Cognitive Beamhopping for Spectral Coexistence of Multibeam Satellites

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SUMMARY

Herein, the spectral coexistence scenario of two multibeam satellites over a common coverage area is studied where a primary satellite produces larger beams while a secondary satellite has smaller beams. A novel cognitive beamhopping satellite system is proposed assuming that the secondary gateway is aware of the primary's beamhopping pattern. The performance of the proposed system is evaluated and compared with that of conventional multibeam and beamhopping systems in terms of throughput. It is shown that the proposed system significantly enhances the Spectral Efficiency (SE) in comparison to other systems. Furthermore, a power control technique is applied on the secondary transmission in order to adhere to the primary's interference constraint. It is noted that the total SE increases with the number of secondary users in the full frequency reuse approach. Moreover, the Exclusion Zone (EZ) principle is applied to exploit the regions in which the secondary system can operate without causing harmful interference to the primary system. It is shown that the EZ radius of 8.5 dB is sufficient to protect the primary system perfectly with a significant gain in SE. Finally, it is shown that power control and the EZ methods are suitable for lower and higher values of secondary aggregated interference respectively.

KEY WORDS: Beamhopping, Spectral Efficiency, Cognitive Communication, Multibeam Satellites

1. INTRODUCTION

The usable satellite spectrum is becoming scarce due to continuously increasing demand for broadcast, multimedia and interactive services. In this context, we consider the problem for enhancing Spectral Efficiency (SE) in multibeam satellite networks. Next generation Satellite Communications (SatComs) systems target enhanced throughput and higher SE. To enhance system capacity, satellite systems have moved from payloads generating a single beam to multi-beam platforms [1]. Multibeam satellites are used widely by satellite operators such as KaSat (82 Ka-band spot beams) by Eutelsat, Wildblue-1 and Anik F2 (66 Ka-band spot beams) by Wildblue and Viasat1 (72 Ka-band spot beams) by ViaSat. These systems have mostly been used for fixed interactive broadband applications since a finer splitting of the coverage area allows for parallel data stream transmissions. As in terrestrial cellular systems, multibeam satellite systems use frequency planning and reuse to achieve enhanced capacity.

Current wireless networks are characterized by a static spectrum allocation mechanism in which international ITU-R bodies assign frequency bands to the license holders on a long-term basis for different geographical regions and services. With regard to satellite communications, Fixed Satellite Services (FSS) use C and K band frequencies and for Mobile Satellite Services (MSS), L and S frequency bands are better suited since they permit small on-board antennas due to better foliage penetration and smaller impact of atmospheric affects. There is continued pressure

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on satellite bands, especially in L and C bands due to the introduction of new terrestrial services such as 3G mobile telephony, LTE, WiMax and WiFi services. Due to high demand of broadband services and limited availability of L and S-band frequency resources, higher frequency bands i.e., Ku and Ka bands have also been assigned for MSS systems [2]. At present, Ku band based MSS systems are available to provide broadband services to many vehicular users such as trains, boats, planes, and cars. In this context, exploring efficient frequency sharing techniques to enhance SE while guaranteeing Quality of Service (QoS) is a highly relevant and challenging problem. This has led to the concept of cognitive SatComs which exploits the opportunities for spectrum sharing between two satellite systems or between satellite and terrestrial systems [3]. The most common cognitive techniques in the literature can be categorized into Spectrum Sensing (SS) or interweave, underlay, overlay and database techniques. In SS only techniques, Secondary Users (SUs) are allowed to transmit whenever Primary Users (PUs) do not use that specific band, whereas in underlay techniques, SUs are allowed to transmit as long as they meet the interference constraint of the PUs.

The spectrum coexistence literature is more mature in the terrestrial context but has received limited attention in the satellite context. Recent work exploiting spectrum sharing opportunities in the context of cognitive SatComs includes [3, 4, 5, 6, 7, 8, 9, 10, 11]. Furthermore, most of the current contributions in this context focus on hybrid coexistence scenario of satellite and terrestrial systems and only a few contributions address dual satellite coexistence scenarios [4, 7, 9, 10, 11]. Recently, cognitive SatComs have received interest in different research projects and communities. Examples include ACROSS (Applicability of Cognitive Radio (CR) to Satellite Systems) [12], CoRaSat (Cognitive Radio for Satellite Communications), Co2SAT(Cooperative and Cognitive Architectures for Satellite Networks) [3, 4, 5], ISI (Integral SatCom Initiaitve) [13] , SATNEX (European Network of Experts for satellite communications) [14] etc.

In conventional multibeam systems, partial frequency reuse can be used to enhance the system capacity. However, it may be impractical to apply full frequency reuse due to excessive co-channel interference which is difficult to remove using existing interference mitigation techniques. A beamhopping satellite system can operate by using full frequency reuse over a certain beamhopping pattern [15]. The main difference between conventional multibeam and beamhopping systems is that frequency sharing among multiple beams within a cluster takes place in different domains, i.e., frequency and time domains respectively. Several contributions exist in the literature in the context of beamhopping systems [15, 16, 17, 18]. Since in a beamhopping system, only a single beam of a cluster is active during a particular time slot, there exists an opportunity to reuse the full frequency using smaller beams of another secondary satellite in the same time slot.

In this direction, we propose a cognitive beamhopping system with the objective of enhancing the system SE while protecting the PUs. We consider a dual satellite spectral coexistence scenario of two multibeam satellites with a primary satellite having larger beams and a secondary satellite having smaller beams. The cognition is achieved by sharing the beamhopping pattern and the timing information of the primary multibeam system to the secondary multibeam system using a signalling link between their corresponding gateways. The timing information is exchanged to guarantee the proper synchronization of the primary and secondary transmissions. The primary multibeam system is considered to be an already deployed system and its performance should not be degraded beyond the prescribed threshold by the deployment of the secondary satellite systems. The secondary satellite dynamically adapts its beampattern and transmit power ensuring the unobstructed operation of the primary system. In this context, the performance of the proposed cognitive beamhopping system is evaluated and compared with the performance of conventional multibeam and beamhopping satellite systems in terms of SE (bits/sec/Hz). Furthermore, we consider a scenario where multiple SUs are present within an inactive primary beam and evaluate the system performance of the proposed system. For this purpose, we consider full frequency reuse and frequency sharing among the SUs. Furthermore, a power control technique is considered at the secondary satellite to protect the primary satellite terminals using a predetermined interference threshold. Moreover, we apply the Exclusion Zone (EZ) principle to investigate the opportunity for secondary transmission in the switched-off regions of the primary satellite system. The main objective is to find the regions in which secondary satellite can operate ensuring protection against harmful interference for the primary systems. In addition, the power control and the EZ techniques are compared in terms of the total system throughput considering the same aggregated secondary interference.

The remainder of this paper is organized as follows: Section 2 reviews conventional satellite systems. Section 3 discusses the system model for the proposed cognitive beamhopping system. Section 4 presents the signal and channel model used for analysis. Section 5 provides the theoretical expressions for evaluating the performance of different techniques. Section 6 evaluates the system performance with the help of numerical results. Section 7 provides related discussion and technical challenges from practical perspectives. Section 8 concludes the paper.

2. RELATED LITERATURE

2.1. *Existing Satellite Systems*

2.1.1. Conventional Multibeam System : In conventional multibeam systems, the total available bandwidth (W) in the forward link is divided into K segments, where the parameter K is the frequency reuse factor. Then the bandwidth allocated to the i-th user beam (W_i) can be written as: $W_i = W/K$. The set of the beams which share the total bandwidth defines a beam cluster. The total gain in terms of frequency reuse obtained by using a multibeam satellite in comparison with a monobeam satellite depends on the number of clusters in that region which would be covered by a single beam of the monobeam satellite. The bandwidth allocated per beam can be written as: $W_i = N_i W_\mathrm{c}$, where N_i is the number of carriers in the i-th beam and W_c is the bandwidth of each carrier. As the value of K decreases, the available bandwidth per beam increases but the co-channel interference also increases. Since the system capacity depends on both the available bandwidth and the co-channel interference, the value of K should be chosen in such a way that the maximum system capacity is achieved. The smallest possible value of K in conventional satellite systems is 3 [19].

2.1.2. Flexible Multibeam System : In comparison to the conventional systems, the flexible system uses a non-regular frequency reuse pattern and non-uniform power/carrier allocation. In practical situations, at least one carrier per beam is allocated i.e., $N_i \in \{1, 2, ..., N_{max}\}$, where $N_\mathrm{max} = N_\mathrm{c} - (K-1)$ and $N_\mathrm{c} = W/W_\mathrm{c}$ is the total number of available carriers. Let N_b be the total number of beams in the system, then the $N_\mathrm{c} \times N_\mathrm{b}$ bandwidth allocation matrix $\mathbf{C}$ can be defined as [18]:

$$\mathbf{C} = \begin{bmatrix} C_{11} & C_{12} & \dots & C_{N_\mathrm{b}1} \\ C_{12} & C_{22} & \dots & C_{N_\mathrm{b}2} \\ \vdots & \vdots & \ddots & \vdots \\ C_{1N_\mathrm{c}} & C_{2N_\mathrm{c}} & \dots & C_{N_\mathrm{b}N_\mathrm{c}} \end{bmatrix}, \tag{1}$$

where C_{ij} represents the j-th carrier allocated to i-th beam. The number of carriers allocated to i-th beam can be calculated as: $N_i = \sum_{j=1}^{N_\mathrm{c}} C_{ij}$, where $C_{ij} \in \{0, 1\}$ indicates whether the j-th carrier is allocated to i-th beam or not.

2.1.3. Beamhopping Multibeam System : In this system, a limited number of beams are simultaneously illuminated with a regular repetition pattern. This is referred to as a beamhopping technique. Such a technique helps to reduce the number of amplifiers on board as well as the power demands on the payloads [13]. This technique can be implemented with full frequency or partial frequency reuse. In case of full frequency reuse, a regular time window is periodically applied to the beamhopping system and the entire available bandwidth is allocated to each illuminated beam. The duration for each illuminated beam should be selected to satisfy the user transmission delay requirement. In case of partial frequency reuse, the total bandwidth is segmented and each beam can be illuminated with a fraction of W. Let N_t be the number of time slots in each time window, then the $N_{\rm t} \times N_{\rm b}$ beam illumination matrix $\mathbf{T}$ can be written as:

$$\mathbf{T} = \begin{bmatrix} T_{11} & T_{12} & \dots & T_{N_{\rm b}1} \\ T_{12} & T_{22} & \dots & T_{N_{\rm b}2} \\ \vdots & \vdots & \ddots & \vdots \\ T_{1N_{\rm t}} & T_{2N_{\rm t}} & \dots & T_{N_{\rm b}N_{\rm t}} \end{bmatrix}, \qquad (2)$$

where T_{ij} indicates that the j-th time slot is allocated to the i-th beam. The total number of time slots allocated to the i-th beam can be written as: $N_{i,{\rm t}} = \sum_{j=1}^{N_{\rm t}} T_{ij}$, where $T_{ij} \in \{0, 1\}$ indicates whether the j-th time slot is allocated to i-th beam or not.

2.2. *Cognitive Satellite Communications*

In the field of satellite communications, the main available literature related to satellite-terrestrial coexistence has considered hybrid or integrated satellite networks [20, 21, 22, 23]. Furthermore, the cognitive related satellite literature can be divided into the following two categories: (i) hybrid satellite-terrestrial coexistence scenario [3, 5, 6, 14, 24, 25, 26, 27, 28], and (ii) dual satellite coexistence scenario [3, 7, 9, 10, 29, 30, 31]. Since we focus on dual satellite coexistence scenario in this paper, we provide a brief review on the literature related to the dual satellite coexistence scenario. In [3], the polarization domain has been considered as an additional spectrum sharing dimension for dual polarized Additive White Gaussian Noise (AWGN) channels considering a dual satellite coexistence scenario. In [29], the analysis of the interference between Complementary Ground Component (CGC) base station and Mobile Earth Station (MES) has been carried out for frequency sharing purpose in satellite systems. In the frequency sharing scenario between CGC base station and MES, the interference from the adjacent beams must be considered. In [9], the problem of distributed power control has been considered for cognitive satellite networks. In [32], sharing alternatives for up to four Code Division Multiple Access (CDMA) MSS systems operating in the same spectrum have been investigated considering both the downlink and uplink cases. It has been concluded that 4 CDMA systems may share the same band and terminal specifications are the main factors for ensuring the proper sharing. In [36], the frequency sharing of High Altitude Platform Station (HAPS) gateway links with the uplinks of Fixed Satellite Services (FSS) in 6 GHz band has been studied and the interference from the HAPS gateway uplinks into the FSS uplink has been evaluated. In [10], an interference alignment technique has been applied for the spectral coexistence of a multibeam and a monobeam satellites.

3. PROPOSED SYSTEM AND TECHNIQUES

3.1. *System Model*

We consider a dual satellite coexistence scenario as shown in Fig. 1. We consider both satellites to be multibeam satellites covering the same geographical region and operating in the normal forward mode [3]. Both satellites are assumed to be co-located in the same Geostationary (GEO) orbit and are connected to different gateways on Earth. These gateways are connected with the help of a high speed terrestrial link (e.g., optical fiber, microwave). In addition, both satellites operate in the Ka-band frequencies ($20-21$ GHz forward link). The primary satellite is an already deployed satellite for providing high priority broadband multimedia services to the fixed users. The secondary satellite can be used for providing services requiring low QoS such as interactive services to the fixed users. In this context, we assume the proposed cognitive beamhopping system to be compatible with the second generation of Digital Video Broadcasting over satellite (DVB-S2) or the next generation of DVB (DVB-Sx) standards.

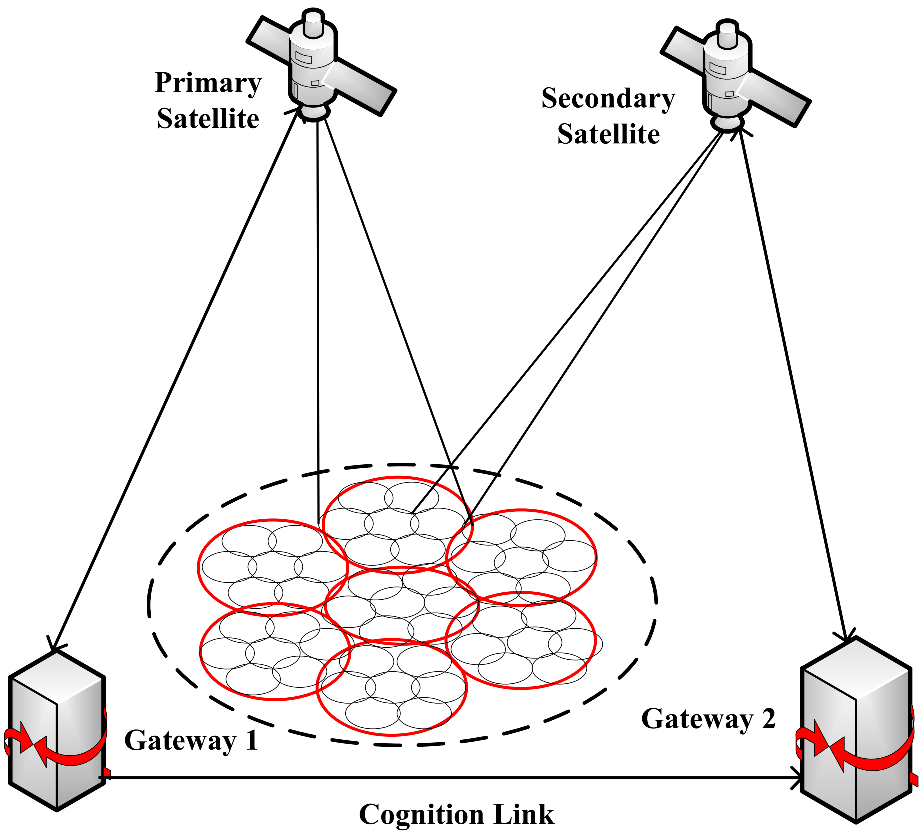

Figure 1. Spectral coexistence scenario of two multibeam satellites in the same geographic region

The primary satellite is operated with larger beams and the secondary satellite with smaller beams in the same coverage area†. We consider a coverage area with larger primary beams and many spot-beams within each primary beam and these spot-beams are the beams of the secondary satellite. The cognition is achieved by sharing the beamhopping pattern and the timing information of the primary satellite to the secondary satellite with the help of a signalling link between the gateways. Based on this a priori knowledge of the beamhopping pattern, the secondary satellite's beamhopping pattern is designed so that it does not degrade the primary's operation. Furthermore, the primary and secondary transmissions can be synchronized with the help of the exchanged timing information. The secondary satellite is supposed to be more dynamic and be equipped with smaller transponders (as reflected by link budget parameters presented in Table I). We consider a Single Feed per Beam (SFPB) type antenna sub-system for the primary system and an array fed reflector i.e., Multiple Feeds per Beam (MFPB) type antenna sub-system for the secondary system. As noted in [33], although both the SFPB and MFPB architectures are comparable in terms of the cost and mass, the MFPB architecture is preferable for smaller satellites due to the requirement of only two reflectors, one for transmission and the another for reception [33, 34]. Furthermore, it is possible to design the secondary link to have low Signal to Noise Ratio (SNR) at the center of the beam (in comparison to the receive SNR at the primary beam center) due to smaller coverage areas of the secondary beams while meeting the same edge requirements [37, 38]. Moreover, partitioning a beam into many sub-beams performs well towards the spot beam edge meeting the edge gain requirements.

† Due to recent advances in multibeam antenna technology, it is feasible to create coverage cells of less than $0.5°$ diameter [35, 33].

In this context, the importance of spot-beams is increasing due to their low peak gains and low contour levels resulting in smaller antenna aperture and lower hardware costs [37]. Although it is possible to illuminate a portion of beams simultaneously with the full frequency reuse or the fractional frequency reuse in a beamhopping system, we focus on the full frequency reuse approach in our considered scenario. In the following subsection, we present different techniques which can be applied for the spectral coexistence of two multibeam satellites.

3.2. Applicable Techniques

Since the primary satellite only illuminates a small fraction of beams out of a large number of beams deployed under the beamhopping system, the rest of the beams remain idle at that time waiting for their transmission slots. If we could deploy a secondary satellite within the same spectrum in such a way that it has a beamhopping sequence different from that of the primary one and it does not produce harmful interference with the primary system, the overall system spectrum efficiency can be enhanced. The idea is that the primary satellite shares its beamhoping pattern to the secondary satellite and based on this knowledge, the secondary satellite's beamhopping pattern is designed so that it does not affect the primary system's operation. For this purpose, interaction between primary and secondary systems is required as the secondary system has to be aware of the primary satellite's beamhopping pattern. This can be achieved with the help of a cognition link between the gateways. This scheme can be considered as a Beamhopping Pattern Planning (BPP) scheme. In this context, different techniques such as an EZ principle [39, 40] and a power control method can be applied.

3.2.1. Power Control Method : In the context of terrestrial CR networks, this method has been applied in various settings [41, 42]. In this paper, we apply this method for the considered dual satellite coexistence scenario. The power of the secondary satellite can be calculated based on the aggregate interference level provided by the secondary system to the primary. This can be applied to all the secondary beams over the considered region or only the secondary beams which are located within a certain range from the primary receiver. For power control within a certain region, this method can be combined with the EZ method. If the secondary satellite beams lie in between the white region and the black region i.e., in the grey region‡ [40] , we can implement power control in those secondary beams to maintain the interference threshold level of the PUs. In this combined method, the beams which are located in the black region are not activated and the beams which are located in the white region can be supplied with full power within a particular beamhopping slot. The sequence of active and inactive secondary beams should be changed in different time slots. This can be carried out easily based on the knowledge of primary beamhopping pattern. Furthermore, it is possible to apply dynamic power control method based on the distance from the primary active beam. In this method, less power is allocated to the secondary beams which are near the primary active beam and the transmitted power of the secondary beams can be increased as the distance from the primary active beam increases. It should be noted that there is a trade-off between power control and the achievable secondary throughput.

3.2.2. Exclusion Zone Method : This method has been investigated in the literature in various settings. The EZ principle is applied in [43] in the context of integrated satellite and terrestrial mobile systems. In [39], the Primary Exclusive Region (PER) for a CR network is proposed using the spatial spectrum holes. A CR network consisting of a single primary transmitter and multiple SUs has been considered and bounds on the radius of the PER has been proposed based on the aggregated secondary interference and outage guarantee to the PU. In [40], the bounds for black, grey and white regions have been investigated. These contributions have considered a single primary transmitter scenario considering the application of TV white spaces. In this scenario, the EZ region is confined within a certain region and the secondary system is allowed to operate beyond this specific region. However, in terrestrial cellular systems as well as in the multibeam satellite systems, there

‡Readers are referred to [39] and [40] for the definitions of different regions.

exist multiple co-channel primary transmitters within a coverage region. In this context, secondary systems should not be allowed to operate within the EZ regions of all the co-channel primary beams to ensure sufficient protection for all the PUs.

In this paper, we apply the EZ principle to investigate the operating region for the secondary satellite. The secondary satellite operates in such a way that its active beam lies beyond the EZ of all the primary active beams. The EZ concept can be used to find out the region in which the secondary satellite can transmit with full power and the regions in which the secondary satellite has to adjust its power. The secondary satellite beams are activated with full power in the region from which the aggregate interference to the primary satellite terminal is below some acceptable limit. Furthermore, the secondary beams which fall in the EZ of the primary beams can be activated with the limited power depending on how far they are from the beam centre position of the active primary beams[§]. The size of the EZ has a great impact on the QoS of the primary satellite since it affects the level of secondary interference that needs to be tolerated and on the secondary satellite capacity since it affects the available amount of primary spectrum at a given location.

4. SIGNAL AND CHANNEL MODEL

Let us consider a multibeam satellite system that employs a satellite antenna with N_{b} beams using a beamhopping pattern. At a particular time slot, only $M = N_{\mathrm{b}}/K$ beams are active transmitting independent information streams to M fixed terminals located in different active main beams. During a particular time slot, each satellite terminal suffers from the interference from other co-channel beams. This multibeam satellite channel can be modeled with M single user interfering links and is represented by an $M \times M$ channel matrix $\mathbf{H}$, each element of $\mathbf{H}$, h_{ij} representing the channel coefficient from beam j to user i.

For the cognitive coexistence of two satellites within the same spectrum while covering the same geographical region, the footprint of these satellites should be taken into account. The beam gain of the j-th beam for the i-th user position can be denoted by B_{ij} and can be written as [3]:

$$B_{ij} = G_{\max}.\left(\frac{J_1(u(i,j))}{2u(i,j)} + 36\frac{J_3(u(i,j))}{u(i,j)^3}^2\right)^2, \tag{3}$$

where $u(i,j) = 2.01723 \sin\left(\theta(i,j)\right)/\sin(\theta_{3\mathrm{dB}})$, J_m is the first kind of Bessel's function of order m, and $G_{\max}$ is the maximum antenna gain, $\theta_{3\mathrm{dB}}$ is the 3-dB angle and $\theta(i,j)$ represents the angular position of the i-th user from the j-th beam center with respect to the satellite. Let N_{b1} be the total number of beams in the primary satellite and M be the total number of users to be served by the network. Denote the received power at the output of the decoder of user i by $P_{\mathrm{r},i}$. It is related to the input power at beam j as:

$$P_{\mathrm{r},i} = h_{ij}P_{\mathrm{t},j}, \tag{4}$$

where $j = \{1, ..., N_{b1}\}$, $i = \{1, ..., M\}$, $P_{\mathrm{t},j}$ is the input power to beam j. Under clear sky conditions, this channel coefficient can be calculated as [44]:

$$h_{ij} = \frac{B_{ij}G_{\mathrm{r},ij}}{(4\pi d_{ij})^2}, \tag{5}$$

where $G_{\mathrm{r},ij}$ is the gain of the i-th user antenna towards the j-th beam and can be considered to be constant as it does not show significant variation in time. The parameter d_{ij} is the slant distance of the i-th user from the satellite which can be written as: $d_{ij}^2 = r_{ij}^2 + D_j^2$, where r_{ij} is the distance of i-th user position from the j-th beam centre position and D_j is the height of the geostationary satellite from the j-th beam center position.

[§]We use the beam center position as the reference point but the interference threshold is adjusted in order to guarantee the sufficient protection to the beam edge PUs as well.

For each user i, the following condition should be satisfied to have a reliable link: $\gamma_i \geq \gamma_{\text{th}}$, where γ_i is the Signal to Interference plus Noise Ratio (SINR) of the i-th user which is defined for different systems in Section 5, γ_{th} is the minimum SINR required by the user to have the desired QoS. Therefore, the power allocated to each beam should be calculated in the following way

$$P_{\text{t},j} = \frac{\gamma_{\text{th}} \cdot I_{\text{cn}}}{\min_{i \in j} |h_{ij}|^2}, \tag{6}$$

where I_{cn} is a parameter including the noise and the interference from co-channel beams, the notation $i \in j$ means that i-th user is served by the j-th beam. The above equation represents the power allocated to the j-th beam under clear sky conditions.

5. SYSTEM PERFORMANCE

The following coexistence scenarios may be considered: (i) operating SUs only in the white region where no secondary interference is present, (ii) implementing power control in the secondary transmission, and (iii) by carrying out dynamic spectrum sensing and allocating idle bands to the SUs. In this work, we focus on the first two scenarios. Furthermore, we consider scenarios where a single SU and multiple SUs are present within each inactive primary beam.

5.1. *Throughput Analysis*

In this section, we present the theoretical expressions for evaluating the performance of different systems. In this analysis, we assume fixed carrier and power allocation for conventional multibeam and beamhopping systems. Furthermore, we assume a band-limited Gaussian line of sight channel contaminated with cochannel interference and consider that the interference is uncorrelated with the desired signal. It can be noted in [45] that while considering DVB-S2 with Adaptive Coding and Modulation (ACM), the spectral efficiency curve follows the Shannon curve with a certain gap. Assuming that suitable modulation and coding is available to recover the supported SNR range, the Shannon capacity can be used as a suitable metric for evaluating the system performance¶.

5.1.1. Conventional Multibeam System : In this case, the multibeam satellite coverage with frequency reuse factor of K is considered. The dominant interference in this case is the co-channel interference from neighboring co-channel cells. The SINR of the i-th user is given by;

$$\gamma_{\text{CV},i} = \frac{|h_{ii}|^2 P_{\text{t}}}{P_{\text{t}} \sum_{j \in S_{\text{P}}} |h_{ij}|^2 + \sigma^2}, \tag{7}$$

where σ^2 denotes the noise power, P_{t} represents the transmitted power and S_{P} represents the set of co-channel beams. It can be noted that we include all possible co-channel cells in a given area and adjacent channel interference is not included in (7). The system throughput for this system can be written as [1]:

$$C_{\text{CV}} = \frac{W}{K} \sum_{i=1}^{N_b} \log_2(1 + \gamma_{\text{CV},i}), \tag{8}$$

where N_b is the number of beams in the system.

5.1.2. Beamhopping System In this case, a beamhopping system with slot reuse factor of K is considered. Each active beam uses full frequency instead of fractional frequency reuse in the conventional multibeam systems. This is equivalent to frequency reuse factor in the frequency

¶In practice, we need to take account of channel fading, coding and modulation parameters depending on the type of modulation and coding scheme employed while evaluating the overall system capacity [45].

domain. The SINR of the i-th user is given by;

$$\gamma_{\mathrm{BH},i} = \frac{|h_{ii}|^2 P_{\mathrm{t}}}{P_{\mathrm{t}} \sum_{j \in S_{\mathrm{B}}} |h_{ij}|^2 + \sigma^2}, \tag{9}$$

where S_{B} represents the set of beams which are active in a particular beamhopping slot. The system throughput for this system can be written as:

$$C_{\mathrm{BH}} = W \sum_{i=1}^{N_{\mathrm{b}}/K} \log_2(1 + \gamma_{\mathrm{BH},i}), \tag{10}$$

where N_b/K represents the number of beams which are active per beam slot.

5.1.3. Cognitive Beamhopping System : Since only a certain fraction of total available beams are active in a particular time slot, we can explore the possibility of using those frequencies in the secondary satellite system in a secondary way. The primary system is a beamhopping system with larger beams with slot reuse factor of K. The secondary system can also be considered to be a beamhopping system with smaller beams and lower transmit power. The total system throughput in this system can be expressed as:

$$C_{\mathrm{CB}} = C_{\mathrm{PS}} + C_{\mathrm{SP}} = W \left(\sum_{i=1}^{N_{\mathrm{b}}/K} \log_2(1 + \gamma_{\mathrm{CP},i}) + \sum_{i=1}^{N_{\mathrm{s}}} \log_2(1 + \gamma_{\mathrm{CS},i}) \right), \tag{11}$$

where C_{PS} and C_{SP} denote primary/secondary throughput in the presence of secondary/primary system respectively, $\gamma_{\mathrm{CP},i}$ represents the SINR of the PU, $\gamma_{\mathrm{CS},i}$ represents the SINR of the SU and N_s denotes the number of active secondary beams. The expression for $\gamma_{\mathrm{CP},i}$ can be written as:

$$\gamma_{\mathrm{CP},i} = \frac{|h_{\mathrm{P},ii}|^2 P_{\mathrm{pt}}}{P_{\mathrm{pt}} \sum_{j \in S_{\mathrm{P}}} |h_{\mathrm{p},ij}|^2 + P_{\mathrm{st}} \sum_{j \in S_{\mathrm{S}}} |h_{ij,\mathrm{s}}|^2 + \sigma^2}, \tag{12}$$

where P_{pt} is the transmit power of the primary system, P_{st} is the transmit power of the secondary system, S_{S} represents the set of secondary active beams in a particular slot. The parameter $h_{\mathrm{p},ij}$ represents the channel gain of the i-th PU from the j-th primary beam and $h_{ij,\mathrm{S}}$ denotes the channel gain of the i-th PU from the j-th secondary beam. Similarly, the expression for $\gamma_{\mathrm{CS},i}$ can be written as:

$$\gamma_{\mathrm{CS},i} = \frac{|h_{\mathrm{S},ii}|^2 P_{\mathrm{st}}}{P_{\mathrm{pt}} \sum_{j \in S_{\mathrm{p}}} |h_{ij,P}|^2 + P_{\mathrm{st}} \sum_{j \in S_{\mathrm{S}}} |h_{\mathrm{S},ij}|^2 + \sigma^2}, \tag{13}$$

where $h_{ij,\mathrm{p}}$ is the channel gain of i-th SU from the j-th primary beam and $h_{\mathrm{s},ij}$ is the channel gain of i-th SU from the j-th secondary beam.

5.2. Power Control Method

In this method, firstly, the aggregate interference from the secondary satellite beams to the PU is calculated and based on this interference level, the transmit power of the secondary satellite is adjusted to meet the interference threshold level of the PU. Let I_{T} be the interference threshold level of the PU to have sufficient protection‖ and I_{AGG} be the aggregate interference from secondary beams to the PU. Then the expression for I_{AGG} at a particular slot can be written as: $I_{\mathrm{AGG}} = P_{\mathrm{st}} \sum_{j \in S_{\mathrm{S}}} |h_{ij,\mathrm{s}}|^2$. The transmit power of the secondary satellite can be adjusted in the following way to guarantee sufficient protection for the PU

$$P_{\mathrm{st}} = \frac{I_{\mathrm{T}}}{\sum_{j \in S_{\mathrm{S}}} |h_{ij,\mathrm{s}}|^2}. \tag{14}$$

‖It can be noted that primary system has to sacrifice some throughput corresponding to this interference tolerance level.

It can be noted that as the number of SUs within an primary inactive beam increases, the denominator term of the above equation increases and the secondary satellite has to reduce its transmission power.

5.3. Exclusion Zone Method

We apply the EZ principle mentioned in Section 3 for the coexistence of two multibeam satellites. Investigating the exact exclusion zone for the primary active beam in our considered scenario is one important research problem. Furthermore, by sacrificing a certain tolerable primary throughput, the secondary satellite can coexist with the primary depending on the EZ radius. If the EZ radius is too small, the primary terminals need to tolerate more interference from the secondary satellite and if the EZ radius is too large, the total SE of the system needs to be sacrificed. In this context, we address the trade-off problem of primary throughput sacrifice and the total SE of cognitive beamhopping system. Furthermore, our interest is to investigate the minimum distance from the primary active beam center at which the secondary satellite can serve its users ensuring perfect protection to the PUs. The application of the EZ principle in our proposed cognitive beamhopping system is described below.

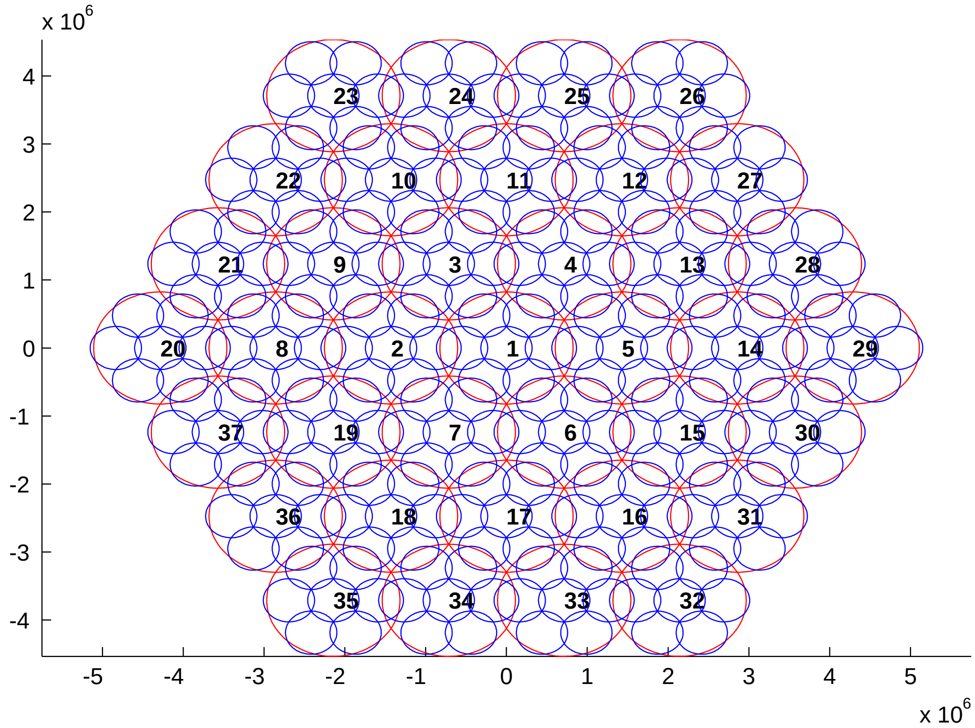

Figure 2. Overlay pattern of two satellites obtained during simulation of the proposed system ($N_\mathrm{b} = 37$, $K = 7$, θ_{3dB1} =1.3125°, $\theta_{3dB2} = 0.5052°$)

We consider a geographic region covered with the beampatterns of the primary and secondary satellites as shown in Fig. 2. Each primary beam consists of N_s number of secondary beams and only a fraction of total primary beams are active within a particular time slot. Let θ_{3dB} be 3 dB beamwidth of the primary beam and can be calculated as:

$$\theta_{\mathrm{3dB}} = \tan^{-1}(r/D), \tag{15}$$

where r is the radius of the primary beam corresponding to the 3 dB beamwidth and the D is the height of the satellite from the center of the beam. By increasing the value of θ_{3dB} by some amount Δ i.e., $\theta_{\mathrm{new}} = \theta_{\mathrm{3dB}} + \Delta$, we can calculate the new value of r corresponding to the particular value of

θ_{new}. During a particular time slot, only the secondary beams which lie outside the EZ of the active primary beams are made active[**]. This is done by comparing the nearest distance of the secondary beam from the center of the primary active beam with the EZ radius. While doing this, distances from all the active primary co-channel beams is taken into consideration to ensure the protection for all the PU terminals in the considered region.

6. NUMERICAL RESULTS

We consider the following three systems for comparison: (i) conventional multibeam system (Section 5.1.1), (ii) beamhopping system (Section 5.1.2), and (iii) proposed cognitive beamhopping system (Section 5.1.3). The simulation parameters are presented in Table I. In the proposed cognitive beamhopping system, each beam of the primary system includes 7 sub-beams which are served by the secondary satellite.

6.1. Performance Metrics

The system performance is evaluated using total SE in bits/sec/Hz and primary rate protection ratio. The total SE of the conventional multibeam, beamhopping and the proposed cognitive beamhopping systems are obtained using (8), (10) and (11) respectively. The primary rate protection ratio can be denoted by PR and is defined as:

$$\mathrm{PR} = \frac{C_{\mathrm{PS}}}{C_{\mathrm{PO}}}, \tag{16}$$

where C_{PO} is the primary only throughput in the absence of the secondary system.

6.2. Methodology

We evaluate the performance of the proposed cognitive beamhopping system using two different approaches. The primary system is supposed to be a beamhopping system with a fixed beamhopping pattern and the secondary system is supposed to be an intelligent system which can adjust its beampattern based on the primary beamhopping sequence. In the first approach, the secondary system applies power control to the active beams in order to provide the sufficient protection to the primary users. In this context, we investigate both the full frequency reuse and frequency sharing-based approaches among the secondary users in each primary inactive beam. In the second approach, we apply the exclusion zone principle, in which only the secondary beams which lie inside the exclusion zone of all the active primary beams at a particular time instant are switched off. It should be noted that in the EZ approach, the secondary system does not need to implement power control in order to protect the PUs. Furthermore, the proposed solution can be considered as a special case of overlapping coverage of multibeam systems which is closer to a real implementation on integrated satellite-terrestrial systems for multibeam satellites combined with ground complementary components [43].

We calculate the beamwidth using the expression given by (15), in which the corresponding cell radius i.e., the value of r can be found by accommodating the N_b number of beams in the considered coverage area (5000 km) and N_s number of secondary beams in each primary beam. Then we calculate the peak antenna gain values for primary and secondary systems using $G(\mathrm{dB}) = 10\log(29,000/(\theta_{3\mathrm{dB}})^2)$ considering antenna efficiency to be 60 % [47], which results in higher antenna peak gain for the secondary system in comparison to the primary system. This allows system designers the flexibility of using less transmit power per beam for the secondary system than that in the primary system meeting the same edge gain requirements. Since the size of the satellite is partially determined by the required transmit power, designers can save payload weight on the secondary satellite. In our analysis, we divide our considered area into smaller cells with the

[**]It can be noted that a secondary beam should not be active even if a part of it lies within the EZ of active primary beams since we are considering normal forward scenario.

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considered number of beams and consider the maximum SNR in the center of the beam closer the receive SNR value provided by the link budget calculation in Table I. For interference calculation, we calculate 4 different beam matrices using (3) for the following scenarios: (i) from primary beams to the SUs, (ii) from secondary beams to the PUs, (iii) from primary beams to the PUs, and (iv) from secondary beams to the SUs. Then we evaluate the system performance using capacity expressions provided in Section 5 and present results in the following subsections.

Table I. Simulation and link budget parameters

Parameter	**Symbol**	**Value**
Orbit		GEO
Satellite height	D	35800 km
Frequency band		Ka (20 GHz)
User link bandwidth	W	500 MHz
Coverage area radius	R	5000 Km
Parameters for primary Satellite		
Interference tolerance threshold	I_0	-123 dBW
Slot reuse factor	K	3,7
Number of primary Beams	N_{b}	37
3 dB beamwidth	$\theta_{3\text{dB1}}$	1.3125°
TWTA RF power @ saturation	P_{pt}	20 dBW
Max satellite antenna gain	G_{t}	42.26 dBi
Free space path loss	FL	209.5 dB
Fading margin		3 dB
Noise power @ 500 MHz	N_o	-117 dBW
Max user antenna gain	G_{r}	45 dBi
Receive SNR at the beam center		11.76 dB
Parameters for Secondary satellite		
Number of secondary beams per primary beam	N_s	7
3 dB beamwidth	$\theta_{3\text{dB2}}$	0.5052°
TWTA RF power @ saturation	P_{st}	10 dBW
Max satellite antenna gain	G_{t}	50.55 dBi
Free Space Path loss	FL	209.5 dB
Fading Margin		3 dB
Noise Power @ 500 MHz	N_o	-117 dBW
Max user antenna gain	G_{r}	45 dBi
Receive SNR at the beam center		10.05 dB

6.3. *Throughput Comparison*

Figure 3 shows the SE (bits/sec/Hz) versus SNR for different systems for $K = 3, N_{\text{b}} = 19$ and $P_{\text{st}} = P_{\text{pt}}$. During this simulation setting, only one SU was considered at the center of each inactive primary beam. From the figure, it can be noted that the SE for the beamhopping system is slightly greater than for the conventional multibeam system. Furthermore, it can be noted that the primary only SE slightly decreases at higher values of SNR in the presence of secondary system whereas the total SE of the cognitive beamhopping system increases. The increase in the secondary throughput in comparison to the primary throughput in Fig. 3 comes from the fact that there are more number of active secondary beams (smaller) with the same transmit power during a particular beamhopping slot. Moreover, it should be noted that the value of the SE plotted in our results is the SE obtained over the considered area instead of the SE of a single link.

Figure 4 shows the SE versus secondary transmit power (P_{st}) for $K = 3, 7$ and $N_{\text{b}} = 37$. The primary transmit power (P_{pt}) was considered to be 10dBW. From the figure, it can be noted that the total SE of the cognitive beamhopping system for $K = 7$ is higher than for $K = 3$ and it increases with the secondary transmit power for both the values of K. Figure 5 shows the PR versus secondary

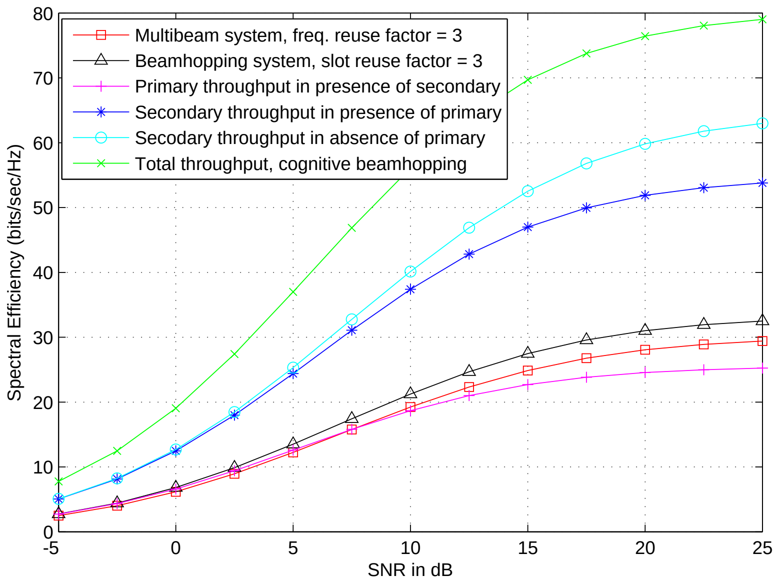

Figure 3. Throughput comparison of different systems ($K = 3, N_{\rm b} = 19, P_{\rm st} = P_{\rm pt}$)

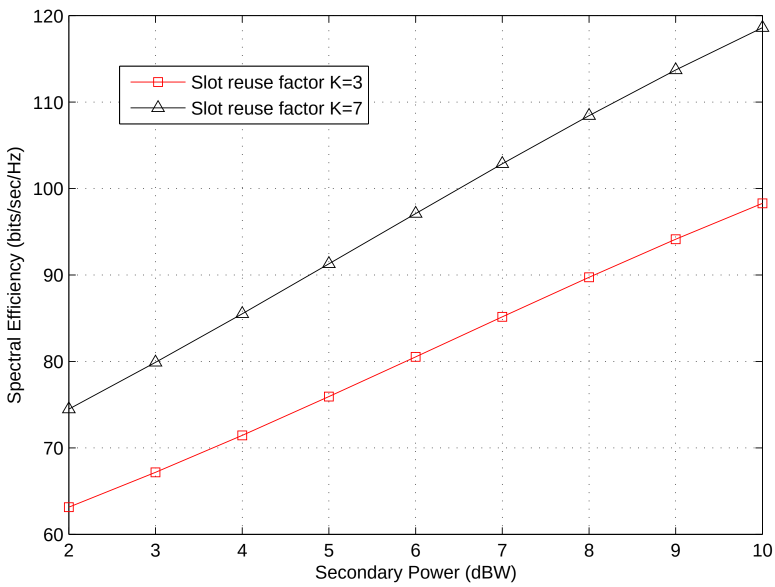

Figure 4. Spectral efficiency versus secondary power in cognitive beamhopping system ($N_{\rm b} = 37, P_{\rm pt} = 10{\rm dBW}$)

power for $K = 3, 7$ and $N_{\rm b} = 37$. From this figure, it can be noted that the primary rate protection ratio is higher for the case of $K = 3$ than for the case of $K = 7$. While comparing Figs. 4 and 5, it can be concluded that for lower value of reuse factor e.g., $K = 3$, less number of primary inactive beams are available resulting in less number of secondary active beams in a particular time slot. Therefore, the total SE for the case of $K = 7$ is higher than the case of $K = 3$ due to large increase in secondary SE. On the otherhand, the primary system is more protected for $K = 3$ case than for $K = 7$ since only few secondary beams are active in the former case than in the later case. Therefore, the choice of the factor K should be made in order to make a trade-off between the total SE and the PR. It should be noted that there is a lower bound on the size of the beams due to electromagnetic properties of satellite antenna arrays and propagation characteristics of satellite channels.

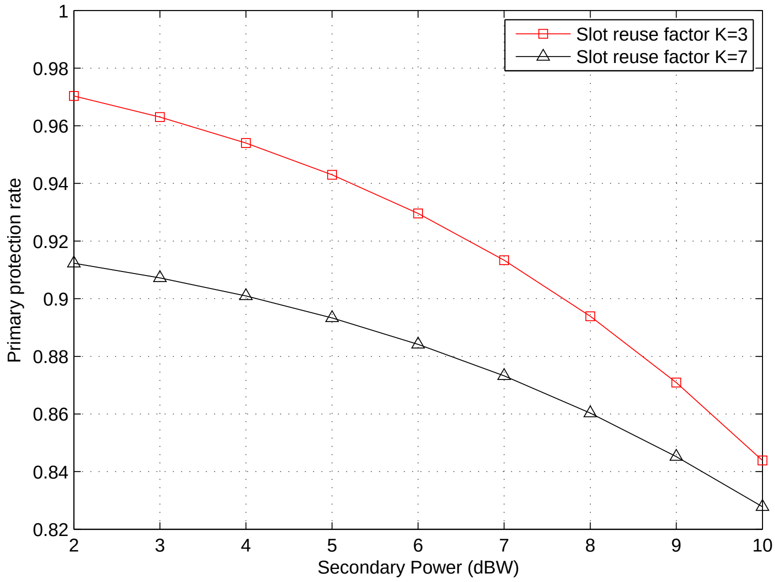

Figure 5. Primary rate protection ratio versus secondary power in cognitive beamhopping system ($N_{\rm b} = 37, P_{\rm pt} = 10{\rm dBW}$)

Table II. Throughput Comparison for different scenarios in a cognitive beamhopping system

K	$N_{\rm b}$	Power ($P_{\rm pt} = 10dBW$)	$C_{\rm PO}(bps/Hz)$	$C_{\rm PS}(bps/Hz)$	$C_{\rm PR}(bps/Hz)$	$C_{\rm SP}(bps/Hz)$	$C_{\rm CB}(bps/Hz)$
3	37	$P_{\rm st} = P_{\rm pt/2}$	37.53	34.29	0.913	50.86	85.16
3	37	$P_{\rm st} = P_{\rm pt}$	37.53	31.69	0.84	66.63	98.32
3	37	$P_{\rm st} = 2 \times P_{\rm pt}$	37.53	27.68	0.73	80.76	108.44
7	37	$P_{\rm st} = P_{\rm pt/2}$	22.61	20.18	0.89	67.63	87.82
7	37	$P_{\rm st} = P_{\rm pt}$	22.61	18.34	0.81	85.28	103.62
7	37	$P_{\rm st} = 2 \times P_{\rm pt}$	22.61	15.67	0.69	99.68	115.35
3	19	$P_{\rm st} = P_{\rm pt/2}$	21.21	19.83	0.93	28.44	48.27
3	19	$P_{\rm st} = P_{\rm pt}$	21.21	18.66	0.88	37.47	56.14
3	19	$P_{\rm st} = 2 \times P_{\rm pt}$	21.21	16.78	0.79	45.91	62.69
7	19	$P_{\rm st} = P_{\rm pt/2}$	9.88	8.47	0.86	51.98	60.45
7	19	$P_{\rm st} = P_{\rm pt}$	9.88	9.10	0.92	40.61	49.72
7	19	$P_{\rm st} = 2 \times P_{\rm pt}$	9.88	7.48	0.76	61.82	69.31

Table II shows the primary only throughput $C_{\rm PO}$, primary throughput in presence of the secondary $C_{\rm PS}$, secondary throughput in presence of the primary $C_{\rm SP}$, primary rate protection ratio $C_{\rm PR}$ and total throughput $C_{\rm CB}$ of the cognitive beamhopping system. This table presents the above mentioned performance metrics for the values of $K = 3, 7$ and $N_{\rm b} = 19, 37$ for the following power ratio cases: (i) secondary power half of the primary power i.e., $P_{\rm st} = P_{\rm pt}/2$, (ii) secondary power equal to the primary power i.e., $P_{\rm st} = P_{\rm pt}$ and (iii) secondary power double than that of the primary power i.e., $P_{\rm st} = 2 \times P_{\rm pt}$. From the table, it can be noted that the value of $C_{\rm PS}$ decreases from the case (i) to (ii) and further decreases from case (ii) to case (iii) for all combinations of K and $N_{\rm b}$. As a result, the primary rate protection ratio also decreases from case (i) to case (iii) for all combinations of K and $N_{\rm b}$. For example, for $K = 3$ and $N_{\rm b} = 37$, the primary protection rate is 0.913 for case (i), 0.84 for case (ii) and 0.73 for case (iii). Furthermore, it can be noted from the table that the value of $C_{\rm SP}$ as well as the value of $C_{\rm CB}$ increases from the case (i) to the case (iii) for all the combinations of K and $N_{\rm b}$. From these comparative results, it can be concluded the primary rate is more protected with less secondary power in comparison to the primary power while secondary throughput and the total throughput is the maximum for the highest secondary transmitted power. While comparing the cases for $K = 3$ and $K = 7$ for a specific value of $N_{\rm b}$, it can be noted that the primary rate protection ratio for $K = 7$ is less than for $K = 3$ while the secondary throughput as well as the total

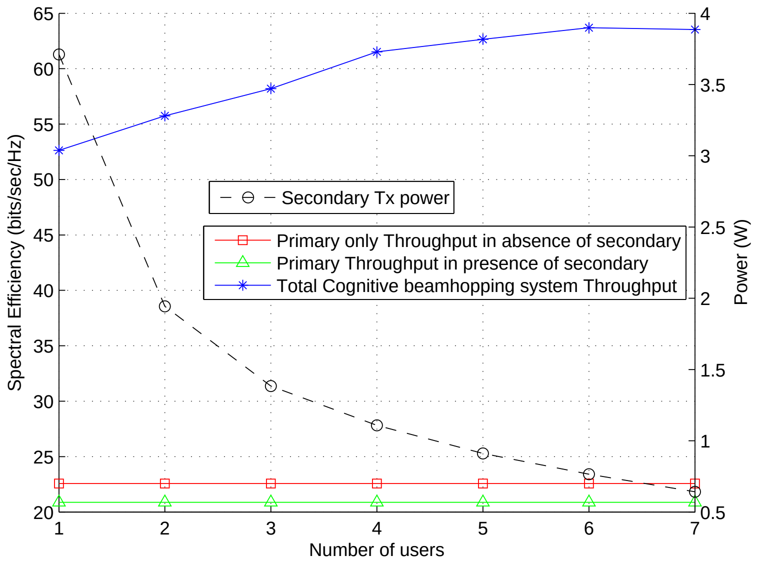

Figure 6. SE versus number of SUs in cognitive beamhopping system with full frequency reuse ($K = 7, N_{\mathrm{b}} = 37, P_{\mathrm{pt}} = 10\mathrm{dBW}$)

throughput increases for the $K = 7$ case than for the $K = 3$ case for all the considered power ratio cases.

6.4. *Power Control Method*

To calculate the number of SUs which can be served in switched off region of the primary beams, simulations were carried out considering the presence of multiple SUs per inactive primary beam. Figure 6 shows SE versus number of users for cognitive beamhopping system. In this simulation settings, the SUs were placed at the center of sub-beams in each inactive primary beam and the number of users was varied from 1 to 7. The full frequency reuse is considered for both primary and secondary systems. For the result in Fig. 6, the parameters considered were $K = 7, N_{\mathrm{b}} = 37, P_{\mathrm{pt}} = 10\mathrm{dBW}$. The interference tolerance threshold of each PU for the considered user link bandwidth (500 MHz) was considered to be $-123\mathrm{dBW}$[††] and based on this interference threshold, power of the secondary satellite was calculated for considered number of SUs. From the figure, it can be noted that SE increases with the number of users and it almost saturates while increasing the user number from 6 to 7. Furthermore, it can be noted that the secondary satellite has to reduce its transmitted power as the number of SUs increases in order to protect the primary rate with tolerable level of interference. Moreover, the simulations were carried for the cases of $K = 3, N_{\mathrm{b}} = 37$, $K = 7, N_{\mathrm{b}} = 19$ and $K = 3, N_{\mathrm{b}} = 19$. It has been noted from the results that for a specific value of N_b, the total cognitive beamhopping throughput is greater for $K = 7$ case for all the considered number of users but the primary throughput for the primary system is higher for $K = 3$ case. Furthermore, the primary protection rate is slightly less in $K = 3$ case than in $K = 7$ case provided the same interference threshold limit for each PU.

To evaluate the performance of proposed cognitive beamhopping system in the presence of multiple users with frequency sharing, simulations were carried out by sharing the spectrum resource among the SUs in the same inactive primary beam. In this case, each SU uses only a fraction of the spectrum resource and this fraction depends on the considered number of users. Figure 7 shows SE versus number of users for cognitive beamhopping system with frequency sharing among the SUs in the secondary system with $K = 7, N_{\mathrm{b}} = 19, P_{\mathrm{st}} = 10\mathrm{dBW}$. From the figure, it can be

[††]This value was chosen to ensure that the aggregated interference to noise ratio does not exceed $-6\mathrm{dB}$ [46].

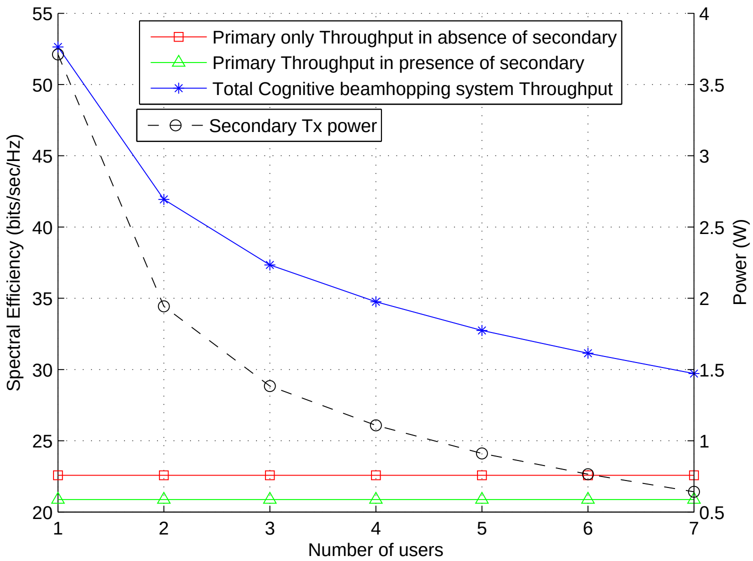

Figure 7. SE versus number of SUs in cognitive beamhopping system with frequency sharing among the SUs ($K = 7, N_{\mathrm{b}} = 37, P_{\mathrm{pt}} = 10\mathrm{dBW}$)

noted that the total throughput of the cognitive system decreases as the number of SUs increases. Furthermore, the power of secondary user has to be adjusted as per black line drawn in the figure to meet the interference threshold limit of the PUs. Similarly, the simulation experiment was carried out for the case of $K = 3, N_{\mathrm{b}} = 19, P_{\mathrm{pt}} = 10\mathrm{dBW}$ and it is noted that overall throughput decreases in this case for all number of SUs but the primary throughput increases for $K = 3$ case. Furthermore, the primary rate is slightly less protected in $K = 3$ case than in $K = 7$ case provided the same interference threshold limit for each PU.

From the comparison of two cases with full frequency reuse and frequency sharing in the secondary system, it can be concluded that the SE increases with the number of users in the frequency reuse case and the SE decreases with the number of users in the frequency sharing case. Furthermore, the frequency sharing among users is not that much suitable from practical perspectives. Therefore, the cognitive beamhopping system can achieve significant enhancement in the total throughput than the primary only system by using full frequency reuse in secondary system in practical scenarios.

6.5. *Exclusion Zone Method*

Figure 8 shows the SE versus EZ radius (dB) for $K = 7, N_{\mathrm{b}} = 37, P_{\mathrm{pt}} = P_{\mathrm{st}} = 10\mathrm{dBW}$. In this simulation settings, one SU was considered at the center of each inactive primary beam. For a particular beamhopping slot, all the secondary beams which are inside the EZ of all the primary active beams were not taken into account for calculating interference as well as the total SE of the system i.e., only the beams which lie outside the EZ regions of the all the active primary beams were considered. The EZ radius of the beam was varied from 3 dB to 9 dB. From the figure, it can be noted that the primary throughput in the presence of secondary increases i.e., the primary protection rate is increased with the increase in the EZ radius as expected whereas the total SE decreases. It can be noted that after the EZ radius of 8.5 dB, the primary rate is almost protected with a significant gain in the total SE. In this aspect, we can enhance the total SE using the EZ principle in the proposed cognitive beamhopping system ensuring sufficient protection to the primary system. Similarly, Fig. 9 shows the plot of SE versus EZ radius (dB) for $K = 7, N_{\mathrm{b}} = 37, P_{\mathrm{st}} = 10\mathrm{dBW}$ considering the presence of single SU at the center of each inactive primary beam. In this simulation settings, the secondary power i.e., P_{st} was considered to be half of the primary power P_{pt}. From the comparison

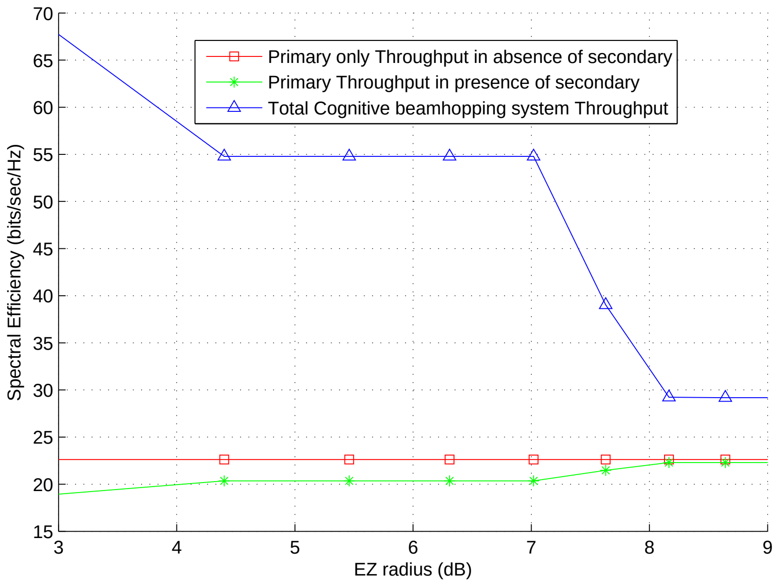

Figure 8. SE versus EZ radius (dB) for cognitive beamhopping system considering single SU in the center of inactive primary beam ($K = 7, N_\mathrm{b} = 37, P_\mathrm{pt} = P_\mathrm{st} = 10\mathrm{dBW}$)

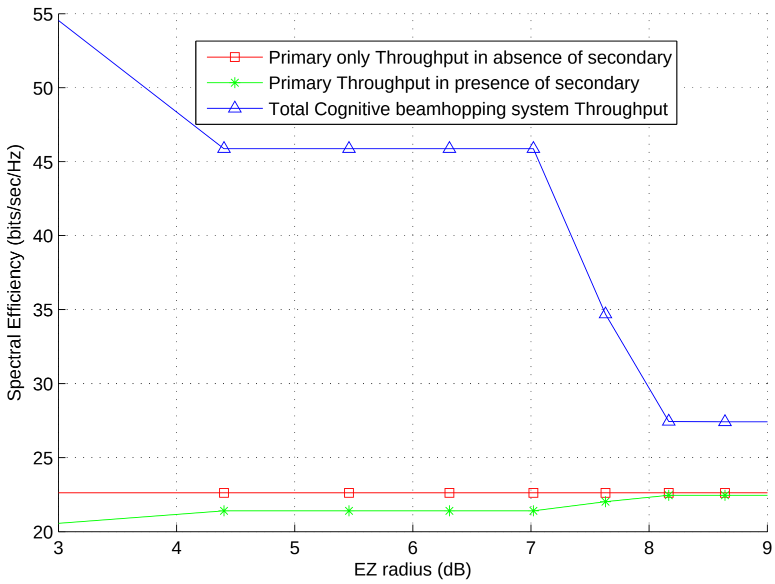

Figure 9. SE versus EZ radius (dB) for cognitive beamhopping system considering single SU in the center of inactive primary beam ($K = 7, N_\mathrm{b} = 37, P_\mathrm{st} = P_\mathrm{pt}/2, P_\mathrm{pt} = 10\mathrm{dBW}$)

with Fig. 8, it can be noted that the total SE decreases in this case and the primary is more protected for all the values of EZ radius.

Figure 10 depicts the SE versus EZ radius (dB) for $K = 7, N_\mathrm{b} = 37, P_\mathrm{pt} = 10\mathrm{dBW}, P_\mathrm{st} = P_\mathrm{pt}/2$ considering the case of multiple SUs in each inactive primary beam. The following three scenarios have been considered for comparison (i) Best position of the SUs (Beam centre), (ii) Random position of the SUs, and (iii) Worst position of the SUs (Beam edge). The above different positions of the SUs are illustrated in Fig. 11 considering a segment of the coverage area. While simulating the best case scenario, SUs were placed at the centers of secondary beams within each inactive

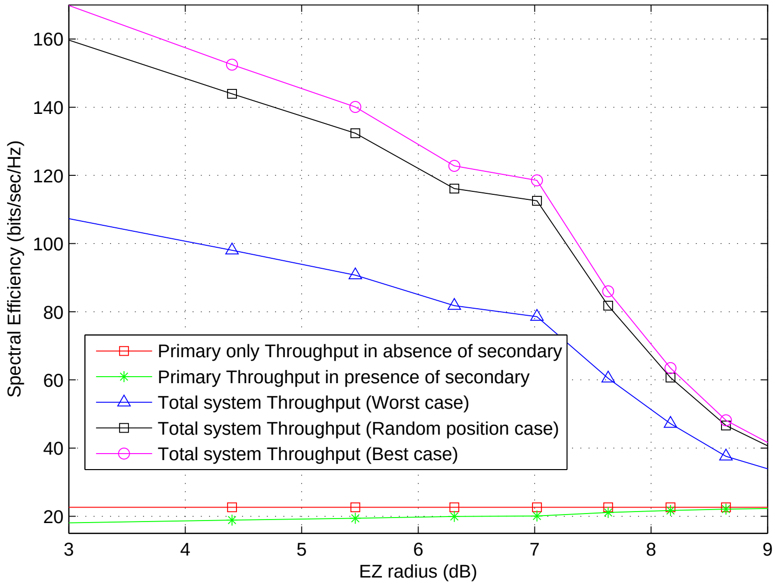

Figure 10. Comparison of SE versus EZ radius (dB) for different SU positions (considering multiple SUs within each inactive primary beam) ($K = 7, N_{\text{b}} = 37, P_{\text{pt}} = 10\text{dBW}, P_{\text{st}} = P_{\text{pt}}/4$)

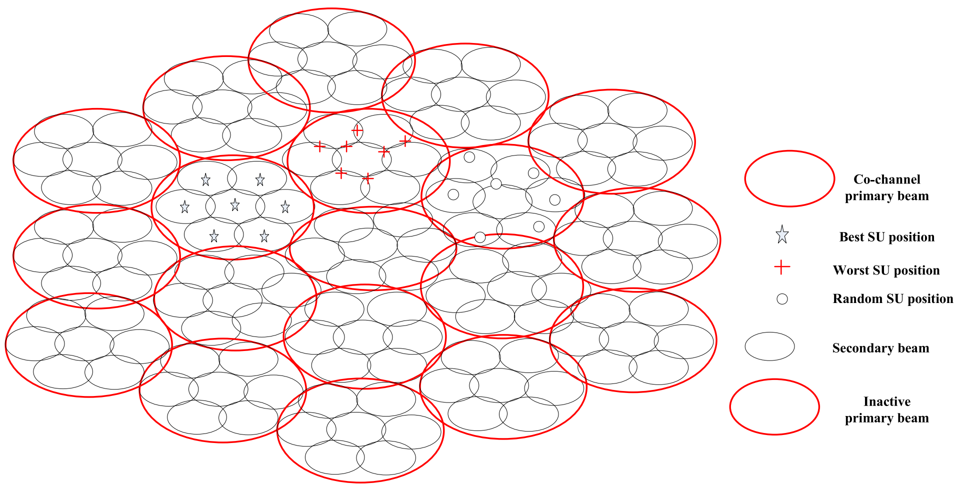

Figure 11. A segment of the considered coverage area showing co-channel primary beams and different user positions

primary beam. For the random scenario, positions of the SUs were generated randomly with uniform distribution while for the worst case scenario, the SUs were placed just on the border of the secondary beams within each inactive primary beam. From the figure, it can be depicted that the best case scenario achieves the highest total system throughput in comparison to other scenarios. Furthermore, the performance of the random users scenario is closer to the best case scenario as depicted in the figure. From practical perspectives, the worst case scenario is more realistic than other scenarios.

6.6. Comparison of EZ and power control Methods

In order to compare the above two methods, simulations were carried out with parameters $K = 7, N_{\text{b}} = 37$. To have a fair comparison of these two methods, the aggregated interference from

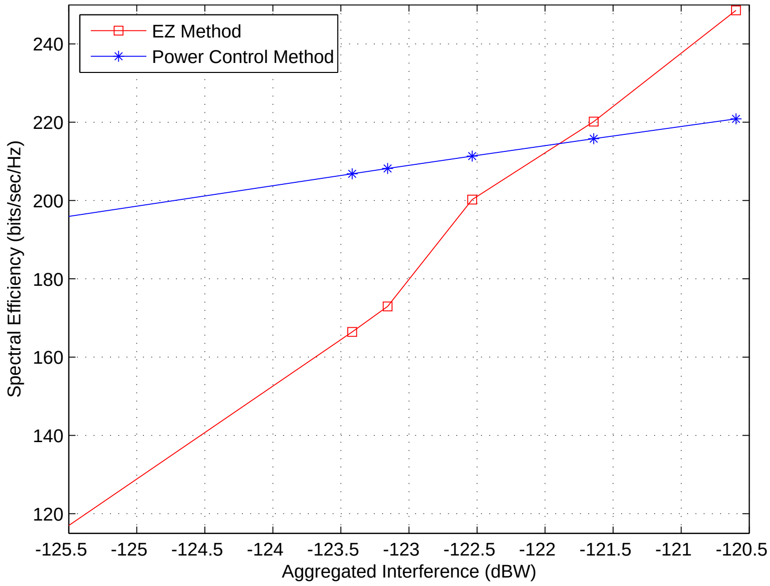

Figure 12. Comparison of power control and EZ methods $K = 7$, $N_{\rm b} = 37$

the secondary system to the primary system was kept fixed in both systems. While simulating the EZ method, the value of $P_{\rm st}$ was considered to be half of the value of $P_{\rm pt} = 10{\rm dBW}$ and the power control was applied on the secondary transmission using the same aggregated interference obtained in EZ method. Figure 12 shows the comparison of SE obtained using these methods versus aggregated interference. The aggregated interference was varied from $-125.5{\rm dBW}$ to $-120.5{\rm dBW}$. It can be noted that power control method shows less variation in SE over the considered range than the EZ method. Furthermore, it can be deduced that the power control method achieves higher SE than the EZ method for low values of the aggregated interference and after a certain value of aggregated interference ($-121.9{\rm dBW}$ in Fig. 12) the EZ method achieves higher SE than the power control method. Therefore, it can be concluded that the power control method achieves higher system throughput in the presence of low secondary aggregated interference while the EZ method is better suited for high secondary aggregated interference.

7. DISCUSSION AND TECHNICAL CHALLENGES

We have proposed a novel cognitive beamhopping technique allowing the coexistence of multibeam satellite systems. The primary system can be a multibeam satellite with a predetermined beamhopping pattern. In this context, the application of beamhopping in multibeam satellite systems has been already discussed in various contributions [15, 16, 17, 18]. In this paper, we studied the feasibility of using another multibeam satellite system having smaller beams in a secondary way in order to enhance the overall spectral efficiency of the system. The system performance of the proposed system has been evaluated using the theoretical expressions presented in Section 5. It was noted that operating the SUs in the inactive regions of the primary system significantly enhances the spectral efficiency of the overall system. However, the secondary cochannel beams may provide harmful interference to the active primary users, hence degrading the quality of primary links. To address this issue, we have considered two different techniques, more specifically, power control and EZ based approaches, in order to protect the PUs considering the tolerable interference threshold of the PUs. In the power control based approach, the secondary system has to reduce transmission power of its active beams ensuring that the aggregated interference towards the PUs remains below the PU interference threshold limit. Whereas, in the EZ based approach, only the secondary beams which lie outside the EZ of the primary beams are active without reduction in the transmission power. Besides presenting results for individual cases, we have compared these two approaches in terms of the SE. It should be noted that we have not discussed the combined case of these approaches in this paper. The combination of power control and EZ based approaches may lead to further increase in the SE since different power control strategies can be applied on different regions while protecting the PUs. Furthermore, the combination of dynamic spectrum sensing with these techniques may lead to better spectrum utilization by exploiting spectrum holes in both the temporal and spatial domains.

Despite the significant advantages of the proposed cognitive beamhopping system for enhancing overall spectral efficiency of the satellite systems, there are several technical challenges in order to fully implement this system in practice. In this context, we present technical challenges of implementing the proposed system from practical perspectives below.

1. In order to operate the secondary system in the switched off regions of the primary system, the secondary system should be aware of the primary beamhopping sequence as mentioned in Section 3. For this purpose, a high speed backhaul link needs to be established between the gateways of primary and secondary systems.
2. The operation of primary and secondary systems should be synchronized in time for proper operation of both the systems. For this purpose, timing information needs to be exchanged with the help of the backhaul link between the gateways or intersatellite links between two satellites.
3. In case the primary system employs flexible beamhopping system whose beamhopping pattern changes based on the traffic demand, the beamhopping pattern should be updated frequently to the secondary system in order to avoid interference between the two systems.
4. For the secondary system, there exists a flexibility to choose lower transmit power while meeting the edge gain requirements since the antenna peak gain becomes higher for smaller beams. The requirement of low transmit power results in smaller transponder size, hence reducing the payload cost. However, the complexity of the antenna sub-system may increase while designing the spot beams depending on the technique used for creating multiple spot beams. Therefore, a trade-off is required between the smallest possible beamsize and the complexity of the antenna sub-system.
5. Designing smaller beams of the secondary system over the coverage area of each primary beam seems to be challenging. However, due to recent progress in the spot beam technologies, it is feasible to create smaller coverage cells having less than $0.5°$ diameter as mentioned in Section 3.1. Furthermore, it is also possible to divide one spot beam into many sub-beams with the reduction in peak antenna gain, hence resulting in smaller antenna aperture, while maintaining the edge gain requirements [37, 38]. Besides these possibilities, there still exist challenges to design low complexity antenna structures for multiple spot beams.
6. Since the secondary system employs smaller beams in comparison to the primary system, faster handover is needed for serving mobile users.
7. If the secondary system can use significantly smaller beams, the coexistence of the two multibeam systems can be related to the case of a new generation system being deployed on top of existing legacy systems. In this context, the time to market of the proposed system seems to be long since the beamhopping technique is not widely employed in current satellite systems.
8. Although it may appear redundant if both satellites belong to the same operator, the primary and secondary satellites can be used for providing different services to same/different categories of users, hence enhancing the overall spectral efficiency of the system. As an example, the primary satellite can be used to provide high priority broadband multimedia services and the secondary satellite to provide low QoS services such as interactive services as stated in Section 3.1. Furthermore, there may arise a situation where the operator has to launch another satellite to meet the increased traffic demand in order to enhance capacity in the same coverage area. On the other hand, if primary and secondary satellites belong to different operators, the primary operator may not share the beamhopping sequence with

the secondary operator. In this context, different strategies can be used depending on the employed spectrum assignment policy. For example, if the spectrum is exclusively licensed to the primary system, some financial and regulatory incentives can be provided to the primary operator in order to facilitate the spectrum sharing provided that sufficient QoS is guaranteed for both systems. If the spectrum is allocated on co-primary basis, the secondary operator can use sensing measurements in order to sense the multibeam pattern as well as the beamhopping pattern and subsequently use underlay approaches such as exclusion zone and power control based techniques in order to protect the primary system. However, sensing the primary beamhopping pattern may be challenging requiring dense sensor deployment and handling delayed measurements. In this context, exploring innovative sensing mechanisms in order to address the above issues is an important research challenge.

8. CONCLUSIONS

The performance of the proposed cognitive beamhopping system has been evaluated and compared with the conventional multibeam and beamhopping systems. It can be concluded that the proposed system significantly improves the SE over other techniques. In addition, based on the comparison of the two approaches, it can be concluded that the SE increases with the number of SUs in the full frequency reuse approach and decreases with the number of SUs in the frequency sharing approach. Furthermore, it has been noted in most of the cases that primary rate is perfectly protected after EZ radius of 8.5 dB for the set of considered parameters with a significant gain in the total SE. Moreover, it has been observed that the power control approach is suitable for the case of low secondary aggregated interference and the EZ approach for the case of high aggregated interference. We consider the combination of dynamic spectrum sensing as well as the EZ principle for exploiting spatio-temporal spectral holes as our future work. Furthermore, we plan to extend this work to find a proper switching sequence for the secondary system in order to increase its throughput while respecting the interference threshold of the PUs in our future work.

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