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Database-Assisted Spectrum Sharing in Satellite Communications: A Survey

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***Abstract*—In this survey paper, feasibility of sharing the spectrum between satellite telecommunication networks with terrestrial and other satellite networks is discussed based on a comprehensive study carried out in the frame of European Space Agency (ESA) Advanced Research in Telecommunications Systems (ARTES) 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 dedicated licensed spectrum. Potential spectrum sharing scenarios are classified as a) secondary use of satellite spectrum by terrestrial systems, b) satellite system as a secondary user of spectrum, c) extension of a terrestrial network using 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 feasibility of spectrum sharing between geostationary orbit (GSO) and non-geostationary orbit (NGSO) satellite systems. The performance is analyzed primarily based on widely accepted recommendations of the Radiocommunications sector of the International Telecommunications Union (ITU-R). Finally, future research directions are identified.**

***Index Terms*—Dynamic Spectrum Access, Millimeter Wave Communication, Database systems**

I. Introduction

DURING the last decade, significant effort has been spent on spectrum sharing research, especially in terrestrial networks, see e.g., [1]-[3]. Satellite industry is on a big transformation phase currently due to rapid technological advances in small satellite systems, very high throughput satellite systems, and the trend of moving from broadcasting to the broadband connectivity. As demand for broadband access and more bandwidth is intensified, spectrum sharing studies are extended from the terrestrial domain to satellite systems as well [4]–[17]. Even though dynamic spectrum management techniques have been studied rigorously for terrestrial systems, there are still several technical challenges to apply those techniques in satellite systems.

An important part of the 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, one needs to decide how to allocate resources in order to fulfill the performance targets. Spectrum databases are currently seen as the most favoured approach for spectrum awareness in the terrestrial domain due to 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 in terrestrial systems: Databases provide better protection to incumbent users of the spectrum even though their use can be limited in very dynamic spectrum sharing scenarios. Recent industry-driven spectrum sharing approaches such as Licensed Shared Access (LSA) [21] and Spectrum Access System (SAS) [22] are based on a database concept. *We define database-assisted spectrum sharing as a scheme where the spectrum awareness for decision making on radio resource use is obtained from the spectrum database.*

Previous satellite band sharing studies have concentrated 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 on 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 Ka band sharing in [15]. In addition, there are satellite related survey papers on propagation impairments and mitigation [23], multiple-input multiple-output (MIMO) techniques [24], and mobile satellite systems in general [25]. However, there have not been a survey paper on database-assisted spectrum sharing for satellite communications yet.

We have collected potential frequency bands in Table I, introducing also satellite services in those bands. Due to millimetre-wave operation in coming 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 and focusing specifically on the use of spectrum database

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

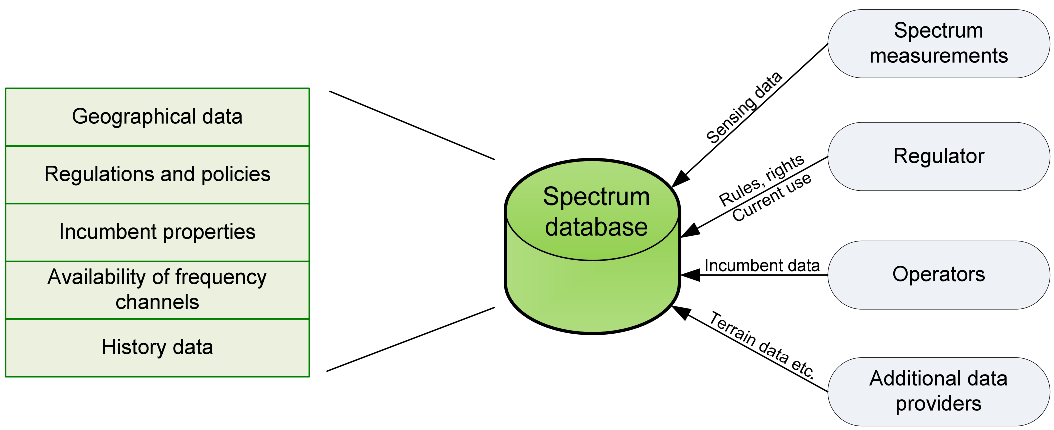

Fig. 1. A general spectrum database model [32].

techniques in those areas. We define the most promising frequency bands and cognitive sharing techniques in order to obtain a thorough view on the feasibility of spectrum sharing in satellite bands. This is a consolidated view resulting from a study between research institutes and satellite industry under an ESA research contract [16]. We have previously published some results but we extend the work with a large-scale survey and one satellite-satellite sharing case. We will take a deeper look at the feasibility of a specific sharing scenario between a GSO and a low Earth orbit (LEO) satellite system, which is stimulated by the recent surge of announcements about planned mega-constellation satellite networks composed of hundreds of LEO satellites, like SpaceX, OneWeb and LeoSat [29]–[31]. We will analyse the feasibility of this sharing concept in Ka band, propose cognitive techniques to enable coexistence, and describe how a spectrum database could be used in controlling and assisting the adaptations.

The rest of the article is organized as follows: Database-assisted spectrum sharing is described with other relevant techniques in Section II. Also differences to terrestrial spectrum sharing are outlined. We classify potential spectrum sharing scenarios in Section III and define an example use case for each scenario. We describe how database techniques can be used in all use cases. Feasibility analysis of spectrum sharing between different satellite systems is given in Section IV. We define future challenges and recommendations for further work in Section V. 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 database that the channel it intends to operate is free at the location of the device [32]. The general spectrum database model is presented in Fig. 1 showing what kind of information can be stored and shared through it and what the information providers are.

Table II. Advantages and risks associated with the 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 third party for sharing, requires additional infrastructure
Spectrum sensing [4], [45]–[48]	Autonomous operation for secondary users, can provide support for database	Cannot guarantee interference-free operation for 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 beam hopping pattern by 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, highly effective	Requires modifications to satellite receivers
Small cells and D2D [11], [61]–[65]	Requires to modify only terrestrial system, smaller power and shorter protection range	More complex to control, aggregate interference
Beacon signaling [45], [66]	Exact interference information regarding each receiver	Requires modifications to both systems, reserves additional control channel
Terrestrial-CID [16], [68], [69]	Efficient to determine the interfering base station. Does not require to know 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

Spectrum measurements can be used to gather occupancy information from the 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. The REM is an integrated database including information about the radio frequency (RF) signal environment, relevant regulations and policies, physical locations of devices, available services, and relevant historical experiences. Interference map [34]–[36] is a special case of the REM, describing specifically 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 on the availability of the frequency band and access in the spectrum, most probably for a fee since they have paid a significant amount of money for their licenses to operate in the band. In addition to license-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 licensed basis, under an LSA approach [21]. In this approach the incumbent operators are required to provide a priori information about their spectrum use over the area of interest to this database, 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 knowledge about location such as whether the device is located indoor or outdoor [36]–[39]. Terrain data can be obtained from service providers such as U. S. National Geospatial Intelligence Agency. The database includes also data on relevant policies and spectrum regulations and is able to provide this data to secondary users. Policies might dictate e.g., what the maximum allowed transmission power is in a certain channel at a certain location. Incumbent properties such as used standards, interference tolerance of the receivers, and coverage of base stations (BSs) allow the database to do calculations for the requesting secondary users and tell them what channels they are able to access at their location if any. Availability of frequency channels in different frequency bands may be provided with several bandwidths, i.e., the database is able to provide a set of channels based on the bandwidth of a requesting device. In addition, history data can be used in predicting the future spectrum use to allocate most promising channels for requesting users [40]–[42].

B. Setting up the database and gathering required information 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. Selection of that third party and having trust to this database operator or operators does not happen in a blink of eye. Regulatory authorities test and verify commercial operators and their database solutions. There are verified TVWS, LSA, and SAS database operators such as Google, Spectrum Bridge, and Fairspectrum already in the US and UK markets. Technical requirements and details including messaging protocols of the databases can be found e.g. in [43] and [44].

The data to be gathered to the database depends on the spectrum sharing systems in the band of interest. The general model in Fig. 1 describes the main sources of data. The database may include also contact information of the device owners to be able to contact them e.g. in the interference situations. The data is also dependent on the other techniques to be used in conjunction to the database. Detailed resource allocations are possible when information of the capabilities of the controlled secondary network is available e.g. from operators. For example, in Finnish LSA and SAS trials we have used carrier aggregation and active antenna systems. 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, decisions on how to share the spectrum in a controlled manner are based on the data available in the database that should include capabilities of the controlled devices. A controller or spectrum manager takes information from the database and makes smart decisions on the resource use in order to fulfill the service requirements. We will review many sharing techniques in the following section and discuss several practical use case examples in Sections III and IV defining how the databases are used to enable spectrum sharing in the depicted scenarios.

C. Spectrum sharing techniques to be used in conjunction with the spectrum database

Spectrum database is an enabler for spectrum sharing. The operation of a spectrum sharing system requires also other functionalities and the operation of a spectrum database is enhanced when it is used in conjunction with other techniques. Table II summarizes spectrum sharing techniques that could be deployed in satellite communication bands. Advantages and risks of each technique are given. We have also included references for each technique so that an interested reader is able to find more details.

1) Spectrum sensing

Spectrum sensing can be defined as a task of obtaining awareness about the spectrum use in a given geographical area [36], [45]–[48]. Sensing aims to detect transmitters but receivers are actually suffering from interference which causes real challenges in protecting them. To ensure that there are 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 computational 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 mentioned problems sensing cannot guarantee 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 e.g. by phasing the antenna array elements and using an algorithm to steer the main beam to desired direction and nulls toward the interferers. 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, and may also require location information from the primary system such as satellite terminals. Transmitter-based interference mitigation is called also precoding i.e., 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 waiting 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 make decisions about 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 be done also 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 still 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

Table III. Comparison summary of satellite orbits, path loss 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

values 20, 30, and 40 dB are used to protect VSAT stations in ITU-R recommendations [11], [60]. This is a simple way to reduce the interference range but can be costly when implemented to a vast amount 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 compared to centralized communication are required [63], [64]. Partly the same motivation can be given to small cell operation as well 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 introduce complications in terms of interference control overhead and protocols [62], [65].

7) Beacon signaling

Beacon signaling 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 the channel, adding the beacon transmitter e.g., at the FSS terminal, and including the beacon receiver at the secondary terrestrial stations. This might be an interesting study item but is not likely to be employed in practice due to several modifications required in both the 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 is a method of embedding a unique identification code on a satellite carrier. It consists in a spread-spectrum signal to be transmitted by all 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 interferences in case of spectrum sharing between satellite systems. An interesting approach could be to extend the use of the DVB-CID concept and having it implemented also by terrestrial base stations, to allow 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 implemented in the sharing cellular system would be to determine whether an interference situation is caused by a terrestrial system or by another satellite system: if no CID signal is detected, then the problem is not coming from a terrestrial base station.

D. Differences to terrestrial operations

At least the following differences between terrestrial and satellite systems can be identified, affecting the way spectrum sharing has to be applied to satellite bands. 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 a terrestrial cell. 3) Transmission latencies are much higher due to much longer links, and 4) technological solutions need to be defined several years before the beginning of services and the space segment needs to use a fixed design during its entire lifetime (ca 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 in any satellite band. Power limitation requires high gain antennas both for transmission as well as in detection of the signal. Due to large coverage areas, aggregate interference in uplink direction is a challenge. Large beams also limit 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 system due to link latencies. A spectrum database adds a possibility to use predictions and proactive decision making that will tackle partly the latency challenges. Since databases affect mostly the ground segment that part can be updated during the lifetime of a satellite. In addition, introduction of software-defined network (SDN) technologies [70]–[72] will make it possible to update also the space segment in the future.

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

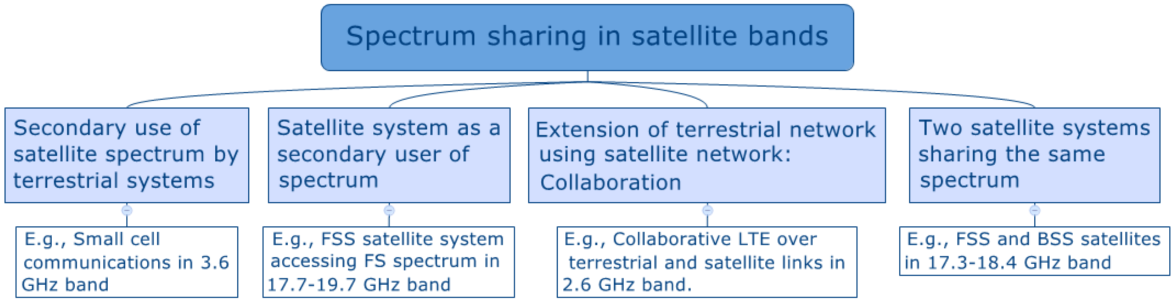

Fig. 2. Application scenarios for spectrum sharing techniques in satellite communications.

Table IV. Summary of scenarios studied in the 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

Characteristics of satellite systems such as used orbit affect strongly the way databases will be implemented and used. Table III provides a comparison between LEO, medium-Earth orbit (MEO), and GEO satellite systems using key parameters that affect database design. Footprint defines the ground area where a satellite offers coverage. 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. Therefore, 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 the Earth's geocentric gravitational constant. Pass time or possible connection time from a specific location on the ground to a passing satellite from horizon to horizon is then

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

The pass time also defines the maximum handover time from a satellite to another. In practice the time is somewhat less 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 the case of GEO satellites where the coverage and visibility of the satellite is almost fixed. Coverage of spot beams in a certain frequency channel may differ considerably from the coverage due to the use of powerful antennas. For example, Inmarsat I-4 satellites use 228 spot beams with 1000 km diameter [32], [75]. The I-4 satellite system is able to use four-coloring scheme for frequency reuse. The size of a spot beam means that in most European countries a single spot beam covers the whole country. Smaller spot beams are used in some systems. For example, the O3b satellites in the MEO orbit have spot beams with 700 km in diameter [76] and the Iridium system operating in the LEO orbit have spot beams with 400 km diameter [77]. Finally, the latest powerful high throughput GEO satellites are able to use 100-200 km diameter spot beams directly below the spacecraft. Any other angle creates an ellipse of varying size depending on the angle. Thus, the orbit is not the only defining factor for coverage calculations. Spot beam diameter is an important parameter for the database.

We will discuss the database design in more detail in the following section where classification and examples of spectrum sharing scenarios are given.

III. Classification of Spectrum Sharing Scenarios

Application scenarios for satellite communications can be classified into four main categories as shown in Fig. 2. In the first two categories the sharing follows traditional cognitive radio approach by using primary and secondary users of the spectrum. Primary user (PU) is the incumbent of the spectrum, having higher priority or legacy rights on the usage of a specific part of the spectrum. A secondary user (SU) is a user who has a lower priority and therefore exploits the spectrum in such a way that it must not cause interference to PUs and must accept incoming interference from the latter. In other two categories the spectrum sharing is coordinated among co-primary users. The scenarios are shortly described in the following subsections. Different example scenarios with their distinctive characteristics are summarized in Table IV.

A. Secondary use of satellite spectrum by terrestrial systems

Like for terrestrial systems, the actual occupancy of the satellite spectrum is often much less than 100%. There are periods or areas when no one is using the spectrum or the level of usage is low. A satellite operator may have reserved frequencies for their 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 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 use 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 transmission power of the secondary system has to be controlled based on the knowledge of the 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]. On the contrary, the database approach can better guarantee the quality of service (QoS) of both secondary and the primary system and is therefore the preferred option for all frequency bands. It has also the advantage of implementing some control on the spectrum access, protecting systems from unexpected interference emissions, as they can be controlled and cease emission following the occurrence 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 to be used both in terrestrial and satellite bands. A limited number of users obtains the right to use the band while the LSA controller, using the information from the database called LSA repository, ensures predictable QoS for all spectrum rights of use holders. With this model 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 not using those resources anymore [79]. The information is communicated from the database to the secondary licensed terrestrial system using an LSA controller. The concept could be used e.g., when an International Mobile Telecommunications (IMT) system accesses satellite C band which is depicted in Fig. 3. LSA controller needs network internal information from 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 LSA controller and OA&M are part of the mobile network accessing the band as a secondary licensed user.

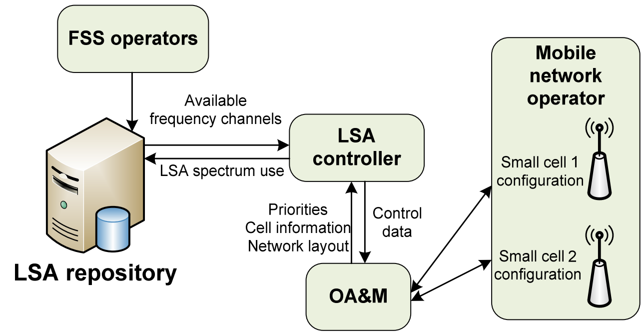

Fig. 3. LSA concept for C band operation.

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

SAS concept: Another spectrum sharing approach proposed in the 3.5 GHz band is called SAS. Compared to LSA it is more flexible but also a complex sharing model [22], [81]. It provides a good support for deployment of small cells. While LSA is a two-tier model, 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 current use of spectrum. This is required to detect military naval radars that are operating in the band. In order to protect FSS earth stations, Federal Communications Commission (FCC) has adopted a rule that requires satellite operators to register their stations annually [81]. The SAS obtains this information from the FCC database and uses the data when it grants or denies access to users willing to operate in the same band. SAS maintains a list of locations

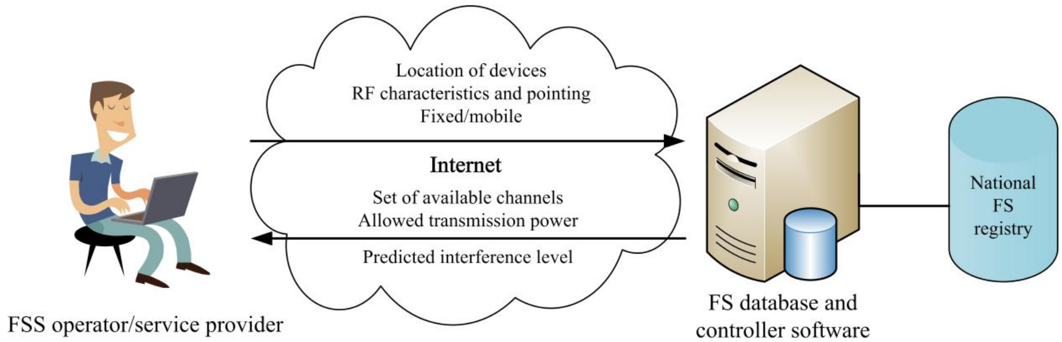

Fig. 4. FS database and related query information.

and look angles of earth station receivers in order to protect their operation. Both LSA and SAS concepts have been successfully field trialed with latest 3GPP Long Term Evolution (LTE)-Advanced compliant base stations [79], [82].

An important part of the 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, e.g., in [8], showing that long separation distances - from several tens of kilometers to in excess of hundred kilometers - are required between the interfering service and the satellite stations. The studies have been conducted assuming rather powerful interfering terrestrial systems. Differently from these studies, also small cell operation and possibility to use low power transmitters is considered in [11]. This reduces the required protection distances even below 500 meters. The interference produced by small cells is further reduced by the fact that they are mainly operated indoor and, thus, the walls will attenuate the signals significantly before they will interfere with the satellite receivers. Thus, determination of protection zones and the zones inside which coordination is needed to avoid excessive aggregated interference remains still an active research topic.

B. Satellite system as a secondary user of spectrum

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

The locations of the terrestrial link nodes are fixed in the defined part of the Ka band, therefore, this service is referred to as fixed service (FS). The location information of the registered stations can be obtained in many countries in Europe from national registries and regulatory authorities [83]. A possible disadvantage is that all the links are often not 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, joint use of carrier allocation and beamforming can improve the performance of the system considerably [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. Database approach has been studied and developed in [83], [85] and mathematical procedures and guidelines given. Results of these studies have been included also in the regulatory reports; see [86] and [87].

Spectrum database provides the means to enable Ka band sharing in practice 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, a process already taking place for FS stations in many countries through a national FS registry. The FS database (FSDB) and related query information are shown in Fig. 4. The user of the FSDB that is most probably located at the national regulator premises is the FSS operator or service provider. It 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; heaviest use of links is in the areas of 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

[1] The formats of national registries differ for each administration. Thus, a preferable way is to have a separate controller software and FS database for each country.

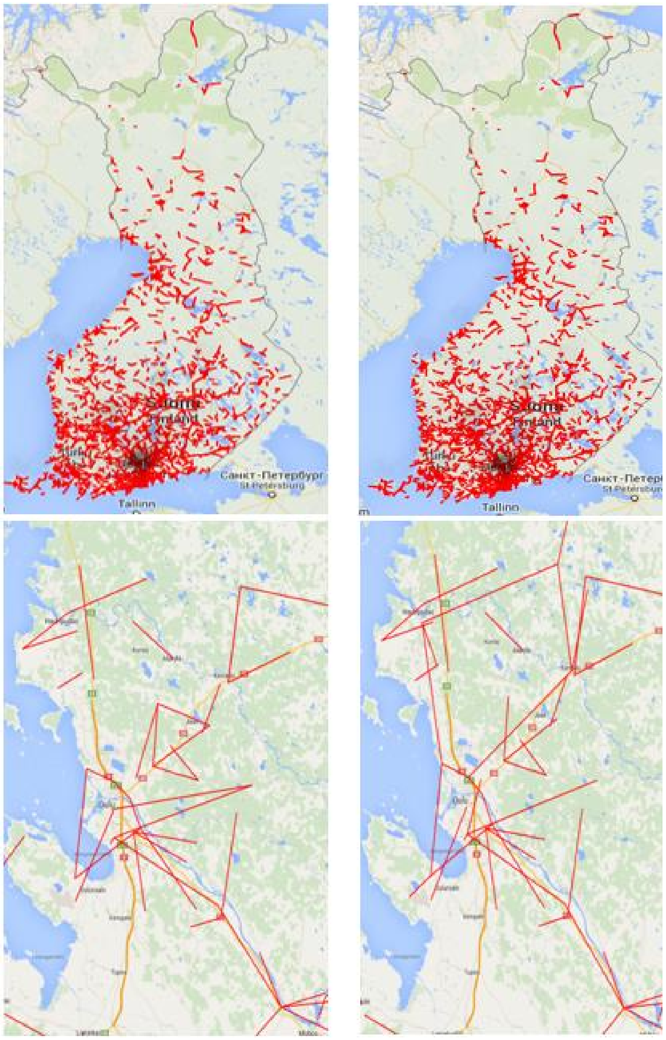

Fig. 5. FS links in Finland and specifically in Oulu, 16th May (left) and 17th October (right) 2014, respectively.

are some points in Helsinki area where there can be more than 10 link ends at the same location [83]. The links are two-way links, reserving same bandwidth in both directions. Thus, a single link can reserve 2 × 55 MHz = 110 MHz from 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 area is underusing the studied part of the Ka band and other countries in Europe have same kind of situation [83], [85].

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

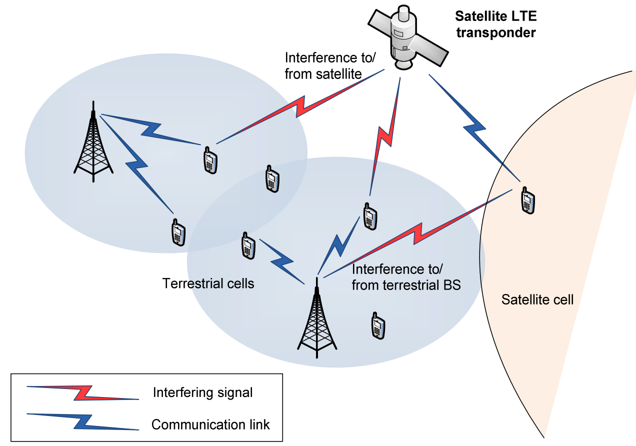

Fig. 6. Collaborative LTE transmission over terrestrial and satellite links in the S band (2500-2690 MHz).

C. *Extension of terrestrial network using 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 restricts significantly use of dynamic interference avoidance approaches applicable in the terrestrial systems for fast adaptations.

The coverage of terrestrial systems is typically adjusted with the base station (BS) installation based on the capacity and coverage requirements. However, providing the coverage on 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 that has been designed for mobile broadband access providing high data rates in a power limited mobile environment, thus requiring 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 increase the reliability of the terrestrial system in case of disasters. 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 satellite to cope with the failures of the terrestrial system). The satellites could be also used to assist the operation of cognitive terrestrial networks [91], [92] or by providing the spectrum required for signalling purposes.

Sharing the same band between satellite and terrestrial components requires careful system design and a cognition based hybrid system for controlling the interference between the terrestrial and satellite segments. Recently, Globalstar has

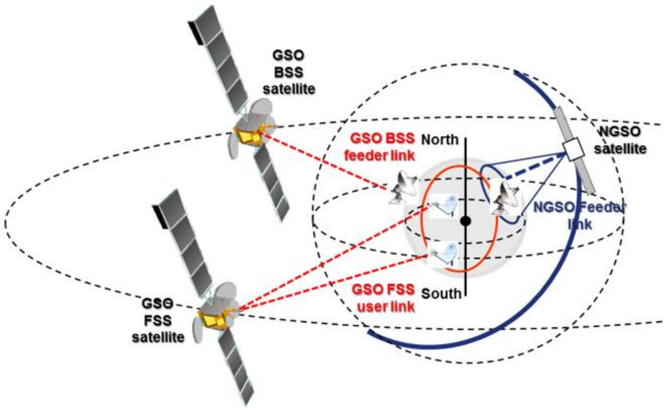

Fig. 7. Frequency sharing between FSS, BSS, and NGSO satellites in the 17.7–19.7 GHz band.

proposed and tested so called terrestrial low power service (TLPS) for sharing the 2.4 GHz satellite band with Wi-Fi type services while still protecting satellite services from harmful interference [93]. Link budget analysis and simulations have shown that there is potential in the spectrum sharing between the terrestrial and satellite system in the collaborative LTE scenario [90]. However, the satellite link is very sensitive to the 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 case in 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 e.g., 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 capabilities across satellite services and operators. This should lead to an enhancement of 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 with 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 BSS stations [15]. The number of BSS feeder links is quite limited, e.g., five in UK [94]. The protection distance can be calculated according to transmission power, antenna gains, and path loss model taking into account 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 then the database would 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 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. Also spectrum sensing can be used e.g., 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.

Importance of finding spectrum sharing possibilities between NGSO and GSO systems is rising rapidly due to appearance of the mega-constellation concept where hundreds of LEO satellites would provide global Internet coverage [29], [97]. The plans for those systems 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 the concern of 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. Simulations have been carried out to calculate the interference statistics between the links of GSO Spaceway and LEO Teledesic networks in Ka band in [99]. The effect of NGSO interference to 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 e.g., [101], [102]: 1) Selection of another visible NGSO satellite in view and 2) the cessation of 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 coexistence of GSO and medium earth orbit (MEO) O3b satellite system [76] are 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 previous studies in [98]–[103], we will analyze a specific use case in 19.3–19.7 GHz band to investigate sharing possibilities between LEO NGSO and GSO satellite systems, reporting on new results from the ESA supported study [16]. The link budget calculations are based on the set of parameters that are obtained from regulatory recommendations [104]–[107] as well as from typical satellite systems operating in the studied band. However, we will not fix our parameters based on a certain system that has already been planned or in operation. Rather we would like to show what is needed for sharing to be possible. We extend the work by

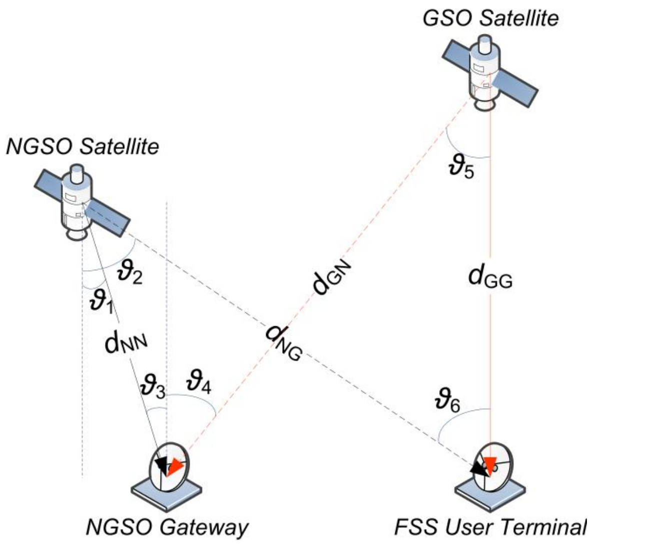

Fig. 8. Signal (the solid lines) and interference (the dashed lines with arrows) links in the downlink coexistence scenario of NGSO and GSO satellites: GSO satellite interferes with the NGSO gateway.

defining timescales of operation, assuming adaptive power control of GSO transmission, and by 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 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 up on the basis of the "first arrived, first served".

The GSO satellite is in orbit at roughly 35786 km above the equator and it is orbiting at the same rotational speed as the earth, thus it is stationary with respect to the earth. NGSO satellites on the other hand are orbiting at low and medium orbits clearly below GSO. Uncoordinated GSO FSS user terminals have their high-gain narrow antenna beams pointed at the satellite. Thus, 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 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

Table V. 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	10lg(kTB) + Q dB where k = $1.38{\cdot}10^{-23}$ J/K is Bolzmann constant, T is temperature, and Q = 7 dB is the margin
	Parameters for whole 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]

toward its uncoordinated FSS user terminals. Parameters for the study are defined in Table V. 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 GSO and 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;
- 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 NGSO transmitter and NGSO receiver;
- d_{NG} – the physical distance between NGSO transmitter and GSO receiver;

- d_{GG} – the physical distance between GSO transmitter and GSO receiver; and
- d_{GN} – the physical distance between GSO transmitter and NGSO receiver.

B. Coexistence analysis

Let I_{th} denote the maximal interference power that the GSO receiver can tolerate, that is, $I_{\mathrm{G}} \le I_{\mathrm{th}}$. At the same time, the received signal quality at the NGSO receiver should be ensured as well. 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 NGSO transmitter and receiver. $A_{\mathrm{G,t}}$ is the antenna gain of 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., $\gamma_{\mathrm{N}} \ge \Gamma_{\mathrm{N}}$ and $\gamma_{\mathrm{G}} \ge \Gamma_{\mathrm{G}}$, where Γ_{N} and Γ_{G} are the thresholds of a NGSO receiver and a GSO receiver, respectively.

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

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

In other words, the optimization aims at maximizing the throughput of the GSO link while satisfying the SINR requirements at both at 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 for protecting the NGSO gateway. In the 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

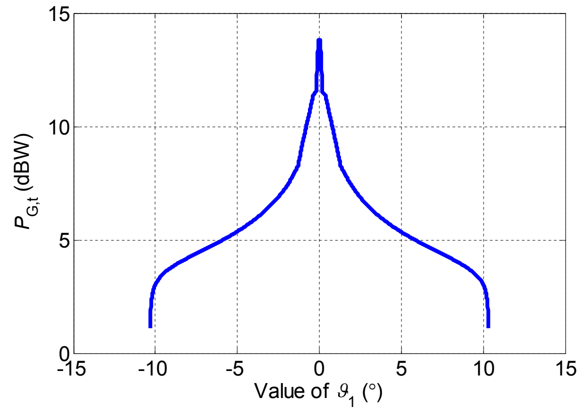

Fig. 9. The transmit power of a GSO satellite versus the position of an NGSO satellite.

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

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

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

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

It is obvious that the solution $P_{\mathrm{G,t}}$ depends on the position of NGSO satellite, that is, 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 NGSO satellite position.

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 so-called flexible Travelling Wave Tube Amplifiers (flex-TWTA) or from Multi-Port Amplifiers.

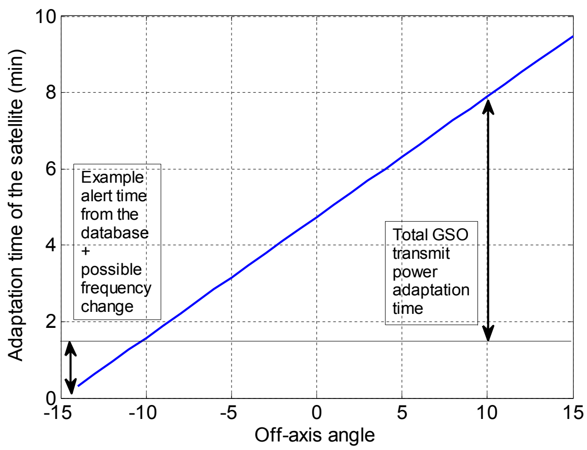

Fig. 10. Timescales for adapting transmission and database operations.

Fig. 10 shows related timescales for operation based on the orbital period of the satellite that can be calculated using the Kepler's third law given in (3). Since this defines the time for total 360 degrees' period, it is simple to calculate how fast depicted power adaptations need to be done. The value region in Fig. 9 shows that GSO adaptation starts from -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 done very fast.

When the NGSO satellite moves far away enough from the receivers but the link between 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 possible interference situation and start either the power adaptation or frequency change process. An example timescale of 1.5 minutes is shown in Fig. 10 assuming that 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 the transmission power is possible by increasing the size of the NGSO gateway antenna. However, this is quite an expensive option. Thus, the change of the operating frequency in the feeder link is a favourable option if the power control cannot achieve the QoS target.

A database assisted spectrum sharing enables 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.

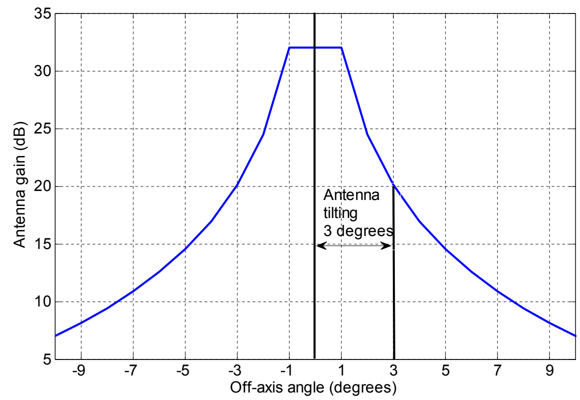

Fig. 11. Gain pattern of NGSO satellite antenna and related gain reduction due to tilting of antenna.

Table VI. 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	

The database could then 1) alert in advance each system of any interference situation by predicting when and where it will happen and 2) assist in adopting the appropriate interference mitigation strategy for these cases. In addition, the database could 3) answer to requests for more bandwidth from each system and allocate spectrum accordingly. Table VI 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 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 protect. This can be expressed in terms of remaining margin in dB above the service level regarding a certain beam. Then, based on this data and the information loaded 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 quite in advance 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 this 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], [109]. The idea is to protect GEO from interference by gradually and slightly tilting satellites as they approach the equator to make sure NGSO satellites do not cause, or receive, interference from GSO ground stations and user terminals. The effect of the tilting is shown in the gain pattern figure of NGSO satellite in Fig. 11.

Already three-degree tilting reduces the interference gain towards GSO system by 12 dB and rapidly increases with an increasing angle. Instead of mechanical tilting of a whole satellite, transmission beams can be mechanically or electronically tilted as a satellite approaches the equatorial plane [109]. 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 enable also this technique as one possible interference mitigation strategy in the system.

V. FUTURE DIRECTIONS

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

Sharing between satellite and cellular networks: Coming 5G systems will include cellular operation both below 6 GHz and in the mmW bands. There will be a clear need to share the spectrum with satellite systems. Especially important part of the C band to study is 3600-3800 MHz since this has been allocated to mobile on a secondary basis in Europe already in WRC-12 but due to existing FSS and FS usage 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 3600-3800 MHz and, where appropriate, the implementation of LSA at a national level [110]. In USA, the work in 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 additions, 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 coming 5G networks is finding and defining the frequency bands to operate and study whether some of those bands are applicable for sharing between different networks while fulfilling the requirements set by the applications and use cases. European Commission (EC) has defined three 5G pioneer bands in Europe [111] that are:

1) 694-790 MHz for wide area coverage and new services such as connected cars and smart sensors. Can provide also 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) 24.25-27.5 GHz 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 the bands 2) and 3) are important from this paper point of view, i.e., to study the sharing between satellite and terrestrial users in these bands. Authors' opinion is that the LSA is maybe the most promising approach to implement sharing in the pioneer bands.

Mega-constellations: We have analyzed here 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 coming mega-constellations, more complex scenarios need to be analyzed to account for the accumulated interference of multiple NGSO satellites to a GSO satellite. However, we assume that also in that case there will be one main interferer at the time and the impact of other satellites at a given moment is clearly lower.

NGSO modifications: Adaptation of the NGSO satellite feeder downlink transmission power is already feasible today. The satellite power reduction would be varied 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 level received by FSS terminals would be to use spread spectrum signals in NGSO system. However, this would impact significantly the downlink capacity as the bandwidth size is given. Increasing the NGSO MSS gateway antenna size would allow decreasing the NGSO satellite power and reduce the interference received by FSS satellite terminals.

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 nonuniformly the power between few beams or carriers. From a technology point of view, several solutions already exist or are under developments to support this idea.

- *Flexible filters* are filtering equipment of the satellite payload able to selectively filter a portion of the spectrum out of a beam to redirect this portion toward a given power amplifier which could be set differently from the other power amplifiers of the payload.
- *Multi-Port Amplifier* is an amplifying equipment 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. Such equipment have been used since a long time in L-band and they are now being developed to be used in Ka-band.

- *Digital processor* is able to digitalize signals, filter the spectrum precisely, route them and selectively amplify the signals of part of a beam or a carrier and to perform on board beamforming function.

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

Spectrum databases: We believe that spectrum databases is one of the main techniques to concentrate in the near future regarding any spectrum sharing scenario involving satellite systems. It is foreseen that adoption of 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. 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 development of those techniques specifically to 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 based on rules that can be transparently adapted over time and space to fit to any changes in the context. The general applicability of this approach could lead to the emergence of a new ecosystem to design and develop applications and services inside and around the databases. Such genericity would in the end benefit to all the actors that need to share spectrum.

Economic studies and role of operators: There is a clear need for continuing and deepening the techno-economic studies of sharing techniques especially in new frequency bands. Capital costs of launching a NGSO constellation is usually very large and this is especially true regarding the mega-constellations. The lifespan of a LEO satellite is typically only around 7 years as compared with around 15 years for a GSO satellite. Therefore, LEO satellites require a 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 service. 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 investments are not reasonable. Thus, it is of utmost importance to look at spectrum sharing possibilities both from technical and economic perspectives.

Key players in all 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 provide complementary services. Due to political pressures, there is a significant risk in just trying to defend the current assets and positions and not to consider sharing at all. In the worst case the political pressure might 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 save both the use of spectrum to the current services as well as the position of incumbent operator for current operators*. By allowing sharing, incumbents could continue their operations in the bands to fulfil their obligations defined by the society with minimum additional investment.

Due to 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 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 are classified and a practical use case is given for each scenario. Current state-of-the art in these scenarios is presented and the most suitable techniques with their advantages and risks are identified. This survey focused on defining how to apply database techniques in defined use cases and scenarios and what other sharing techniques are needed to guarantee fluent operation.

As a novel use case we studied a satellite-satellite sharing that is very timely due to appearance of the mega-constellation initiatives. According to conducted analysis, sharing the spectrum between NGSO and GSO FSS satellites systems seems to be feasible, assuming that the necessary controls are put in place. Different strategies have been envisaged in case of an interference situation: 1) Change to an alternative spectrum band. The best candidate to switch spectrum would be the NGSO system rather than the GSO system. 2) Adapt the transmission power of the 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 put in place a database approach, the database being 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, particularly the cumulative interference coming from multiple NGSO satellites. In addition to technical work, economic viewpoints should be considered more deeply.

There are many research challenges for the future in 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 millimeter-wave bands. A key to success of coming 5G is adoption of advanced techniques, forward looking policies, and unlocking new spectrum assets. The 5G and beyond generations will have a key role for satellites. Thus, development of spectrum sharing techniques ensuring coordinated coexistence of multiple systems in the same band is essential in near future.

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