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Database-Assisted Spectrum Sharing in Satellite Communications: A Survey

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ABSTRACT This survey paper discusses the feasibility of sharing the spectrum between satellite telecommunication networks and terrestrial and other satellite networks on the basis of a comprehensive study carried out as part of the European Space Agency's Advanced Research in Telecommunications Systems programme. The main area of investigation is the use of spectrum databases to enable a controlled sharing environment. Future satellite systems can largely benefit from the ability to access spectrum bands other than the dedicated licensed spectrum band. Potential spectrum sharing scenarios are classified as: a) secondary use of the satellite spectrum by terrestrial systems, b) satellite system as a secondary user of spectrum c) extension of a terrestrial network by using the satellite network; and d) two satellite systems sharing the same spectrum. We define practical use cases for each scenario and identify suitable techniques. The proposed scenarios and use cases cover several frequency bands and satellite orbits. Out of all the scenarios reviewed, owing to the announcement of many different mega-constellation satellite networks, we focus on analyzing the feasibility of spectrum sharing between geostationary orbit (GSO) and non-geostationary orbit (NGSO) satellite systems. The performance is primarily analyzed on the basis of widely accepted recommendations of the Radiocommunications Sector of the International Telecommunications Union. Finally, future research directions are identified.

INDEX TERMS Dynamic spectrum access, millimetre-wave communication, database systems.

I. INTRODUCTION

Over the last decade, significant effort has been devoted to spectrum sharing research, especially in terrestrial networks, see e.g., [1]–[3]. The satellite industry is currently undergoing a major transformation due to the rapid technological advances in small satellite systems and very high throughput satellite systems, as well as the trend of moving from broadcasting to broadband connectivity. As the demand for broadband access and more bandwidth has intensified, spectrum sharing studies have extended from the terrestrial domain to also cover satellite systems [4]–[17]. Although dynamic spectrum management techniques have been rigorously studied in the context of terrestrial systems, there are still several technical challenges involved in applying those techniques to satellite systems.

An important element of spectrum sharing is spectrum awareness, since it is essential to know the current spectrum use before new users can access the same frequency resources. After obtaining spectrum awareness, it must be decided how to allocate the resources in order to fulfil the performance targets. Spectrum databases are currently considered the most favoured approach to achieve spectrum awareness in the terrestrial domain due to the uncertainties and difficulties related to the spectrum sensing approach [18]–[20]. The reason why database approaches have been proposed for satellite communications is basically the same as for terrestrial systems: databases provide better protection to incumbent users of the spectrum even though their use can be limited to highly dynamic spectrum sharing scenarios. Recent industry-driven spectrum sharing

TABLE 1. Frequency bands for potential satellite communications scenarios and related references.

Satellite band	Frequency range	Uplink (UL)/Downlink (DL)	Orbit	Satellite services
L band [4]	1525.0–1559.0 MHz 1626.5–1660.5 MHz	DL UL	GSO NGSO	Mobile satellite services (MSS)
S band [5], [7]	1980-2010 MHz 2170-2200 MHz 2500-2520 MHz 2520-2670 MHz 2670-2690 MHz	DL UL DL DL UL	GSO GSO NGSO GSO NGSO	Broadcasting satellite services (BSS) BSS Fixed satellite services (FSS), MSS BSS FSS, MSS
C band [8], [11]	3400-3800 MHz	DL	GSO	FSS
Ku band [12]	10.7-12.75 GHz 12.75-13.25 GHz 13.75-14.5GHz	UL DL DL	GSO GSO GSO	FSS, BSS FSS FSS
Ka band [5], [6], [10], [14], [15]	17.3-17.7 GHz 17.7-19.7 GHz 27.5-29.5 GHz	DL DL UL	GSO GSO, NGSO GSO	BSS FSS, BSS (up to 18.4 GHz) FSS
Q/V band [17]	37.0-38.6 GHz 39.5-40 GHz	DL DL	GSO and NGSO	FSS FSS
W band	71-76 GHz 81-86 GHz	DL UL	GSO and NGSO	FSS FSS

approaches, such as Licensed Shared Access (LSA) [21] and Spectrum Access System (SAS) [22], are based on a database concept. *Here 'database-assisted spectrum sharing' means as a scheme where spectrum awareness for the purpose of allocating radio resources is obtained on the basis of a spectrum database.*

Previous studies on satellite band sharing have focused on L band [4], S band [5], [7], C band [8], [11], Ku band [12], Ka band [5], [6], [10], [14], [15], and Q band [17] activities and techniques such as the definition of exclusion zones around satellite receivers, spectrum awareness techniques, power control and channel assignments, adaptive antenna techniques, and small-cell communications for managing and avoiding interference between the coexisting systems. Potential techniques for a satellite-terrestrial scenario were outlined in [9], and possible application scenarios for satellite bands were presented in [5], and specifically for sharing of the Ka band in [15]. In addition, satellite band-related papers have been published on propagation impairments and mitigation [23], multiple-input and multiple-output (MIMO) techniques [24], and mobile satellite systems in general [25]. However, there are no previous survey papers on database-assisted spectrum sharing for satellite communications.

We have collated potential frequency bands in Table 1, as well as the satellite services available in those bands. Due to the millimetre-wave operation in the upcoming fifth generation (5G) systems and beyond, spectrum sharing in bands above 20 GHz is becoming a hot topic [26]–[28]. The contribution of this article is to extend the previous work in [5], [9] and [15] by defining a more complete set of possible sharing scenarios, focusing specifically on the use of spectrum database techniques in those areas. We define the most promising frequency bands and cognitive sharing techniques in order to obtain a thorough view of the feasibility of spectrum sharing in satellite bands. This is a consolidated view formulated on the basis of a study conducted between various research institutes and the satellite industry under a ESA research contract [16]. We have previously published some results of the study, but here we extend the work with a large-scale survey and one satellite-satellite sharing case. We will take a closer look at the feasibility of a specific sharing scenario between a GSO and a low Earth orbit (LEO) satellite system. The idea was stimulated by the recent surge of announcements concerning the plans to implement mega-constellation satellite networks composed of hundreds of LEO satellites, such as SpaceX, OneWeb and LeoSat [29]–[31]. We will analyse the feasibility of this sharing concept in the Ka band, propose cognitive techniques to enable coexistence, and describe how a spectrum database could be utilised in controlling and assisting the adaptations.

The rest of the article is organized as follows: Database-assisted spectrum sharing and other relevant techniques are described in section II. Differences to terrestrial spectrum sharing are also outlined in the section. A classification of the potential spectrum sharing scenarios is provided in section III, which also defines an example use case for each potential scenario. We also describe how database techniques can be used in all the use cases. A feasibility analysis of spectrum sharing between different satellite systems is presented in section IV. In section V, we define future challenges and recommendations for further work, and finally, we conclude the work in section VI.

II. DATABASE-ASSISTED SPECTRUM SHARING

A. GENERAL DATABASE MODEL

The basic principle of a spectrum database approach is that the secondary device is not allowed to access the spectrum until it has successfully received information from the

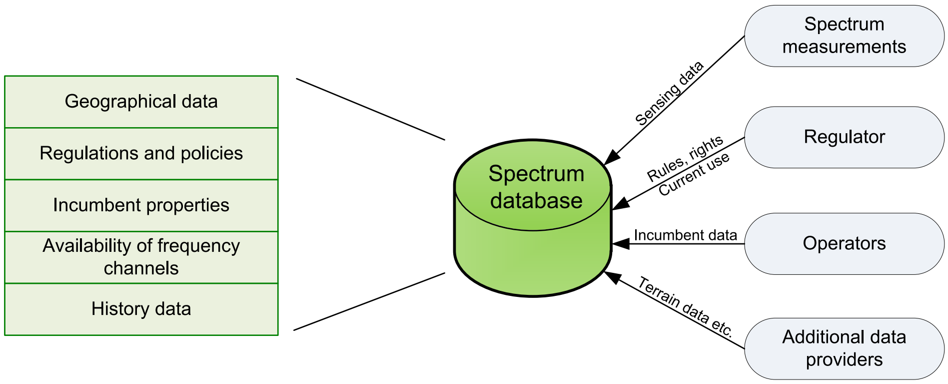

FIGURE 1. **A general spectrum database model [32].**

database that the channel on which it intends to operate is free at the location of the device [32]. The general spectrum database model is presented in II, showing what kind of information can be stored and shared through the model and the sources of information.

Spectrum measurements can be used to gather occupancy information from frequency channels of interest with a certain time resolution. Spectrum data collected via multiple devices need to be processed and combined in order to assess the situation in a certain area. The radio environment map (REM) proposed in [33] is one of the methods to make context awareness possible in future networks. REM refers to an integrated database containing information about the radio frequency (RF) signal environment, relevant regulations and policies, physical locations of devices, available services, and relevant historical experiences. The interference map [34]–[36] is a special case of the REM, specifically describing the level of interference over an area of interest in a certain frequency band. It is obtained by combining measurements performed by multiple entities with the location coordinates of those entities across the area.

Operators may provide actual data about the availability of the frequency band and access to the spectrum, most probably against a fee since operators have paid a significant amount of money for their licence to operate in the band. In addition to the licence-exempt access to spectrum considered in several spectrum sharing scenarios, such as TV white spaces (TVWS) [37], [38], it has been proposed that the spectrum could be shared on a licence basis, under an LSA approach [21]. In this approach, the incumbent operators are required to provide the database with *a priori* information about their spectrum use over the area of interest, telling where, when and which parts of the frequency bands are available.

Geographical data may include local terrain data and locations of devices, including additional location information such as whether the device is located indoors or outdoors [36]–[39]. Terrain data can be obtained from service providers such as the US National Geospatial-Intelligence Agency. The database also contains data about relevant policies and spectrum regulations, and it is allowed to share this data to secondary users. Policies can dictate, for example, what the maximum allowed transmission power is in a certain channel at a certain location. Incumbent properties, such as the standards used, interference tolerance of the receivers, and coverage of the base stations (BSs), allow the database to perform calculations for the requesting secondary users to tell them which channels they are able to access at their location, if any. The availability of frequency channels in different frequency bands may be provided through several bandwidths; i.e., the database is able to provide a set of channels on the basis of the bandwidth of the requesting device. In addition, history data can be used in predicting the future spectrum use in order to allocate the most promising channels for the requesting users [40]–[42].

B. SETTING UP THE DATABASE AND GATHERING THE INFORMATION REQUIRED FOR SPECTRUM SHARING

Setting up a database to enable spectrum sharing between wireless networks is not a trivial task. It requires technical, economic and political effort. Since operators may not be willing to share their information between each other and reveal how they are actually using the precious radio resources, there is a need for involvement of a third party as a spectrum database operator. Selecting that third party and building trust towards this database operator or operators does not happen in the blink of an eye. Regulatory authorities test and verify commercial operators and their database solutions. There are already verified TVWS, LSA and SAS database operators such as Google, Spectrum Bridge and Fairspectrum in the US and UK markets. Technical requirements and details, including the messaging protocols of the databases, can be found, for example, in [43] and [44].

The data required to be gathered into the database depends on the spectrum sharing systems in the band of interest. The general model presented in Fig. 1 describes the main sources of data. The database may also include the contact information of the device owners to enable contacting them, for example, in the event of interference. The data is also dependent on the other techniques used in conjunction with

TABLE 2. Advantages and risks associated with spectrum sharing techniques in satellite bands.

Technique	*Advantages*	*Risks*
Database, LSA [21]–[33]	Controlled interference and channel allocations. Guaranteed quality of service (QoS).	May require a third party for sharing. Requires additional infrastructure.
Spectrum sensing [4], [45]–[48]	Autonomous operation for secondary users. Can provide support for the database.	Cannot guarantee interference-free operation for the satellite receiver. Requires specific infrastructure just for sensing.
Smarter antennas, beamforming [5], [17], [49]–[53]	Enables denser networks. Less interference to unwanted directions.	More complex and expensive equipment. May require location information from both satellite and terrestrial stations.
Beam hopping [54], [55]	Improves flexibility, agility and throughput of satellite systems.	Requires sharing of the beam hopping pattern by the primary operator.
Channel allocations and power control [7], [56]–[59]	Satellite users can optimize their spectrum use among available channels.	Aggregated interference. Chaotic situations possible if the systems are autonomously learning their allocations.
Shielding [11], [60]	Simple to implement and highly effective.	Requires modifications to satellite receivers.
Small cells and D2D [11], [61]–[65]	Requires modifying only the terrestrial system. Smaller power and shorter protection range.	More complex to control. Aggregate interference.
Beacon signalling [45], [66]	Exact interference information regarding each receiver.	Requires modifications to both systems. Reserves an additional control channel.
Terrestrial-CID [16], [68], [69]	Efficient for determining the interfering base station. Does not require knowing the position of Satcom terminals.	Requires modifications of satellite terminals to be compatible with carrier identification (CID) extraction. More complex for device-to-device (D2D) communications.

the database. Detailed resource allocations are possible when information about the capabilities of the controlled secondary network is available, for example, from operators. For example, in Finnish LSA and SAS trials, we have used carrier aggregation and active antenna systems. When using carrier aggregation, the LSA or SAS system can use a licensed carrier and the shared band carrier together to enhance capacity. Active antennas and beamforming can be used to reduce interference and create exclusion zones more flexibly compared to the conventional antennas.

Thus, the decision on how to share the spectrum in a controlled manner is based on the data available in the database, which should include the capabilities of the controlled devices. This enables a controller or spectrum manager to retrieve the information from the database and make a smart decision on the resource use in order to fulfil the service requirements. We will review several sharing techniques in the following section. In sections III and IV, we will discuss several practical use case examples and define how databases are used to enable spectrum sharing in the depicted scenarios.

C. SPECTRUM SHARING TECHNIQUES TO BE USED IN CONJUNCTION WITH THE SPECTRUM DATABASE

A spectrum database is an enabler for spectrum sharing. The operation of a spectrum sharing system also requires other functionalities and can be enhanced when used in conjunction with other techniques. Table 2 provides a summary of the spectrum sharing techniques that could be deployed in satellite communication bands. The table also presents some advantages and risks involved in each technique and provides references for additional information for interested readers.

1) SPECTRUM SENSING

Spectrum sensing can be defined as the task of obtaining awareness about the spectrum use in a given geographical area [36], [45]–[48]. Sensing aims to detect transmitters but causes receivers to suffer from interference, which consequently also causes challenges in protecting them. To ensure that there is no interference to incumbents, it is expected that the sensing range of a secondary user (SU) is greater than the interference range of SU plus the communication range of the incumbent. Some gain can be achieved with cooperative sensing. A control channel is needed to share the sensing results in the cooperative case, as well as when sensing is used to enhance the operation of a spectrum database. Spectrum sensing is an easy and computationally attractive way to find unused frequencies and enables autonomous operation. It is compatible with existing transmitters, and its infrastructure costs are relatively low. However, due to the above-mentioned problems, sensing cannot guarantee an interference-free environment.

2) SMART ANTENNAS AND BEAMFORMING

Smart antennas and beamforming techniques enable multiple users to exploit same frequency resources at the same time and in the same geographical area [17], [49]–[51]. Beamforming can be implemented, for example, by phasing the antenna array elements and using an algorithm to steer the main beam to the desired direction and nulls toward the interferers. The advantage of beamforming and use of smart antennas is that this technique enables denser networks and produces less interference to unwanted directions. A disadvantage is the need for more complex and expensive equipment. It may also require location information from the primary system, such as satellite terminals. Transmitter-based interference mitigation is also called precoding, i.e., the generalization of beamforming to support multi-stream transmission in multi-antenna wireless communications [52], [53].

3) BEAM HOPPING

Beam hopping is an emerging technology that provides an ability to switch the transmitting power from beam to beam as a function of time [54], [55]. Each beam is adaptively activated and deactivated according to the actual traffic demands. Illumination typically consists of only a subset of the satellite beams through an appropriately designed beam illumination pattern. Since the primary satellite only illuminates a small fraction of beams out of a large number of beams deployed under beam hopping systems, the rest of the beams remain idle at that time and wait for their transmission slots. Then, another satellite system with a smaller spot beam diameter or a terrestrial system can operate in the same area and use the free resources.

4) CHANNEL ALLOCATIONS AND POWER CONTROL

A key challenge in a spectrum sharing system is to take into account all the available information, such as locations of devices, sensing information, regulations, database information etc., and to make the decision on where in the spectrum to operate at any given moment and how much power to use in that band. Frequency and power should be allocated in a way that optimizes the use of available resources while keeping the interference at an acceptable level [15], [45], [56], [57]. Resource allocation strategies such as power control can be used to optimize the capacity of the terrestrial link while guaranteeing a specified outage probability [58] for the satellite link [7]. Carrier allocation can also be done jointly with beamforming to optimize the use of spatial resources [59]. History information can be stored in the database to enable prediction and proactive decision making.

5) SHIELDING

A potential modification to the satellite ground segment is to add shielding on a very small aperture terminal (VSAT) antenna in the direction of interferers, while still allowing line-of-sight (LOS) towards the satellite. The corresponding signal attenuation is usually between 0 and 40 dB, depending on which type of shielding is used to protect the receiver. Shielding values 20, 30, and 40 dB are used to protect VSAT stations in the ITU-R recommendations [11], [60]. This is a simple way to reduce the interference range but can be costly when implemented for a large number of satellite terminals.

6) SMALL CELLS AND D2D

Small cells and device-to-device (D2D) communication are promising ways to increase spectral efficiency and reduce communication delay in dense heterogeneous networks [11], [61], [62]. Direct communication between devices is used to reduce energy consumption (if devices are close enough) and interference, and to enable better load balancing in a cellular system. D2D communication increases the efficiency of using the resources, since approximately half of the resources are required compared to centralized communication [63], [64]. To some extent, the same also applies to small cell operation, since with a lower transmission power, it will also produce less interference while being able to increase the capacity of a system. It is predicted that small cells will need to carry substantial part of the total traffic volume in the future. However, these novel communication paradigms also introduce complications in terms of interference control overhead and protocols [62], [65].

7) BEACON SIGNALLING

Beacon signalling means that the interfered receiver sends beacon signals over a specific beacon channel. It is a way to inform the transmitters to avoid transmitting in the same frequencies [45], [66], [67]. This requires setting up a channel, adding a beacon transmitter, for example, at an FSS terminal, and including a beacon receiver at secondary terrestrial stations. This would be an interesting study item, but it is not likely to be employed in practice due to the several modifications required in both systems. One closely related solution already in use is the carrier identification concept.

8) CARRIER IDENTIFICATION

Digital Video Broadcasting-Carrier Identification (DVB-CID) was recently standardized with the purpose of detecting the presence of unintentional sources of interference [68]. The DVB-CID involves embedding a unique identification code into a satellite carrier. The method requires a spread-spectrum signal to be transmitted by new satellite modulator equipment in order to allow their identification [69]. The DVB-CID concept is used in satellite systems as a way to prevent interference in the case of spectrum sharing between satellite systems. An interesting approach could be to extend the application of the DVB-CID concept to terrestrial base stations to enable satellite systems to catch the CID of interferers sharing the same frequency band [16]. This would, however, require adaptations to terrestrial systems and to satellite terminals, as well. A clear advantage when

TABLE 3. Comparison summary of satellite orbits; path loss was calculated assuming 3.6 GHz carrier frequency.

Orbit	*LEO*	*MEO*	*GEO*
Typical orbit height (km)	200–1400	10000–20000	35786
Path loss (dB)	150–166	184–190	195
Footprint diameter, theoretical maximum (km)	3150–8000	14900–16900	18100
Number of satellites for global coverage	40–70	10–12	3
Orbital period (h)	1.5–2	6–12	24
Pass time (min)	7–22	130–300	-
1-way latency (ms)	0.7–5	33–67	119

implemented in sharing cellular systems would be being able to determine whether an interference situation is caused by a terrestrial system or by another satellite system: if no CID signals are detected, the problem does not originate in a terrestrial base station.

D. DIFFERENCES TO TERRESTRIAL OPERATIONS

At least the following differences between terrestrial and satellite systems, affecting the way spectrum sharing has to be applied to satellite bands, can be identified: 1) Power limitation due to the large Earth-space distances often requires the use of highly directional antennas. 2) The beam coverage of a satellite is several orders of magnitude larger than that of a terrestrial cell. 3) Transmission latencies are much higher due to much longer links. 4) The required technological solutions need to be defined several years before the commencement of the services, and the space segment needs to use a fixed design during its entire lifetime (around 15 years for GSO services), with limited possibilities of evolution and maintenance after its launch.

All these characteristics have to be taken into account when designing a database-assisted sharing system for any satellite band. Power limitation requires high-gain antennas both for the transmission and for the detection of the signal. Due to large coverage, aggregate interference in the uplink direction is a challenge. The large beam also limits the use of satellites as a secondary system, but there are still possibilities for that as well. Very fast link adaptations are not possible in the same way as in terrestrial systems due to link latencies. A spectrum database adds a possibility to use predictions and proactive decision making, which will partly resolve the latency challenges. Since databases mostly affect the ground segment, that part can be updated during the lifetime of a satellite. In addition, the introduction of software-defined network (SDN) technologies [70]–[72] will also enable updating the space segment in the future.

Thus, a careful redesign of spectrum databases is needed before they can be applied in the satellite domain.

Characteristics of satellite systems such as the orbit used strongly affect the way databases can be implemented and used. Table 3 provides a comparison between LEO, medium-Earth orbit (MEO) and GEO satellite systems using some key parameters that affect the database design. *Footprint* refers to the ground area covered by a satellite. Its maximum theoretical diameter is given in [73] as

$$D = 2R_{\mathrm{e}}\arccos\left(\frac{R_{\mathrm{e}}}{R_{\mathrm{e}}+h}\right) \tag{1}$$

where $R_{\mathrm{e}} = 6378$ km is the Earth radius and h is the orbit height defining the distance between the ground station and the satellite. Consequently, the maximal total coverage is defined as

$$S_{\mathrm{M}} = 2\pi R_e^2\left(1-\frac{R_{\mathrm{e}}}{R_{\mathrm{e}}+h}\right). \tag{2}$$

Orbital period can be calculated with Kepler's third law in seconds as [74]

$$T = 2\pi\sqrt{(R_{\mathrm{e}}+h)^3/\mu} \tag{3}$$

where $\mu = 398600.5$ km^3/s^2 is Earth's geocentric gravitational constant. *Pass time*, i.e. the possible connection time from a specific location on the ground to a passing satellite from horizon to horizon, is then

$$T_{\mathrm{p}} = \frac{T}{\pi}\arccos\left(\frac{R_{\mathrm{e}}}{R_{\mathrm{e}}+h}\right). \tag{4}$$

Pass time also defines the maximum handover time from a satellite to another. In practice, the time is somewhat shorter than that, since a safety margin is needed to guarantee connectivity. Short pass times of LEO satellites lead to a much more dynamic database than in the case of GEO satellites, where the coverage and visibility of the satellite is almost fixed. The coverage of spot beams in a certain frequency channel may considerably differ from the coverage due to the use of powerful antennas. For example, Inmarsat I-4 satellites use 228 spot beams with a diameter of 1000 km [32], [75]. The I-4 satellite system is able to use a four-colour scheme for frequency reuse. The size of the spot beam means that in most European countries, a single spot beam can cover the entire country. Smaller spot beams are used in some systems.

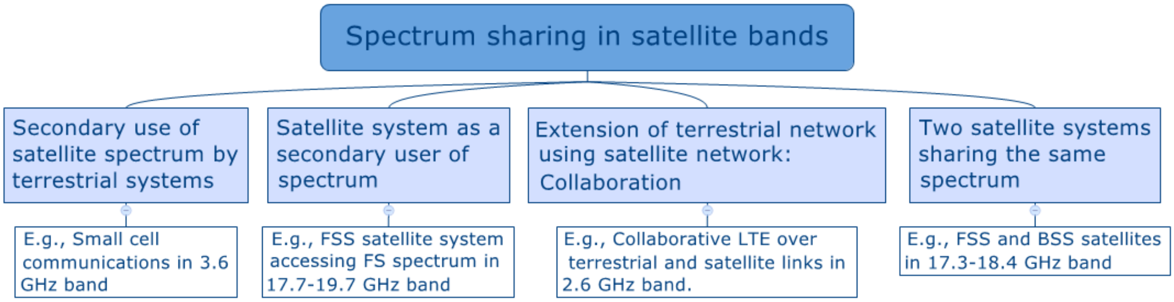

FIGURE 2. Application scenarios for spectrum sharing techniques in satellite communications.

TABLE 4. Summary of the scenarios studied in the present paper.

	Secondary use of satellite spectrum by terrestrial systems	Satellite system as a secondary user of spectrum	Extension of terrestrial network using satellite network: Collaboration	Two satellite systems sharing the same spectrum
Frequency band	3.6–3.8 GHz	17.7–19.7 GHz	2.5–2.69 GHz	19.3–19.7 GHz
Satellite orbit	GEO	GEO	LEO	GEO/LEO
Priority	Primary	Secondary	Co-primary	Co-primary
Satellite services	FSS	FSS	MSS	FSS
Sharing with terrestrial	Yes	Yes	Yes	No

For example, the O3b satellites in the MEO orbit have spot beams with a diameter of 700 km [76], and the Iridium system operating in the LEO orbit has spot beams with a diameter of 400 km [77]. Finally, the latest powerful high-throughput GEO satellites are able to use spot beams with a diameter of 100– 200 km directly below the spacecraft. Any other angle creates an ellipse of a varying size, depending on the angle. Thus, the orbit is not the only defining factor in coverage calculations. Spot beam diameter is an important parameter when defining the database.

We will discuss the database design in more detail in the following section, which also provides a classification and examples of spectrum sharing scenarios.

III. CLASSIFICATION OF SPECTRUM SHARING SCENARIOS

Satellite communications application scenarios can be classified into four main categories, as shown in Fig. 2. In the first two categories, spectrum sharing is based on the traditional cognitive radio approach, in which users are categorised into primary and secondary users of the spectrum. A primary user (PU) is the incumbent of the spectrum and has a higher priority or legacy rights with respect to the use of a specific part of the spectrum. A secondary user (SU) has a lower priority and may only use the spectrum if the use does not cause interference to PUs. Furthermore, SUs must accept incoming interference from PUs. In the other two categories, spectrum sharing is coordinated between co-primary users. The scenarios are briefly described in the following subsections. The different example scenarios and their distinctive characteristics are summarized in Table 4.

A. SECONDARY USE OF SATELLITE SPECTRUM BY TERRESTRIAL SYSTEMS

As in terrestrial systems, the actual occupancy of the satellite spectrum is often much lower than 100%. There are periods or areas where no-one is using the spectrum, or the level of usage is low. A satellite operator may have frequencies reserved for its systems while other wireless systems in the same area may struggle with insufficient spectral resources. That is the consequence of the spectrum allocation policy, which tends to fragment the spectrum with access rights. If these frequency bands were allowed to be used to provide secondary terrestrial coverage, a significant capacity boost could be offered to the wireless users operating in the same area. This is, however, quite a challenging scenario due to the sensitivity of the satellites, their wide coverage area, and their power-limited nature.

Due to low satellite signal levels and their directionality, sensing cannot be performed with the same type of energy detection devices as in terrestrial systems. To be able to detect satellite signals, one has to use fixed sensing stations with high-gain antennas, or more sophisticated methods such as matched filter detection or feature detection, to achieve decent performance [4], [5]. Since active spectrum sensing only tells the situation in the vicinity of the sensor, the

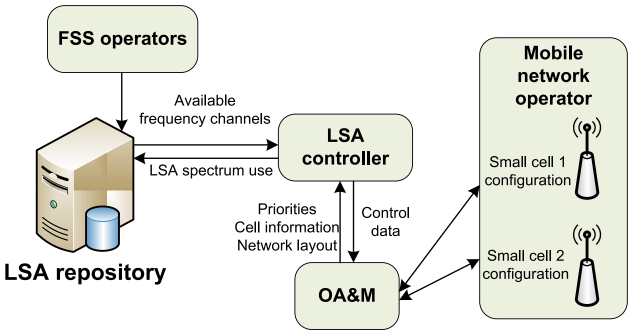

FIGURE 3. LSA concept for C band operation.

transmission power of the secondary system has to be controlled based on the knowledge about a) primary transmission, b) interference tolerance of the receivers, and c) the performance of sensing. It has been shown that for secondary operation in the S-band, sensing mainly supports short-range communication, especially in urban scenarios [78]. In contrast, the database approach can better guarantee the quality of service (QoS) of both the secondary and the primary system and is therefore the preferred option for all frequency bands. It also has the advantage of implementing some control over the spectrum access, protecting systems from unexpected interference emissions, if they can be controlled, and ceasing emissions in the event of an interference situation.

The ability to control and limit the number of users is naturally included in the **LSA model,** where the spectrum is shared on a licensed basis [19]–[21], [79], [80]. In this model, only licensed secondary users are allowed to use the spectrum. The model is a promising concept for both terrestrial and satellite bands. A limited number of users can obtain the right to use the band, while the LSA controller, utilising information contained in the database called LSA repository, ensures predictable QoS for all the holders of the spectrum use rights. This model enables the incumbent user may set a number of frequency channels that can be accessed, request multiple protection areas, define a type of protection based on the used services and devices, and remove the protection from the LSA repository if it is no longer using those resources [79]. The information is communicated from the database to the secondary licensed terrestrial system using an LSA controller. The concept could be used, for example, when an International Mobile Telecommunications (IMT) system accesses the C band, which is depicted in Fig. 3. The LSA controller needs network internal information from the-operational administration and management (OA&M). This information includes IMT user characteristics and their priorities, network layout, and cell information such as transmission power, locations, and antenna patterns. Both the LSA controller and the OA&M are part of the mobile network accessing the band as a secondary licensed user.

The first phase of the LSA is to negotiate the sharing framework and LSA license between the incumbent satellite operator, administration, and LSA licensees. The information defined at this stage, such as spectrum bands, geographical areas, and transmission power limits, will remain stable throughout the validity of the LSA license. The satellite operator can, for example, block certain areas outside the sharing agreement if it is highly probable that the availability of the LSA band to other services would be very low and sharing would be too risky or challenging. During the operation, the FSS operator has the right to request LSA users (such as a mobile operator) to terminate transmission in the shared band at any time and in any geographical area.

1) SAS CONCEPT

Another spectrum sharing approach proposed in the 3.5 GHz band is called SAS. Compared to LSA, SAS is more flexible but also a more complex sharing model [22], [81]. It provides a good support for the deployment of small cells. While LSA is a two-tier model, the SAS model includes a third tier called general authorized access (GAA) to facilitate opportunistic spectrum use. A clear difference to the LSA is the use of spectrum sensing in obtaining information about the current use of spectrum. This is required to detect any military naval radars operating in the band. In order to protect FSS earth stations, the Federal Communications Commission (FCC) has adopted a rule that requires satellite operators to register their stations annually [81]. SAS obtains this information from the FCC database and uses the data when granting or denying access for users willing to operate in the same band. SAS maintains a list of locations and look angles of earth station receivers in order to protect their operation. Both LSA and SAS concepts have been successfully field trialled with latest 3GPP Long-Term Evolution (LTE)-Advanced-compliant base stations [79], [82].

An important part of spectrum databases is the exclusion zone [9] or protection zone [11], i.e., an area inside which the transmission is prohibited to avoid interference. Some sharing studies have been conducted in the C-band (see e.g., [8]), showing that long separation distances from several tens of kilometres to in excess of a hundred kilometres are required between the interfering service and the satellite stations. The studies were conducted assuming rather powerful interfering terrestrial systems. Contrary to those studies, small cell operation and the possibility to use low-power transmitters were also considered in [11]. These techniques can reduce the required protection distances even under 500 metres. Interference produced by small cells is further reduced by the fact that as small cells are mainly operated indoors, walls will significantly attenuate the signals before they can interfere with the satellite receivers. Thus, determination of the protection zones and the zones within which coordination is needed to avoid excessive aggregated interference still remains an active research topic.

B. SATELLITE SYSTEM AS A SECONDARY USER OF SPECTRUM

The main incentive for providing secondary accesses to terrestrial frequencies is to gain more spectrum for the satellite

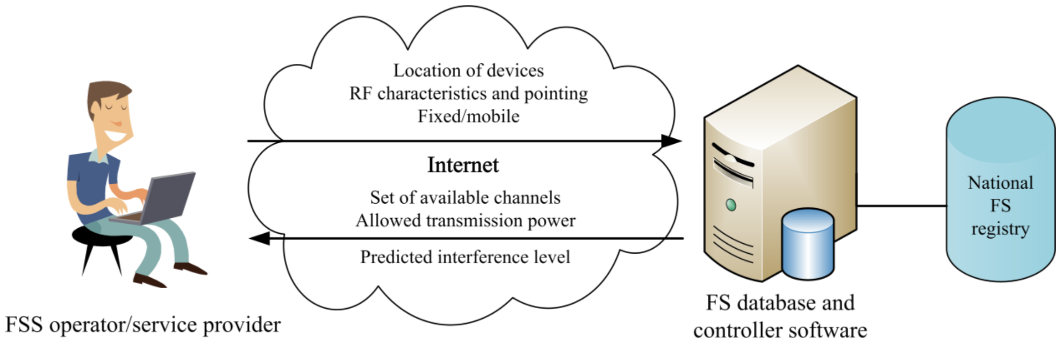

FIGURE 4. **FS database and related query information.**

systems and consequently to increase the satellite system capacity. Especially the Ka band, in which the terrestrial systems deploy microwave links, provides interesting opportunities and is under active investigation. Sharing is currently considered both in the 27–29.5 GHz downlink band and in the 17.7–19.7 GHz uplink band. Research results (see e.g., [15] and [83]) show that interference between the systems can be avoided by exploiting the spatial isolation offered by directional antennas, and that usage of this sub-band for satellite terminals can be dramatically increased.

The locations of the terrestrial link nodes are fixed in the defined part of the Ka band, which is why this service is referred to as fixed service (FS). The location information of the registered stations can be obtained in many European countries from national registries and regulatory authorities [83]. A possible disadvantage is that not all the links are registered in most countries. In addition to directional antennas, power control can be used to maximize the ergodic capacity of the cognitive satellite system without deteriorating the communication quality of the incumbent terrestrial link [15], [57]. Moreover, the joint application of carrier allocation and beamforming could considerably improve the performance of the system [84].

A clear challenge, however, is to develop a database that takes all the relevant information into account and provides reliable and efficient spectrum access for the secondary users while protecting the primary user from any harmful interference. The database approach has been studied and developed in [83], [85], which also provide relevant mathematical procedures and guidelines. Results of these studies have also been included in regulatory reports; see e.g. [86] and [87].

A spectrum database enables the sharing of the Ka band between FS and FSS stations. Database calculations can be used both to check whether a new FSS station can be operated at a specific location and to determine if a new FS station would cause interference to existing FSS earth stations. Thus, both FS and FSS station locations need to be included in the databases to be able to control the operation adequately. This process is already taking place for FS stations in many countries through their national FS registry. The FS database (FSDB) and related query information are shown in Fig 4. The user of the FSDB most probably located in the premises of the national regulator is the FSS operator or service provider. In Fig. 4, this party is depicted as a laptop user to emphasize the possibility to remotely access the system through internet. The FSDB obtains information about FS operations from the national FS registry.[1] Using both this data and FSS information from the query message as input for the controller software, the FSDB calculates whether the requesting FSS user can access the spectrum from a particular location.

The placement of FS links in Finland, obtained from the national registry, is shown in Fig. 5. The distribution of the links seems to follow the Finnish population distribution; the heaviest use of links occurs in the areas of the largest cities. Almost half of the links reserve 55 MHz for transmission, the other half uses less bandwidth. This means that in most locations in Finland, only a small fraction of the total 2 GHz is used by the FS system. There are some points in the Helsinki region where there can be more than 10 link ends at the same location [83]. The links are two-way links, reserving the same bandwidth in both directions. Thus, a single link can reserve 2×55 MHz $= 110$ MHz in the band. This means that in some urban areas, the 17.7–19.7 GHz band may be almost fully used by FS, or the prospect of reaching saturation is possible. In sparsely populated areas, it is likely that the saturation will never be reached. In most locations, the number of links is limited to a maximum of one. Analysis reveals that more than 90% of the Finnish territory is underusing the studied part of the Ka band. The situation is also similar in other countries in Europe [83], [85].

The proposed database design, which imitates in part the currently used TV white space databases [88], and the LSA approaches show how the sharing could be done in the band. A more detailed description about the use of the ITU-R channel model and the inclusion of FS and FSS station characteristics in the estimation of interference and allowed transmission power is given in [83] and [85]–[87].

[1] The format of the national registry differs between the administrations. Thus, the preferred way is to have a separate controller software and FS database for each country.

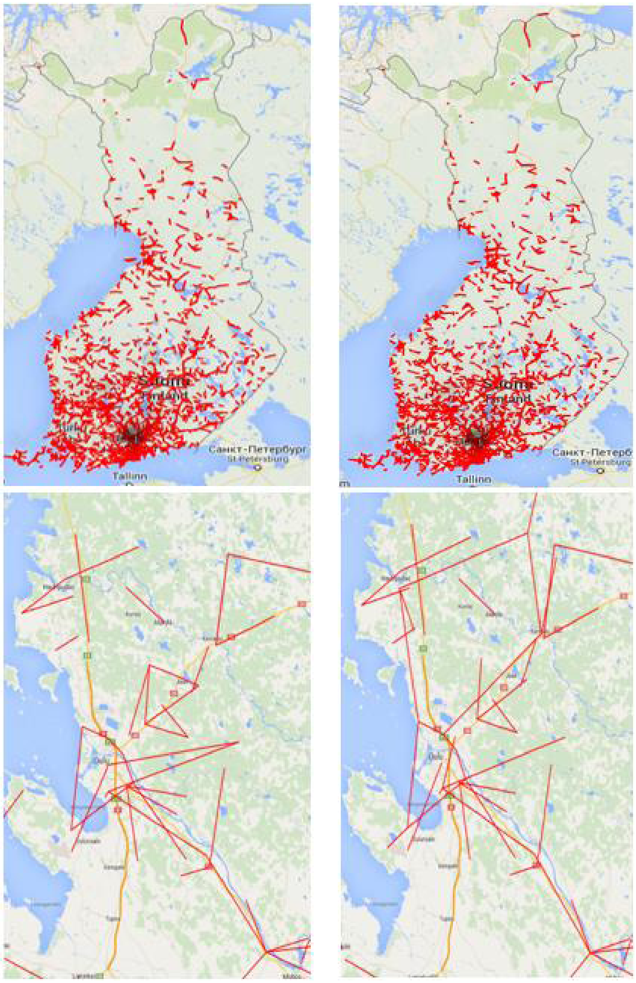

FIGURE 5. FS links in Finland and specifically in Oulu, 16^{th} May (left) and 17^{th} October (right) 2014, respectively.

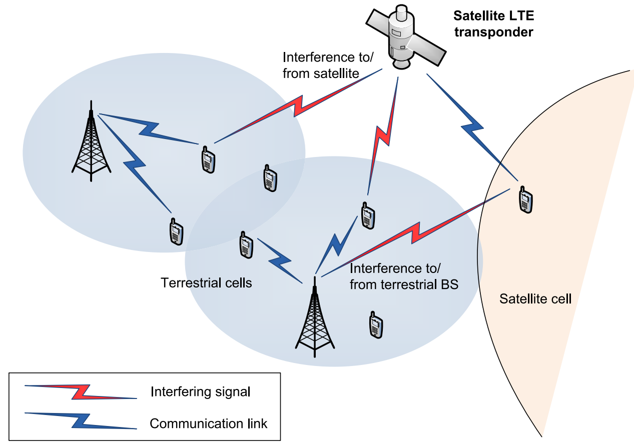

FIGURE 6. Collaborative LTE transmission over terrestrial and satellite links in the S band (2500–2690 MHz).

C. EXTENSION OF TERRESTRIAL NETWORKS USING A SATELLITE NETWORK: COLLABORATION

It has been envisioned that a significant part of the future satellite systems will be integrated with the terrestrial systems [71], [89]. Spectrum sharing techniques can be applied to improve the operation of a combined satellite and terrestrial system that uses both satellite and terrestrial components to provide services to end users [90]. One of the main challenges in this scenario is related to the long propagation delays of satellite systems compared with terrestrial communication. This significantly restricts the application of dynamic interference avoidance approaches to terrestrial systems for fast adaptations.

The coverage of terrestrial systems is typically adjusted with the base station (BS) installation according to the capacity and coverage requirements. However, providing the coverage in sparsely populated areas is not always good business for terrestrial operators due to the costly infrastructure that must be deployed. This is particularly important for new systems such as LTE, which has been designed for mobile broadband access providing high data rates in a power-limited mobile environment, and thus requires a dense network of access points. An interesting possibility is to deploy satellite systems sharing the same frequency band with terrestrial systems to extend the coverage in rural areas and to increase the reliability of the terrestrial system in the event of a disaster. Most probably, spectrum sharing would require the use of dual-mode handsets for both terrestrial and satellite systems, as depicted in Fig. 6. In any case, even partial sharing would enhance the overall spectral efficiency. The sharing could be envisaged both in space (e.g. coverage of rural and urban areas) and in time (e.g. use of a satellite to cope with failures of the terrestrial system). Satellites could also be used to assist the operation of cognitive terrestrial networks [91], [92] or to provide the spectrum required for signalling purposes.

Sharing the same band between satellite and terrestrial components requires a carefully designed system and a cognition-based hybrid system for controlling the interference between the terrestrial and satellite segments. Recently, Globalstar has proposed and tested a terrestrial low-power service (TLPS) for sharing the 2.4 GHz satellite band with Wi-Fi-type services while still protecting satellite services against harmful interference [93]. Link budget analysis and simulations have shown that there is potential for spectrum sharing between the terrestrial and satellite systems in the collaborative LTE scenario [90]. However, the satellite link is very sensitive to terrestrial interference. To guarantee an acceptable level of availability of the satellite link, the satellite component should also have its own dedicated slice of the frequency band, which it could use in any situation as backup. The system should be able to monitor the level of terrestrial interference and decide whether to deploy the shared frequencies or the dedicated satellite frequencies. The spectrum use of different components should be kept up-to-date, for example, in an internal spectrum database.

D. TWO SATELLITE NETWORKS AS CO-PRIMARY USERS OF THE SPECTRUM

The spectrum sharing scheme between satellite networks focuses on techniques to increase the spectrum sharing

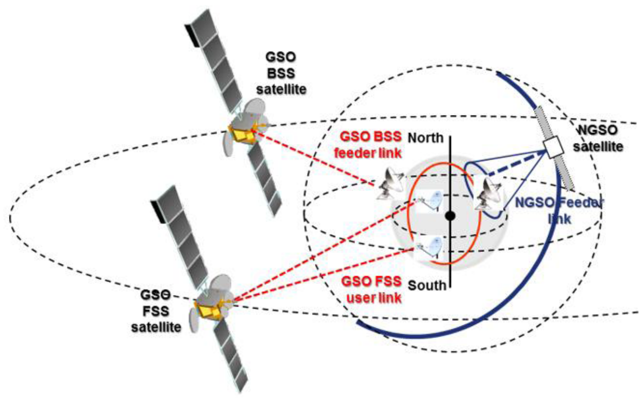

FIGURE 7. Frequency sharing between FSS, BSS, and NGSO satellites in the 17.7–19.7 GHz band.

capabilities across satellite services and operators. This should enhance the use of the radio resources, and consequently contribute to the mitigation of the global spectrum saturation for satellite services. Sharing can be enabled between geostationary (GSO) and non-geostationary (NGSO) satellite networks at the same priority level, as well as the sharing between FSS and BSS both using a GSO infrastructure. The situation is depicted in Fig. 7.

Sharing between FSS downlink and BSS feeder links can be based on a simple coordination mechanism by defining protection zones around the BSS stations [15]. The number of BSS feeder links is quite limited, for example, five in the UK [94]. The protection distance can be calculated according to the transmission power, antenna gains, and path loss model, taking into account the maximum tolerable interference level at the FSS terminals [95]. The coordination can be implemented via a database approach where the database would include the locations and parameters of BSS feeder links and would then calculate where the FSS systems are allowed to operate. The operation in this case is quite close to what is depicted in Fig. 4.

Awareness of other systems' operational characteristics, such as frequency allocations, orbital positions, and antenna patterns, is a key for a successful coexistence between satellite systems in the same band. A tight coordination between the systems is required, and could be achieved through a database approach. In addition, spectrum sensing can be used, for example, to adjust the frequency hopping (FH) sequence for communications over a satellite link to be able to adjust the sequence on the basis of channel quality and stability [96]. However, it is foreseen that database-based operation is required to make the sharing coordinated and successful.

The importance of finding applicable spectrum sharing possibilities between NGSO and GSO systems is rapidly increasing due to the foreseen mega-constellation concepts where hundreds of LEO satellites would provide a global internet coverage [29], [97]. The plans include Ka band and Ku band scenarios where the mega-constellation satellites would be operating at the same frequencies that are currently used by GSO satellites, a fact which has raised concerns among GSO satellite operators.

Spectrum sharing between NGSO and GSO systems has been studied in multiple papers starting from [98], where an analytical method for assessing interference between satellite systems was proposed. In [99], simulations were carried out to calculate the interference statistics between the links of GSO Spaceway and LEO Teledesic networks in the Ka band. The effect of NGSO interference on the bit error rate of a GSO system was studied in [100]. An important problem to consider is the in-line interference, which arises whenever an NGSO satellite passes through a line-of-sight path between an earth station and a GSO satellite. An earth station that is in line with GSO and NGSO satellites may receive and create interference through its main beam. Interference mitigation techniques to avoid in-line interference include, for example, [101], [102]: 1) selecting another visible NGSO satellite in view and 2) ceasing transmissions whenever such in-line coupling instances occur. In the former case, multiple satellite coverage for serving a given ground terminal location is required. In the latter case, the system should be capable of accepting the loss of coverage and the interruption of links whenever an in-line event occurs. Recently, in-line interference mitigation techniques for ensuring coexistence of GSO and medium Earth orbit (MEO) O3b satellite systems [76] were studied in [103]. The authors propose an adaptive power control technique for NGSO transmissions in order to mitigate the interference.

IV. SPECTRUM SHARING BETWEEN GSO FSS AND NGSO SATELLITES IN THE Ka BAND

To complement the previous studies in [98]–[103], we will analyse a specific use case in the 19.3–19.7 GHz band to investigate the sharing possibilities between LEO NGSO and GSO satellite systems, on the basis of new results from the ESA-supported study [16]. The link budget calculations are based on a set of parameters obtained from the relevant regulatory recommendations [104]–[107], as well as from typical satellite systems operating in the studied band. However, we will not set our parameters based on a certain system that has already been planned or is in operation but would rather like to show what is required for sharing to be possible in the first place. We extend the previous work by defining timescales of operation, assuming an adaptive power control of GSO transmission, and defining some operational guidelines for database-assisted spectrum sharing.

A. SYSTEM MODEL

In the ITU-R Radio Regulations [104], GSO FSS satellites and GSO BSS satellites have priority over NGSO satellites in most cases. This priority is provided by Article 22.2 of the Radio Regulations [104]. However, the Regulations also identify several frequency bands where this GSO satellite protection is removed. This is the case in the 19.3–19.7 GHz band under consideration. In this band, a footnote in the

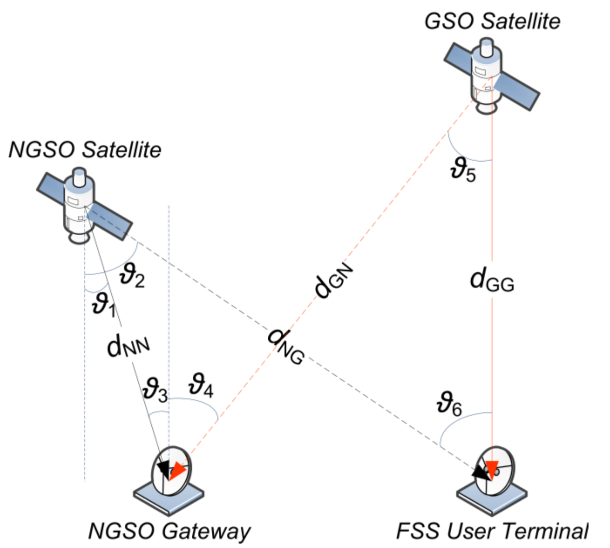

FIGURE 8. Signal (the solid lines) and interference (the dashed lines with arrows) links in the downlink coexistence scenario of NGSO and GSO satellites: GSO satellite interferes with the NGSO gateway.

ITU-R Frequency Table of Allocation, RR No. 5.523D, removes the GSO FSS downlink protection versus the NGSO satellites using FSS downlink transmissions as feeder links for MSS. A formal ITU-R coordination is set on the "first come, first served" basis.

The GSO satellite is orbiting Earth at the altitude of around 35786 km above the equator and at the same rotational speed as Earth, and thus it is stationary with respect to Earth. The NGSO satellites, instead, are orbiting in low and medium Earth orbits clearly below the GSO satellite. Uncoordinated GSO FSS user terminals have their high-gain narrow antenna beams pointed at the satellite. Thus, the NGSO satellites are only visible to these terminals when they are close to in-line conditions with the GSO satellite and GSO terminals, causing in-line interference. Similarly, the NGSO gateway has its steerable narrow antenna beam pointed towards the moving NGSO satellite. In this case, the GSO satellite will only be visible to the NGSO gateway when the GSO and the NGSO satellites are fully or approximately in-line.

The coexistence situation is shown in Fig 8, where we consider a general sharing scenario between GSO and NGSO satellites operating in any orbit. In this context, we focus on the downlink transmission from the NGSO LEO satellite to the gateway interfered by the transmission from the GSO satellite toward its uncoordinated FSS user terminals. The study parameters are defined in Table 5. The objective of the study and subsequent analysis is to: 1) look at the feasibility of sharing in this band and 2) to define what kind of cognitive techniques both the GSO and the NGSO system could apply in order to enable coexistence. In the figure, we denote by:

- ϑ_1 – the angle under which the NGSO receiver (i.e., the NGSO gateway) can be seen from the NGSO transmitter with respect to the bore-sight of the main lobe;

TABLE 5. GSO and NGSO system parameters.

	System parameters	
GSO satellite system, VSAT terminals	Frequency band	19300–19700 MHz (*f* = 19500 MHz in calculations)
	Reference bandwidth *B*	1 MHz
	Satellite effective isotropic radiated power (EIRP) in *B*	40 dBW (Appendix 7 of Radio Regulations)
	Orbit altitude	35786 km
	Antenna diameter	1.2 m
	Elevation angle α	20°–50° (Europe)
	Antenna pattern and antenna gain	max receiving gain is 53.2 dB, pattern according to [106]
	Permissible interference	$10\lg(kTB) + Q$ dB where $k = 1.38\cdot10^{-23}$ J/K is Bolzmann constant, *T* is temperature, and *Q* = 7 dB is the margin
NGSO satellite gateway (LEO)	**Parameters applied to the entire system**	
	EIRP	42.7 dBW
	Orbit altitude	1400 km
	Reference bandwidth	1 MHz
	Antenna diameter	8.1 m
	Antenna pattern and gain	Max gain = 62.1 dB, pattern according to [107]

- ϑ_2 – the angle under which the GSO receiver can be seen from the NGSO transmitter with respect to the bore-sight of the main lobe;
- ϑ_3 – the angle under which the NGSO transmitter can be seen from the NGSO receiver with respect to the bore-sight of the main lobe;
- ϑ_4 – the angle under which the GSO transmitter (i.e., the GSO satellite) can be seen from the NGSO receiver with respect to the bore-sight of the main lobe;
- ϑ_5 – the angle under which the NGSO receiver can be seen from the GSO transmitter with respect to the bore-sight of the main lobe;
- ϑ_6 – the angle under which the NGSO transmitter can be seen from GSO receiver the with respect to the bore-sight of the main lobe;
- d_{NN} – the physical distance between the NGSO transmitter and NGSO receiver;
- d_{NG} – the physical distance between the NGSO transmitter and GSO receiver;
- d_{GG} – the physical distance between the GSO transmitter and GSO receiver; and
- d_{GN} – the physical distance between the GSO transmitter and NGSO receiver.

B. COEXISTENCE ANALYSIS

Let I_{th} denote the maximal interference power that the GSO receiver can tolerate, that is, $I_G \leq I_{th}$. At the same time, the received signal quality at the NGSO receiver should also be ensured. The received SINR at the NGSO receiver can be written as

$$\gamma_N = \frac{P_{\mathrm{N,t}} A_{\mathrm{N,t}}(\vartheta_1) A_{\mathrm{N,r}}(\vartheta_3) \left(\frac{\lambda}{4\pi d_{\mathrm{NN}}}\right)^2}{P_{\mathrm{G,t}} A_{\mathrm{G,t}}(\vartheta_5) A_{\mathrm{N,r}}(\vartheta_4) \left(\frac{\lambda}{4\pi d_{\mathrm{GN}}}\right)^2 + \sigma}, \quad (5)$$

where $P_{\mathrm{G,t}}$ is the transmit power of the GSO transmitter, $A_{\mathrm{N,t}}$ and $A_{\mathrm{N,r}}$ are, respectively, the antenna gains of the NGSO transmitter and receiver, $A_{\mathrm{G,t}}$ is the antenna gain of the GSO transmitter, λ is the wavelength, and σ is the background noise power. The SINR at the GSO receiver is given by

$$\gamma_{\mathrm{G}} = \frac{P_{\mathrm{G,t}} A_{\mathrm{G,t}}(0) A_{\mathrm{G,r}}(0) \left(\frac{\lambda}{4\pi d_{\mathrm{GG}}}\right)^2}{P_{\mathrm{N,t}} A_{\mathrm{N,t}}(\vartheta_2) A_{\mathrm{G,r}}(\vartheta_6) \left(\frac{\lambda}{4\pi d_{\mathrm{NG}}}\right)^2 + \sigma}. \quad (6)$$

The NGSO satellite works with a constant transmit power, and its movements, which can be represented by the value of angle ϑ_1, result in dynamics of both the received interference power at the GSO FSS user terminal and the received signal power at the NGSO gateway. Therefore, SINR thresholds need to be introduced to ensure the QoS for the receivers on earth surface, i.e., $\gamma_{\mathrm{N}} \geq \Gamma_{\mathrm{N}}$ and $\gamma_{\mathrm{G}} \geq \Gamma_{\mathrm{G}}$, where Γ_{N} and Γ_{G} are the thresholds of the NGSO receiver and the GSO receiver, respectively.

We consider that the GSO satellite is able to perform adaptive power allocation according to the position of the NGSO satellite, which can be formulated by the following optimization problem:

$$\begin{aligned} &\max_{P_{G,t}} \quad \log(1+\gamma_{\mathrm{G}}) \\ &\text{s.t.} \ \ \gamma_{\mathrm{G}} \geq \Gamma_{\mathrm{G}}, \\ &\gamma_{\mathrm{N}} \geq \Gamma_{\mathrm{N}}. \end{aligned} \quad (7)$$

In other words, the optimization aims at maximizing the throughput of the GSO link while satisfying the SINR requirements at both the NGSO and the GSO receivers. While increasing the transmission power at the GSO satellite may enhance the quality of the GSO link, it may also cause interference to the NGSO link operating in the same frequency. The reason for selecting to apply adaptive power allocation in the GSO is to protect the NGSO gateway. In more typical cases, where the GSO system has priority, it is easy to define the symmetrical problem where adaptive power control is carried out on-board the NGSO. The problem (7) can be easily solved and we may have the solution expressed as

$$P_{\mathrm{G,t}}(\vartheta_1) = \begin{cases} \Psi(\vartheta_1), \\ \text{if}\Omega \leq \Psi(\vartheta_1); \\ 0, \\ \text{otherwise}, \end{cases} \quad (8)$$

where Ω and $\Psi(\vartheta_1)$ are given by

$$\Omega = \frac{P_{\mathrm{N,t}} A_{\mathrm{N,t}}(\vartheta_2) A_{\mathrm{G,r}}(\vartheta_6) \left(\frac{\lambda}{4\pi d_{\mathrm{NG}}}\right)^2 + \sigma}{A_{\mathrm{G,t}}(0) A_{\mathrm{G,r}}(0) \left(\frac{\lambda}{4\pi d_{\mathrm{GG}}}\right)^2} \Gamma_{\mathrm{G}}, \quad (9)$$

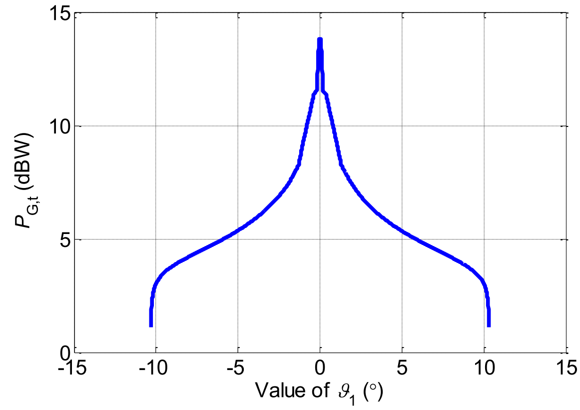

FIGURE 9. The transmit power of a GSO satellite versus the position of an NGSO satellite.

$$\Psi(\vartheta_1) = \frac{\left(\frac{P_{\mathrm{N,t}} A_{\mathrm{N,t}}(\vartheta_1) A_{\mathrm{N,r}}(\vartheta_3) \left(\frac{\lambda}{4\pi d_{\mathrm{NN}}}\right)^2}{\Gamma_{\mathrm{N}}} - \sigma\right)}{A_{\mathrm{G,t}}(\vartheta_5) A_{\mathrm{N,r}}(\vartheta_4) \left(\frac{\lambda}{4\pi d_{\mathrm{GN}}}\right)^2}. \quad (10)$$

It is obvious that the solution $P_{\mathrm{G,t}}$ depends on the position of the NGSO satellite, i.e., the optimal transmission power of GSO satellite $P_{\mathrm{G,t}}(\vartheta_1)$ is a function of angle ϑ_1. This means that in practice, there needs to be a method such as a database to ensure that the GSO satellite will be aware of the position of the NGSO satellite.

Fig. 9 shows the optimal transmitter power of the GSO satellite given the position of the NGSO satellite. The maximal value of ϑ_1 in the figure is calculated by the minimum SINR requirement for ensuring the QoS of NGSO receiver, which means that the NGSO satellite can only work within the value region shown in the figure even if the GSO satellite does not transmit. The main reason for the maximum ten-degree separation comes from the antenna pattern.

From the curve, it is easy to see that the GSO satellite should increase the transmission power if the NGSO satellite moves closer to the GSO receiver, and vice versa. This is feasible within the limits of the Regulation, as the calculations are made using ITU-R models, and of the available power on-board the satellite. Ideally, the transmission power should only be increased by the GSO satellite within the interfered coverage portion, which requires some on-board flexibility to distribute the power differently among the beams. This flexibility may come from the flexible Travelling Wave Tube Amplifiers (flex-TWTA) or from Multi-Port Amplifiers.

Fig. 10 shows the related timescales for operation based on the orbital period of the satellite, which can be calculated using Kepler's third law given in (3). Since this defines the time for the total 360 degree period, it is simple to calculate how fast the depicted power adaptations need to be done. The value region in Fig. 9 shows that the GSO adaptation starts from a -10 degree off-axis angle and the maximum power is naturally when the angle is zero. It takes roughly three minutes for the NGSO satellite to move this distance, so the adaptation does not need to be performed very fast.

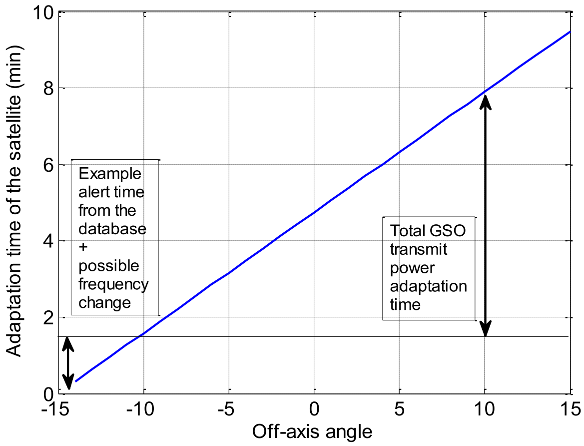

FIGURE 10. Timescales for adapting transmission and database operations.

When the NGSO satellite moves enough far away from the receivers but the link between the NGSO satellite and NGSO gateway is still active, the GSO satellite might also choose to transmit over another feasible channel rather than reducing the transmitter power in order to achieve good transmission performance. However, the best candidate to switch spectrum would generally be the NGSO system rather than the GSO system since the GSO terminals are uncoordinated.

C. DATABASE ASPECTS

The movement of the NGSO satellite can be used in predicting when to alert about a possible interference situation and start either the power adaptation or the frequency change process. An example timescale of 1.5 minutes is shown in Fig. 10, assuming that the alert is generated when the NGSO satellite is still five degrees away from the start of the adaptation phase. In addition, maintaining the performance of the NGSO system while reducing transmission power is possible by increasing the size of the NGSO gateway antenna. However, this is quite an expensive option. Thus, changing the operating frequency in the feeder link is a favourable option if power control cannot achieve the QoS target.

Database-assisted spectrum sharing applies all the identified strategies to reduce interference, assuming the database being populated by parameters coming from both the NGSO satellites and the GSO satellites. The advantage of an NGSO satellite is the good predictability of its position over time, known as ephemeris, which can be used to anticipate an interference situation and to slightly relax the real-time constraints of the database system design.

The database could then: 1) alert in advance each system of any interference situation by predicting when and where it will happen, 2) assist in adopting the appropriate interference mitigation strategy for these cases, as well as 3) answer to requests for more bandwidth from each system and allocate spectrum accordingly. Table 6 presents an example of a list of parameters to be sent to the database system in order to support the described operation. The database will have to be

TABLE 6. Parameters to be included in the database.

NGSO System	*GSO System*
Orbital parameters to determine ephemerides	Orbital slot
Satellite altitude	Coverage contour
Position of gateways	QoS threshold
QoS threshold	Spectrum used
Spectrum used	

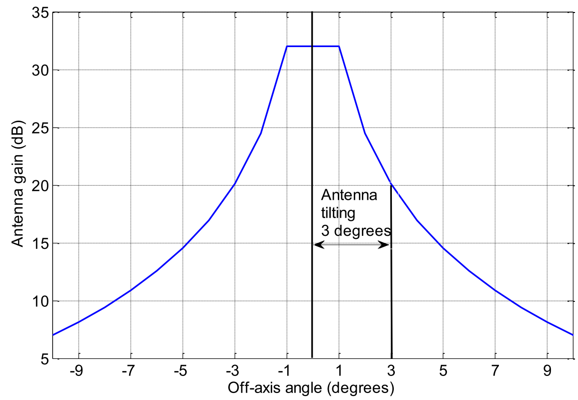

FIGURE 11. Gain pattern of NGSO satellite antenna and related gain reduction due to tilting of antenna.

loaded with the NGSO satellites' ephemeris and associated power level received on the ground.

The GSO system and all the service providers leasing capacity on this satellite will have to be connected to this database in order to be alerted right before the system enters an adaptation period.

On its side, the GSO system will have to upload the geographical contour to be protected. This can be expressed in terms of the margin in dB remaining above the service level regarding a certain beam. Then, based on this data and the information uploaded by the NGSO system, the database system will generate alerts. The advantage of knowing the ephemeris of the NGSO satellites is that alerts can be generated in good time, thus leaving enough time for the GSO system to be prepared and reconfigured. It is possible to refine the "interference zone" *a posteriori* using a learning process where interference situations are collected and correlated with the position of the NGSO satellites at that time. It could help in optimizing power and spectrum allocation strategies and associated time periods.

Finally, an interesting interference management technology has been proposed for LEO satellites in [108] and [109]. The idea is to protect the GEO from interference by gradually and slightly tilting satellites as they approach the equator to make sure that NGSO satellites do not cause, or receive, interference from GSO ground stations or user terminals. The effect of the tilting is shown in Fig. 11 in the gain pattern figure of an NGSO satellite.

Already three-degree tilting reduces the interference gain towards the GSO system by 12 dB and rapidly increases with an increasing angle. Instead of mechanically tilting the entire satellite, transmission beams can be mechanically or electronically tilted when the satellite approaches the equatorial plane [109]. The authors claim that using this technique, an angular separation sufficient to prevent interference between the satellite's radio signals and GEO radio signals at all satellite positions is maintained, and, as a result, good coverage is provided to all ground locations. Database assistance can be used to also enable this technique as one possible interference mitigation strategy in the system.

V. FUTURE DIRECTIONS

Recent studies have mainly focused on defining and analysing the potential of the multiple scenarios proposed for spectrum sharing. There have been some breakthroughs in the study of sharing techniques, such as the small cell, beamforming, power control, and database techniques discussed in this article, but more research and development work especially on dynamic sharing approaches will be needed in the future. Particularly further demonstrations and field tests with implemented solutions for the selected techniques are required to validate the practical applicability of the proposed approaches. In the following, we present some ideas for future work on spectrum sharing for satellite bands. Some ideas specifically concern the NGSO-GSO sharing scenario, for which we analyse the modifications required in both satellite systems.

A. SHARING BETWEEN SATELLITE AND CELLULAR NETWORKS

The upcoming 5G systems will cover cellular operation both below the 6 GHz band and in the mmW bands. There will be a clear need to share the spectrum with satellite systems. An especially important section of the C band to study is the 3600–3800 MHz band since although it has been allocated to mobile use on a secondary basis in Europe already in WRC-12, due to the existing FSS and FS usage, it still cannot be used in a harmonized manner. Currently, this part of the band is actively used by FSS systems. Electronic Communications Committee (ECC) Project Team 1 (PT1) has published an ECC Report providing operational guidelines for spectrum sharing in the 3600–3800 MHz band and, where appropriate, the implementation of LSA at a national level [110]. In the US, the work concerning the C band concentrates on the SAS concept. Research efforts are needed especially in higher frequency bands to determine what kind of spectrum awareness techniques, resource allocation schemes, and adaptive antenna techniques should be used to guarantee successful operation for coexisting systems and their end users. In addition, many primary systems with several secondary systems might coexist simultaneously in the same band. Interference-free coordination of this complex scenario is a challenging research topic for the future.

One of the crucial aspects of the upcoming 5G networks is finding and defining the frequency bands to operate in, and studying whether some of those bands are applicable for sharing between different networks while also fulfilling the requirements set by the applications and use cases. The European Commission (EC) has defined three 5G pioneer bands in Europe [111]:

1) The 694–790 MHz band for wide area coverage and new services such as connected cars and smart sensors. Can also provide indoor coverage.
2) The main pioneer band 3.4–3.8 GHz, suitable for urban broadband connectivity. This band can provide carrier bandwidths of 100 MHz and allow single Gbps data rates.
3) The 24.25–27.5 GHz band for hot spots and real enhanced mobile broadband (eMBB) services. Carrier bandwidths of several 100 MHz are expected to allow >10 Gbps data rates.

Thus, especially bands 2 and 3 are important from the perspective of this paper, i.e., studying the possibilities for sharing between satellite and terrestrial users in these bands. The authors' opinion is that the LSA may be the most promising approach to implement sharing in the pioneer bands.

B. MEGA-CONSTELLATIONS

In this paper, we have also analysed the feasibility of a sharing scenario that includes a single NGSO satellite. The complexity of the sharing scenario depends upon the size of the NGSO constellation considered (between one to several tens or hundreds of satellites) and the characteristics of the orbits (inclined, equatorial, polar, etc.). Due to the foreseen mega-constellations, more complex scenarios need to be analysed to account for the accumulated interference of multiple NGSO satellites to a GSO satellite. However, we assume that in that case there will also be one main interferer at a time, and the impact of other satellites at a given moment is clearly lower.

C. NGSO MODIFICATIONS

Adaptation of the NGSO satellite feeder downlink transmission power is already feasible today. Satellite power reduction would vary over time (controlled from the ground or preloaded) and only when the NGSO satellite enters the ''sharing zone'' where it is interfering GSO receivers. However, this power reduction must be compensated on the ground by more gain in order to maintain the expected level of feeder QoS and data rate. This modification does not require new technological developments. Interestingly, this solution could be used by NGSO satellites already in orbit today. Another way of reducing the interference received by FSS terminals would be to use spread spectrum signals in the NGSO system. However, this would significantly impact the downlink capacity as the bandwidth size is given. Increasing the size of the NGSO MSS gateway antenna would allow decreasing the NGSO satellite power and reducing the interference received by FSS satellite terminals.

D. GSO MODIFICATIONS

An alternative or complementary solution to transmission power control in the NGSO system is adaptation of the GSO satellite transmission power, with the possibility to distribute non-uniformly the power between a few beams or carriers. From the technology point of view, several solutions already exist or are under development to support this idea.

- *Flexible filters* are filtering devices of the satellite payload capable of selectively filtering a portion of the spectrum out of a beam to redirect this portion towards a given power amplifier, which could be set differently from the other power amplifiers of the payload.
- *Multi-Port Amplifier* is an amplifying device of the satellite payload capable of setting differently the level of amplification of the various input signals connecting to its various ports. It includes several input and output ports and one power amplifier per port. Similar devices have been used for a long time in the L-band, and they are now being developed for the Ka band.
- *Digital processor* is able to digitalize signals, filter the spectrum precisely, route signals, and selectively amplify the signals of part of a beam or a carrier, as well as perform on-board beamforming functions.

Thus, considering the existing technology, spectrum sharing in this scenario does not create new needs for specific technological developments, but rather a need for proof-of-concept through demonstrations.

E. SPECTRUM DATABASES

We believe that spectrum databases are among the main techniques to concentrate in the near future when considering any spectrum sharing scenario involving satellite systems. It is foreseen that the adoption of an LSA-type concept in satellite communication systems should be studied further both from the business and technical point of view in different frequency bands and scenarios. A database approach is seen as a fundamental brick also in the analysed GSO-NGSO scenario.

Even though databases have been implemented in terrestrial networks, there are still challenges in the development of those techniques, specifically concerning the satellite environment. In particular, the requirements for the database format, the overall deployment architectures, and the level of reactivity in the complete control loop from interference detection to an interference-free situation must be refined. The database approach is flexible and certainly more realistic for operational systems than a fixed method. It offers the possibility to tune differently the control algorithms depending on the requirements of each system. It is important to highlight that it is based on a certain level of cooperation between actors in order to share spectrum efficiently. A database approach allows controlling spectrum access on the basis of rules that can be transparently adapted over time and space to adapt to any changes in the context. The general applicability of this approach could lead to the emergence of a new ecosystem for designing and developing applications and services inside and around databases. Such a general approach would in the end benefit all the actors that need to share spectrum.

F. ECONOMIC STUDIES AND ROLE OF OPERATORS

There is a clear need for continuing in-depth techno-economic studies of sharing techniques, especially in terms of the new frequency bands. The capital costs of launching an NGSO constellation are usually very significant, and this is especially true in terms of mega-constellations. The lifespan of a LEO satellite is typically only around seven years compared to around 15 years for a GSO satellite. Therefore, LEO satellites require more frequent replacement. In addition, building up a customer base is likely to take many years before there will be enough income coming from the services. Therefore, enough spectrum resources should always be available in order to have enough capacity and to be able to deliver decent service to end customers. Otherwise the investment is not reasonable. Thus, it is of utmost importance to look at spectrum sharing possibilities both from technical and economic perspectives.

The key players in all the proposed sharing scenarios are the incumbent operators and the "challenger" operators willing to access the same spectrum. The best strategy for the incumbent operator is to use spectrum sharing to decrease costs and increase efficiency of the resource use, while the challenger operator should focus on innovation and providing complementary services. Due to political pressure, there are significant risks involved in just trying to defend the current assets and positions and not considering sharing at all. In the worst case, the political pressure could eventually lead to losing the spectrum assets to other wireless services considered more valuable to the society. *Controlled sharing is thus an attractive option since in some cases it can secure the use of spectrum to the current services, as well as the current operators' position as an incumbent operator*. By allowing sharing, current incumbent operators could continue their operations in the bands in question to fulfil their obligations defined by the society with minimum additional investment.

Due to the above-discussed reasons, the proposed spectrum sharing techniques need to be regulatory compatible, economically attractive and viable, and technically efficient. In addition, energy efficiency will play a key role in the future, affecting the selection of the most suitable sharing techniques in different scenarios and use cases.

VI. CONCLUSIONS

Spectrum databases are being developed to enable coexistence in different spectrum sharing environments. This paper has provided a survey on database-assisted spectrum sharing in satellite communications. Multiple potential sharing scenarios were classified, and a practical use case was given for each scenario. The current state-of-the-art in these scenarios was discussed, and the most suitable techniques and their advantages and risks were identified. The survey focused on defining how to apply database techniques in the defined use cases and scenarios and what other sharing techniques are needed to guarantee smooth operation.

As a novel use case, we studied a satellite-satellite sharing scheme, which is very timely due to the recent mega-constellation initiatives. According to the analysis, sharing spectrum between NGSO and GSO FSS satellite systems seems to be feasible, assuming that necessary controls are put in place. Different strategies were also envisaged in the event of interference: 1) Changing to an alternative spectrum band. The best candidate to switch spectrum would be the NGSO system rather than the GSO system. 2) Adapting the transmission power of satellites to maintain the QoS. 3) Increasing the size of the NGSO gateway antenna. 4) Tilting the antenna of the NGSO satellite. The safest way to enable spectrum coexistence would be to implement a database approach where the database would be populated by parameters coming from both the NGSO satellites and the GSO satellites. Even though the results seem promising, more analysis work is needed in the future to understand more complex settings, and particularly the cumulative interference coming from multiple NGSO satellites. In addition to technical work, economic viewpoints should also be considered more deeply.

There are many research challenges for the future in the study of database-assisted spectrum sharing in satellite bands. One of the most important ones is studying the coexistence of mobile cellular systems and satellite systems not only below 6 GHz but also in millimetre-wave bands. A key to ensure the success of the upcoming 5G is to adopt advanced techniques and forward-looking policies, and to unlock new spectrum assets. The 5G and beyond generations will play a key role in terms of satellite technology. Therefore, developing new spectrum sharing techniques to ensure coordinated coexistence of multiple systems in the same band is essential in the near future.

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