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A Discussion on Cognitive Radio Techniques to Ultra-High Data Rate Downlink for Satellite Communications

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Abstract. *Upcoming Earth Observation Satellite (EOS) missions will require ultra-high data rates for downlink transmissions, emphasizing Adaptive Modulation and Coding (MODCOD) techniques combined with Cognitive Radio (CR) techniques. These combinations: 1) increase the RF power and bandwidth efficiencies; 2) achieve efficient use of the available spectrum; and 3) promise to be the best solution in the next years. Among them, the 1) Dynamic Spectrum Access and 2) Spectral Sharing techniques are being extensively studied and standardized. So, this paper discusses cognitive radio techniques to ultra-high data rate downlink for satellite communications. This begins with essential aspects of CR Spectral Awareness and Spectral Exploitation to provide a basis for spectral enhancement for SatCom. Then, it proposes and evaluates an Adapted MODCOD technique (ACM), based on the DVB-S2 standard, supported by CR approaches. Its mean information rate of 494.15 Mbps promises better Thesis results.*

Keywords: Cognitive Radio; Spectrum Awareness; Spectrum Exploitation; MODCOD; ACM.

1. Introduction

The expanding demand for wireless broadband spectrum communication systems to provide high data throughput has forced the need for flexible and efficient use of spectrum resources. At the same time, the supply is limited and underutilized because of spectrum segmentation and the dedicated frequency allocation for standardized wireless systems (BUDIARJO et al., 2008). Most of the available spectral resources are licensed, and there only is a range to add new services if some existing licenses are discontinued. Spectrum allocation policy neutralizes the desired free mobility of radio communication equipment.

This scarcity has motivated the progression of CR communication (MITOLLA, 2000), which comprises a variety of techniques enabling the coexistence of licensed and unlicensed systems (licensed/primary user - LU/PU and cognitive/secondary user - CU/SU) over the same spectrum.

Cf. (ETSI, 2016), "the CR system employs a technology that allows the system to obtain a knowledge of its operational and geographical environment, established policies, and internal state, to dynamically and autonomously adjust its operational parameters and protocols according to its obtained knowledge in order to achieve predefined objectives".

According to (SHARMA et al., 2015), in terrestrial and satellite contexts, there are two widely used approaches for enhancing the spectral efficiency of current wireless systems: 1) by utilizing opportunistic spectrum access, named **Dynamic Spectrum Access**; and 2) by sharing the available spectrum between primary and secondary systems, called **Spectrum Sharing**. The basic operational techniques available in all the proposed CR systems can be described as the continuous cognitive cycle in the sequence shown in Figure 1.

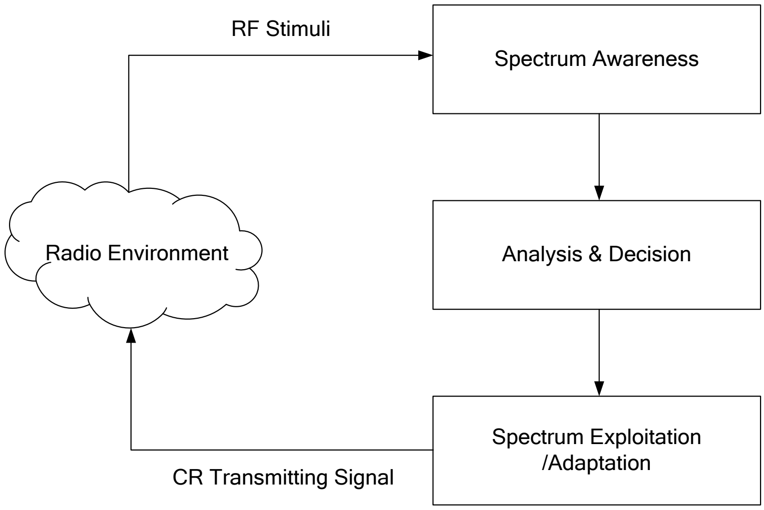

Figure 1. A simplified cognitive cycle.

Spectrum awareness: the first task for a CR is to be aware of its surrounding radio environment,

Analysis and decision: to analyze the acquired information and to take an intelligent decision on how to use the available resources effectively, and

Spectrum exploitation/adaptation: the CR autonomously adapts its operational parameters, such as transmit power, operating frequency, modulation and coding schemes, antenna pattern bean or polarization, etc., to any environmental conditions in order to exploit the available spectral opportunities effectively.

2. Methodology

2.1. Spectrum Awareness Techniques

Depending on the awareness level and required metric for spectrum exploitation purpose, different methods of spectrum awareness can be employed.

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As shown in Figure 2, spectrum sensing (SS), database, and beacon transmission-based methods are applied to acquire spectrum occupancy information. They promote information about SNR and channels of PU, suitable SNR, and channel estimation using specific algorithms. For performing overlay communication, PU signal waveform characteristics must be necessary, such as modulation and coding (MODCOD) scheme, cyclic frequencies, pilot/header information, etc. For this, suitable MODCOD detection and classification, frame header/pilot estimation approaches can be employed.

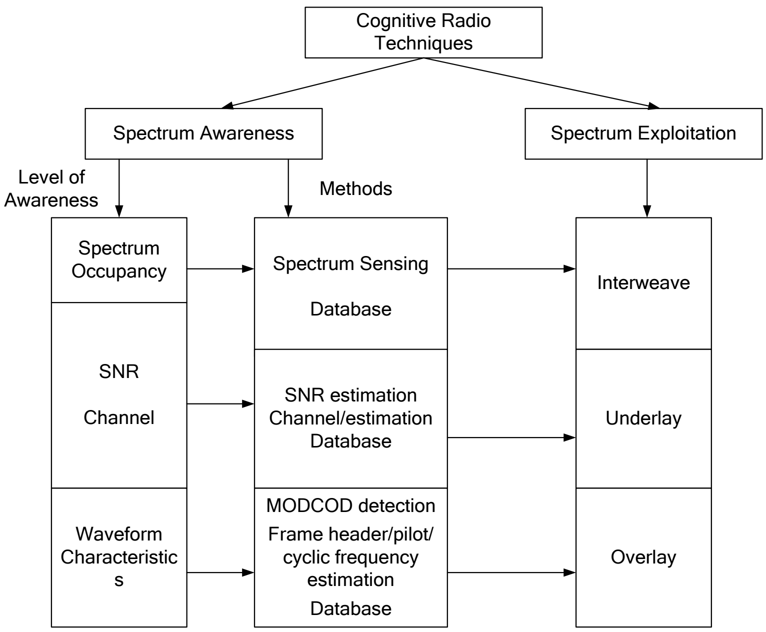

Figure 2. Mapping of spectrum awareness exploitation techniques.

A. Database:

A geolocation database is an alternative to the spectrum awareness approach to obtain knowledge of the radio environment. It is used to query various levels of information required by CR. This scheme saves primary system spectrum usage parameters in a centralized database, such as the location area, time, frequency, etc. (MALEKI et al., 2014). When an SU needs to use a portion of the primary spectrum, it must request the database system to check availability and grant access to unoccupied channels. This approach involves frequently maintaining the centralized database with information on regional spectrum usage, including the location of PTs, coverage areas, operating frequencies, transmission powers, radio technologies, etc.

B. Beacon Signals:

This awareness method is based on the beacon signals of regional broadcasting in the proper signaling channels by primary systems; CR establishes information about spectrum occupancy by detecting these signals. The beacon signals may carry information about spectrum usage, traffic trends, future frequency usage, etc. This approach requires an agreement between secondary and primary system operators to share the real-time spectrum usage information from PU to SU.

C. Spectrum Sensing:

SS is an essential mechanism for acquiring spectrum occupancy information of the PU spectrum. It exploits the spectral holes in various domains such as time, frequency, space, polarization, and angular. We assumed that the secondary transmitter (ST) system operates with a sensing RF chain capable of detecting the presence or absence of PUs using signal processing techniques. According to (AXELL et al., 2012), there are several SS techniques.

2.1. 1. Spectrum sensing techniques

- *Energy Detection:*

ED is the most common SS approach because of its low computational and implementation complexities (HERATH et al., 2011). This technique allows the detection of the PU signal by comparing the output of an energy detector with a predetermined threshold, which depends on the environment noise floor. This method is simple to implement but has drawbacks such as the inability to differentiate interference from PUs and the noise, and poor performance under low SNR values.

- *Matched Filter Based Detection*

Matched filtering is the optimum method for PU detection when the transmitted signal is well-known (PROKAIS, 1995). The main advantage of the matched filter is that it requires less time to achieve a specific target probability of false alarm or probability of missdetection as compared to other methods since of its coherent functionality. This approach has two disadvantages: 1) the necessity of a dedicated receiver channel for each PU type; and 2) its requirement for synchronization between transmitter and receiver, which can be challenging to achieve in practice since two different operators may administrate the primary and secondary systems.

2.2. Spectrum Exploitation Techniques

Based on the knowledge of the PUs transmitting signals reported in Figure 2, we can broadly classify the existing spectrum exploitation techniques into interweave, underlay, and overlay techniques (SHARMA et al., 2015).

A. Interweave:

This spectral coexistence approach incorporates interference avoidance or opportunistic techniques whose objective is enabling CR to communicate opportunistically using spectral holes in space, time, and frequency that are not occupied by the PUs. Therefore, there occurs no interference in the ideal case. The surrounding environment can be constantly identified and monitored to predict the underutilization of each fraction of the spectrum to be accessed by SUs until the main activity remains idle. We can consider polarization and angular dimensions as additional spectrum exploration purposes in interweave communication.

B. Underlay:

In this paradigm, simultaneous cognitive and non-cognitive transmissions are allowed in the same frequency band as long as the interference level on the PU side remains acceptable at the threshold-defined level. The interference temperature concept can model the maximum allowable interference level on the PU, and the local federal policy (FCC, 2003) regulates the limits. Moreover, underlay communication is performed using one or a combination of the following methods: (i) beamforming with the use of multiple antennas or phased array; (ii) dynamic resource allocation (carrier and power) in the ST; (iii) spread spectrum approaches by spreading the secondary signal below the primary signal noise floor and then dispreading at SR; (iv) by using Exclusion Zone (EZ) principle. PU system information such as SNR, channels, and DoAs are useful for realizing the underlay techniques.

C. Overlay:

The mitigation of the interference using advanced coding and transmission strategies at the ST defines the overlay networks. Also, when the SU is transmitting simultaneously with PU, the interference caused by the ST to PR can be compensated by using a part of the SU power to relay the PU message. PU shares information about their signal codebooks and messages in this paradigm with SU. Thus, the cognitive devices may enhance and assist the primary transmission rather than vying for spectrum access. More precisely, SU overhears the messages sent by PU sources and uses these messages either to eliminate the interference generated by the primary communication on the SR side or to improve the performance of the primary transmission by relaying the accumulated messages to the PR. This latter case allows the ST to transmit both signals simultaneously, as long as its overall transmitting power is enough to cover the energy necessary for its communication jointly with its relaying operation. Overlay techniques are the most suitable for integrated systems with high cooperation between satellite and terrestrial networks.

Figure 3 shows the signal representation of these three exploitation techniques.

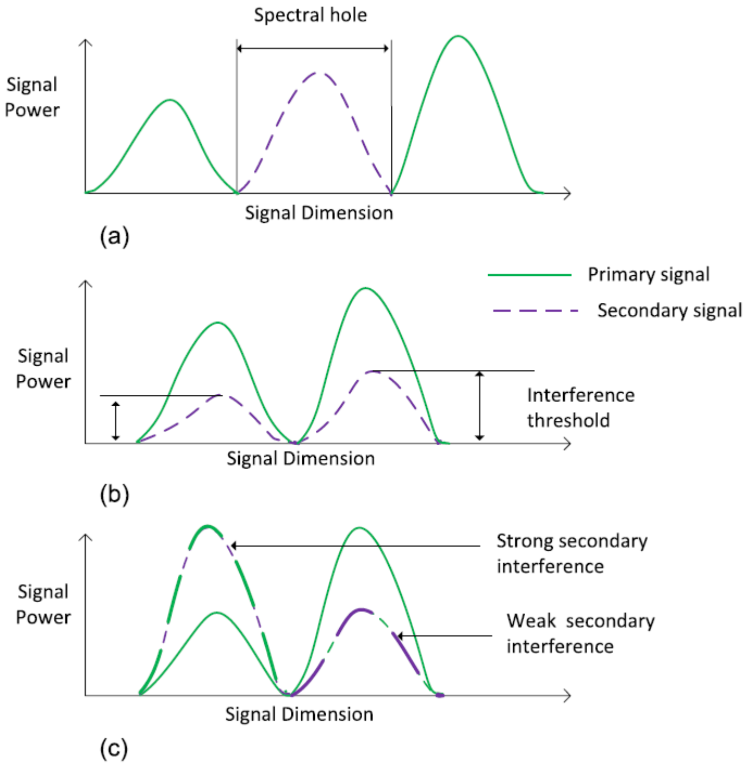

Figure 3.Representation of interweave, underlay, and overlay techniques.

2.3. Cognitive Radio Modulation Techniques

In terrestrial systems, they employ modulation strategies to perform coexistence between the SU and PU systems so the SU becomes invisible to the PU. As mentioned before, the cognitive access of an unoccupied PU band is considered the interweave paradigm.

- *OFDM*

According to (BUDIARJO at al., 2008), Orthogonal Frequency Division Multiplexing (OFDM) is a spectrally efficient modulation mode due to its overlapped carrier spectrum, which remains orthogonal to each other. It gives a higher bit rate than the single carrier transmission in a fading transmission channel. Different subcarriers may be separated into the receiver due to this orthogonality; the frequency division is achieved not by classical band-pass filtering but by doing a product between the received signal and a signal base vector. This operation is realized with baseband signal processing.

OFDM has been applied as a strong multicarrier modulation scheme in CR applications, such as spectrum pooling (WEISS et al., 2004). The rationale is that any CR system needs to sense the spectrum, and this involves some sort of spectral analysis. Fast Fourier Transform (FFT) can be used for spectral analysis while at the same time acting as an OFDM demodulator, as shown in Figure 4.

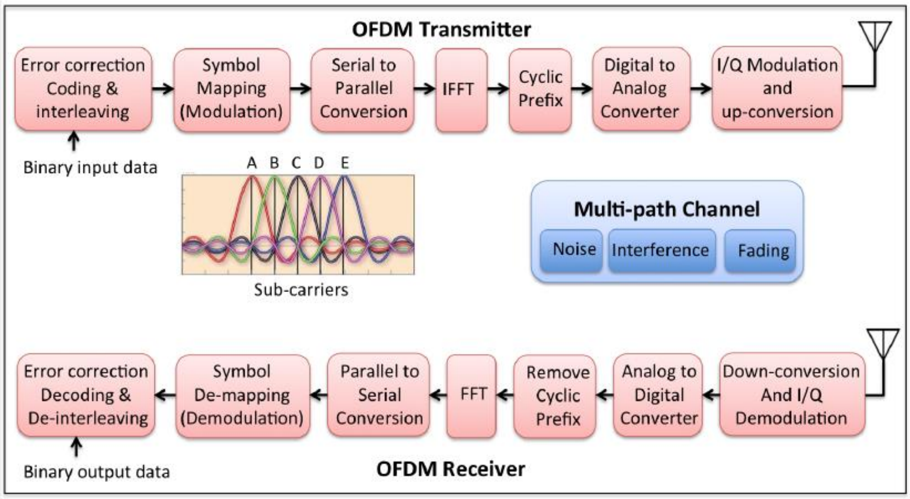

Figure 4. OFDM overall communication system.

OFDM also has the capability to notch the parts of its carriers, which are coincidentally within the region of the PU band. Such OFDM flexibility simplifies the application of CR dynamic spectrum access.

2.4. Adaptive Coding and Modulation (ACM) Techniques

Despite the fact that ACM techniques are not usually referred to as a CR approach, herein its concept are introduced, and will be possible to discover how this technique can be used to achieve better bandwidth efficiency and power utilization

Advanced High Data Rate (HDR) downlink techniques are based on an adequate use of MODCOD in ACM mode. The Low Density Parity Check (LDPC) coding followed by Amplitude Phase Shift Keying (APSK) modulation will be the next generation standard for HDR data downlink (ADDABBO, 2014), under the DVB-S2 standardization by (CCSDS, 2013). The fundamental idea under LDPC codes is to use a simple encoder that is able to produce long code-words with exceptional word-distance properties and low complexity techniques based on the predefined structure of the encoder. APSK constellation works better than PSK or QAM in the presence of non-linear distortions caused by solid state or TWT amplifiers working in the saturation region. The system parameter to be controlled can be summarized as: i) code performance at the defined Bit Error Rate (BER). For LDPC codes there is a region after which the performance flattens, this region is called the error floor and the work point shall be located reasonably far from the error floor; ii) code rate selection given the expected performance; iii) encoding/decoding complexity.

DVB-S2 is the second-generation standard for Digital Video Broadcasting. This MODCOD format is based on LDPC codes combined with five selected modulation formats (QPSK, 8PSK, 16APSK, and 32APSK) and with a wide range of code rates (1/4 to 9/10), ranging in spectral efficiency from 2 bit/s/Hz to 5 bit/s/Hz. ACM is introduced here in order to optimize the transmission, thus allowing the transmission parameters to be changed on a frame by frame basis depending on the particular conditions of the delivery path. The main transmission scheme can be considered for data downlink using the ACM for which the MODCOD is adapted according to the link elevation angle. This adaptation can be implemented with feedback return channel. If feedback can be provided and instantaneous channel quality estimation can be implemented (SNR detection), the ACM scheme for which MODCOD is adapted in real-time to channel conditions can be adopted.

3. Results and Discussion

3.1. CR technique – the CoRaSat proposal

The CoRaSat project aims at investigating, developing, and demonstrating CR techniques in European satellite communication systems for spectrum sharing. Outcomes of the study will drive the definition of strategic roadmaps to be followed by industry stakeholders, institutions and Governmental actors in Europe towards regulatory and standardization groups in order to ensure that the necessary actions are undertaken to open new business perspectives for SatCom through CR communications in support of the Digital Agenda for Europe in the next years. For the frequency plan described below, interference scenario is defined as follows (MALEKI et al., 2015). In a Scenario of coexistence of FSS downlink with the FS links in 17.7 GHz – 19.7 GHz (Figure 5), FS databases can help to reduce or even eliminate the complexity of wideband sensing across large geographical areas. A specific database needs a number of parameters of the FS links. They can be used to verify locations where the FS will not interfere in the FSS reception. The FS station information itself may not be sufficient when released to the FSS operator and a database user interface may provide the necessary information for a dedicated FSS earth station location in question, thus avoiding data protection and non-public information issues.

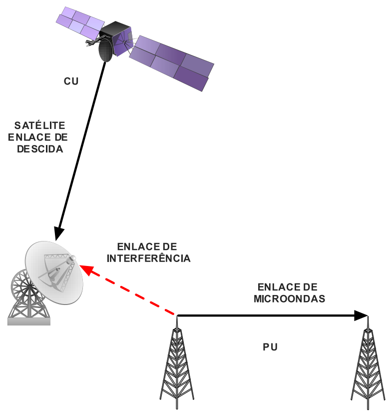

Figure 5. CoRaSat scenario.

If there are clear gaps in the terrestrial channel occupancy, then it could straightforwardly apply the database approach. In this context, another promising technique for avoiding harmful interference is sensing the FS transmission. For this, the characteristics of FS link such as power, directivity and bandwidth is important to find the correct sensing threshold. When an FSS terminal detects FS transmitter interference, the FSS needs to apply some cognitive actions such as switching to exclusive bands, resource/ carrier allocation techniques or beamforming to get the desired QoS for its cognitive link.

3.2. ACM proposal according to CCSDS

Using a combination of transmission modes as suggested by (CCSDS, 2013), and reported in Table 1, for a 200 Msymbol rate, the mean information rate is given by 30×1.655+25×1.981 +40.6×2.228+28.4×2.479+50×2.967+26×3.300 = 494.15 Mbps.

Table1. ACM proposed based on CCSDS. [Source: CCSDS (2013)

DVB-S2 MODCOD	Efficiency bit/symbol	E_S/N_0 for BER=10^{-7}	% of being in this mode-CCSDS
QPSK 5/6	1.6547	5.2	15.0
8PSK 2/3	1.9806	6.7	12.5
8PSK 3/4	2.2281	8.0	20.3
8PSK 5/6	2.4786	9.4	14.2
16APSK 3/4	2.9667	10.3	25.0
16APSK 5/6	3.3002	11.7	13.0

4. Conclusion

The purpose of this paper was to discuss cognitive radio techniques to ultra-high data rate downlink for satellite communications, based on a literature review of CR approaches. It proposed and evaluated an adaptive MODCOD techniques, based on the DVB-S2 standard, combined with CR techniques. The mean information rate of 494.15 Mbps of the proposed ACM based on the CCSDS standard demonstrates the method's effectiveness.

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