Licensed shared access field trial and a testbed for satellite-terrestrial communication including research directions for 5G and beyond

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Summary
This paper describes a licensed shared access (LSA) testbed and field trials using a live network. The testbed includes real 4G base stations and up to 1000 virtual base stations, in the spectrum sharing scenario between satellite and cellular systems. The trials focus on 5G pioneer bands 3.4–3.8 GHz and 24.25–27.5 GHz where a satellite system is operating in the downlink direction and a cellular system is accessing the same band. The designed testbed supports both frequency bands. The performance evaluation concerns evacuation and frequency change times using different types of base stations in 3.6 GHz, that is, how fast the system relinquishes the shared band to the primary user and continues transmission using another band. We show that our LSA system is scalable and able to support large number of base stations. In addition, we investigate how satellite systems could reuse International Mobile Telecommunication (IMT) bands to offer enhanced satellite communication services for land, maritime, and aeronautical applications. Preliminary simulations and analysis confirm the possibility to reuse IMT spectrum for satellite systems without causing harmful interference to the terrestrial system.

KEYWORDS
5G, cognitive radios, IMT, satellite, spectrum sharing

1 INTRODUCTION

5G and beyond systems will be a network of networks, consisting of heterogeneous interfaces to support wide range of services and applications. There is an ongoing standardization work in 3GPP aiming to integrate satellite and terrestrial systems in 5G and beyond, covering also airborne systems such as drones and high-altitude platform station (HAPS) under the designation of non-terrestrial-networks (NTN). 3GPP standardization addresses both direct and indirect access connectivity using NTN including geostationary (GSO) and non-GSO satellites with both bent-pipe and regenerative payloads.1–3 In direct access mode, user equipment (UE) will be using slightly modified new radio (NR) interface to cater for the NTN links characteristics. Besides, 3GPP...
Services and Architectures Working Group (SA2) considers also the use of satellite as transport/backhaul link offering the interconnection of local access networks to 3GPP core network. Several R&D activities support the NTN standardization activities such as in previous studies.\textsuperscript{24-6}

Finally, terrestrial and satellite networks may use different or the same radio frequencies in the operation. In the latter case, it is possible for systems to coexist in the same band, and the operations of the integrated end-to-end satellite terrestrial network are managed by the spectrum management entity that governs the shared spectrum use for both systems.

Spectrum sharing in satellite bands has been studied actively over the last decade.\textsuperscript{7-11} and database-assisted systems have been found to provide a way to share the spectrum while proving sufficient certainties for the interference-free operation. Especially, the licensed spectrum sharing\textsuperscript{12} provides means to protect incumbents by using an approach where only a limited number of licensed secondary users can access the shared bands.

The novelty of this study compared with previous work is that it presents the first implementation and trials of LSA technology to share spectrum between satellite and terrestrial systems. The system includes prototype implementation of interference estimation models, protocol interfaces to control secondary network, a user interface (UI) to be able to input relevant data, and adaptive power and frequency control algorithms, which could be used in operational networks.

We extend our previous results\textsuperscript{13,14} by providing performance results achieved with our LSA testbed. The testbed includes two real 4G base stations (BSs) and simulated BSs operating in 5G pioneer frequency bands 3.6 and 26 GHz. The real BSs used in the testbed can be controlled remotely. The trial covers two main parts:

1. Development of the sharing concept, which could be applicable to 5G and beyond scenarios in any frequency band, and
2. Actual implementation and performance measurements of the LSA system in 5G pioneer bands. The testbed includes real 4G BSs and simulated BSs.

2 | REGULATORY STATUS AND 5G PIONEER BANDS

ITU-R defines the high-level regulatory framework at the international level through World Radio Conferences (WRCs). It allocates spectrum resources to radio services depending on analysis and compatibility studies which are carried out by Member States. This high-level regulatory framework is then detailed at regional and further detailed at national level with the definition of technical parameters to operate an application in a frequency band. Furthermore, as appropriate, the necessary coordination procedures to be applied at the borders of countries are defined to ensure interference-free operation of an application.

In Europe, the Electronic Communications Committee (ECC) of the European Conference of Postal and Telecommunications Administration (CEPT) is responsible for the compatibility and sharing studies and is the entity which details the technical parameters and coordination procedures which may be applicable at regional level.

5G pioneer band is a commercial designation that is mainly used at European Union level to designate 3.4–3.6 GHz and 24.25–27.5 GHz frequency bands. European Commission (EC) has defined two 5G pioneer bands for enhanced mobile broadband (eMBB) services\textsuperscript{15}:

1. The main pioneer band 3.4–3.8 GHz, suitable for urban eMBB. This band can provide carrier bandwidths of 100 MHz and allows single Gbps data rates.
2. Pioneer band 24.25–27.5 GHz for hot spots and real eMBB services. Carrier bandwidths of several 100 MHz to allow higher than 10 Gbps data rates are expected.

Several new frequency bands have been under consideration at the ITU and allocations were made during the WRC-19\textsuperscript{16}; 26 GHz was identified for International Mobile Telecommunication (IMT) at WRC-19 as a landmark decision. There are many studies approved and recommended for the next WRC conference in 2023 as a follow up of the result from WRC-19. As an example, studying coexistence of satellite communications in recently approved IMT2020 bands 24.25–27.5 GHz, 37–43.5 GHz, and 66–71 GHz.

Additional dynamic spectrum sharing related study items identified for WRC-23 on nonterrestrial systems include the following:\textsuperscript{17}:

1. Agenda item 1.4: To consider, in accordance with Resolution 247 (WRC-19), the use of high-altitude platform stations as IMT base stations (HIBS) in the mobile service in certain frequency bands below 2.7 GHz already identified for IMT, on a global or regional level.
2. Agenda item 1.6: To study and develop technical, operational, and regulatory measures, as appropriate, to facilitate the use of the frequency bands 17.7–18.6 GHz and 18.8–19.3 GHz and 19.7–20.2 GHz (space-to-Earth) and 27.5–29.1 GHz and 29.5–30 GHz (Earth-to-space) by non-GSO fixed-satellite service (FSS) Earth stations in motion, while ensuring due protection of existing services in those frequency bands.
3. Agenda item 1.19: To consider a new primary allocation to the FSS in the space-to-Earth direction in the frequency band 17.3–17.7 GHz in Region 2, while protecting existing primary services in the band.
Regulatory decisions have been made to open the mentioned 3.6 and 26 GHz bands for IMT networks. In addition to regulatory decisions and framework, technologies enabling flexible and dynamic spectrum sharing while ensuring proper protection to satellite communications are needed.

Licensed shared access is a regulatory approach that provides a way to control that only licensed users are allowed to use the spectrum. With the LSA concept, an incumbent user is able to share the spectrum with one or several LSA licensees according to negotiated sharing framework and sharing agreement.

The LSA system framework has been defined in regulatory and standardization documents. For example, ETSI standardization states “main advantage of embracing the LSA framework is that it aims to ensure a predictable level of QoS at a defined location for all spectrum resource users, i.e. LSA licensees and incumbents.”

The LSA reference architecture model is shown in Figure 1, based on the ETSI standard document. There are two main elements in the architecture to protect the rights of incumbents and to manage dynamics of the LSA spectrum use: The LSA repository (LR) and the LSA controller (LC). The repository enables the entry and storage of the information about the characteristics of the applicant network (BS location, power, antenna, and pointing), availability and protection requirements of the incumbent, and usage of spectrum together with operating terms and rules. A limited number of users obtain the right to use the band, whereas the LC, using the information from the LR, grants a permission to access the spectrum for the mobile network.

With this model, the regulator may set a number of frequency channels that can be accessed, define multiple protection areas, the type of protection based on the used services and devices, and remove protection from the repository if the incumbent is not using certain resources anymore.

The LC is connected to the licensee’s mobile network via operation, administration, and management (OAM) tools. It maps LSA resource information into radio transmitter configurations commands and receives the respective confirmations from the network. The reference model allows connecting the LSA system to the mobile network by implementing the appropriate messaging protocols. In this case, LC provides control messages to the BSs, and the mobile network takes care of configuring both BSs and user terminals accordingly. The commands are based on the interference estimates, which the LSA system computes using the characteristics of the attached transmitters and receivers and their capabilities.

Thus, the implemented LSA system is able to estimate interference effects and dynamically control the secondary system in order to protect the primary system from interference. The LSA interfaces between different elements have only been defined as general level requirements. The model has been validated already in field trials in the 2.3–2.4 GHz band in multiple countries including Finland, Italy, and France. In addition, regulatory documents have been published on operational guidelines in the 3.6–3.8 GHz band.

![Fig. 1](Colour figure can be viewed at wileyonlinelibrary.com)

### TABLE 1 Overview of studied use cases

| Secondary use of satellite DL spectrum by terrestrial system | Secondary use of satellite UL spectrum by terrestrial system | Secondary use of satellite DL spectrum by terrestrial system | Secondary use of cellular band by satellite system |
|-------------------------------------------------------------|-------------------------------------------------------------|-------------------------------------------------------------|--------------------------------------------------|
| Frequency band                                              | Priority                                                    | Priority                                                    | Priority                                        |
| 3.6 GHz                                                     | Satellite as primary cellular as secondary                   | Satellite as primary cellular as secondary                   | Cellular as primary satellite as secondary       |
| 27–27.5 GHz                                                 | Satellite as primary cellular as secondary                   | Satellite as primary cellular as secondary                   | Satellite as primary satellite as secondary      |
| 25.5–27 GHz                                                 | Satellite as primary cellular as secondary                   | Satellite as primary cellular as secondary                   | Satellite as primary satellite as secondary      |
| 900 MHz                                                     | Satellite as primary cellular as secondary                   | Satellite as primary cellular as secondary                   | Satellite as primary satellite as secondary      |
| Priority                                                    | Priority                                                    | Priority                                                    | Priority                                        |
| Fixed-satellite service (FSS)                               | Fixed-satellite service (FSS)                               | Earth exploration-satellite service (EESS), FSS             | Mobile-satellite service (MSS)                   |
| Fixed and mobile Earth stations                             | Satellite                                                   | Fixed and mobile Earth stations                             | IMT base stations and user equipment             |
| Protected                                                   | Protected                                                   | Protected                                                   | Protected                                       |
| Satellite                                                   | Satellite                                                   | Satellite                                                   | Satellite                                       |
| IMT base stations and user equipment                        | IMT base stations and user equipment                        | IMT base stations and user equipment                        | IMT base stations and user equipment             |
There are also other database-assisted approaches implemented and trialed in recent years such as Citizens Broadband Radio Service (CBRS) system in 3.55–3.7 GHz band.\textsuperscript{24} It includes standardized messaging protocols, which can be applied in LSA system as well. Finally, TV white space (TVWS) technology relies also on database-assisted approach. Information on implemented systems and coexistence measurements can be found in Murty et al. and Kalliovaara et al.\textsuperscript{25,26}

4  |  SECONDARY USE OF SATELLITE DL SPECTRUM

The use cases, which we studied, are presented in Table 1. Three use cases consider secondary terrestrial system accessing the satellite spectrum and one use case is dedicated to studying secondary satellite system accessing terrestrial (IMT) spectrum (see Section 5).

4.1  |  Secondary use of satellite spectrum

This is the scenario where the satellite network is the primary user of the frequency bands and the terrestrial network or other wireless systems operate as secondary users of the spectrum. Spectrum sharing can only be allowed if the terrestrial system is not causing harmful interference to the primary satellite system, that is, satellite system can continue to operate transparently without quality of service (QoS) degradation.

We studied sharing with the satellite downlink in 5G pioneer bands at 3.6 and 26 GHz. The trial with real BSs focused on spectrum sharing situation between space services and 5G mobile terrestrial systems in the 3.6 GHz band. We used both real 4G BSs and simulated 5G BSs.

4.2  |  Testbed architecture

From the dynamic spectrum management viewpoint, the system is divided into two main subsystems including their respective functionalities as follows:

1. The LSA system, which
   - Assesses the aggregate interference generated by the cellular system on satellite receivers,
   - Iteratively adjusts the transmission power, and
   - Manages the dynamic frequency assignments.
2. Real hardware tests with the BS controller, which
   - Includes capabilities of adaptive power and frequency control, and
   - Manages evacuation and frequency change times.

LSA system functionalities were implemented in an end-to-end testbed used also for the live trials. The testbed architecture and UI are presented in Figure 2. The LSA system consists of an LR and an LC. The LR contains information about satellite Earth stations and IMT BSs characteristics as well as protection criteria and associated technical rules for sharing. The incumbent data are entered into the repository through a UI. In addition, some characteristics such as the location and characteristics of the licensed radio transmitters can also be uploaded from a national regulatory authority (NRA) license database, for example, as a CSV file.

FIGURE 2  Implemented testbed for spectrum sharing between satellite and cellular systems in 5G pioneer bands [Colour figure can be viewed at wileyonlinelibrary.com]
A dedicated protocol for the LC to control the operating parameters of the terrestrial cellular BS was developed. We also developed a BS controller, which maps the calls to vendor specific commands. In the testbed, the LSA system is used to estimate the interference level received by the satellite Earth stations and to manage the emission of two commercial BSs in such a way that interference will not occur on the satellite system. Further performance assessments of the LSA approach on large networks using a mix of real and emulated BSs was also investigated. The algorithms of the LC were validated by measurements.

Three kinds of BSs were used in 3.6 and 26 GHz experiments in the system including commercial off-the-shelf devices, research BSs, which were implemented using software-defined radio (SDR) platforms, and software BSs in which we can freely change all parameters including the high radio frequencies. Then, we also implemented a controlling interface and signaling protocol for all BSs. The satellite Earth station was modeled with software in the testbed, that is, it is not an operational system with a hardware receiver.

Finally, a remote access UI allows control and connection to the testbed anywhere over the Internet. The basic action to be achieved through this interface is just to monitor what is going on in the testbed. The UI could also be used to perform network configuration such as adding new FSS Earth stations to the satellite system (Figure 3). The elevation and azimuth angles are automatically calculated in the system based on the satellite and Earth station locations. The UI can be used to change operation and parameters of the testbed to run different kinds of tests remotely.

4.3 | Messaging protocol

The testbed uses a protocol developed to make requests from the mobile network to the LSA system using a BS controller (BSC). The protocol is a simplified version of CBRS spectrum access system (SAS)—CBRS devices (CBSD) protocol [27]. The protocol specifies the messages and their content and sequences needed to register a device to the LSA, obtain permission to transmit, and to stop using the allocated resources.

The protocol includes two main methods: registration and spectrum inquiry. The registration request contains the information of the mobile BSs, and the response includes the operating parameters for all mobile BSs in the request. The availability of the radio spectrum is queried with spectrumInquiryRequest. The related information exchange, when an FSS system is added by using the UI, is described in Figure 4. The BSC decreases power, changes frequency, or even shuts down the BS to protect FSS station from the interference.

The main configuration commands from the BSC to control the BSs are as follows:

![FIGURE 3 Web user interface (UI) interface for entering satellite data: fixed-satellite service (FSS) registration [Colour figure can be viewed at wileyonlinelibrary.com]](image-url)
• **LOCK**: The command used to turn off the air interface at the BS in order to release the current LSA frequency under use.
• **UNLOCK**: The command is used to open the air interface at the BS to let the BS start its services. The used frequency needs to be decided by the LC based on the information in the LR.
• **SET FREQUENCY**: The command is used to change frequency at the BS to an available LSA frequency provided by LR.
• **SET POWER**: The command is used to change transmission power at the BS to avoid interference with incumbent users.
• **GET STATUS**: The request message to the BS to update status of air interface parameters, frequency used and transmission power.

### 4.4 Iterative power and frequency allocation

Interference computations of the system use two loops in the estimation: (a) the outer loop goes through all satellite receivers and (b) the inner loops go through the mobile BSs. If the BS and satellite ground stations do not have overlapping bands, the BS is skipped. The path loss between the BSs and ground stations is computed according to ITU-R P.452-16.28 The antenna direction of the BS to satellite ground station and vice versa is computed using FCC model.29 The BS antenna gain towards the ground station is computed according to F.1336,30 and the ground station antenna gain towards the BS according to S.2196.31 The interference from all BSs to the ground station is aggregated.
The resource optimization of the system begins after the initial interference computation according to Figure 5. This algorithm has also two loops: (a) the outer loop goes through all satellite ground stations and (b) the inner loops go through the registered BSs until no harmful interference is experienced by the ground station.

If the ground station does not experience interference, the next ground station is selected. The transmit power of the most interfering BS is decreased by 1 dB at each round. After each round, the most interfering BS is selected. The power of the most interfering BS is decreased until there is no interference at ground station or the minimum transmit power of the BS is reached, in which case the BS center frequency is changed. If there are no free frequency channels available, the BS is shut down.

### 4.5 Trial and performance measurements

The key performance indicators (KPIs) of the described testbed are shown in Table 2. We evaluated the testbed using the selected KPIs and assessed the scalability of the testbed.

Regarding the registration time (KPI-1), the analysis in Finland showed that we were able to acquire up-to-date regulatory data regarding the use of certain frequency band and use that in the LSA system. The data include, for example, locations of IMT BSs and operational parameters. Obtaining the incumbent data typically differs between countries, incumbent types, and frequency bands. The process of handling the incumbent data from the incumbent notification, possibly processing it at the regulator and inserting it to the LSA system is taken into account in communicating the system performance to incumbents and licensees. In some countries, the national regulator may not know all technical operational information required for the LSA implementation. In this study, we analyzed only the delay caused by the LSA system.

The delay can be significant for two reasons: (a) the amount of incumbent data is huge requiring a long time for data transfer and insertion into the database or (b) the incumbent data need preprocessing, for example, if part of processing is done for all incumbent and geographic data before any requests come to the LSA system.

Here, we did not have any preprocessing and the amount of data was not causing any significant delays. The incumbent data were entered through a web page. For an experienced user, entering the incumbent information took typically about 30–60 s.

### 4.6 Evacuation and frequency change times

The measurement setup to evaluate KPIs is depicted in Figure 6 showing the LSA system, the BSC and the controlled BSs, including commercial and research BSs. The commercial small cell BSs are 3GPP Release 12 BSs, operating in the lower C-band (3.4–3.6 GHz). The research BSs are universal software radio peripheral (USRP) devices. They are equipped with the controller PC and an long-term evolution (LTE) framework,32 which is a software add-on that provides a real-time physical layer LTE implementation. Thus, we have a real-time prototyping setup that enables very dynamic operations in contrast to commercial systems, which are not yet designed for fast frequency changes.

Evacuation time: The evacuation process is defined as the necessary time duration to complete the LOCK process defined in Section 4.3. The results are shown in Table 3. The average result from the measurements regarding the research BSs is roughly 0.75 s whereas with the commercial BSs the result is close to 9 s. The evacuation time defines, for example, how much earlier one needs to know the appearance of a nomadic satellite station to avoid interfering with it.

The frequency change time is defined as the time when the BS unlocks itself and opens the air interface in the new frequency. The total frequency change time is combined UNLOCK time and SET FREQUENCY time. When the research BSs are used, the mean frequency change time is very close to 1 s. When the commercial BSs are used, the result is much higher, in the order of 17 s.

| TABLE 2 KPIs of the testbed |
|-----------------------------|
| **ID** | **Name** | **Category** | **Description** | **Assessment method** |
|-------|---------|--------------|-----------------|----------------------|
| KPI-1 | Registration time | Latency metric | Time for registering relevant data and setting up the sharing system. | Inspection and analysis |
| KPI-2 | Frequency change time | Latency metric | How fast the testbed can change the operational frequency and continue on another band. | Inspection/measurements |
| KPI-3 | Frequency evacuation time | Latency metric | How fast the testbed can evacuate the transmission on a current band when the incumbent user appears/needs it. | Inspection/measurements |
| KPI-4 | System modifications | Complexity metric | Modifications required compared to the current systems. This will include the LSA as such and additional techniques to be used jointly. | Analysis and inspection |
Thus, the results show clearly that the SDR platforms provide better dynamic capability. The commercial BSs should be developed to support faster frequency changes in order to minimize the likelihood of interference and to facilitate spectrum sharing. This is one of the identified system modifications related to KPI-4.

In general, the commercial 3GPP devices can be connected to the LSA system without any modifications, which is clearly one of the advantages of the approach. The main additions to current cellular systems would be just (a) inclusion of the LSA system and its interfaces, (b) developing vendor specific control interface in the system, and (c) adding advanced spectrum sharing mechanisms such as smart antennas or physical layer filtering for interference management.

### 4.7 Scalability of the testbed

The implemented LSA system can handle large amount of real and simulated BSs. In order to study the scalability of the testbed, we made performance measurements considering that the FSS Earth station in the C-band would be located in the Paris area. We registered up to 1000 BSs in the LSA system using the real network parameters obtained from the French regulatory authority public database using locations of 2.6 GHz BSs and converting them to 3.5 GHz devices. The average results over multiple experiments regarding the registration of the BSs to the LSA system and the spectrum inquiry times are shown in Figures 7 and 8, respectively.

The registration of a single BS takes 275 ms. It is easy to register simultaneously multiple BSs using the same registration file where locations and operational parameters are stored in the system. The registration of 100 BSs increases the time to 515 ms and further increase to 1000 devices takes 1851 ms, which is less than seven times the registration time of a single BS.

Then, we measured the spectrum inquiry times, which include power and frequency allocation calculations of the LSA system. The aggregated interference to the FSS Earth station is included in the calculations. The results shown in Figure 8 reveal that calculation for a single station takes
245 ms, 10 stations 1 s, 50 stations take 5 s, 100 stations take 10 s, and 1000 stations more than 100 s. Thus, the LSA system can handle a large number of controlled BSs and their resource allocations. The computation times can be reduced by leasing more computational power, that is, it can be also scaled down to the level required by the dynamic SAS and the selected use case. Thus, the conducted field trials show that the implemented LSA system is able to keep interference generated by a scalable number of BSs at an acceptable level for satellite receivers.

5 | SECONDARY USE OF IMT SPECTRUM

Previous sections have presented how a terrestrial system could access satellite band using LSA technology. However, the possibility of satellite systems to gain more spectrum resources with spectrum sharing technology is also a relevant research direction. We identified a potential use case covering the reuse of IMT frequency bands by satellite systems to provide services in the maritime and aeronautical domain. The presented concept is applicable to any IMT band.

5.1 | System description

IMT spectrum is currently allocated in several UHF bands, from 450 to 2690 MHz for multiple different systems such as global system for mobile communications (GSM), universal mobile telecommunication system (UMTS), and 3GPP LTE. Without losing generality, we decided to study the reuse of GSM spectrum at 900 MHz to validate this concept without prejudging of the suitability of other IMT-identified ultra-high frequency (UHF) frequency bands.

The high-level architecture and the frequency band allocations of this use case are presented in Figures 9 and 10, respectively. The cellular network management system provides information to the LSA about the coverage areas and the satellite system is allowed to access the same spectrum freely in the areas outside the cellular coverage and with limited power in the cellular coverage areas. This is done with the protection zone computation in the system.

The amount of GSM spectrum is $2 \times 35$ MHz (duplex) and could be completely reused by the satellite system. In our example, the interferer is a large multibeam geostationary Earth orbit (GEO) satellite with 121 beams providing voice and data communication using a Digital Video...
Broadcasting—Satellite (DVB-S2) waveform. The reuse factor is four and the bandwidth of each beam is 8.75 MHz. A roll-off factor of 25% has been taken into account leading to an effective band of 6.56 MHz per beam and the selected/operated beam is the beam providing the maximum gain towards the victim (i.e., the contribution from beams other than the main beam are ignored).

We modeled the satellite system and evaluated through simulation the maximum possible equivalent isotropic radiated power (EIRP) from the satellite (i.e., downlink) that would not cause harmful interference to the cellular system (i.e., respect the interference to noise $I/N$ level below $−6$ dB). The interferences at the mobile terminals and at the BSs were analyzed with Systems Tool Kit (STK). We modeled terrestrial terminals with omni-directional antennas and BSs with directional antennas with 13 dBi gain in the boresight direction.

By using STK simulations, we computed the maximum EIRP, which is acceptable for the victims assuming $I/N$ criteria of $−6$ dB. We then converted $I/N$ criteria into a power flux density (PFD) in the downlink direction. The PFD limits are commonly used in coordination studies to guarantee that systems can coexist in the same band. The parameters used in the analysis are given in Table 4. Due to the mismatch in the polarization, a conservative assumption of 10 dB isolation has been taken into account between linear and circular polarizations.
5.2 | Satellite interfering with mobile terminals (allocation in the same direction; circular polarization of satellite emissions)

We assumed an omnidirectional antenna with a 0 dBi gain for the mobile terminal. The assessment of the maximum permissible satellite EIRP without causing interference on IMT terminals is relatively constant and varies between 12 and 12.5 dBW on land. At sea areas, it is possible to increase the EIRP by 3 to 9 dB without interfering the IMT systems.

The link budget analysis shows that quasi-error free reception is possible with omnidirectional satellite terminals on all sea areas as presented in Figure 12. The quasi-error free reception means that the rate of errors is not yet visible in the video reception. The modulation is a quadrature phase shift keying (QPSK) modulation providing around 5 Mbps of aggregated throughput. The use of a small parabolic antenna of 45 cm diameter provides enough gain to have a quasi-error free reception even over land areas.

5.3 | Case 2: Satellite interfering with a BS (opposite allocation direction; circular polarization for satellite emissions)

The BS has a directive antenna providing 13 dBi of gain, which is a typical value for a macro BS. The antenna height is 40 m. The down tilt of the antenna is 6°, corresponding to a cell radius of 22 km.

Because of the directivity of the antenna of the BS and due to its low elevation, the worst case corresponding to the maximum interference from the satellite to the BSs of the IMT terrestrial network is on the edge of satellite coverage areas, when satellite emissions are received on the main lobe of the BS. The situation is depicted in Figure 11. The permissible satellite EIRP varies from 44 dBW at the border of the satellite coverage to 74 dBW at the nadir of the satellite.

The link budget analysis shows that quasi-error free reception is possible with omnidirectional satellite terminals except at the edge of coverage (dark and blue cells). The use of a small parabolic antenna of 70 cm diameter would provide enough gain to have a quasi-error free reception over the whole coverage area.

5.4 | PFD limits

The analysis showed that the allocation of the satellite band and the polarization of the signal have a large impact on the PFD limits in downlink. Tables 5 and 6 detail the estimated power flux limits for the different cases. The underlined cells indicate the highest limit (i.e., best for satellite usage).
FIGURE 11  Maximum permissible satellite equivalent isotropic radiated power (EIRP) without causing interference on International Mobile Telecommunication (IMT) base station (considering circular-polarized satellite emissions) [Colour figure can be viewed at wileyonlinelibrary.com]

FIGURE 12  Interference to noise \((I/N)\) at user terminal (considering circular-polarized satellite emissions) [Colour figure can be viewed at wileyonlinelibrary.com]
Based on the results, it can be concluded that:

- Circular polarization offers always the best isolation so it has higher limits than linear polarization.
- Allocation in the opposite direction is interesting for high elevation angles (above 30°).
- Allocation in the same direction is interesting for low elevation angles (below 30°).

For integrated satellite and terrestrial systems, it is necessary that the satellite system uses linear polarization and the same allocation. The PFD limit is fixed (independent of the elevation):

- 135.4 dBW/m² for 1 MHz band
- 149.4 dBW/m² for 40 kHz.

For separate systems, the constraint on polarization can be relaxed and the circular polarization will provide the highest limits. If these strict power flux limits are obeyed, there is no interest in applying a LSA system. The knowledge of the elevation is enough to determine the maximum EIRP in each satellite beam.

The advantage of LSA is that it enables to increase the spectrum usage in areas where terrestrial systems are not deployed: seas, mountains, deserts, or in case of disasters. The knowledge of the position of the satellite can be used to determine more precisely the power, which can be transmitted without interfering with terrestrial systems.

### 6 | DISCUSSION AND FUTURE CHALLENGES ON DYNAMIC SPECTRUM ACCESS IN INTEGRATED NETWORKS

The paper has presented an LSA testbed to study spectrum sharing between satellite and terrestrial networks in 5G pioneer bands. We further showed with simulations that cellular frequencies can be reused to increase satellite capacity and provide attractive worldwide maritime and aeronautical services. Besides, we identified several topics, which we believe would require further studies. These topics are addressed next.

### 6.1 | Measurement studies

Developed computation models in the testbed have been implemented using state-of-the-art channel models and information about coming 5G systems. Now, commercial 5G systems are becoming available both in the 3.6 GHz and in the 26 GHz bands. Measurements with 5G commercial BSs in combination with LSA computations would allow to fine-tune interference calculation models.
6.2 | **Reuse of IMT spectrum**

Further work regarding the reuse of IMT spectrum by satellites is required to assess the level of uplink interferences generated by the satellite terminals (towards cellular BSs and user terminals) and determine the best band allocation as well as the benefits of LSA for IMT frequency sharing. This case use opens new opportunities to satellite systems and should be further investigated.

In addition, a future activity should look at nongeostationary satellite orbit (NGSO) systems and dynamic cases. Could, for example, the emerging LEO constellations use IMT spectrum for their services and how LSA systems could be used to manage the dynamic spectrum use?

6.3 | **Interference criteria definitions**

Our analysis implies that the coexistence of a satellite service with terrestrial systems in the same bands is possible, both for a satellite band allocation in the same direction and in the opposite direction from the terrestrial system. Further work is required to assess:

1. If and how variable PFD limits or $I/N$ criteria could be used in a regulatory framework to enable:
   a. The definition of different PFD limits for land and sea areas for circular and linear polarization (in the case of same direction).
   b. To take into account the position of the satellite on the GEO arc (in the case of opposite direction band allocation).
2. If an alternative method to equivalent power flux density (EPFD) could be used to evaluate interference generated in the uplink direction.

6.4 | **LSA for higher frequency bands**

Future networks both in terrestrial and satellite domains are being planned with additional capacity from the higher frequency bands such as 40 GHz and above 70 GHz spectrum. It should be analyzed and studied how those bands could be most efficiently used for different services and where coordinated spectrum sharing solutions such as LSA could be applied. Some ideas have been presented, for example, in Gupta et al. and references therein.

6.5 | **Uplink interference assessments**

Future work regarding the sharing of satellite spectrum include the assessment of the impact of large scale 5G networks on satellite receivers for GEO and NGSO constellations as well as the assessment of uplink interference for the 26 GHz use case. Our initial analysis implies that the interference from the cellular UEs becomes harmful in the satellite receiver, when the number of BSs is in the millions range. However, more advanced modeling taking into account the fact that significant number of terrestrial users are located indoors is needed to make justified conclusions on this sharing possibility. Initially, we suppose that the stochastic geometry analysis as in Okati et al. could provide useful means for analytical studies.

6.6 | **Dynamic local arrangements**

According to our analysis, the LSA system is best suited for controlling private 5G networks operating in limited areas. There is so-called evolved LSA concept (eLSA) recently defined by ETSI for more dynamic local arrangements. In the current model, licenses to operate in a given area for a given time period and in a given spectrum resource (frequency allocation) are authorized before the licensee can start transmitting. The eLSA allows to apply licenses also during the operation supporting more dynamic arrangements. Suitability of this model for future sharing arrangements should be studied further.

6.7 | **Development of BSs for dynamic operations**

In addition to making the LSA system itself more dynamic, the current hardware in 5G commercial mobile networks should be developed to support faster frequency changes. In our testbed, the use of a tailored BS controller (BSC) makes frequency changes and evacuations much faster compared with the large-scale network management system applied, for example, in Palola et al. Several proposals for improving the situation are described in Höyhtyä et al., including predictive spectrum use. In addition, hierarchical spectrum management for integrated satellite-terrestrial systems can improve the dynamicity of the operations.
6.8 | Multilayered 3-D networks

Future networks are envisioned to be multilayered 3-D networks, integrating terrestrial, airborne, and space borne networks to provide communication and positioning services seamlessly to end users anywhere globally. Interference management and dynamic spectrum sharing techniques are essential in the envisioned multilayered architectures to increase the total system capacity and enable more services to the users. It remains to be studied how spectrum sharing and interference management is done in this kind of complex setting and which radio frequency bands the different links should use.

6.9 | AI technologies

Machine learning is being applied in various areas or in different phases of spectrum management, including planning, sharing, authorizing, monitoring, and pricing. The efficiency of spectrum sharing can be improved by machine learning and application of artificial intelligence (AI) in LSA is a recommended topic to be further investigated.

7 | CONCLUSIONS

We have developed an LSA testbed to study spectrum sharing between satellite and terrestrial systems. The results on studies related to 5G pioneer bands (3.6 and 26 GHz) reveal that the implemented system is scalable and able to control hundreds of BSs simultaneously. In addition, achieved evacuation times using our research BSs outperform commercial BSs and state-of-the-art values of previous studies in the C-band. Due to unavailability of 5G commercial equipment during the course of the work, we were not able to use them in the trials. However, the proposed live testbed and obtained results clearly indicate how commercial mobile networks can be used and controlled in a spectrum sharing scenario where they are secondary users. All the implemented protocols and approaches can be used with 5G (and beyond) networks.

Regarding the reuse of IMT bands by satellites, the simulations confirmed the possibility of the sharing. We have showed that the direction of the bands allocated to the satellite has a very important impact on the design and performance of the satellite system. Further investigations should be conducted to evaluate the possible optimization of the space segment (reduced coverage, position of the satellites, use of LEO constellations) and the service offer. Of particular interest are maritime and aeronautical applications, which are not well served by terrestrial systems. In addition, the new integrated satellite and terrestrial services, including Internet of Things (IoT) could benefit of the opportunities offered by the sharing of IMT bands.

Multiple recommendations for future work related to studied scenarios were given including development of new interference criteria, conduction of measurements and application of machine learning in the future studies.

ACKNOWLEDGMENTS

The work has been funded by the European Space Agency ARTES Project “ASCENT: Demonstrator for license assisted spectrum access satellite networks, contract no. 4000123000/18/NL/WE.” The authors would like to acknowledge fruitful discussions with the advisory board members of the project, that is, Eutelsat, Intelsat, Avanti, Inmarsat, and Nokia. The views expressed in the paper are those of the authors and do not reflect the official opinion of the European Space Agency or the advisory board.

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How to cite this article: Höyhtyä M, Majanen M, Hoppari M, et al. Licensed shared access field trial and a testbed for satellite-terrestrial communication including research directions for 5G and beyond. Int J Satell Commun Network. 2021;39:455–472. https://doi.org/10.1002/sat.1380