COGNITIVE RADIO NETWORK ARCHITECTURE FOR GEO AND LEO SATELLITES SHARED DOWNLINK SPECTRUM

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Abstract – *The fixed spectrum assignment policy in the space sector and large constellations of Low Earth Orbit (LEO) satellites left little or no spectrum available for future LEO satellite communications services. Cognitive Radio (CR) technology enables spectrum sharing between primary and secondary users without limiting the transmission power, and thus is of great interest to commercial and defense entities. A number of Radio Environment Map (REM) techniques have been making Cognitive Radio Networks (CRNs) practical by constructing a comprehensive map of the CRN by utilizing multi-domain information from geolocation databases, characteristics of spectrum use, geographical terrain models, propagation environment, and regulations. In this paper, we investigate spectrum sharing for a network comprised of a Geostationary Orbit (GEO) and a LEO satellite with a multibeam antenna array. A CRN architecture of GEO and LEO satellites shared downlink spectrum is proposed and details are provided covering its architecture, REM structure and channel utilization data aggregation, as well as a frequency slot assignment mechanism.*

Keywords – Channel monitoring, cognitive radio networks, geostationary orbit satellites, low Earth orbit satellites, radio environment map, spectral sensing

1. INTRODUCTION

The increasing demand for wireless connectivity and spectrum allocation based on specific band assignments have led to current crowding of licensed spectrum and left little or no spectrum available for emerging wireless services. Attempts to share spectrum in a fundamentally new way are of great interest to commercial and defense entities. Cognitive Radio (CR) technology, one of the most promising technologies for spectrum sharing, has attracted tremendous attention to improve spectrum and radio transmission efficiency.

Proposed in 1990, cognitive radio allows secondary users to access and utilize the unoccupied/unused spectrum of the authorized primary user [1]. The Radio Environmental Map (REM) was proposed as an enabler for practical Cognitive Radio Networks (CRNs). The REM provides comprehensive multi-domain information about the radio environment, such as the geographical features, available services, spectral regulations, locations and activities of radios, policies of the user and/or service providers, and past experiences [2, 3, 4, 5]. The REM is the key to enabling Dynamic Spectrum Access (DSA) in CRNs by utilizing multi-domain information from geolocation databases, characteristics of spectrum use, geographical terrain models, propagation environments, and regulations [6, 7].

In recent years, many accomplishments have been made to make full use of the frequency resources assigned to satellites. In [8], a Spectrum Opportunity-based Routing Protocol (SORP) was proposed to improve the transmission performance. The coexisting downlink interference between LEO and GEO systems was analyzed in [9], and Rate Splitting Multiple Access (RSMA) was utilized for cognitive radio GEO-LEO coexisting satellite networks in [10] to maximize the spectral efficiency of the secondary LEO system. The co-linear interference issue caused by LEO satellites while passing through the coverage area of the GEO satellite's beam was addressed in [11] through continuous power allocation optimization to allow the LEO satellites to provide services for multiple LEO ground users. In [12], to achieve spectrum coexistence, a spectrum sensing strategy for the Non-Geostationary (NGEO) satellites to access the GEO spectrum was proposed using hypothesis testing to differentiate the GEO signal from the interfering NGEO signals. An optimization algorithm combining beam hopping and adaptive power control techniques was proposed in [13], with a view to enhancing the spectral sharing efficiency between GEO and LEO systems. In practical terms, O3b and OneWeb systems have shared part of the same frequency with a GEO satellite [14].

In the space sector, the convergence of GEO satellite communications infrastructure provides seamless connectivity and communication services and large constellations of LEO satellites such as Starlink are necessary to cater for future demand [15]. The future satellite ground terminals therefore need to integrate and coexist with the crowded GEO/LEO satellite systems. Motivated by this premise, we propose the idea of cognitive radio network architecture for GEO and LEO satellites with shared downlink spectrum, and investigate the impact of imperfect spectrum sensing in terms of miss-detection and false alarm.

The rest of the paper is organized as follows: Section 2 presents the system model and channel availability simulation and analysis. The proposed cognitive radio network architecture is discussed in Section 3, while Section 4 provides details and structure of the REM. Aggregation of channel utilization data and frequency slot assignment are discussed in Sections 5 and 6 respectively, with simulation results provided in Section 7. Concluding remarks and future work are given in Section 8.

2. SYSTEM MODEL AND ANALYSIS

2.1 System model

A scenario where the GEO and LEO satellites share the same spectrum is illustrated in Fig. 1. In this scenario, the GEO satellite system is the primary user occupying the authorized spectrum and the LEO satellite system is the secondary user providing access to secondary user ground terminals. The LEO satellite is assumed to be equipped with multibeam antenna with onboard processing capability to facilitate secondary user traffic to the secondary user ground terminals.

Assuming that the GEO satellite system has some unoccupied channels, which can be detected at secondary user Earth station locations via its downlink signal, the onboard processor can conduct spectrum sensing [16] on the primary user downlink signal to monitor the primary user channel occupancy. The LEO satellite system will construct the REM and maintain the REM data for secondary user channel assignments and decision-making. This aids efficient channel resource allocation. A REM database will be located onboard the LEO satellite.

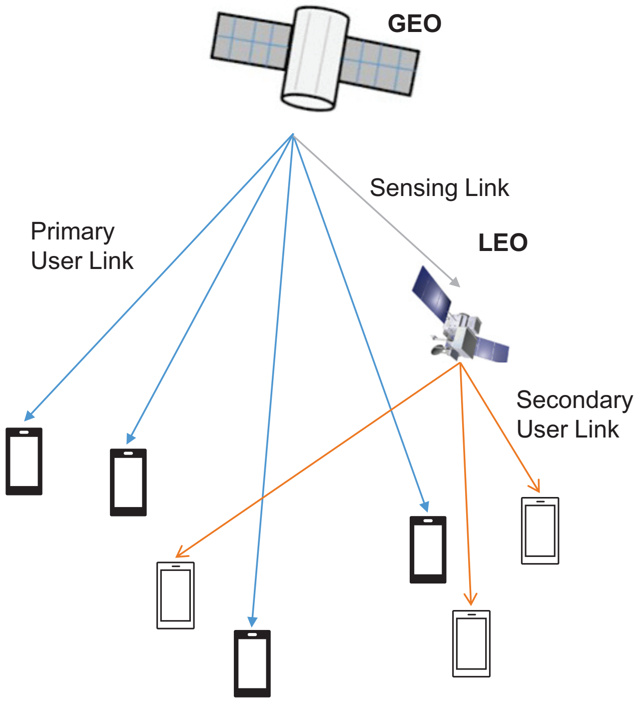

Fig. 1 – An illustration of a cognitive GEO and LEO satellite network where GEO satellite is the primary user and the LEO satellite is the secondary user.

2.2 Analysis of channel availability

The parameters used for a preliminary secondary user channel availability simulation are detailed in Table 1. Further, during the simulation the GEO satellite beam is assumed to have a capacity of 100 channels. The number of primary users arriving which require access to the network is modelled by a Poisson process with intensity $\lambda = 1$ users per second. The results of the simulation showing the primary user channel availability, time-frequency channel occupancy and channel usage are shown in figures 2 – 4, respectively.

Considering the secondary users, the number of secondary users requiring access to the network is also modelled by a Poisson process but with intensity $\lambda = 0.2$ users per second. The resulting time-frequency channel occupancy is shown in Fig. 5.

As can be observed from Fig. 2, for the duration of the simulation period, $\approx 60\%$ of the channels are

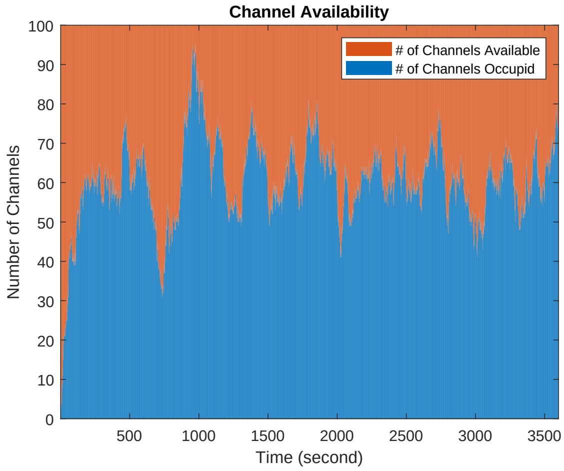

Fig. 2 – Channel availability

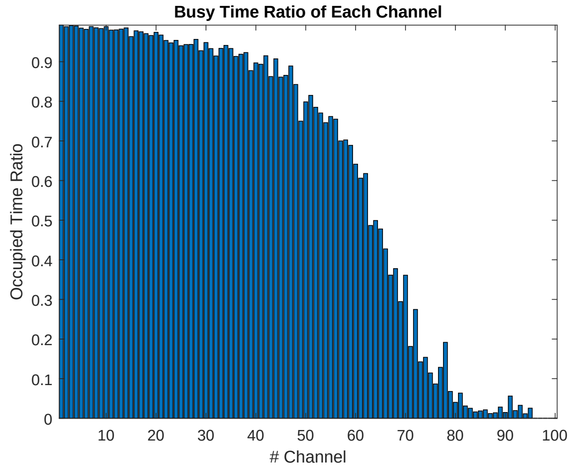

Fig. 4 – Channel usage

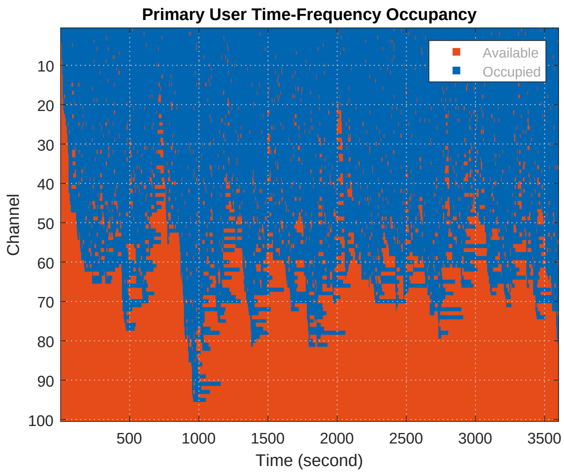

Fig. 3 – Primary user channel time-frequency occupancy

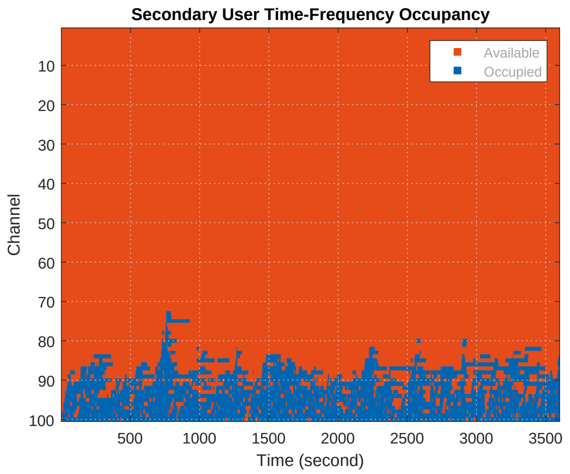

Fig. 5 – Secondary user time-frequency occupancy

occupied on average. Considering the channel time-frequency occupancy for each time slot, as shown in Fig. 3, $\approx 40\%$ of the channels are available for use by secondary users.

For the purpose of this preliminary channel use simulation, we adopted a simple channel allocation scheme whereby the available channels are indexed according to their occupancy length in history record and the channel with the smallest index number which refers to a busier channel is allocated to the new primary user. As a result, the channels with smaller indices are busier than those with large indices as shown in Fig. 4. In future work, we plan to replace this simplistic channel allocation with an artificial intelligence-based one which will generate a figure of merit for each available channel enabling better channel selection from a list of available channels.

Table 1 – Simulation parameters for GEO/LEO network

Parameters	Value
Simulation Step	1 second
Simulation Period	$3,600$ seconds
Number of GEO Channels	100
Primary User Arrival Model	Poisson Distribution ($\lambda = 1$)
Primary User Service Time	Exponential Distribution with mean of 60 seconds
Secondary User Arrival Model	Poisson Distribution ($\lambda = 0.2$)
Secondary User Service Time	Exponential Distribution with mean of 60 seconds

3. NETWORK ARCHITECTURE

A potential network architecture is proposed to enable secondary users to use the available channels of the GEO network. With the proposed architecture, as depicted in Fig. 6, the occupied GEO satellite frequency and time slots are observed by the

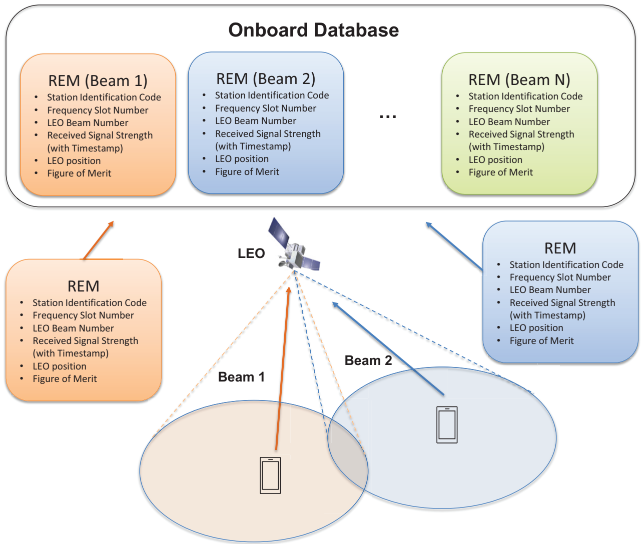

Fig. 6 – REM database architecture

secondary user Earth stations located within the GEO and LEO beam areas which have link coverage at any given time to the LEO satellite. This observed channel occupancy information is transmitted from the secondary user Earth stations to the LEO satellite via an uplink control channel, which may be a random- access channel.

As shown in Fig. 6, the LEO satellite maintains an onboard database which contains the geographic locations (latitude and longitude) of the secondary user Earth stations in the network which are indexed by the station identification codes. The station identification code is a unique number assigned to each secondary Earth station in the network.

With the proposed network architecture, the LEO satellite is responsible for constructing and maintaining the REM which is used for secondary user channel assignment. In the initial version of the system, the secondary user channel assignment will be carried out as detailed in Section 2, whereby the available channel with the lowest index number is assigned to a secondary user. In the next iteration of the system, the channel assignment will be based on a Figure Of Merit (FOM) generated for each available channel with each LEO satellite beam, and the available channel with the highest FOM will be assigned to the secondary user requesting a channel. How FOM is generated, and used for channel allocation is detailed in Section 4.

As shown in Fig. 6, there is a REM database associated with each LEO satellite antenna beam (Beam $1, \dots, $ Beam N) as part of the onboard database. This REM structure will be sufficient for a LEO satellite with a single antenna beam or a LEO satellite with multiple antenna beams.

The advantage of a LEO satellite with multiple antenna beams is that LEO downlink transmission can potentially interfere with primary users only in the LEO transmit antenna footprints and not in areas covered by other LEO beams, thus minimizing the risk of disrupting primary users outside these designated regions. The multiple beam antenna LEO enables much greater secondary user throughput. By strategically dividing the coverage into distinct beams, each with its own dedicated footprint, the LEO system can serve multiple secondary users with higher efficiency and data throughput. This enhanced throughput capability is a direct result of the optimized utilization of resources and the ability to tailor communication beams to meet the needs of different regions or user groups.

4. REM DATA AND STRUCTURE

The received signal power in each frequency slot is sensed by the secondary user Earth stations. These secondary user Earth stations transmit the sensed information to the LEO satellite on an uplink control channel. This information is time-tagged and stored in the LEO onboard REM as short-term primary user channel occupancy information. The unoccupied primary user channels are candidates for assignment to secondary users for downlink transmission from the LEO satellite.

The information contained in the REM dataset are:

- The unique station identification code for the secondary user uplinking station.
- The frequency slot number (signal strength measurements are recorded for each frequency slot).
- The LEO satellite beam number corresponding to the signal strength measurement (For a multibeam LEO satellite).
- The quantized signal strength measurement, which was uplinked via the control channel.
- The Time Of Day (TOD) of the received signal strength measurement report. (Based on an onboard clock slaved to GPS).
- The LEO satellite position at the time the signal strength measurement was received.

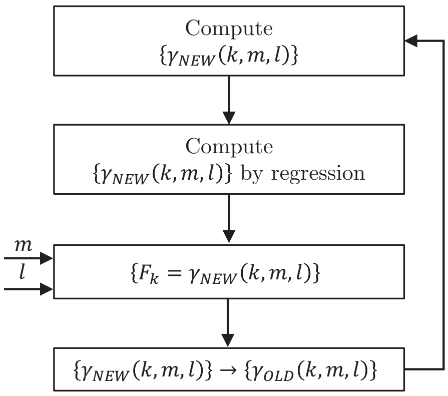

Fig. 7 – Figure Of Merit (FOM) computation flowchart

- The current figure of merit for the assignment of each channel slot for each LEO beam (For a multibeam LEO satellite).

With this REM structure and content design, we can demonstrate how to calculate and update the FOM which is the key to formulating a channel assignment policy and algorithm.

The FOM is calculated as:

$$\begin{aligned} F_k &= \gamma_{NEW}(k, \underline{U}_{LEO}, T_{TOD}) \\ &= (1-\lambda)\,\gamma_{OLD}\left(k,\, \underline{U}_{LEO}, T_{TOD}\right) \\ &+ \lambda\,\alpha\left(k,\, \underline{U}_{LEO},\, T_{TOD},\, B_k, \theta_k\right) \end{aligned} \quad (1)$$

where F_k is an analytical function obtained by regression of the data points $\gamma_{NEW}(k, \underline{U}_{LEO}, T_{TOD})$ and $\gamma_{NEW}(k, \underline{U}_{LEO}, T_{TOD})$ is the FOM for frequency slot k, LEO location $\underline{U}_{LEO}$, and time interval T_{TOD}.

Primary user beams can be quantized into M cells with cells number $1 \le m \le M$. The TOD can be quantized into L regions which are indexed by $1 \le l \le L$. Then the quantized version of Equation *(1)* can be updated as:

$$\begin{aligned} \gamma_{NEW}(k,m,l) &= [1-\lambda(k,m,l)]\gamma_{OLD}(k,m,l) \\ &+ \lambda(k,m,l)\alpha(k,m,l,B_k,\theta_k) \end{aligned} \quad (2)$$

where $\gamma_{NEW}(k,m,l)$ is the quantized FOM for frequency slot k, LEO location m, and time interval l, $\lambda(k,m,l)$ is the learning factor, B_k is a measure of the burstiness of frequency slot k, and θ_k is a measure of the primary user occupancy of frequency slot k. B_k is a monotonically increasing function of burstiness, and θ_k is a monotonically increasing function of the channel primary user occupancy

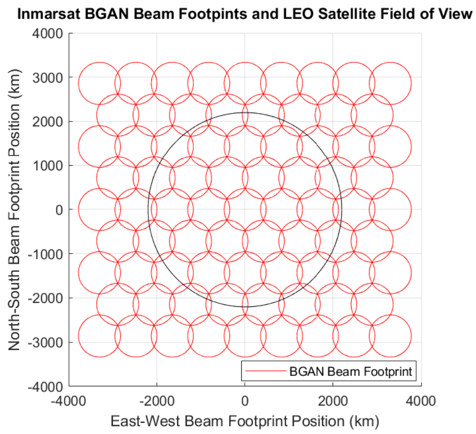

Fig. 8 – Inmarsat BGAN beam footprints and LEO satellite field of view

and $\alpha(k, m, l, B_k, \theta_k)$ is monotonic decreasing for B_k and θ_k. The FOM computation and update process flowchart is shown in Fig. 7.

The learning factor can be calculated as:

$$\lambda(k,m,l) = \begin{cases} 0 & P_k < \eta, \\ J & P_k \ge \eta. \end{cases} \quad (3)$$

where η and J are constants.

5. ONBOARD AGGREGATION OF CHANNEL UTILIZATION DATA

The onboard processor on the LEO satellite is responsible for processing the received downlink signal from a GEO satellite to aggregate the time-tagged primary user channel use information. Since the GEO beam footprints are much smaller than the LEO beam footprints as shown in Fig. 8, channel use information can be computed onboard the LEO satellite for each GEO beam visible to the LEO satellite. Further, since the secondary user reporting stations' locations are known along with the primary user beam assignments, the signal strength aggregation for each LEO beam can be done onboard the LEO satellite.

As a case study, the beam footprints of Inmarsat-4 (I-4) F2, a GEO satellite, and the field of view of a LEO satellite at a 400 km orbit is shown in Fig. 8. For the LEO satellite, the footprint of the field of view has a 4401.67 km diameter. The Inmarsat BGAN beam footprint has a beam footprint diameter of 952.9 km. Therefore, approximately 37 Inmarsat BGAN beams fit, or partially fit, within the LEO field of view.

The spectrogram of the received Inmarsat BGAN I-4

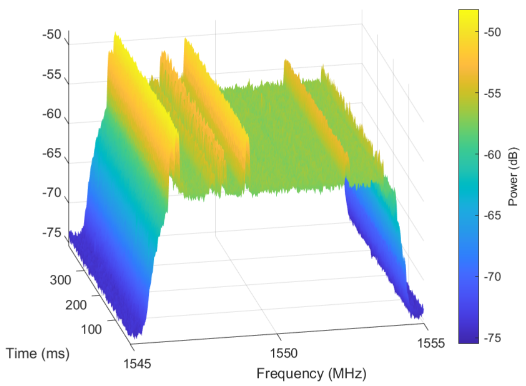

Fig. 9 – Received Inmarsat BGAN signal spectrogram

F2 signal captured using SDRplay RSPduo software defined radio is shown in Fig. 9. The RSPduo is equipped with a 14-bit dual receiver operating between 1 kHz – 2 GHz with up to 10 MHz of bandwidth. By processing the received signals, channel occupancy and channel burstiness indexed by a Inmarsat BGAN satellite beam number for a given time of day can be generated and used.

The onboard Master Control Station (MCS) shall do statistical and artificial intelligence processing on the aggregated data and will generate a time and LEO spacecraft-dependent FOM function for each GEO satellite channel. The FOM function will be monotonically increasing as a function of secondary user assignment desirability. Statistics, which will be extracted for each frequency slot from the aggregated channel occupancy data, include the percentage of time that the frequency slot is used by primary users and a measure of the burstiness of use of primary users. It is desirable to assign a frequency slot to a secondary user transmission that has low primary user occupancy and low burstiness of occupancy. A reasonable measure of the burstiness of a channel may be obtained as an application of the Lempel-Ziv complexity measure [17].

The FOM functions shall be computed as a function of the day of the week, the time of day, and the LEO satellite location associated with the channel occupancy observations. The long-term trends and periodicities of the channel assignment policies implemented for the GEO satellite downlink transmission and of the characteristics of the user traffic will be captured from the FOM functions. The FOM functions are stored as long-term memory in the REM onboard the LEO satellite.

6. FREQUENCY SLOT ASSIGNMENT

Typically, there will be a list of available frequency slots that can be assigned to secondary users for downlink transmission. The FOM functions are used in the selection of the best available frequency slot to be assigned for secondary user downlink transmission. The selection of a frequency slot with a large FOM tends to maximize the secondary user data throughput by reducing the overhead associated with frequent secondary user frequency slot reassignment and relocation.

The channel assignment processor onboard the LEO satellite uses both the short-term and the long-term REM data. A channel assignment algorithm is used to select the best available frequency slot for secondary user downlink transmission. The secondary user Earth stations continuously send observed channel utilization data to the LEO satellite so that the list of available frequency slots is updated in near real time.

In the case of multiple LEO satellites, frequency slots that are detected as occupied may be due to either GEO network user transmission, secondary user transmission from an LEO satellite that has assigned the frequency slot for secondary user transmission, or secondary user transmission from another LEO satellite whose assigned secondary user frequency is unknown to the first LEO satellite. A given LEO satellite is aware of the frequency slots that it has assigned to secondary users, but it is not aware of frequency slots that are assigned by other LEO satellites to secondary users.

The least complex approach to deal with this is secondary user frequency slot relinquishment as soon as transmission from another transmitter is detected on the frequency slot. The discrimination between an LEO-assigned secondary user and a GEO primary user in a frequency slot may involve digital demodulation and detection of encoded information in frame preambles at secondary user stations. This issue needs further detailed investigation, and forms part of our future work.

7. SIMULATION RESULTS

The primary user channel time-frequency occupancy shown in Fig. 3 represents an ideal scenario with no detection errors, which is theoretically optimal but rarely occurs in practice. To investigate the interference and conflicts arising from secondary

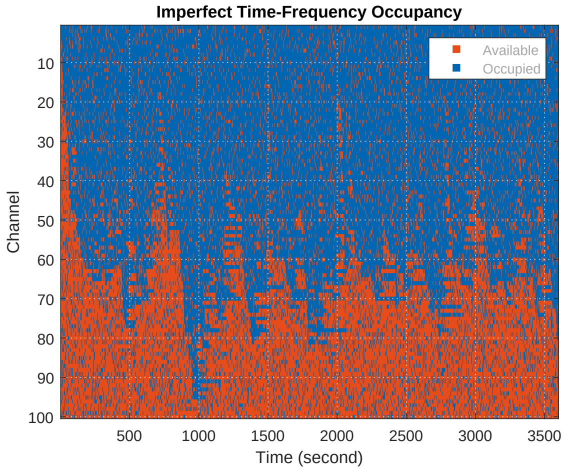

Fig. 10 – Imperfect time-frequency occupancy with miss-detection (0.1) and false alarm (0.2)

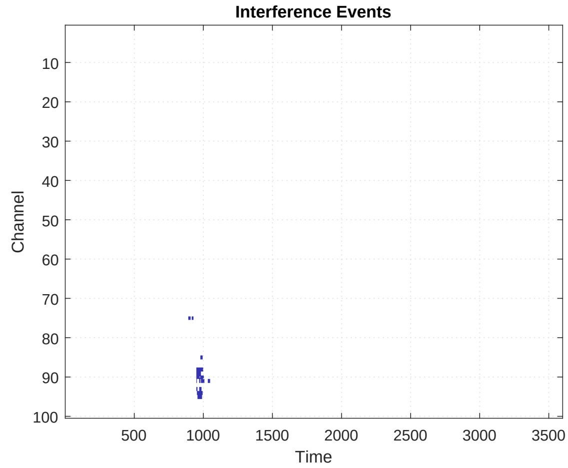

Fig. 11 – Interference events during simulation period

users, simulations were conducted emulating two primary types of detection errors during spectrum sensing: false alarms and miss-detections. A false alarm occurs when a cognitive user incorrectly detects a licensed channel as busy when it is actually idle, while a miss-detection occurs when an idle channel is erroneously detected as busy.

To assess the impact of miss-detections and false alarms, various combinations of these possibilities were selected and simulated. We conducted 1000 simulations for each parameter set to determine the average number of interference events over a simulation period of 3600 seconds. The channel time-frequency occupancy of primary users, in the absence of any secondary users, with false alarm and miss-detection probabilities of 0.2 and 0.1, respectively, is shown in Fig. 10. Interference caused by the secondary users to the primary users in the presence of false alarm and miss-detection is shown in Fig. 11 with results tabulated in Table 2.

As it can be observed form Table 2, with perfect spectrum sensing e.g., zero false alarm and miss-detection probability, the average number of interference events during one simulation period was 78.2. This number increased to 115.1 when miss-detection (0.10) and false alarm (0.20) occurred.

8. CONCLUSION

A fundamental architecture is introduced for the downlink spectrum sharing of a geostationary satellite and a low Earth orbit satellite utilizing cognitive radio network concepts. Further, the broad conceptual framework is also outlined. However, detailed algorithms need to be developed and their performances assessed. In addition, the achievable secondary user throughput and the performance impact on the primary user system analysis form part of our future work.

Table 2 – Secondary to primary user interference analysis

Parameter	Value				
Miss-detection	0	0.01	0.02	0.05	0.10
False Alarm	0	0.02	0.04	0.10	0.20
Interference Events(Average)	78.2	94.3	86.0	91.0	115.1

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