Validation framework for building a spectrum sharing testbed for integrated satellite-terrestrial systems

Invited Paper

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***Abstract*—Development of a testbed for spectrum sharing is a multi-step process requiring systems engineering understanding. The ASCENT project is building a testbed to study licensed spectrum sharing between satellite systems and between satellite and terrestrial systems. The work has been carried out as part of the European Space Agency's (ESA) Advanced Research in Telecommunications Systems (ARTES) programme. The 5G frequency bands currently under study are the 3.6 GHz band and the 26 GHz band. Validation is needed to check that all the requirements are fulfilled and consequently to understand in detail how the spectrum could be shared in the studied bands and what the benefits of different techniques such as licensed shared access (LSA) and power control could be. This paper describes the validation framework that provides guidance for the actual validation and enables creation of an efficient validation plan for different use cases and frequency bands. We also define the architecture for the LSA testbed.**

Keywords—Spectrum databases, 5G, cognitive networks

I. Introduction

5G and beyond networks will aim to integrate satellite and terrestrial networks into a same system to support seamless broadband connectivity and mobile systems such as aircrafts, vessels, and other moving platforms anywhere in the world [1]–[4]. Even though mobile cellular systems have penetrated significant parts globally, satellite connectivity is needed particularly in areas where it would not be economically feasible to build terrestrial networks, such as sparsely populated or distant areas, including the sea, air traffic or frontier areas. Satellites are included as part of 3GPP standardization and multiple important use cases are described, see, e.g., [5], [6]. 3GPP has initiated plans to include significant contributions related to satellite communications in Release 16 which is scheduled to be ready by the end of 2019 or early 2020. An important part of the integrated satellite-terrestrial systems to fulfil resource needs of future applications is to select right frequencies into use and enable efficient spectrum sharing in the bands where several systems may coexist.

Spectrum sharing has been studied for satellite communications actively in recent years [7]–[10]. The studies have mostly concentrated on developing techniques using simulations and mathematical analysis. Examples include spectrum sensing, adaptive antenna techniques, power control and channel assignments, and database-assisted spectrum sharing.

Recent industry-driven spectrum sharing approaches, such as Licensed Shared Access (LSA) [11], [12] and Spectrum Access System (SAS) [13], are based on a database concept. Here 'database-assisted spectrum sharing' means as a scheme where spectrum awareness for the purpose of allocating radio resources is obtained on the basis of a spectrum database. Analysis on how these techniques could be used in satellite bands have been given in [10], analyzing also risks associated to the satellite industry. However, there has been a lack for good testbeds that could be used to study the licensed sharing between satellite networks and between satellite and terrestrial networks using real devices. Previously testbeds have been built for terrestrial communication networks to study, e.g., LSA and SAS [12], [13].

Several new frequency bands are under consideration at International Telecommunication Union (ITU) for the deployment of future 5G mobile systems. (see, e.g., World Radio Conference 2019 Agenda Item 1.13). Among those, European Conference of Postal and Telecommunications Administrations (CEPT) has identified 5G pioneer bands 3.4 – 3.8 GHz band and the 24.25 GHz – 27.5 GHz band [14] that may include both satellite and terrestrial services.

The ASCENT project is building a LSA testbed to study how different systems could coexist in 5G pioneer bands and what are the techniques that could be used in addition to LSA to enable efficient sharing between incumbents and secondary users. For example, shielding, active antenna systems, adaptive transmission power, and use of small cells and D2D communications could be used in the C-band use case. The testbed is used to study selected scenarios that have been defined in collaboration with research organizations, industrial partners, ESA, and satellite operators.

This paper concentrates on defining the steps and the validation framework to build the testbed and to confirm suitability of it to the designed purpose. The paper is organized as follows. Section II describes the framework and defines key performance indicators. Section III uses the framework to define the testbed architecture for the 3.6 GHz band. Section IV concludes the paper.

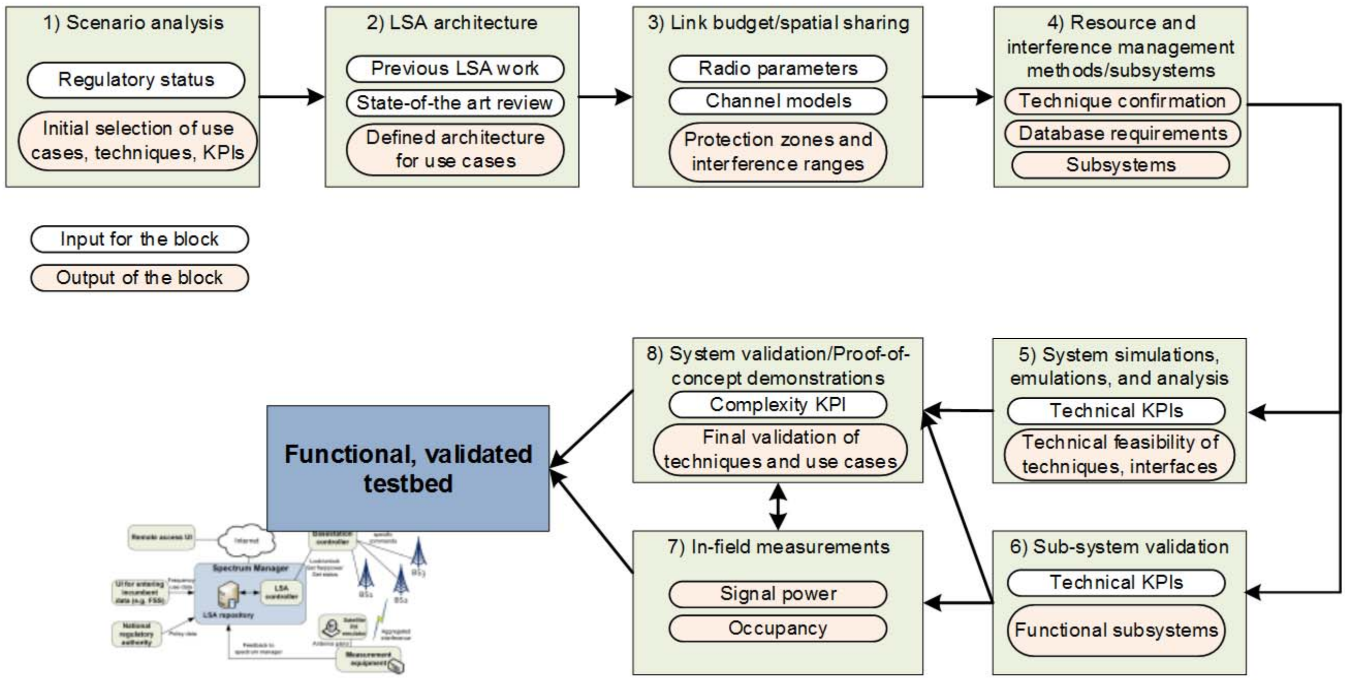

Figure 1. Validation framework for creating a functional testbed.

II. VALIDATION FRAMEWORK

Validation and testing of LSA and other spectrum sharing techniques is done through a variety of tools. The aim of the validation process is to assess the suitability of the techniques in selected scenarios and use cases, taking both technical and regulatory viewpoints into account.

Main validation tools for our purposes include analysis, simulations and emulations, in-field measurements, and proof-of-concept demonstrations. Important parts of the analysis are:

1) Link budget calculations and spatial sharing opportunities
2) Interference management options for each use case
3) System level analysis including acquisition time for relevant data and complexity analysis for implementations

Emulations are needed for satellite system demonstrations since we cannot use actual satellite systems and also 26 GHz band mobile network equipment is not yet available. Related tasks are described in more detail in the validation methodology framework where needed inputs for the proper analysis are also defined. The validation framework of the ASCENT project is depicted in Figure 1 as a flowchart process. Each numbered block in the framework is opened below with their inputs and outputs:

Scenario analysis: First, scenarios are analysed and use cases and techniques are selected with relevant key performance indicators (KPIs). Relevant regulatory data is very important input information for the analysis. The work has started with studying the regulatory status in 5G pioneer bands (3.4–3.8 GHz and 24.25–27.5 GHz) to understand both static and dynamic sharing possibilities in satellite uplink and downlink scenarios. In addition, cellular network bands and their usability to secondary satellite communications have been considered. The outcome of this block includes the selection of the best use cases for the work in collaboration with the advisory board including satellite operators. Additionally, suitable techniques for those use cases are analysed and selected at this stage as well as performance metrics for the practical validation activities are defined. The KPIs are selected to have a thorough understanding of the sharing including the setting up of the system, achieved performance and complexities involved when implementing the techniques.

LSA architecture: Based on the previously implemented software (SW) and hardware (HW) implementations of LSA and the defined use cases, LSA testbed architecture is defined. The architecture includes possibility to use a simulator and an emulator for satellite system studies. The project team has done extensive state-of-the art review on scientific literature and relevant standardization documents, e.g., [11], [15]–[17] both to find best possible techniques to be used and to ensure the wide applicability of the proposed architecture. The defined architecture includes technical subsystems such as LSA repository and LSA controller, satellite and terrestrial systems and the required interfaces as well as graphical user interfaces for accessing the testbed to input, e.g., regulatory data or to visualize the operation remotely.

Link budget/spatial sharing: The spectrum sharing in many use cases is controlled by LSA with spatial separation. Link budgets and protection zones are defined using radio parameters and channel models that need to be known, e.g., the most relevant ITU-R channel models such as [18]. The general goal of a link budget analysis is to estimate the received signal-to-noise ratio (SNR) and that information can be used in determining the possibility for spectrum sharing in spatial domain. The interference generated when users co-exist in the same or close enough spectrum needs to be limited or avoided based on the interference tolerance of the victim receivers. On the other hand, target signal-to-interference-and-noise (SINR) levels determined by regulators are used in the interference link budgets. This analysis provides a first level of understanding but would not replace more detailed calculations or large-scale measurements.

Resource and interference management methods/ subsystems: Actual techniques to be used in addition to LSA in the simulations, emulations, and demonstrations are confirmed and requirements for the database system set to be able to perform needed activities. Subsystem implementations for simulations, emulations and for the real network starts according to testbed architecture design and the defined requirements. Subsystems include, e.g., spectrum manager doing the protection zone calculations, user interfaces, base station controller, and the satellite emulator.

System simulations, emulations, and analysis are used to understand technical feasibility of the techniques in each use case. Interfaces, e.g., between the LSA controller and the satellite emulator and related messaging protocol is implemented. The aim is to create a messaging protocol between the LSA controller and the satellite network management system to be used in system level demonstrations. Parts of the system are tested and analysed. As an input for this and the following step, technical KPIs depicted in Table I are considered.

Sub-system validation aims at validating functionality of the needed subsystems before integration of all subsystems in to a large system/testbed. This includes testing that the user interfaces and visualization fulfil the requirements. We will also validate that the actual base stations and the measurement equipment can be used with the selected interference management techniques. Some subsystems are integrated together already at this point since there are existing interfaces available for example between the LSA repository and the LSA controller.

In-field measurements can be separately done and also during proof-of-concept (PoC) demonstrations, e.g., to verify protection ranges and to measure occupancy values. Some subsystems can be also validated using measurements such as a terrestrial phone used to measure interference caused by a base station towards satellite Earth stations. Measurements can be used in defining received signal power values at the locations of interest as well as estimating spectrum occupancy values.

Proof-of-concept demonstrations are the final step in the validation process where the whole system is tested with the actual hardware. All the subsystems are integrated together and the demonstration activities in the selected use cases conducted. During the demonstrations the remote user interfaces, regulatory interfaces, and incumbent interfaces are in use to control and visualize the demonstrations. An important KPI to be considered is the complexity KPI, i.e., the amount of modifications needed for the whole system considering LSA and additional techniques in each relevant use case and frequency band.

As an example of a quantitative benchmark value the previously implemented C band testbed [13] achieved evacuation times (KPI-3) around 100 seconds with commercial base stations and the full-scale network management system. With our own base station controller, we were able to reduce evacuation times below 10 seconds. In the current testbed, we aim to reduce this further.

Table I. Key performance indicators for the developed testbed.

ID	Name	Category	Description	Assessment method
KPI-1	Acquisition time	Latency metric	Time for acquiring relevant data and setting up the sharing system	Inspection and analysis
KPI-2	Frequency handover 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	Local spectrum occupancy	Spectrum efficiency/occupancy metric	Shows how much the spectrum is used in the location of interest, e.g., testbed activity in a certain location	Inspection/ measurements Analysis and simulations
KPI-5	Spatial occupancy	Spectrum efficiency/occupancy metric	How well the spectrum can be used spatially over a larger area. Can be shown as relative efficiency compared to a non-sharing situation	Analysis
KPI-6	System modifications	Complexity metric	Modifications required compared to the current systems. This will include the LSA as such and also additional techniques to be used jointly.	Analysis and inspection

III. TESTBED ARCHITECTURE

The validation framework is used to develop use case specific plans and a guideline for testbed architecture definition and implementation. As an example we will define here architecture for the 5G pioneer band 3.4–3.8 GHz, i.e., satellite C band sharing with LSA (space to Earth direction for the satellite). The validation plan in this use case includes the real HW-based LSA testbed activities and covers all the blocks in the validation framework presented in Figure 2.

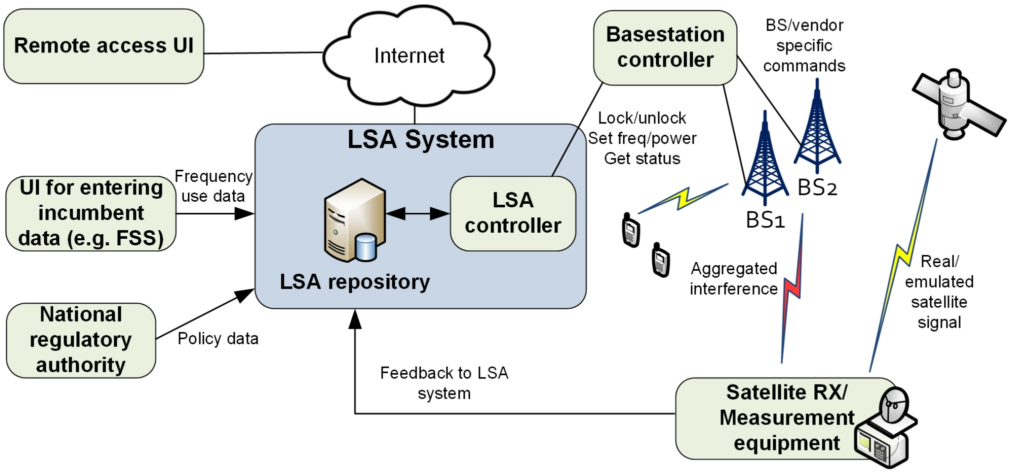

Figure 2. LSA testbed for C band sharing, downlink satellite transmission.

The testbed architecture presented in Figure 2 assumes the satellite system to be the incumbent. The testbed consists of multiple components. The heart of the system is the LSA system that includes both LSA repository and LSA controller.

LSA Repository provides way to enter and store information about incumbent's spectrum use, location, and protection requirements. The aim is to calculate protection zones for fixed satellite services (FSS) Earth stations. Both co-channel and adjacent channel terrestrial base stations are considered in the interference calculations. The radio algorithms for computing the protection ranges need to be validated to ensure that even in the worst case the interference will not go over the acceptable limit. The LSA system software calculates the ranges using channel models such as [18] in computations. The protection zone calculations can be updated with the following spectrum sharing technique choices:

- Shielding (e.g., 20-40 dB) to reduce the protection zone range
- Use of macro base stations vs. small cell base stations and related transmission powers
- Use of directional antennas in terrestrial systems

The database is implemented to fulfil the requirements including, e.g., locations of Earth stations, other radio parameters, and required interfaces to input the data. The LSA system should include identifiers and locations of mobile network base stations.

Authorized **LSA Controller** can get the related availability information from the repository and store their acknowledgement information into the repository. It controls cellular spectrum use via the base station controller. Spectrum usage is controlled by adjusting transmission power of cellular base stations and using cell locking and unlocking. The LSA Controller does not allow cellular communication to operate within areas that may cause interference to satellite network.

The LSA controller sends commands to base stations through the **base station controller** (BSC) that uses base station specific commands to obtain the current state of the base station and its antennas and transmitters and to make modifications to its state. From the BSC viewpoint, the base stations can be real or emulated ones, and the number of them can be defined.

The BSC is a software component running in PC that is connected to one or multiple base stations. BSC is running as operating system service, which takes simple control command (e.g., lock, unlock, set frequency, etc.) as input. In the C-band demonstration, it runs manufacturer specific commands at the base station via its management Ethernet interface. As an output, it provides result of command as succeeded or failed with a failure code. The LSA controller receives the updated base station state and acts upon it is needed. The BSC is able to control individual terrestrial base stations as needed, e.g., to shut down macro base stations in case of interference but continuing with the small cell transmissions.

The locations of **cellular users** need to be known in order to control their use outside exclusion zone. Thus, positioning using, e.g., Global Positioning System (GPS) for the users has to be possible. The base stations can be real or emulated ones and the number of them can be defined. In case of real base stations, we will use measurement devices to determine the interference level at the satellite receiver. The reasoning here is to make sure that the interference level stays at the acceptable level. This helps also in determining the protection distances needed around satellite terminals. The measurement results are fed back to the LSA system so that the transmission can be adapted if needed. The testbed can be accessed remotely over the Internet.

Satellite receiver software is implemented or the actual satellite receiver is used in the testbed. Both options can be used. In this use case the focus is on reception side and the satellite receiver could be emulated by the spectrum measurement system that measures the received power. The effect of the Earth station antenna is taken into account by using ITU-R antenna gain models such as [19].

Mobile devices provide means to inform the location of the mobile FSS ground station to the LSA repository so that they can be used to measure the existence of the mobile base stations before operation of the nomadic ground station. Power level **measurements** can be done to define and verify calculated protection ranges around base stations with different sharing techniques, and to measure local occupancy values (KPI-4). Measurements cover all latency measurements related to KPI-2 and KPI-3 in Table I. Also analysis/inspection on acquisition time (KPI-1) will be done to understand how fast the relevant information can be obtained, e.g., from regulatory databases to set up the sharing system.

User interfaces (UIs) are used to input the incumbent data such as FSS Earth station locations and their parameters to the repository. In addition, remote access UI enables access to the testbed over Internet from any location and provides means to visualize the demonstrations anywhere. The testbed is able to use data from the **national regulatory authorities** that is delivered, e.g., as a Microsoft Excel table. We plan to use information from Finnish Traficom and French ANFR during the project. The policy information includes the up-to-date spectrum use information regarding the geographical areas of interest such as FSS stations and their radio parameters.

The system is integrated and tested as whole. Complexity analysis (KPI-6) is conducted to make feasible choices. All the interfaces between components are implemented. The demonstrations have been planned in detail but the main idea is to test the whole system and use also all the user interfaces during the demonstrations. The idea is to visualize the LSA functionality using the remote interface so that the demonstrations can be easily arranged anywhere over the Internet.

The functional validated testbed enables demonstrations and practical tests regarding the use of integrated 5G satellite-terrestrial systems in the 5G pioneer bands. The testbed architecture defined in Figure 2 is generally applicable to any sharing scenario where the incumbent user is the satellite system transmitting in the downlink direction. We aim to use the testbed also in the 26 GHz band where the same architecture is applicable. However, we cannot use real base stations yet since they are not available. Before having the real base stations available in that band, it is important to use relevant radio parameters, antennas, and channel models in the calculations to achieve meaningful results from the experiments.

IV. CONCLUSIONS

This paper has described a validation framework that can be used in designing a functional practical testbed for spectrum sharing studies in satellite communications, and validating that the testbed is functioning as planned. The framework defines the most important data, relationships, and steps needed to build the system. We have followed the framework principles in an example described in this paper in order to build a testbed for studying the use of LSA for sharing the band between the FSS system and the mobile cellular system in the 3.6 GHz band. The framework is generally applicable to any frequency band and possible services where satellites and terrestrial systems aim to operate in the same band. One interesting future scenario is to analyze the possibility to use cellular frequencies to provide satellite connectivity for airplanes and vessels. We have designed the testbed with the satellite emulator for this purpose as well using the depicted framework. Thus, the main focus in the near future will be doing the system-level tests and demonstrations and measure the performance using the defined KPIs. Another interesting aspect to look at would be integration of the real satellite system to our testbed for further experiments.

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