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Cognitive Satellite Terrestrial Radios

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***Abstract*—In this paper we present the concept of cognitive satellite terrestrial radios (CSTR) for hybrid satellite-terrestrial systems (HSTS). The cognitive radio (CR) technology is being motivated by the radio regulatory bodies for efficient utilization of the radio spectrum. The future satellite ground terminals therefore need to integrate and co-exist with the spectrally crowded terrestrial wireless systems and hence we propose the idea of CSTR. The key issues are addressed and the concepts of developing CR based satellite ground terminals in HSTS for dynamic spectrum access on the ground are presented. Furthermore, the concept of 3D-Spatial reuse of the spectrum is also presented using the CSTR considering low elevated satellite ground stations. Two particular HSTS applications to illustrate the CSTR concept, a) the hybrid satellite-UWB (ultra wideband) communication system for personal area networks (PAN) with short range on ground communications, and b) the hybrid satellite-WRAN (wireless regional area networks) for long range on ground communications are presented. In both the applications the satellite uplink and the terrestrial radios adopt the CR functionalities. The key enabling technologies and their integrated architecture for the CSTR are also presented.**

***Index Terms*—cognitive satellite terrestrial radio, satellite ground terminals, cognitive radios, hybrid satellite terrestrial communications**

I. INTRODUCTION

The convergence of global telecommunications infrastructure is necessary to cater the demand of 'Future Internet', and to provide seamless connectivity and communication services. With such a motivation we consider the convergence of satellite and terrestrial networks leading to the concept of hybrid satellite-terrestrial systems (HSTS) [1]-[4]. The terrestrial wireless communication system continuously keeps advancing with rapid pace and at a certain point gets limited by its coverage range due to the fundamental physical constraints such as power requirements, terrain and infrastructure (obstructions), and antenna types etc. The satellite technology with its own limitations however is able to supplement the drawbacks experienced by terrestrial systems to extend the coverage, and therefore the hybrid system (HSTS) is considered to provide extended global coverage.

Most of the current terrestrial/ground communication systems are deployed without considering the requirements for such hybrid satellite-terrestrial systems. Since changing the existing terrestrial communication systems to suit HSTS are not feasible we consider the future wireless terrestrial systems in our work, namely the cognitive radio (CR) based systems [5]-[6], and study the requirements for it to act as satellite ground terminals (as well as terrestrial terminal) for HSTS. Such CR based satellite ground terminals need to integrate and co-exist with the other terrestrial systems by efficiently sharing frequency, time and spatial resources leading to the concept of Cognitive Satellite Terrestrial Radios (CSTR), which we present in this paper.

CRs have been proposed to efficiently utilize scarce radio resources [5] and strongly encouraged by the radio regulatory bodies around the world. The CR terminal opportunistically utilizes the spectrum when it becomes accessible on a non-interfering basis in a spatio-temporal manner by giving higher priority to the incumbent spectral users (ISU) in the environment. The spectral usage has been proven to be under utilized by the ISUs giving rise to spectral holes. The spectral usage in the space-time-frequency domain can be categorized as [6]: *a) Black Space*-spectral portion occupied by high-power local interferers some of the time, *b) Grey Space*-spectral portion which are partially occupied by low-power interferers, and *c) White Space*-spectral portion free of RF interferers except for ambient noise consisting of natural and artificial forms of noise. The coexistence and integration of satellite (uplink) and terrestrial networks on the same frequency bands can exploit an additional degree of freedom which is normally not available to the terrestrial CR network. (Note that the frequency bands considered here are of course open for discussion). In fact, since the satellite is seen under a high elevation angle (depending on the latitude), proper design of antenna radiation diagrams can allow to reduce mutual interference and therefore enable cognitive frequency reuse. In other words, this can be regarded as a 3D-space time-frequency utilization as oppose to 2D-space time-frequency utilization of the radio resources, which is also presented in this paper considering the CSTR.

The cognitive ground terminal architecture and design which we present in this paper follows from the work done by Mitola [5] and Haykin [6]. Based on the applications, 1) The IEEE802.22 regional area networks (RAN) [7],[8] and 2) The ultra wideband (UWB) based personal area networks (PAN) [9]-[15], we present two specific scenarios (use cases) for the deployment of CSTR for hybrid satellite terrestrial systems.

The rest of the sections are organized as follows. In Section II we present the WRAN/PAN scenarios where the CSTR

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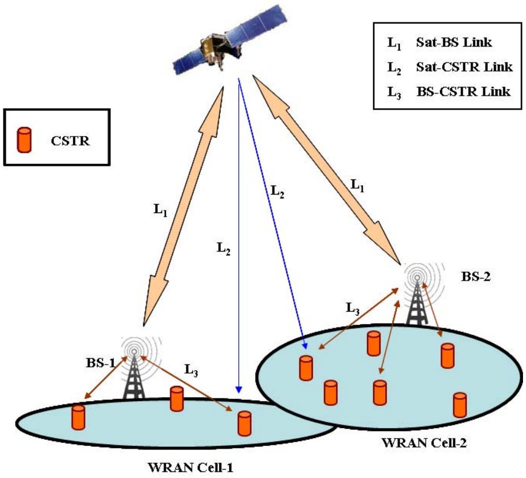

Fig. 1. IEEE 802.22 RAN based HSTS systems with cognitive satellite terrestrial radios

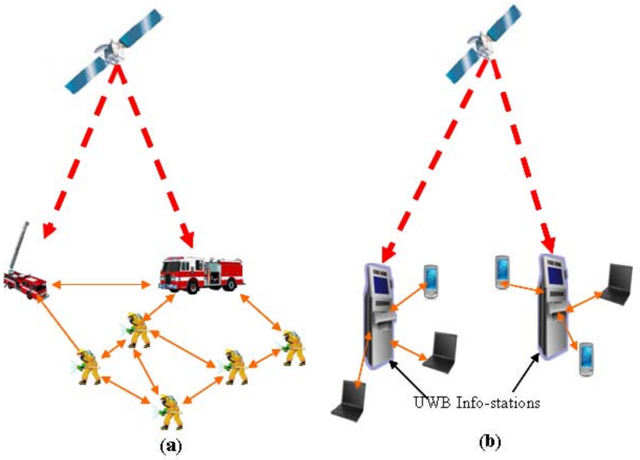

Fig. 2. UWB Personal Area Network based HSTS with UWB cognitive satellite terrestrial radios (a) for low data rate (emergency services) applications (b) for high data rate applications

concept can be deployed for HSTS. In Section III we summarize the existing cognitive functionalities in satellite/terrestrial radios and identify the new ones for future systems. In Section IV we present a detailed architecture of the CSTR with the CR functionalities. In Section V we present the 3D-spatial spectral reuse concept and some concluding remarks in Section VI.

II. APPLICATION SCENARIOS

Two applications are considered, first, the IEEE802.22 CR based wireless regional area networks (WRAN) for long range communication, the first CR standard for opportunistically reusing the tv band spectrum, and second, the CR based UWB communication systems for short range personal area networks. Based on these we present two hybrid systems for HSTS, 1) satellite-WRAN, and 2) satellite-UWB for PANs, for the deployment of CSTRs.

A. Hybrid Satellite-IEEE802.22 Systems for WRAN

The IEEE802.22 WRAN addresses dynamic spectrum access for long range communications using the television bands between 54MHz-862MHz. The IEEE802.22 radio units will opportunistically utilize the spectrum giving higher priority to the incumbent users such as tv broadcasting. A typical size of WRAN can range from 17-32km as oppose to WMAN/WLAN with shorter ranges. Here we consider a hybrid satellite-WRAN terrestrial system as depicted in Figure 1. The IEEE 802.22 WRAN uses a cell structure with a base station (BS), and in our model we also incorporate (single/multiple) satellite(s) as shown in the figure. The downlink transmissions from the satellite covers the BS as well as the CSTRs and the satellite uplink is only performed by the BS. The CSTR in which case communicates with the satellite through the BS.

B. Hybrid Satellite-UWB Systems for PANs

UWB systems in the 3.1 GHz - 10.6 GHz band are ideal candidates for the introduction of cognitive solutions, given their implicit requirements for coexistence with other wireless systems. UWB is presently proposed as a potential solution in two different application scenarios: high rate, short distance communications and low rate, medium distance communications combined with ranging and positioning. The former application scenario led to the definition of the Wi-Media UWB industrial standard, characterized by an OFDM physical layer capable of guaranteeing transfer rates in the order of 500 Mb/s over up to ten meters [10]. The low rate scenario was investigated within the IEEE 802.15.4a Task Group. Within this group, an Impulse Radio Ultra Wide Band (IR-UWB) physical layer was proposed, capable of providing communications up to 25 Mb/s as well as accurate ranging information, required for accurate positioning [11],[14]. Both high rate and low rate UWB applications pose hard challenges in terms of coexistence with legacy and primary systems; as a consequence both of them will be taken into account in this work. Figure 2a) shows a typical low rate hybrid satellite-terrestrial scenario, consisting in an emergency service network with UWB devices exchanging data and carrying out ranging in order to enable mixed indoor/outdoor communications and positioning. Figure 2b) shows an example of a high rate hybrid satellite-terrestrial scenario where UWB-equipped info-stations deployed in an outdoor scenario send information to mobile devices such as laptops and PDAs.

III. COGNITION IN SATELLITE AND TERRESTRIAL SYSTEMS

The satellite and terrestrial systems in general can make use of many realtime information to maximize the usage of the radio resources and to improve the performance of the link. Most of the cognitive functionalities one could think of are already in place in such systems one way or the other which we summarize subsequently.

A. Cognition in Satellite Communications:

Real time intelligence are already in use in many of the satellite communication systems for operational and management purposes and to provide the required QoS. Some of them are ***satellite orbital knowledge:*** such as LEO, MEO, GEO, elliptical or polar etc, ***satellite link knowledge:*** such as rain fading conditions in order to have adaptive coding and modulation (ACM) at the receiver, ***Doppler knowledge:*** such as for frequency synchronization, and also for Doppler assisted satellite tracking, ***satellite network constellation knowledge:*** such as for handover mechanisms etc, and ***satellite services knowledge:*** such as satellite broadcasting, broadband, voice services etc.

B. Cognition in Terrestrial Wireless Communications:

The terrestrial systems also do have some intelligence already incorporated in the transceiver units, some of them are, ***communications channel knowledge:*** such as for channel selection, ***channel state information:*** such as for link adaptation etc. The future wireless systems however, based on the CR technology, will have more intelligence incorporated, and some of them are, ***radio knowledge (RK):*** such as the existing radios (frequency usage) in the environment, ***radio position knowledge (RPK):*** such as the location of the radios in the environment, ***time-frequency knowledge (TFK):*** such as the usage of radio resources in continuous realtime, and ***interference temperature knowledge (ITK):*** such as the total interfering radio power in the environment.

C. Cognition in Hybrid Satellite Terrestrial Systems

The latter mentioned intelligence in Section III-B (RK, RPK,TFK and ITK) forms the core part of CR which enables it to utilize the radio resources more efficiently. For the HSTS, such intelligence however can only be adopted for the terrestrial ground based transmissions and the satellite uplink transmission. The satellite downlink cannot adopt such functionalities due to many practical limitations in controlling the satellite transmissions. One of the major reasons for this is the large area of coverage provided by the satellite, which makes it hard to perform dynamic spectrum sharing. Even using a spot beam coverage for a satellite downlink (with a few 100 kms of coverage), it seems too hard to incorporate CR functionalities due to the potential interference that it could cause to the terrestrial systems in such a large geographical area. Nevertheless, the CR concept is not completely discarded for satellite downlink which can be used for more wider geographical range compared to the range covered by the existing terrestrial systems. However, in the work that we present here we do not consider such cognitive approaches for the satellite downlink transmission. The satellite uplink will cause lesser interference to the terrestrial systems considering highly directional upward transmissions, but at the same time uplink transmissions with low elevation angles tend to interfere more with the terrestrial systems compared to the uplinks with higher elevation angles. The uplink transmissions also share the same radio resources as the terrestrial systems assuming the receiver units in the satellites have the capabilities. The satellite downlinks on the other hand will operate as a standard ISU without any dynamic spectrum access capabilities.

In the following sections we present an architecture for the CSTR incorporating the new functionalities considering the future wireless systems for the HSTS.

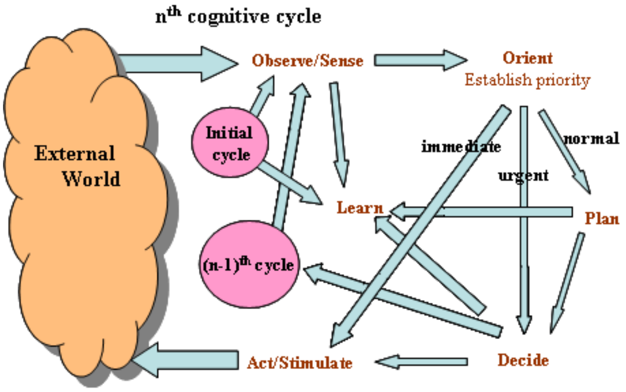

Fig. 3. The cognitive cycle, defined by Mitola [5]

IV. THE COGNITIVE SATELLITE TERRESTRIAL RADIO

The CR oriented satellite-terrestrial ground terminal architecture and the related functional blocks are presented in this section. The CSTR consists of both the satellite and terrestrial radios associated with it. The terrestrial communications and the satellite uplink (at the BS) incorporate the CR functionalities for dynamic spectrum sharing on the ground. Note that, as mentioned before, the CSTR's reverse link with the satellite is managed through the BS where the CSTR returns its transmissions only through the BS. The downlink from the satellite however is received by all the terrestrial terminals including the BSs.

A. The Cognitive Cycle

We consider a cognitive engine (similar to a human brain) to enable intelligence in the radio device. A typical cognitive engine follows a cyclic procedure to continuously monitor and learn the environment to adopt its responses accordingly. Such a cyclic procedure is known as the cognitive cycle [5] and is depicted in Figure 3. Using the 'observations' made on the external (wireless) world the CR 'learns' the radio environment and performs 'planning' and 'decision makings' based on the priorities before 'acting' (transmitting) upon a particular request. In the following sections we adopt this cognitive cycle in the CSTR architecture mapping the corresponding functionalities into specific functional blocks to observe and learn the radio environment in its surroundings to optimize the usage of the radio resources.

B. CSTR Architecture for HSTS

The generic architecture of the cognitive satellite terrestrial radio is depicted in Figure 4, which is derived from [6]. The transmitter and the receiver parts of the radio architecture consist both the satellite and terrestrial hardware components as required. In the architecture we depict the additional functionalities required for the radio to have the necessary intelligence. In the following sections we explain in detail these key functionalities of the CSTR.

C. Manifold User Environment

The HSTS on the ground has a manifold user environment and all the users on the ground are considered to perform dynamic spectrum access. Sophisticated strategies are required

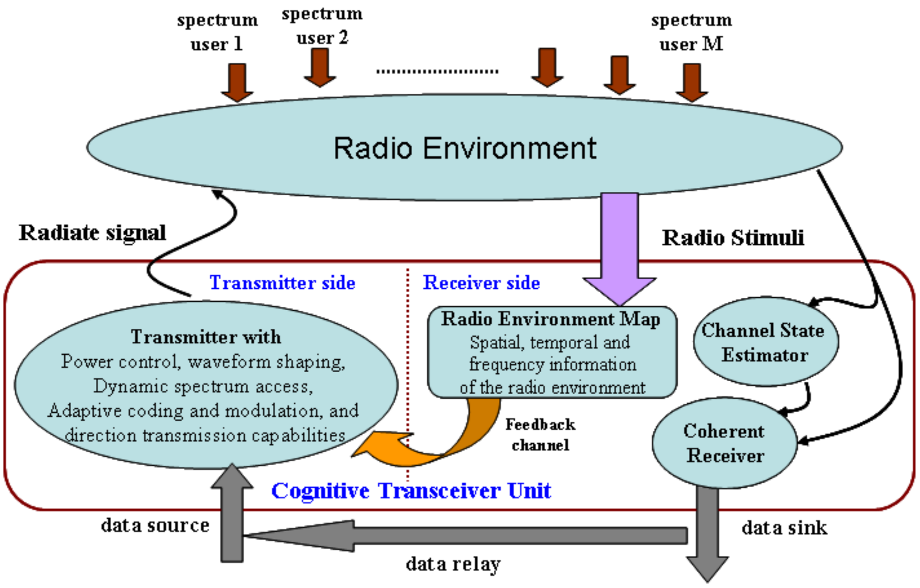

Fig. 4. The generic model of the the Cognitive Satellite Terrestrial Radio for Hybrid Satellite-Terrestrial Systems

for *opportunistic* spectrum sharing in such an environment which we explain in the subsequent sections. Though sharing is increased when the number of users K increases, leading to a reduction in the effective throughput per terminal, the CR network could also benefit from it as we see from the following sections.

D. The Spectrum Sensing Module: For Space-Time-Frequency ISU Occupancy Detection

Spectrum sensing and ISU detection in a CR network is considered to be a very important functionality [16]. The CSTR nodes need to detect any ISU's presence in the radio environment to avoid any interference to them. There are many ways to perform ISU detection by a CSTR ranging from blind to non-blind detection methods and one could refer to [16]-[18] on this. Here we present the simplest and a well known blind ISU detection method 'the energy based detection method' [21], other robust methods also exist with increased complexity [17]. In the energy based detection method the CSTR looks for any signal energy present in the received radio stimuli (from the environment) and makes a decision on whether an ISU is present or not. The main drawback with this method depending on the threshold used for the detection is that low powered signals can be gone undetected (miss detection) or the receiver noise can trigger a detection when no ISU is present (false alarm). Miss detecting ISUs with low received power levels, due to distant ISU or deep channel fading environments, leads to the 'hidden terminal problem'. Such hidden terminal problems could lead to potential interference to the ISU by the opportunistic spectrum users (CSTR). The sensed signal at time t at the i^{th} CSTR node, where $i \in \{1, 2...K\}$ can be represented considering the binary hypothesis H_0; *when an ISU is not present*, and H_1; *when an ISU is present*, as

$$r(i;t) = \begin{cases} \nu(i;t) & ;\text{for } H_0 \\ h(i;t)s(i;t) + \nu(i;t) & ;\text{for } H_1 \end{cases} \quad (1)$$

where, $s(i;t)$ is the signal received from the ISU, $h(i;t)$ is the fading channel, and $\nu(i;t)$ is the additive white Gaussian noise with zero mean and variance σ_i^2. The test statistic for detection $\theta(i;m)$ at the i^{th} CSTR node is then given by,

$$\theta(i) = \int_{t_1}^{t_2} r(i;t)\tilde{r}(i;t)dt \quad \text{for some } t_1, t_2 \in \mathbb{R}^+ \quad (2)$$

where, $\tilde{r}(i;t)$ is the complex conjugate of $r(i;t)$. The performance of the energy based detection technique for detecting the ISU depends on the time-bandwidth product. The decision $\hat{b}(i)$ made at the i^{th} CSTR node, whether an ISU is present or not, is then given by,

$$\hat{b}(i) = \begin{cases} 0 \; ; \; H_0 & \text{for } \theta(i) < \mu_i \\ 1 \; ; \; H_1 & \text{for } \theta(i) \geq \mu_i \end{cases} \quad (3)$$

where, μ_i is the decision threshold used at the i^{th} CSTR. Considering the manifold user environment the CR network can make use of all the decisions made by each CSTR to collectively decide whether an ISU is present or not. The BS fuses the data to perform cooperative decisions on the presence of an ISU. For cooperation, it should be underlined that signalling from CRs to the BS is not granted in general.

E. Location Assisted Systems: For Space-Time-Frequency ISU Occupancy Detection

The availability of position information is a key aspect in the deployment of cognitive systems, thanks to the possibility of collecting and exchanging position-related information about both primary users and cognitive secondary users: Radio Environment Maps (REM) are an example of potential solution enabled by the presence of position information [19]. Whenever available, GPS is by far the simplest way to obtain position information; hardware limitations or unfavorable propagation conditions (e.g. in indoor or dense urban scenarios) may however prevent the use of GPS in some or all of the network terminals. In this case cooperation

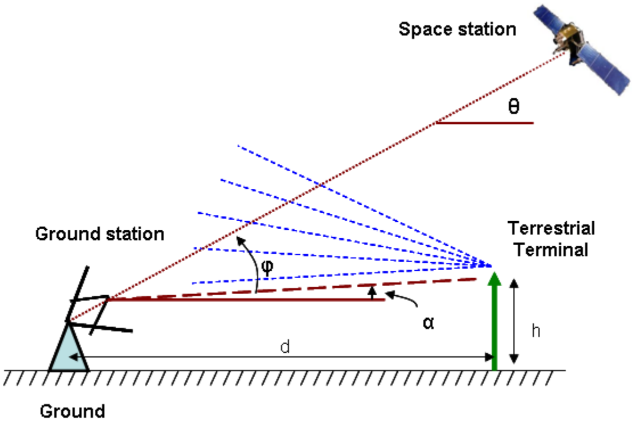

Fig. 5. The 3-D spectrum sensing model considering the ground station

between terminals is required in order to acquire position information. Proposed solutions in the literature usually rely on the combination of distributed positioning algorithms for gathering relative positions of nodes within the network, and absolute position information provided by a subset of terminals in known position (anchor nodes).

Distributed positioning algorithms rely on the capability by terminals of measuring their mutual distances, and require terminals to exchange such distance information in order to build a network map by solving a triangulation problem. The performance of such algorithms is thus highly depending on the degree of accuracy in distance measurements guaranteed by terminals; in this context the adoption of a technology capable of providing highly accurate distance measurement, such as the UWB technology considered in the scenario presented in Figure 3a) [20], can significantly improve the accuracy of the position information, and thus the effectiveness of position-based coexistence techniques such as the above mentioned REM approach.

F. Manifold Access and Interference Temperature

The access and usage of the limited radio resources by multiple users in the CR network are performed by means of either cooperation or competition. In the cooperative strategy, the manifold access problem has a direct solution where a set of protocols are defined to allow equal and fare share of the radio resources by all the CSTR nodes. In the competing strategy, all the CSTRs compete for the radio resources requiring for a sophisticated mechanism. We elaborate a bit here on the competing strategy. The competing for resource problem is viewed as a game theoretic problem with a five-tuple *stochastic game* defined by $\{\mathcal{N}, S, \overrightarrow{\mathcal{A}}, \mathcal{P}, \overrightarrow{\mathcal{R}}\}$, where $\mathcal{N}$ is the set of players $i = 1, 2..K$, $\mathcal{S}$ is the set of possible states, $\overrightarrow{\mathcal{A}}$ is the joint action set available to all the players, $\mathcal{P}$ is the transition probability function related to the joint actions, and $\overrightarrow{\mathcal{R}}$ is a function $\overrightarrow{\mathcal{A}}$ related to the payoff to the players. Then, given a finite action set (for the CSTR to act), an action profile is reached which is the best response to all the other players' action leading to the Nash equilibrium [22]. The CSTR then controls its transmit power according to such action strategies. Unfortunately, Nash equilibrium is not always reached, depending on the temporal variations, bandwidth requirements, interference map etc. In such cases, a possible solution is to introduce a referee with the power to give and take spectral resources.

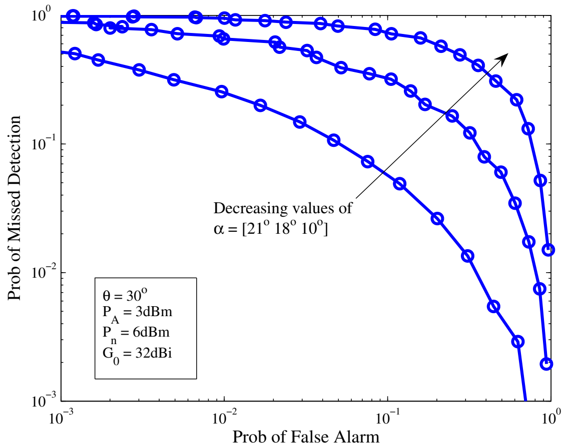

Fig. 6. Complementary ROC curves for 3D-Spatial frequency reuse, in detecting ISU on ground based on the ISU-elevation

The multiple transmissions by the CSTRs will lead to high level of self-interference in the network. Therefore, a new term defined by the radio regulatory body FCC (USA), called the Interference Temperature (similar to the receiver noise temperature) is used as a measure to control the interference. The maximum permissible power spectral density in a given frequency band is given by the interference temperature limit in degrees Kelvin (defined by regulations) multiplied by the Boltzman's constant $k = 1.3807 \times 10^{-23}$.

V. REUSE OF THE SPECTRUM IN THE 3D-SPATIAL DOMAIN WITH CSTR

Having presented the architecture and descriptions of the CSTR now let us see how CSTR enables to reuse the frequency in the 3D-spatial domain. The third spatial dimension however is considered at low elevation angles. Figure-5 depicts the concept of 3D-spectral reuse by the satellite ground terminal acting as a CSTR facilitating frequency sharing (as a secondary user) with the other terrestrial radios, considering the satellite-WRAN HSTS application. In the figure, the terrestrial terminal (TT) (e.g. digital terrestrial transmitter) has the same azimuth angle as the satellite with respect to the ground station (GS) and furthermore, θ: is the satellite elevation angle, α: is the TT elevation angle and φ: is the angle between the antenna mainlobe axis and the direction of interest (i.e. the TT), where $\varphi = \theta - \alpha$. Note that we consider the case where $\alpha > 0$, which might not be true in all the situations. In order to opportunistically access the spectrum in the 3rd spatial domain the CSTR performs spectrum sensing to detect any ISUs in the surroundings. Since the GS typically deploy parabolic dish antennas with highly directive gains the detection of any ISUs on the ground becomes challenging with lower antenna gains (at higher values of φ). Here we consider such a scenario to detect an ISU considering the ITU-R recommended antenna gain requirements for satellite GS with parabolic antennas

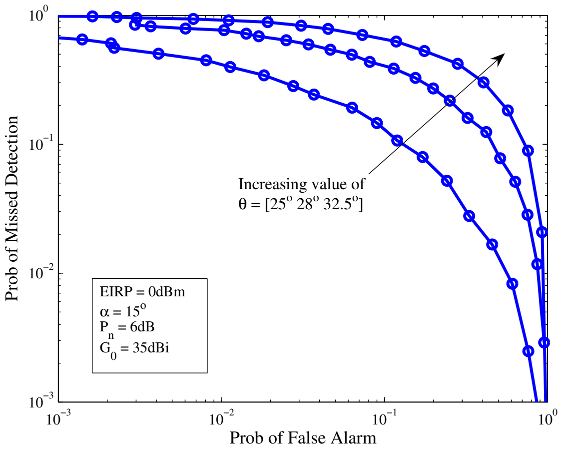

Fig. 7. Complementary ROC curves for 3D-Spatial frequency reuse, in detecting ISU on ground based on the Satellite-elevation

[23], given by $G(\text{dBi}) = G_0 - 25\log_{10}(\varphi)$ for $1^o \leq \varphi < 48^o$, and $G(\text{dBi}) = -10\text{dBi}$ for $48^o \leq \varphi < 180^o$, where $G_0 = 32\text{dBi}$. Please refer to [23] for further conditions on the gain G for various dimensions of the antenna. In the following section we present some simulation results for detecting ISU on the ground by the ground station (CSTR) for opportunistic spectrum access.

A. Detecting Terrestrial Transmitters for 3D-Spectral reuse

Using the energy based spectrum sensing described in Section IV-D we present some simulation results for detecting the TT by the GS. For the scenario considered in Section V, Figure-6 presents the complementary receiver operating characteristic (C-ROC) curves for detecting the TT (as in Figure-5) for various vaues of α. For the simulations we consider a signal power of $P_A = 0\text{dBm}$ at the GS antenna front end and receiver noise power of $P_n = 6\text{dBm}$, with one transmitter-GS pair. From the figure we observe that, due to the directional radiation (gain) pattern of the parabolic antenna, the detection performance for detecting the TT becomes worse when α reduces. Figure-7 on the other hand depicts the C-ROC for the same scenario for various values of θ, as we see from the figure (again due to the antenna gain pattern) the detection performance becomes worse for increasing θ. Therefore, considering the third spatial dimension, the detection of spectrum occupancy on ground becomes harder depending on the directional antenna patterns. On the other hand it is also important to note that such highly directional antennas interfere less with TT when θ increases or α reduces.

VI. CONCLUSION AND CHALLENGES

In this paper we presented the concept of cognitive satellite terrestrial radios on ground for hybrid satellite terrestrial systems. We present the key enabling technologies for the design of such terminals on the ground and their corresponding functionalities. The proposed idea can maximize the utilization of the spectrum in the **3D-spatial** time-frequency domains considering the satellite uplink and the terrestrial ground transmissions. Furthermore, we identify some major challenges, but not limited to, associated with the CR technology that need to be addressed before the deployment of such systems. 1) The complexity associated with the CR network in overall is more and hence its harder to control and manage the network. 2) The current lack of consensus on the needs of policy languages for such a network such as business and regulatory policies. 3) The security and authenticity issues to be addressed carefully due to the manifold networks operating in the considered domains.

ACKNOWLEDGMENT

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