Cognitive Spectrum Utilization

in Ka Band Multibeam Satellite Communications

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Abstract

Multibeam satellite networks in Ka band have been designed to accommodate the increasing traffic demands of the coming years. However, these systems are spectrum limited due to the current spectrum allocation policies. This paper investigates the potentials of applying cognitive radio techniques in satellite communications in order to increase the spectrum opportunities for future generation of satellite networks without interfering operation of incumbent services. These extra spectrum opportunities can potentially amount to 2.4 GHz of bandwidth in downlink, and to 2 GHz of bandwidth in uplink for high density fixed satellite services (HDFSS).

1- Introduction

The Ka band is mainly considered by the SatCom industry for deployment of satellite high speed broadband networks in un-served and under-served areas. To determine the market demand for Ka band, recent R&D studies in Europe [1], [2], show the potential demand for satellite broadband services in rural areas in order to meet the objectives of the Digital Agenda for Europe, i.e. universal availability of broadband speeds of at least 30 Mb/s throughout Europe, with at least 50% of households having access to data rates above 100 Mb/s. Moreover, some studies conclude that the average number of total European households which choose a satellite broadband connection in 2020 is expected to be between 5 to 10 Million [2]. This represents a market potential for several satellite systems and creates the need to access extra spectrum, including the frequency bands shared with other services, in order to accommodate the increasing bandwidth and data rate demand [3].

It is foreseeable that spectrum congestions can make future Ka band deployments more difficult. High Throughput Satellites (HTS) already suffer from spectrum scarcity in Ka band in order to deliver meaningful performance. Only 500 MHz of exclusive Geostationary Satellite Orbit (GSO) incumbent spectrum is available in all ITU Regions for downlink. The access to a further 2.4 GHz of spectrum in Ka band as discussed in this paper, potentially allows satellite operators to meet the demand for HDFSS without prior individual frequency coordination. This in turn justifies the need to investigate cognitive radio (CR) techniques in the SatCom context, in order to allow exploitation of the shared frequency bands while guaranteeing acceptable interference to the incumbent users [3].

Another important aspect to be taken into account is the long-term and persistent interference from the terrestrial services which affects the core business of satellite operators. In this context, CR based solutions can provide relief as well as a measurable utilization and revenue increase to the SatCom business.

In this paper, three scenarios namely A, B, and C are considered as appropriate opportunities for cognitive SatCom in Ka band with the special focus on the European region. As we show later, these scenarios are in line with the current ITU-R regulations, and are based on the European Conference of Postal and Telecommunications Administrations (CEPT) decisions on dynamic spectrum utilization. Scenario A in the band 17.3-17.7 GHz investigates the spectral coexistence of fixed satellite service (FSS) terminals working in the downlink with broadcasting satellite service (BSS) feeder links in the uplink. This scenario is depicted in Figure 1a. In this scenario, the cognitive link is from the GSO satellite to the earth FSS terminal, and the incumbent is from the BSS feeder link to a different GSO satellite employed for broadcasting. Scenario B considers a cognitive FSS downlink scheme in the 17.7-19.7 GHz band where the incumbent users are fixed service (FS) links. As shown in Figure 1b, the cognitive link in this scenario is the same as Scenario A, but the incumbent link is from one FS terminal to another FS terminal. In Scenario C, in the band 27.5-29.5 GHz where FS links are the incumbent users, the FSS terminal provides cognitive uplink communication. This scenario is illustrated in Figure 1c. Unlike previous scenarios, here the cognitive link is from the FSS earth terminal to the GSO satellite, and the incumbent link is the same as Scenario B. It is important to note that for all three scenarios, the incumbent links are assumed to be fixed with no change in their infrastructure possible due to the coexistence. Furthermore, it is assumed that there is no feedback from the incumbent systems to the cognitive links. Also, it is important to note that all these non-exclusive frequency bands in Ka-band under investigation have shared allocation since many years and are actually shared today. Cognitive radio techniques could allow the use of these shared frequency bands by mass deployed satellite terminals (HDFSS) without prior individual frequency coordination, which is needed to satisfy the future market demands.

While the potential gains of cognitive spectrum utilization in Ka band are clear, the required enabling technologies to ensure coexistence within the current regulatory regime need to be developed. These mechanisms include spectrum awareness and spectrum exploitation. Spectrum awareness in turn can be obtained through databases and spectrum sensing. When the spectrum opportunities are known from databases or spectrum sensing, the remaining problem is how to allocate the available carriers in order to optimize the system performance [3].

2- Dynamic Spectrum Utilization for Ka Band Multibeam Systems

As mentioned earlier, to satisfy the future traffic increase, a wider range of frequency bands is required to provide a high service availability with much higher data rates. In this section, we review the spectral regulation in Ka band, and particularly we focus on the potentials of cognitive spectrum utilization in the three bands mentioned in Section 1, i.e. 17.3-17.7 GHz, 17.7-19.7 GHz, and 27.5-29.5 GHz frequency bands.

Table 1 provides the ITU-R table of allocations in the aforementioned frequency bands.

Table 1: ITU-R Table of Allocations in Ka band [4]

Frequency bands	ITU-R Region 1	ITU-R Region 2	ITU-R Region 3
17.3 – 17.7 GHz	FSS (space-Earth) BSS (feeder links) Radiolocation	FSS (space-Earth) BSS (feeder links) Radiolocation	FSS (space-Earth) BSS (feeder links) Radiolocation
17.7 – 19.7 GHz	FSS (space-Earth) BSS (feeder links up 18.1 GHz) FS	FSS (space-Earth) FS	FSS (space-Earth) BSS (feeder links up 18.1GHz) FS
27.5 – 29.5 GHz	FSS (Earth to space) FS MS (Mobile Services)	FSS (Earth to space) FS MS	FSS (Earth to space) FS MS

Considering ITU-R allocation policies as described in Table 1, CEPT has adopted related decisions which give guidance on the use of these bands by FSS. These CEPT decisions are related to the three Ka band scenarios under investigation here and are outlined below [5].

- CEPT has adopted a decision, ECC/DEC/(05)08, which gives guidance on the use of the 17.3 – 17.7 GHz frequency band by the FSS terminals. The Decision stipulates that the incumbent users in this band are BSS feeder uplinks. The deployment of uncoordinated FSS Earth stations is also authorized in these bands. This scenario is depicted in Figure 1a. As we can see, in the downlink mode, the cognitive transmitter (GSO satellite) does not interfere the incumbent receiver (GSO satellite). This is controlled by the orbital separation between the GSO satellites. However, the FSS terminal may receive interference from the BSS links. As shall be shown later, this interference can be managed by employing cognitive techniques.
- CEPT has adopted a Decision, ERC/DEC/(00)07, which gives guidance on the use of the 17.7 – 19.7 GHz frequency band by FSS and FS. The Decision stipulates that FSS terminals can be deployed anywhere, but without right of protection from interference generated by FS radio stations. As shown in Figure 1b, again the cognitive transmitter does not interfere with the incumbent FS receiver due to power flux density limitations. However, it may receive interference from the FS transmitter. Again, the FSS terminal needs to employ cognitive techniques in order to ensure the minimum system performance.
- CEPT Decision ECC/DEC/(05)01 provides a segmentation between FS and FSS stations in the 27.5 – 29.5 GHz frequency band. The FS segment is lightly used throughout Europe in these frequencies. We envisage an uplink cognitive FSS service in this band where the incumbent users are FS links. As we can see in Figure 1c, here the cognitive transmitter which is a FSS terminal may interfere the incumbent FS links. Therefore, employing cognitive techniques to avoid harmful interference to the incumbent users is the main challenge in this scenario.

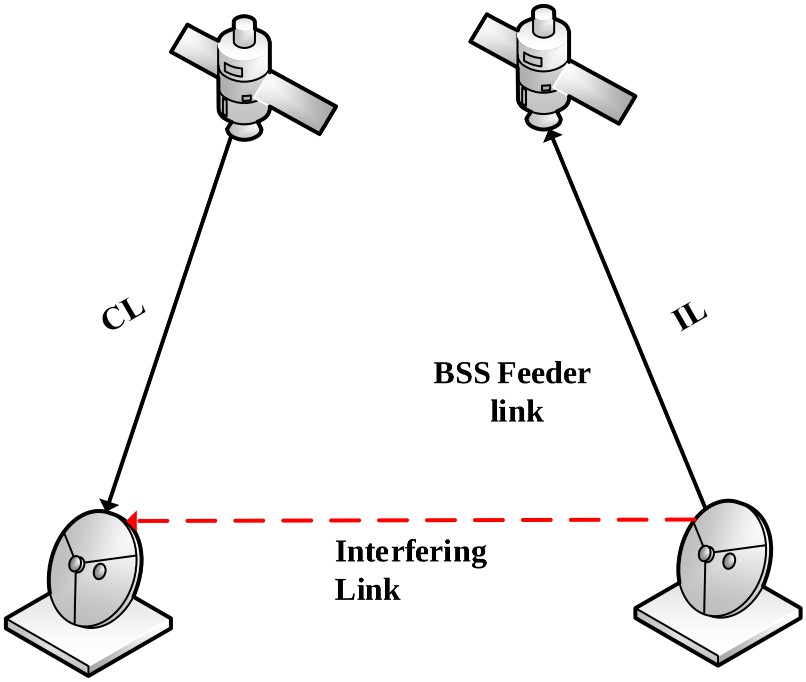

Figure 1a. Cognitive spectrum utilization in 17.3-17.7 GHz band (Scenario A). CL denotes the cognitive link, and IL denotes the incumbent link.

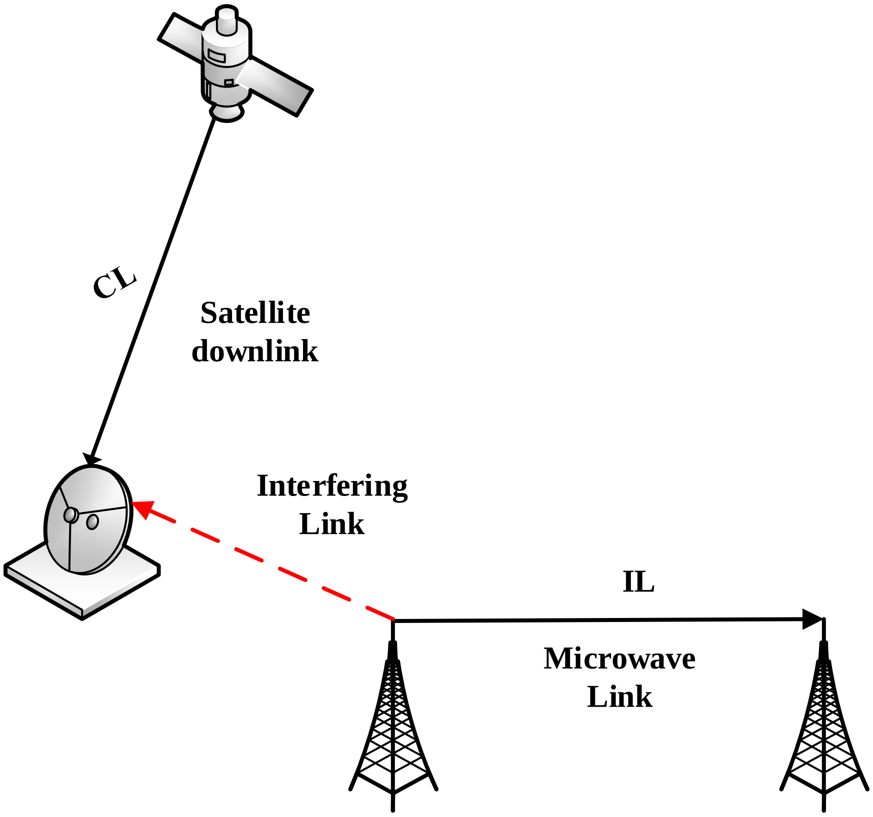

Figure 1b. Cognitive spectrum utilization in 17.7-19.7 GHz band (Scenario B).

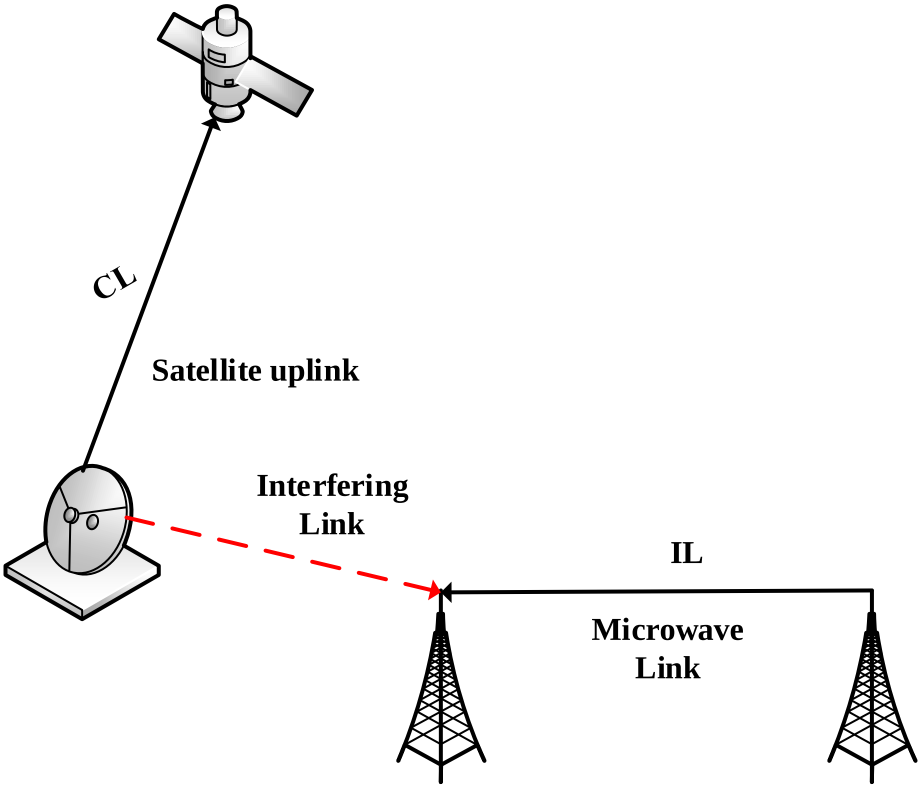

Figure 1c. Cognitive spectrum utilization in 27.5-29.5 GHz band (Scenario C).

The reference frequency plan, which is considered in this paper and is in line with ECC decisions, is depicted in Figure 2. To sum up the regulation situation, in the downlink mode, the cognitive terminals can freely access the spectrum but need to manage the interference received from the incumbent users, and in the cognitive uplink mode, they need to make sure that their transmission does not interfere with the incumbent receivers. To solve these issues, we may need to employ CR mechanisms. These techniques are described in the following section. Note that the frequency plan of Figure 2 is merely illustrative as the techniques can be applied to any Ka band satellite system.

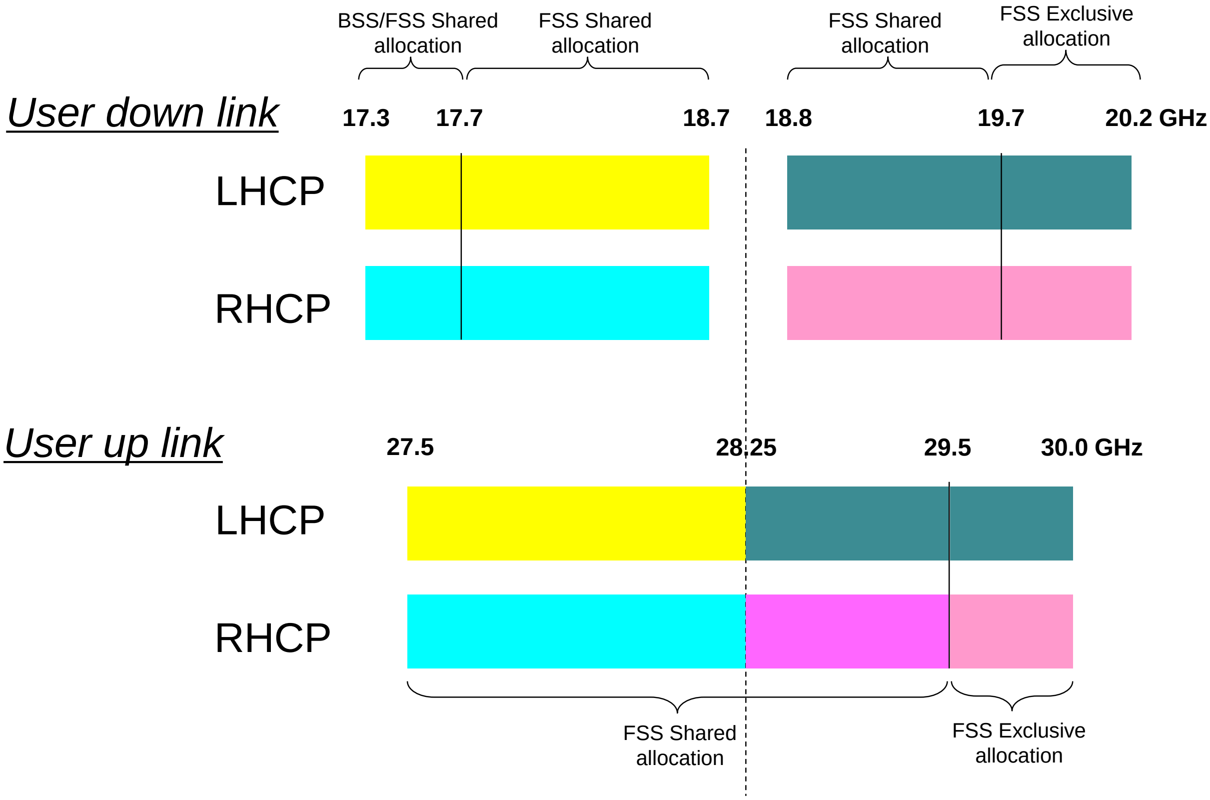

Figure 2. The four color frequency reuse scheme for cognitive multibeam satellite networks.

3- Cognitive Mechanisms for Opportunistic Spectrum Utilization

To enable cognitive spectrum utilization in Ka band, a system architecture as shown in Figure 3 is employed. This system consists of a spectrum awareness unit which provides information regarding the incumbent users, and a network management or spectrum exploitation unit which allocates the carriers and the transmission power to the users. Each of these units are explained in detail in this section.

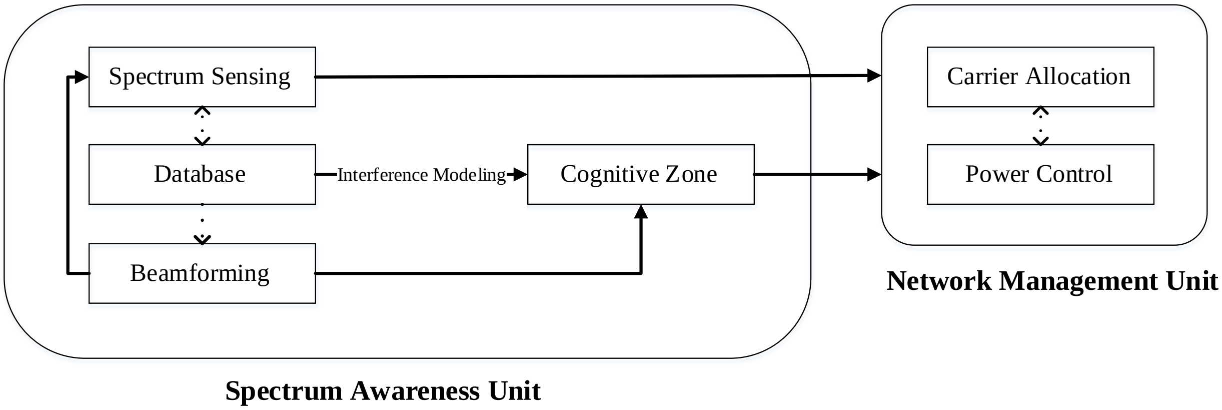

Figure 3. Cognitive System Architecture

3.1 Spectrum Awareness

The spectrum awareness unit is responsible to gain knowledge about the incumbent users, and it is based on a joint interaction among Database, Spectrum sensing and Beamforming functions with the aid of a cognitive zone block as described in this section.

Databases

The aim of the database shown in Figure 3 is to incorporate BSS feeder links and FS characteristics in order to determine the interference levels at any proposed FSS terminal location for any carrier frequency. In this way, the FSS terminals can operate within the carrier frequencies where the regulatory interference thresholds are respected. If the received interference is deemed to be high, then CR mechanisms should be employed in order to mitigate the interference. . In addition, as shown in Figure 3, the database can be connected to a network management unit to optimize the overall resource allocation in the network.

Cognitive Zones

A cognitive zone is defined as the geographical area around an incumbent user where cognitive techniques need to be employed in order to mitigate the interference to an acceptable level. Interference modelling connected to the databases (as in Figure 3) is performed using the ITU P-452-15 terrestrial propagation model. The zone boundaries are determined by the respective regulatory interference to noise ratio (I/N) thresholds. The total interference is obtained by summing all the received interferences at a particular location for the FSS terminal. In the case of Scenarios A and B, the zones are calculated around the FSS cognitive receiver using the databases for BSS and FS, respectively. In the case of scenario C, they are calculated with respect of the FS links, as the incumbent, being potentially interfered from the FSS uplink. Scenario C is different from the two downlink cases as in this case, the FSS terminal is the potential interferer to FS. Cognitive zones can still be used for the FS incumbents. The main challenge here is to gain accurate knowledge about the FS links, and to model the interference accurately, so as to avoid any harmful interference to the incumbent users. A Typical cognitive zone plot for scenario A is depicted in Figure 4. This figure was calculated using the full ITU-R P.452-15 model with terrain effects included. The terrain resolution was 500 m and the interference was calculated for 20% of the year. More detailed analysis regarding the cognitive zone particularly for Scenarios A and B with several databases obtained from regulatory bodies can be found in [6], [7]. It is shown that a vast geographical area can be used freely for cognitive downlink satellite communications. In the few remaining areas, cognitive mechanisms such as spectrum sensing and beamforming as described in the following subsections can be employed to mitigate the interference.

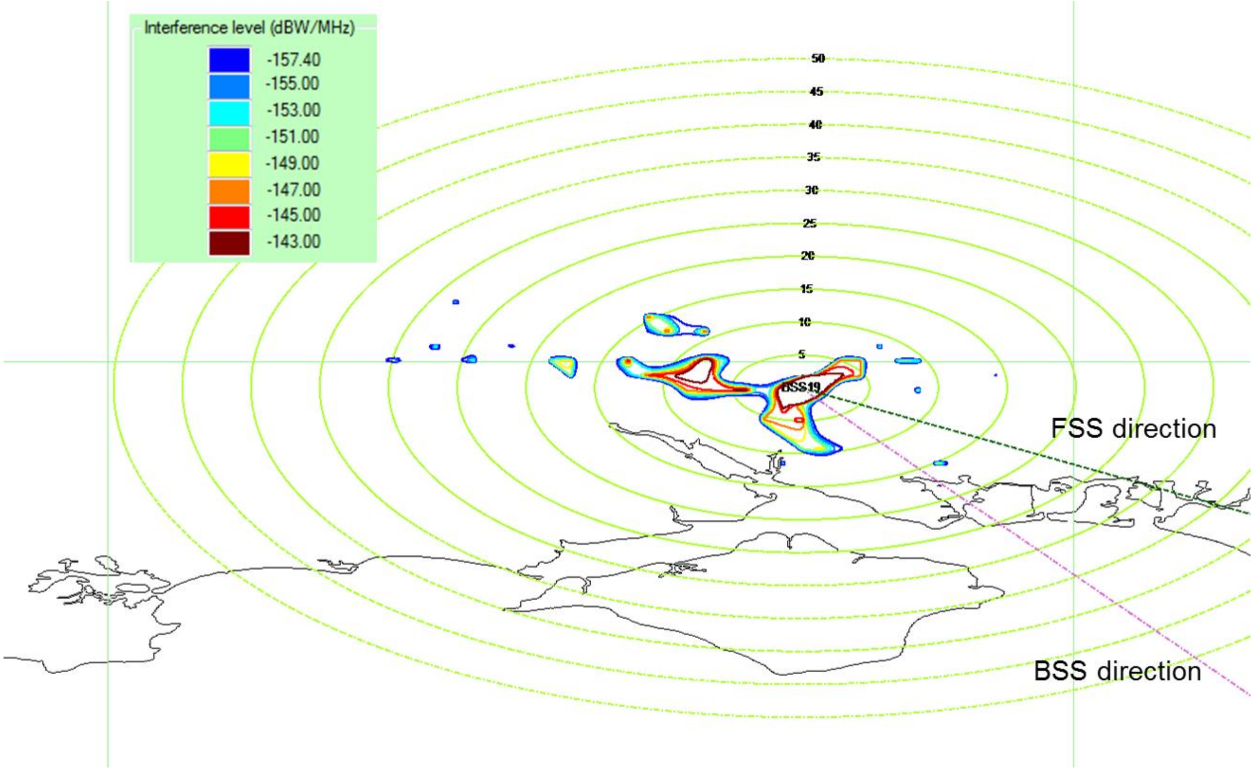

Figure 4. Cognitive zone example based on UK OFCOM BSS database.

Spectrum sensing

Spectrum sensing is a technique in order to acquire spectral knowledge about incumbent user activities within a specific geographical location [8]. Several techniques have been proposed in order to perform spectrum sensing. Among these, energy detection, cyclostationary detection and matched filtering are the most common. When it comes to the satellite communication in Ka band, spectrum sensing can be applied either to detect the incoming interference from the BSS feeder links or FS links for downlink scenarios. In the uplink scenario C, since sensing the passive receivers is practically not viable, spectrum sensing has to be done in the FS link and, therefore, it is not considered as an enabling technique for this specific scenario. As shown in Figure 3, in both cases, the spectrum sensing unit shares the obtained information with the database and network management units. Here again traditional sensing techniques such as energy detection and cyclostationary detection can be applied [9], [10].

The main constraint in the downlink scenarios is how much interference a FSS terminal can tolerate. The FSS terminal producers can determine this value which may amount to I/N=-10dB. Moreover, if the FSS link budget side knowledge is available, a higher interference level can also become acceptable if the quality of the received signal is still satisfactory. This encourages spectrum sensing through Signal to Interference and Noise Ratio (SINR) estimation as described in [6], [11]. The limiting factor here is the presence of the satellite beam. Usually, for reliable sensing results, the cognitive transmitter is quiet. This condition cannot be applied to satellite networks, as the satellite beam cannot be turned off for individual users. To solve this issue, as explained in the following subsections, beamforming techniques can be applied to cancel out the satellite signal.

Beamforming

A beamformer is a spatial filter which operates on the outputs of an antenna array in order to form a desired beam pattern. The signals induced at the different elements of the array are combined to form a single output of the array.

Beamforming techniques can be implemented either in the terminal-side or in the satellite-side in order to improve the received SINR at the cognitive receiver or produce a null at the incumbent receivers. It should be noted that implementation of a beamforming technique requires a significant upgrade in the existing FSS system.A terminal equipped with multiple antennas is required to create a desired beam pattern; this can be achieved by either adding omnidirectional antennas or multiple-LNBs. . In this context, different approaches for applying existing beamforming and precoding techniques in Ka band cognitive communications can be considered.

In a nutshell, as we can see in Figure 3, the beamforming techniques can be applied in the cognitive satellite communications in two ways, (i) beamforming for spectrum sensing/interference detection, and (ii) beamforming for improving the SINR of the satellite terminals. The latter leads to a smaller size cognitive zone and is investigated with promising results in [6], [12].

In Scenarios A and B, a receiver beamformer can be designed in order to detect the harmful FS signals so that the satellite terminal can avoid using the harmful FS carriers, or to enhance the SINR by mitigating the interference using side-lobe cancellation [12].

3.2 Spectrum Exploitation

Dynamic Carrier Allocation

So far we have determined the available cognitive resources in specific times, frequency carriers and geographical locations. In this subsection, we outline the methods which are necessary in order to allocate these resources (particularly the carriers) to the users in network management unit as shown in Figure 3.

Two major approaches can be employed by the network manager in order to perform carrier allocation. In the first approach, the goal is to assign the carriers so as to maximize the sum of the throughput and thus the overall system throughput. In the second approach, the goal is to maximize the availability through assigning the available carriers to as many users as possible according to their requested rate. Under rate constraints, a carrier can only be assigned to a user if it satisfies a specific rate request which is in turn directly related to the received SINR at a specific carrier. Cognitive carriers can be a potential help in this case by increasing the system availability.

While these approaches are efficient in terms of network management, several other factors can be considered for carrier allocation, e.g. carrier assignment priorities, carrier aggregation, and shared carrier assignment.

Power Control

As power control in downlink is well established in the current satellite networks, from cognitive resource allocation viewpoint, we focus on power allocation related to the uplink scenarios such as the one in the band 27.5-29.5 GHz. Here, the transmission power should be determined so as to first increase the system throughput, and second to keep the interference to the incumbent receivers below a specific value.

4- Implementation and Technological Challenges

In the previous section, while describing each enabling technique, we have outlined some of the challenges which the techniques may face in practice. In this section we evaluate these challenges in detail. Note that, the described techniques have been thoroughly examined in a number of practical scenarios in [6]. The obtained results show that the adopted cognitive mechanisms are promising particularly in the downlink scenarios. The described challenges in this section are provided in order to be considered in the implementation of cognitive terminals to achieve better performances with respect to what is achieved in [6].

As mentioned before, databases leverage a network level implementation of cognitive satellite communication. Applicability of database to the considered scenarios, particularly Scenarios A and B is thoroughly investigated in [6], [7]. It is shown that the database in combination of interference modelling, and cognitive carrier allocation can provide significant gain in terms of total achievable throughput, and geographical availability. However, the database techniques face a number of challenges. The database may become outdated by time, and thus the entity which operates the database needs to update it frequently. Further, some of the frequency bands may be assigned to confidential users and public databases do not include the information about these links. In these cases, dynamic database techniques in combination with spectrum sensing such as spectrum cartography based on received observation from field sensors can be employed to localize the incumbent users [13].

One approach in order to obtain a dynamic database is to apply SINR estimation at the satellite terminals. In [6] and [11], a SINR estimation algorithm is introduced which is shown to be effective in producing a dynamic database of the received SINR in Scenarios A and B. However, the specific satellite link conditions create unique challenges for spectrum sensing. In fact sensing of the interference level has the particular challenge that the signal strength variations can be very large, due to highly directional antennas used at the terminals. Furthermore, the FSS signal received from the satellite has significantly lower power spectral density than the terrestrial FS link. Under worst case power imbalance conditions, this may result in a saturation of the front-end low noise amplifier (LNA). To solve this issue special adaptation of LNA is required to prevent the amplifier saturation condition.

Another characteristic that represents a challenge is the heterogeneous feature of the two systems and their signal parameters. The signal parameters of the interferer may therefore be known only to some. This limits applying feature based spectrum sensing techniques. However this is not a critical issue in Scenarios A and B, as in these scenarios, the most important required information is the received SINR.

In addition to the interference detection challenge, as mentioned earlier, the interference could be also mitigated by using a multiple antenna system. The interference mitigation may be possible, if the antenna directivity of the FSS satellite terminal has reconfigurable elements, such as beamforming approaches [14]. These methods require a calibration and configuration of beamforming at the antenna installation and a direction of arrival (DoA) estimation to the interferer. For the FSS downlink scenarios, we can use the reception quality indicators, e.g. SNR estimates and error rates as calibration and configuration feedback. This is however not feasible for the uplink scenario, for which we require a well calibrated and configured setup to ensure that the transmit beamforming direction corresponds to the FS receiver link direction. Because no cooperation between the FS and FSS systems are foreseen so far, this context requires special consideration and possibly a new enabling technology to make the beamforming context work. Successful application of beamforming in interference mitigation for Scenarios A and B is studied in [6], [12].

Another challenge which needs to be taken into account is the effect of atmospheric impairments, especially rain fading, on Ka band communications. This leads to dynamic change of the SINR, which needs to be addressed in the design of dynamic carrier allocation algorithms. However, these are usually short-term effects which can be compensated by adaptive modulation and coding (ACM). In our system and interference modeling (e.g. Fig.4 and the detailed results in [6]), we focus on long term values, which are more useful in the regulatory context.

5- Conclusions

The potentials of CR application to SatCom were identified in this paper. The regulatory issues were discussed, and three major scenarios were analyzed as the immediate opportunities for extra spectrum. Enabling techniques in order to facilitate dynamic spectrum utilization were investigated. It was shown that database techniques can enable a network level implementation of cognitive satellite networks. Further, we concluded that spectrum sensing can be used to update the database knowledge about the incumbent users. Considering the challenges therein, novel spectrum sensing could be developed in order to obtain more accurate results. Further, the database of current incumbent users in Ka band needs to be acquired and managed by an entity to enable efficient network level resource allocation.

With respect to CR applicability in the respective frequency ranges within the Ka band, the following points can be noted:

- 17.3 – 17.7 GHz band: Cognitive utilization of this band in addition to the FSS exclusive band of 19.7-20.2 GHz opens up and additional 400 MHz bandwidth which can potentially increase the total throughput by 90% [6].
- 17.7 – 19.7 GHz band: CR techniques can significantly increase the spectrum utilization allocated to FSS by enabling access to additional frequency spectrum. CR techniques could act as a dynamic protection of FSS downlink from FS interference. 27.5 – 29.5 GHz band: FSS stations can maximize frequency exploitation by dynamic utilization of the FS segment through the adoption of CR techniques in the satellite uplink able to dynamically control the interference generated to the FS stations.

Last but not least, note that the European Telecommunications Standards Institute (ETSI) has recently published the System Reference Document (SRDoc) TR 103-263 v1.1.1 "Cognitive Radio Techniques operating in Ka-band" [15] which is considered to be a major milestone in standardization of relevant CR SatCom activities.

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