due to the nonlinear effects.

Moreover, in the reception side, both design solution could be adopted : (i) different receiving sites system for each signal, which could reduced the interference due to attenuation at the interfering paths or (ii) the same receiving signal with two dedicated demodulators and decoders. In this case the interfering and direct paths will be the same, increasing the interference in both links. On the other hand, the hardware is simplified.

Concerning the techniques described, we point out that due to the superposition the bit rate of the secondary service will be lower in respect to the primary. However, it would generate two practical problems : (i) the DPC presubtraction technique is performed considering the same symbol rate for both signals and (ii) in the superposition technique, the interference generated by CU signal would appears as spikes in the PU bandwidth, making the interference model unrealistic. In order to avoid both constraints and validate this model, the solution is to implement the spread spectrum technique at CU transmission. In this sense, the DPC encoder can be effective and the CU receiver can demodulated at the any designed transmitted data rate.

In some design conditions, a low correlation is observed between the signals X_p and $\hat{X}_c^n$. In this situation, a small degradation is obtained at the PU performance. As a countermeasure, a dithering technique can be implemented at the CU signal.

4 Realistic Use Case

We adopted a scenario where a Cubesat at a height of 600 km and the same orbital parameters as [6], using COTS parts, transmits from the same satellite antenna both signals (primary and cognitive) towards the same earth station, which is equipped with two dedicated demodulators. In this sense, all channel parameters, for direct and interfering paths, are the same. In addition, we are just considering downlink in this case.

The main specification for PU signal are : output power of 1 W [4], operating frequency of 2200 MHz (Earth Exploration Satellite Service downlink band), bit rate of 3.4 Mbps, BER specified to 10^{-5} and coded QPSK modulation with FEC (R=1/2).

The Table 1 presents the link budget of PU without secondary service addition. It is worth noting that a conservative margin for demodulation losses of 6 dB is assumed in order to cover the impairments of the communication chain. The overall link margin is about 3.5 dB, as a function of the BER specified.

In the next step, we use part of the power remaining in this margin to transmit the CU signal. Therefore, we defined that 900 mW are allocated for PU transmission (which maintain a recommended link margin of 3 dB) and 100 mW are used for CU. In this condition, the interference-to-noise ratio (INR) and the link degradation D is given by :

$$INR = \frac{I_c}{N_p} = 4.47; \tag{10}$$

$$D(dB) = 10 * log(1 + INR) = 7.38\, dB.; \tag{11}$$

Table 1- PU Link Budget (QPSK coded FEC R=1/2)

Frequency (MHz)	2200
Throughput Rate (Mbps)	3.4
Transmit Power (W)	1
Satellite Carrier EIRP (dBm)	38.3
Free Space Loss (dB)	-162.2
Depointing Loss (dB)	-10
Ground Station Antenna max gain - 5m, eff 50% (dBi)	38.2
System Noise temperature (K)	130
C/N0 (dB-Hz)	81.8
Eb/N0 (dBHz)	16.5
Demodulation losses (dB)	-6
Eb/N0 required - BER = 1E-5 (dB)	7
Margin (dB)	3.5

Table 2 - CU Link Budget

Transmit Power (W)	0.1*0.15
Satellite Carrier EIRP (dBm)	20.1
Free Space Loss (dB)	-162.2
Depointing Loss (dB)	-10
Ground Station Antenna max gain - 5m, eff 50% (dBi)	38.2
System Noise temperature (K)	130
C/N0 (dB-Hz)	63.6
Demodulation losses (dB)	-6
Eb/N0 required (dB) – for BER = 1E-3	10
Eb/N0 required (dB) – for BER = 1E-5	12.5
Margin (dB)	3
Bit Rate (kbps) – for BER = 1E-3	28.8
Bit Rate (kbps) – for BER = 1E-5	16.2

In order to overcome this PU degradation, the CU performs the superposition strategy. Considering all parameters evolved by (5) we obtain $\alpha = 0.85$.

Once we solved the PU link by this shared power, a simulation for CU link is realized and the Fig. 4 presents the BER results for both links. We highlight that, thanks to the superposition strategy and the DPC encoder (see [2]), the PU users maintain the same performance as in absence CU interference.

By taking the link parameters and the CU BER curve, we can now compute the link budget for CU, presented at Table 2. It is important to note that only 15 % of the power originally allocated for CU is used for its own transmission, by reason of superposition. As a result, we assure that the bit rate of 16 and 28 kbps can be reached, as a function of the BER specified.

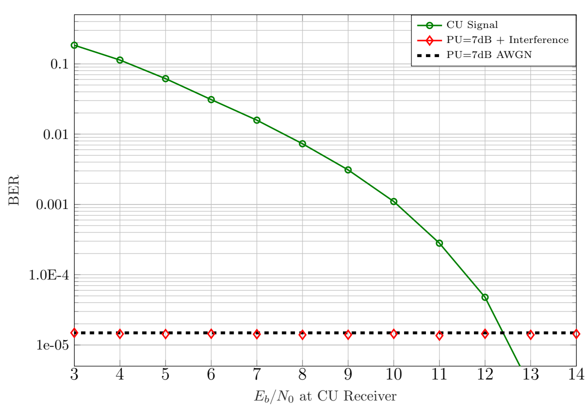

FIGURE 4 – BER CU

5 Conclusion

This paper investigates the feasibility of a low data rate secondary service transmission over an primary user infrastructure. A realistic scenario was presented with COTS parts and the different techniques were implemented to resolve both links interference. As a result, we obtained the same performance for the PU as in absence of CU operation (i.e. the same BER as AWGN channel). Concerning the secondary service, we have reached a data rate greater than 16 kbps.

Considering the further research, we will seek another proof of concept by means of SDR implementation. In addition, the effect of unwanted impairments, typically on satellite communication, will be characterized for the techniques implemented.

Acknowledgment

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