SATELLITE ASSISTED SPECTRUM AGILITY CONCEPT

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ABSTRACT

The proliferation of wireless technologies has created a new dimension in the spectrum domain; mainly spectrum management and utilization. Because of the excessive demand for the radio spectrum, frequency bands are allocated not for just an application but for a variety of applications. Nevertheless, there still seems to be spectrum scarcity. Per contra, the research studies have shown that the spectrum utilization is very low in some certain bands, which leads to the conclusion that there is a problem with spectrum management and allocation not the spectrum itself. Thus, to combat the overcrowding and inefficient spectrum usage, the ideas on a more "clever" spectrum usage have led to the dynamic spectrum access (DSA) concepts. Moreover, the interoperability of the devices using a variety of access technologies is another driving force for more clever radios. The automatic upload and reconfiguration of the radio devices rather than hardware-based reconfiguration is essential especially in emergency communications. The so-called "smart radios" aim to address all these issues. In this paper, we propose a satellite assisted smart radio network architecture where spectrum allocation is done by the satellite depending on the information fed by the smart base stations.

I. INTRODUCTION

Many bidirectional communication devices are hardware-based with predetermined, analog operating parameters. Although device functionality is expanding with new capabilities, it is required to replace the original with new hardware in order to upgrade or change some certain properties of the device. Software Defined Radios (SDRs) change all that by relying on embedded software for their functionality and configuration. These new generation radios-adaptive radios- can adapt their transmission parameters, i.e. power level, waveform and modulation to enhance the transmission quality or system efficiency. Recently, many different definitions of the buzzword "cognitive radio" have been introduced. In general, cognitive radios (CR) which were first presented officially in the article by Joseph Mitola III and Gerald Q. Maguire [1], are the next evolution of adaptive/aware radios through the addition of a layer of intelligence that provides the ability to better satisfy user and network needs. The formal definition of cognitive radio by the IEEE 1900.1 group [2] is as follows: "*A type of radio that can sense and autonomously reason about its environment and adapt accordingly. This radio could employ knowledge representation, automated reasoning and machine learning mechanisms in establishing, conducting, or terminating communication or networking functions with other radios. Cognitive radios can be trained to dynamically and autonomously adjust its operating parameters.*"

The other motivation of the SDR and CR is the interoperability between the user terminals having different technologies like GPS, WiFi etc. The ultimate goal is to produce a "universal wireless device". In a perfect world, with the concept of universal wireless device, one could receive cellular calls, WiFi, Bluetooth or GPS etc. SDR is currently the best solution to solve the communications interoperability problem by providing an immediate, cost-effective solution that does not require the communicating parties to purchase new radios. For instance, a portable SDR device brought to an emergency scene can enable interoperability between selected members of different agencies by creating communication links between different radios and establishing infrastructure where none exists, or supplementing inadequate existing infrastructure by serving as a base station. The unplanned nature of an emergency requires extremely flexible radio systems that are able to adapt to the situation's communications needs, making SDR the ideal technology for public safety radio systems [3].

The rest of the paper is organized as follows. In the next section, we give brief information on smart radios, and discuss the challenges to realize the cognitive radio concept. In Section III, the on-going research is summarized. Additionally, the standardization efforts are

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mentioned in this section. Section IV summarizes the satellite related projects in this area. In the next section, we elaborate on our proposed spectrum management scheme that is essentially based on the use of satellites in such systems. We also present some preliminary results in this section. Finally, conclusions are drawn in Section VI.

II. BACKGROUND AND DEFINITIONS

A cognitive radio can basically sense its environment, and make a set of measurements with its special sensors. Upon collecting environmental information, it can set its new operating parameters. Figure 1 shows a simple cognitive radio framework. The entity called "Cognitive Resource Manager (CRM)" behaves as the *brain* of the system. CRM manages the system in interaction with other parts as *policy database* and applies some machine learning methods from the *Toolbox*.

In this section, we will provide principles of smart radios and mention the challenges in the design and implementation of the concept.

Primary User (PU): A PU or a licensed user is an entity that has a high priority in a given frequency band (e.g. cell phone provider, TV station, emergency services, etc). Since it has paid for the spectrum, it is authorized. PUs are not cognitive radio aware, and there will be no change in the PUs' architecture in the existence of unlicensed users.

Secondary User (SU): An SU or an unlicensed user is an entity that can use the temporarily-unused spectrum opportunistically in case of an idle frequency channel but vacates the spectrum as a PU begins to transmit at that frequency. Therefore the primary users must be detected as quickly as possible by SUs in order not to disturb PU communication. The time for the SU to vacate the channel is usually referred as "*channel move time*" and it is required to be less than 2 seconds in IEEE 802.22 systems [5].

Spectrum Hole: A frequency channel that is idle.

Interference Temperature: It is a measure of the radio frequency power generated by undesirable emitters plus noise sources that are present in a receiver system per unit of bandwidth.

Frequency Scanning: Since the primary users of a frequency band are not continuously using the band, secondary users can transmit on these bands without the consent of those primary frequency owners unless they interfere with the PUs. That means the SUs must be capable of sensing and detecting the existence of PUs, which may be a challenging task. PU detection is quite complex and it may even become more complex due to changing channel conditions like severe shadowing. The time between the appearance and detection of PU, the probability of false negative and false positive, and the time needed to the release the spectrum are points to be studied.

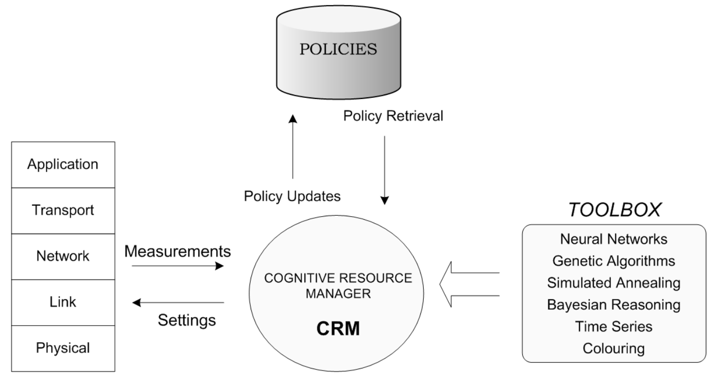

Figure 1. An example cognitive radio framework [4].

Dynamic Policy Awareness: The conventional radio has some hardwired policies defined during the time of manufacturing. However, policies may change and they must be uploaded to the systems. Hence, dynamic policy awareness is an important consideration of cognitive systems. The radio device should be capable of getting the up-to-date policies. Satellites or lower altitude systems like High Altitude Platforms (HAP) can be utilized to update the policies in the cognitive radio devices.

A. Challenges

Although CR is promising for interoperability, flexibility and spectrum utilization, it has many challenges which can mainly be listed as primary user detection, knowledge sharing and synchronization, CR capable hardware equipment design and implementation. More detailed information on the cognitive radio design can be found in [6] and [7].

1) Primary User detection: PU (incumbent) detection is one of the most critical tasks of sensing. Its purpose is to protect PUs against harmful interference from SUs by promptly detecting PUs' presence. As soon as PUs are detected in the home channel, the secondary network has to leave its channel. For example, the IEEE 802.22 standard for unlicensed operation in the TV bands regulates that PUs (in the IEEE 802.22 case, TV signals and FCC Part 74 devices) should be detected within 2 seconds from their appearance [8]. The interference experienced due to the secondary users (self-coexistence) and the hidden PU (the hidden incumbent) issues are addressed in [9]. Authors propose a new MAC for IEEE 802.22 networks and additionally they propose a new spectrum allocation mechanism based on graph coloring.

2) Knowledge representation: Knowledge must be represented in a machine understandable way, using languages such as the Web Ontology Language (OWL) which is based on the XML. It allows both first-order logic, and higher-order, class-based reasoning [10]. Policies might have a limited validity which depends on multiple factors such as the local time, the geographical location of the radio or the country where it is operating. Thus, cognitive radios have to use policies in an adaptive way.

3) Routing in CR networks: In a CR network, there is no guarantee that a channel will be available for use for the entire communication duration between two nodes. A channel can become unavailable due to the return of primary user or due to congestion. If a channel becomes unavailable on a path, that link will be considered broken and all the packets for that link will be dropped. Therefore, it is important to consider how often a channel becomes unavailable on a link while computing the path between source and destination nodes [11].

4) Security issues: SDR enables the automatic configuration and update of the radio software. However this may lead to unintended or malicious software updates. Hence unauthorized and malicious users must be prevented.

5) Design issues and hardware limitations: Any proposed mechanism must have low complexity and must be suitable for implementation. Additionally, it must be scalable. The radio front-end is supposed to listen to a wide range of frequencies; therefore radio hardware must be capable of sensing the spectrum in a wide frequency band. Due to this requirement, smart radios necessitate efficient power control and high capacity power sources.

III. CURRENT WORK AND THE STANDARDIZATION

In the European Union Sixth Framework Programme (EU FP6) priorities list, dynamic spectrum allocation is listed under the topic of "areas requiring increased focus". Additionally, there are some projects collaboratively held by European partners in the dynamic spectrum access issues. The activities End-To-End-Reconfigurability (E2R) and Wireless World Initiative New Radio (WINNER), which are supported by the European Commission, are part of the EU FP6 and are working on the fundamentals of cognitive radio networks. Opportunistic RAdio Communications in unLicensed Environments (ORACLE) is another EU FP6 project [12] that has started in 2006 and will be approximately completed in 2008. It is a joint project collaboratively held by partners from both academy like University of Surrey and the industry like France Telecom. The key objective of ORACLE is to research, develop, and validate concepts, mechanisms and architectures for cognitive radio networks and terminals and to demonstrate the socio-economical advantages of opportunistic spectrum usage.

Most of these research results rely on a theoretical analysis or computer simulations. In order to enable this technology and fully understand system design issues in its implementation, these theoretical results should be verified and demonstrated in realistic scenarios through physical implementation and experimental studies that can facilitate the development of physical and network layer functionalities for cognitive radios [13]. The most well-known emulator is Berkeley Emulation Engine 2 (BEE2) by VirginiaTech. It is a generic multipurpose FPGA based, emulation platform for computationally intensive applications. The radio front-end system operates in 2.4 GHz ISM band over 85 MHz of bandwidth with programmable center frequency and several gain control stages.

Most of the design is based on Software Communications Architecture (SCA) which is configuration management software that is intended to manage multi-band multi-mode software-defined radio systems. However, one of the biggest problems with the SCA is availability of code. Available frameworks are either too expensive or not sufficiently simple to support basic SDR research. Open Source SCA Implementation Embedded testbed (OSSIE) is an open source SDR development effort based at Virginia Tech. OSSIE is primarily intended to enable research and education in SDR and wireless communications [14].

Although the idea of CR is at its infancy, there is an effort for standardizing the general concepts. Mainly, IEEE 802.22- 802.11h, SDR Forum, FCC, IEEE, DARPA and US DoD have worked on standardization issues. The IEEE 1900.1 Working Group aims to develop a standard which will facilitate the development of these technologies by clarifying the terminology and how these technologies relate to each other. This standard will provide technically precise definitions and explanations of key concepts in the fields of spectrum management, policy defined radio, adaptive radio, software defined radio, and related technologies. The document will go beyond simple, short definitions by providing amplifying text that explains these technologies from different perspectives. IEEE 802.22 WG [5] also has noticeable contributions to enable opportunistic spectrum usage in lightly loaded TV bands.

The DARPA neXt Generation (XG) [15] communications technology program is developing a new generation of spectrum access technology. In its report, XG WP has specified its goal as to address the scarcity and deployment difficulty problems. More specifically, DARPA XG WP defines its aim as to make research to derive a new spectrum access behavioral regime consisting of technologies that sense, characterize, and utilize spectrum opportunities in an interference limiting manner. Additionally, they are working to derive a new regulatory control regime consisting of methods and technologies for controlling such opportunistic spectrum access behaviors in a highly flexible, traceable manner using machine understandable policies.

The Joint Tactical Radio System (JTRS) aims to provide a "common architecture for interoperability" to solve the formidable radio interoperability problem of the U.S. military. Interoperability problems are also an obstacle in joint operations, where each nation typically has its own radio systems. Recently, emphasis on peacekeeping, disaster relief, homeland security and other non-combat military operations has created further problems. In these roles, military units must communicate with public safety agencies, humanitarian organizations, and the civilian population [3].

IV. SPECTRUM AGILITY AND SATELLITE NETWORKS

Satellites with relatively long life times of 10–15 years are in the risk of obsolescence during this period. Those satellites already orbiting the Earth should continuously be technologically updated and compatible with terrestrial technologies. Updating a satellite which is already in orbit, represents not only a very difficult task but also a necessity considering the rapid technology growth, new service demands and certainly, the long lifetime satellites are designed for [16]. Therefore applying SDR and CR in space segment can improve the functionalities of a payload/repeater by introducing software updates for new standards and concepts (e.g. adaptive coding and modulation) [17]. In the cognitive and software defined radio field in general, there are very few studies on the flexibility and agility of space segment. The main studies can be listed as [17], [18], [19] and [20].

In WAND project [17], it is concluded that implementation of the SDR technology in the space segment seems an excellent way to overcome Satellite Operator concerns about obsolescence or implementation errors. However, the space technology available to

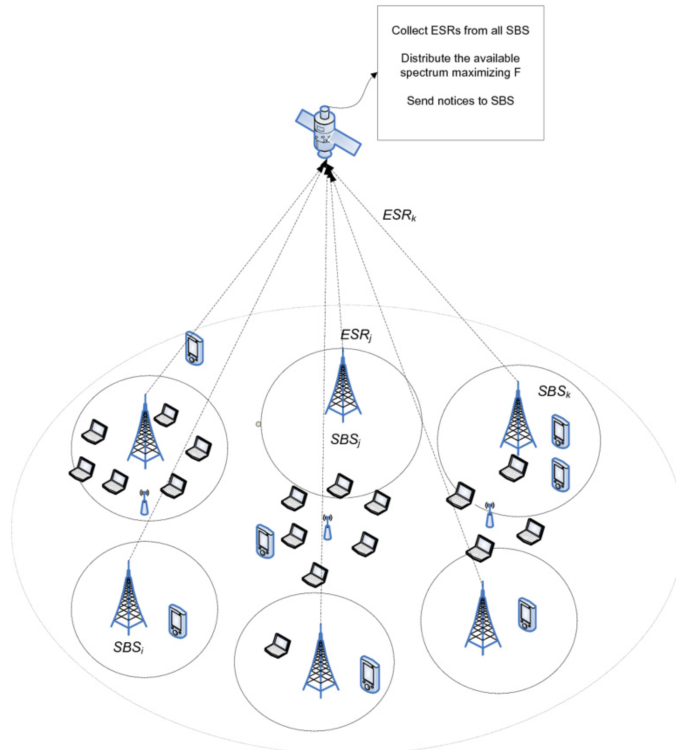

Figure 2. A LEO satellite and the secondary users in SBS coverage regions.

implement it does not seem to be mature enough. More adequate devices for SW Radio Technology (SRAM FPGAs and Processor Arrays) are required; the current ones have now a significant performance gap between ground/space technologies that should be reduced in the following years.

In this study, we concentrate on a different use of satellites in a CR network, to the best of our knowledge which has not been studied before. In the next section, we give a brief description of the proposed architecture and present some preliminary results obtained by simulations.

V. THE PROPOSED ARCHITECTURE: SATELLITE AS A CENTRAL CONTROLLER FOR SMART RADIOS

Satellites with their inherent broadcast and multicast capabilities can be used not only as a policy updater but also as a policy maker. Satellites having a wide footprint depending on their orbital height (i.e. LEO, MEO or GEO) have a wide knowledge about the users and the network in its service region. Hence, the use of satellites in a CR network is manifold. First, it will enable the policy and software updates more easily by a policy update message broadcast. Additionally, being aware of the environment and network state in its footprint the satellite can manage the spectral utilization and allocation in its coverage zone.

A. Assumptions and Problem formulation

In our model, we have considered a LEO satellite, which is at an altitude of about 1200 km. The choice of this orbit is due to low propagation delay. In the Earth segment, there are three types of nodes: smart base stations, secondary users and primary users. *Smart Base Station (SBS)* is a base station that is capable of using the spectrum opportunistically with the secondary users in its footprint. We assume that an SBS can cover up to 30 km in radius as a base station in IEEE 802.22 networks [8]. As shown in Figure 2, each SBS has a direct duplex communication link with the satellite ahead. SBSs periodically collect status information in their service region and send this information to the satellite. This information is called *Environment Status Report (ESR)*. The time period of report collection is called *"reporting interval"* and it is denoted by T_r. SBS_i sends its report ESR_i to the satellite. ESR_i mainly consists of the *SUR*s that correspond to the status reports of the secondary users that are served by SBS_i during the previous time interval. A *secondary user report* SUR_j includes the interference values sensed at each frequency channel by SU_j. Furthermore, the priority level and transmission power of SU_j are also included in the report. SUs are mobile whereas for the sake of simplicity we assume the PUs being static. We also assume that secondary users are equipped with a positioning system like GPS, and they are able to switch to the assigned frequencies by the SBSs.

Upon collecting the ESRs from all the SBSs, the satellite has knowledge of the frequency landscape and will allocate the spectrum maximizing the objective function F. The objective function might be any function, i.e. which depends on the user communication duration or user priority level. In our case, F is the overall throughput of the SUs and will be maximized while considering the priority levels of SUs. The priority may correspond to the price paid for the service like gold subscription or bronze subscription, or it may be type of the communication like emergency communications or just a lower priority background transmission. Therefore the optimization problem is

$$maximize \sum_{i=1}^{N} F_i$$

where F_i shows the utility function for SU_i.

For the topology, we have assumed a 100 km radius region where multiple overlapping SBS networks and licensed incumbents reside and share the spectrum of the available spectrum band. We construct the simulation model using

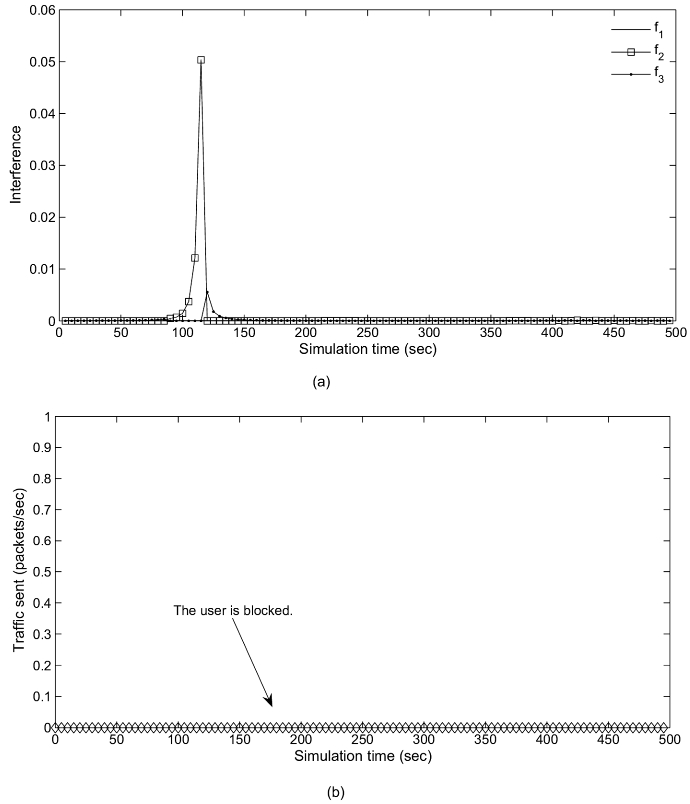

Figure 3. (a) Interference sensed at different frequencies by low (zero) priority user SU_0 (b) Traffic sent by SU_0.

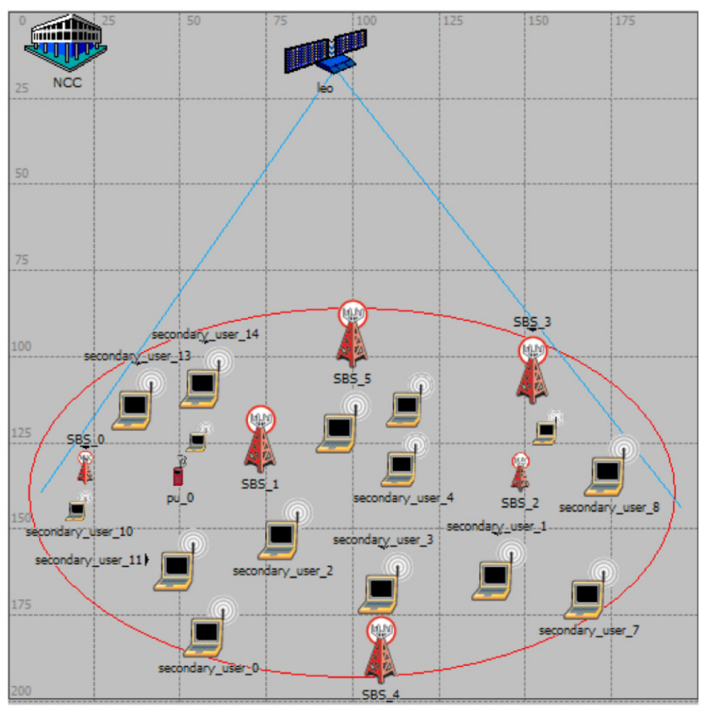

Figure 4. Example network modeled in OPNET simulation environment.

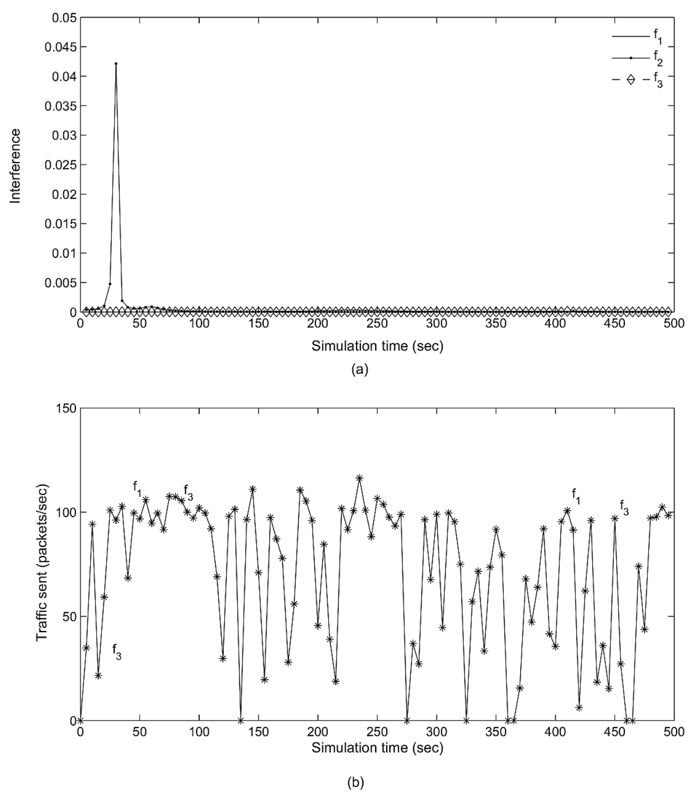

Figure 5. (a) Interference sensed by high priority user SU_2 (b) Traffic sent by SU_2. The frequency used during transmission is written on the graph.

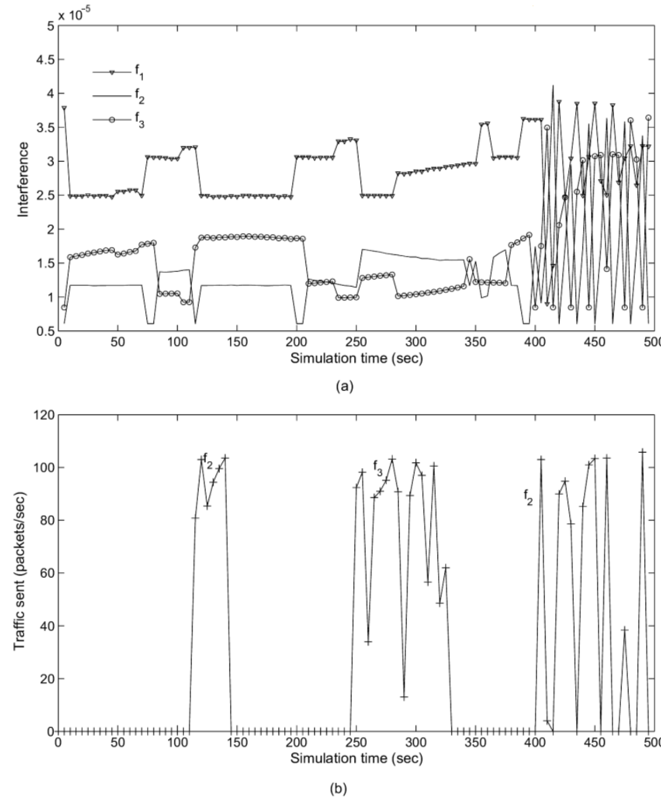

Figure 6. (a) Interference sensed by a medium priority user SU_7 (b) Traffic sent by SU_7.

OPNET Modeler[TM] 11.5 [21]. There are both primary users and secondary users in the system. SUs communicate through SBSs. Primary users operate in the frequency range of IEEE 802.11. There are three opportunistic frequencies and are referred as $f1$, $f2$, and $f3$. Initial communication is set up through a predefined channel that is dedicated for signaling.

In our model, SUs can detect the existence of a PU transmission with some probability of false alarms. SUs periodically scan the frequencies and determine the new candidate operating frequency depending on the interference sensed at each frequency. This information is transmitted to the satellite via SBSs. The LEO satellite fuses the data acquired from the SUs and the dynamic access policy uploaded from the command center for each user and decides on optimal operating settings. These decisions are beamed down to the SUs in the zone. In this study, we assumed three types of users which have different priorities to use an available frequency: *low, medium* and *high priority*. In order to see the extreme cases, low priority is set to "zero priority" which means that this type of user is *blocked* and can never transmit even though there is spectrum hole for its use. Moreover, high priority is set to 1 which means that this type of user can always transmit in case of an available frequency. The simulations are run for 500 seconds and frequency scanning period is taken as 5 seconds.

B. Experimental Results

In our experiments, we observe the traffic sending rate of each user type and the interference experienced by those users. The interference is roughly calculated by a simple formula (P/d^2) where P is the transmitting antenna's power level and d is the distance between the transmitter and the SU. The interference suffered at each frequency, and traffic sending rate of each user are plotted in the Figures 3, 5 and 6.

As the figures show, the policy applied by LEO manages the frequency use depending on the priority of the SU. Although SU_0 experienced very low interference at f_1 and f_3, it cannot transmit because of being blocked (Figure 3). As opposed to SU_0, SU_2 is a high priority user. Thus, it can transmit even though having a similar interference level to that of SU_0. Figure 6 depicts the interference and traffic sending rate of SU_7 which is medium priority user. The operating frequencies are written next to the data points in traffic sending rate graphs. For instance in Figure 5(b), data are transmitted using frequency f_3 till t=50 s, and then SU switches to $f1$ which has a lower interference level.

In our work, the SUs have static priorities which do not change during the whole simulation time. However, dynamic priorities can also be applied which may correspond to location-based priorities. In other words, there can be some zones in which some frequencies are strictly used for specific applications. Therefore no other users are allowed to transmit at those frequencies.

VI. CONCLUSIONS

In this paper, we provided insights to the use of satellites in the spectrum management of next generation agile networks. As wireless technologies proliferate more and more every day, there is a need for dynamic spectrum access. The spectrum agile radio concept has brought a novel paradigm to the wireless communications. Opportunistic spectrum access provides easier deployment, or rapid entry, into regions where spectrum has not been assigned and above all better spectrum utilization and inter-operability. As we have pointed out an alternative use of satellites in a smart radio network, satellites can enable the spectrum management in a more coordinated manner. However, there are many open issues that need to be investigated.

VII. ACKNOWLEDGMENTS

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