An Architecture for Spectrum Management and Coordinated Control in 5G Heterogeneous Networks

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***Abstract*—Achieving the Key Performance Indicators defined for 5G networks will require the implementation of new technologies and the deployment of dense heterogeneous networks, using different Radio Access Technologies and several chunks of the RF spectrum. An important consideration in this context and a main focus point of the COHERENT project, is how the resultant diversity can be controlled and how the valuable radio resources could be managed and controlled effectively. This paper presents a new architecture for spectrum management and sharing on top of a coordinated network control layer in 5G heterogeneous networks. The architecture is based on the abstraction of networks' resources and the virtualization of control aspects in order to support 5G spectrum management and sharing models. We present the architecture and its main functional entities together with its internal and external interfaces. We also provide a mapping of the diverse set of functionalities and requirements identified for Licensed Shared Access to other spectrum sharing models under consideration for 5G networks.**

I. Introduction

A number of very ambitious targets have been set for 5G networks which will be very difficult to achieve with simple evolution of existing network architectures and technologies. These targets are reflected by the Key Performance Indicators (KPIs) identified for 5G networks by 5G-PPP [1] and concern network aspects such as data volumes, connectivity, data rates, energy, latency and ubiquity. Achieving these KPIs will not only require the evolution of existing networking technologies but also the implementation of new ones such as Software–Defined Networking (SDN) and Network Function Virtualization (NFV). Additionally, the footprint of heterogeneous networks utilizing different Radio Access Technologies (RATs) and spectrum bands has to be enlarged and new spectrum management and sharing models have to be incorporated to achieve the large data rate demands in radio access domain. All this will result in large network diversity and require new approaches to spectrum management and control in heterogeneous 5G networks. In this paper, we present an architecture for spectrum management in 5G heterogeneous networks through a Spectrum Management Application (SMA) that, following an SDN paradigm, operates on top of a logically centralized control layer. This layer abstracts the state of heterogeneous networks' resources including the radio resources in a *Network Graph* and provides the necessary control features to the spectrum management application to make spectrum management and sharing decisions.

The rest of the paper is organized as follows. Section II presents the proposed architecture with details of its functional entities followed by a description of internal and external interfaces in section III. Section IV discusses the functionalities and requirements of spectrum sharing in 5G networks and its mapping to different spectrum sharing and utilization models. The paper is concluded with a summary in section V.

II. Spectrum Management Architecture for Virtualized Wireless Networks

One of the key objectives of the COHERENT project is to propose a new architecture for efficient abstraction and virtualization of 5G heterogeneous networks and utilizing it for efficient spectrum management and sharing. In this section, we provide the description of the considered spectrum management and control framework, where we concentrate on both high level architectural aspects and on the lower level spectrum coordination and monitoring functions. In our scope of spectrum management, coordination and control, we consider three groups of users:

- Spectrum Regulators: such as National Regulatory Authorities (NRA), which are responsible for defining the high level rules and regulations for spectrum management and monitoring of its execution.
- Spectrum usage rights holders or licensees: such as mobile network operators (MNO), or virtual mobile network operators (VMNO), incumbents, etc. which benefits from usage of the spectrum
- Mobile users (mobile terminals): the end users or more generally, the clients of the network operators.

In the context of spectrum management, coordination and control, the last group can be omitted as they only utilize the spectrum assigned to them by the spectrum usage right holder. On the other hand, the spectrum regulators play a key role in spectrum management as they provide the guidelines for spectrum utilization. Finally, MNOs possess the rights for spectrum control and coordination within the bands licensed to them. Clearly, these two roles can overlap, i.e., it is possible that MNOs will possess their own, local/private spectrum management systems for the whole set of frequencies assigned to them. Having these observations in mind as well as the key investigation subject of COHERENT project, i.e., the virtualization of network control and coordination, the proposed architecture is based on three main planes, i.e., the spectrum management plane (or equivalently the SMA), the spectrum control and coordination plane and the infrastructure plane. The spectrum control and coordination plane relies on the COHERENT Central Controller and Coordinator (C3) module which abstracts heterogeneous networks control functions through wireless network virtualization. The infrastructure plane refers to the physical network that not only represents the physical network resources but also includes the radio resources i.e., RF spectrum. The complete architecture is illustrated in Figure 1.

A. COHERENT Control and Coordination Plane

The central control entity in the whole system is the Central Controller and Coordinator. As its name suggests, it is responsible for continuous coordination and control of the spectrum assignment and practical realization of high-level directives obtained from the SMA. In other words, C3 is responsible for implementation of the whole set of rules provided by SMA (for example guidelines on the spectrum sharing rules at certain frequency band) in the real network. The interface between the SMA and the control and coordination plane is called Northbound Interface (NBI) and only high level messages are exchanged over this interface. Next, the interface between the real network (abstracted in the form of a network graph) and the C3 entity is called Southbound Interface (SBI) and highly detailed information is exchanged over this interface. The Eastbound Interface (EBI) is used for coordinating the spectrum sharing decisions among involved networks. Another important control entity with a more local and distributed presence is the Real-time Controller (RTC). The RTC not only takes care of the local radio resource management but also realizes spectrum management and sharing decisions of the SMA that are applicable within a small segment of the network such as D2D communication or flexible duplexing.

B. Spectrum Management Plane

The SMA takes charge of all the spectrum management issues including reasoning, optimization and enforcement. Sitting on top of the architectural hierarchy, the SMA takes both long term spectrum management decisions requiring for example, the evaluation of spectrum sharing rules between the operators, querying the NRA managed databases for spectrum utilization rule, etc. and short term decisions requiring inputs from the C3 entity about the state of the network and radio resource utilization. The SMA is also responsible for processing various queries originated from the C3 entity (e.g., network/spectrum status updates, notifications and alarms etc.) As an example, the C3 entity of a MNO can identify that more spectrum would be required in a given segment of the network to maintain a certain performance or quality criteria and this issue will be notified to and addressed by the SMA. For its operational needs, the SMA has access to various databases

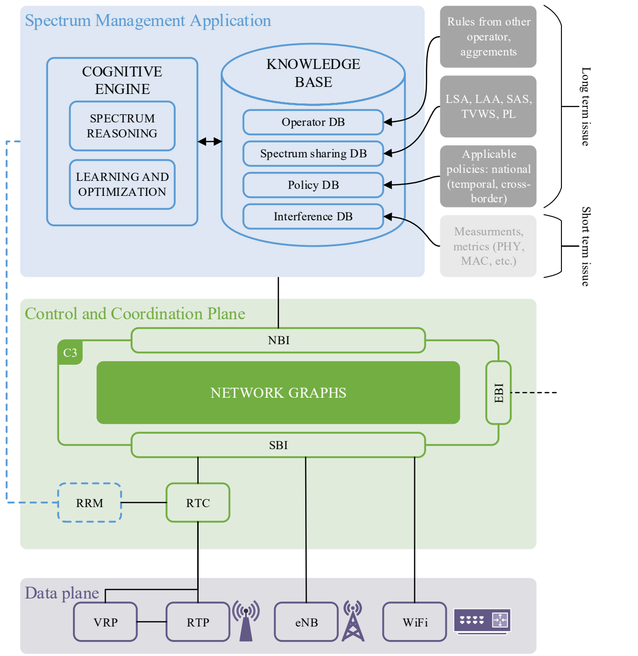

Fig. 1. COHERENT spectrum management, coordination and control system.

such as LSA database, radio-environment map databases, policy repositories, or open databases. These databases can be updated at any time either manually by the dedicated administrators (such as NRA representatives, MNO license managers etc.), or in an automated manner by dedicated monitoring modules (for example entries in the interference maps can be monitored permanently and updated periodically by dedicated sensors). In order to allow such functionality a set of standardized interfaces for database/repository access have to be defined. Besides databases, the spectrum management engine should have access to dedicated storage modules in order to cache some sensitive and frequently accessed data or to store long-term trends or statistics, e.g., in spectrum use to enhance spectrum assignments in the future. Finally, the definition of dedicated protocols for communications with external databases (such as WiFi Passpoint databases accessed through the Access Network Query Protocol (ANQP)) and with other spectrum managers will be required.

C. Infrastructure/Data Plane

The infrastructure plane refers to the underlying physical network and its resources including radio resources. While a network's architecture is generally only loosely coupled with its physical reality, the actual data transmission always takes place over the physically available network resources, i.e., real infrastructure (base stations, remote radio heads, access points etc.) and communications medium (i.e., frequency spectrum). Within the COHERENT project, the physical network state and resources are abstracted and represented to the control layer as a network graph. Such network graph abstraction provides a mapping between the logical entities of the graph and the underlying physical network resources. This is required to ensure that the control plane and therefore the SMA have a realistic view of the network state and resources.

D. Network Graphs

The COHERENT project virtualizes the underlying network in order to manage and control the resources in software domain. However, radio spectrum eventually has to be understood as a physical resource that is used to carry user and control data across the deployed wireless network. We therefore apply the network graph theory in order to enable the C3 efficiently implement the spectrum management and sharing rules defined by SMA on top of a network graph that is an abstraction of the real network, its state and the radio spectrum. The abstraction processes applied in the COHERENT project and the resultant network graphs can be quite diverse depending upon the level of details that are captured from the physical network through different measurements. Once created, the network graph can further be used by the C3 entity for the optimization of spectrum utilization in the network. We call the graph abstraction used by the SMA as spectrum-network-graphs. These graphs constitute the connection between the spectrum coordination and control plane and the physical network of a certain operator. They also reflect, in an abstracted way, how the spectrum resources are assigned to particular nodes and how these resources can be flexibly used for better utilization.

E. Virtualization Aspects

Realizing the benefits of Software Defined Networking (SDN) and Network Function Virtualization (NFV) in 5G networks is an important consideration. Virtualization is a fundamental concept of SDN/NFV and it is evident that many legacy network functions together with their management and control have to be addressed in the new SDN/NFV scope. When a certain functionality is brought to the software domain, it subsequently requires new management and orchestration functions to be present in the virtual infrastructure. This also applies to spectrum management/sharing and therefore, the fundamental entities associated with SMA such as Radio Environment Databases, policy information and cognitive engine etc. have to be revisited and made compatible to the new virtualized architecture.

The COHERENT project also brings many of the management and control functions of heterogeneous networks into the software domain thereby implementation a virtualization layer on top of the physical networks. The underlying physical network shall most likely be a hybrid of legacy LTE eNodeB and Wi-Fi APs together with new radio entities that apply a particular functional split to bring some RAN functions into the software domain (as depicted in figure 1). Such a functional split results in some functionality associated with physical Radio Transmission Points (R-TPs) and the rest with Virtual Radio Processors (VRPs). In COHERENT, these two entities are controlled by the C3 entity which spans.across an operators heterogeneous networks and facilitates the optimization of network functions through software control. The C3 entity exposes the state of the network to higher level network applications such as the SMA and can then enforce the optimization decisions on to the physical network through software control.

Although spectrum manager sits on top of the hierarchy in the COHERENT architecture, its presence at a lower level is ensured though an interface with a local (e.g., cell-specific) Radio Resource Management (RRM) function. This is to acknowledge that certain spectrum management and sharing decisions may apply only within a small geographical scope (e.g., D2D communication). In such cases, the SMA can make decisions that are realized through RRM and RTC in a particular segment of the wireless network.

III. Interfaces

In terms of spectrum management, coordination and control mechanism, the COHERENT C3 entity should exchange messages between other parts of the system using the following interfaces (graphically presented in Figure 2):

- Northbound interface (NBI) or C3-SM which connects the C3 module of a stakeholder with the spectrum management system of the same stakeholder;
- Southbound Interface (SBI) or C3-PR which connects the C3 module with the physical resources of the same stakeholder or dedicated infrastructure provider;
- Eastbound Interface (EBI) or C3-C3 interface which connects the C3 modules belonging to different stakeholders to coordinate spectrum sharing decisions. Moreover, the Spectrum Management Systems belonging to various owners (operators, third parties etc.) should be able to exchange information between themselves. This communication can be realized via the dedicated SM-SM interface. Depending on the realization, C3-C3 interface can be merged logically with the SM-SM interface creating broader EBI.
- One may observe the presence of SM-NRA interface (denoted this using dotted lines), which reflects the way how the stakeholders communicate with the NRA or other legal bodies.

IV. Required functionalities

The ETSI standard TS 103 154 [2] defines the functionalities for the LSA system operating in the 2.3 GHz band. The list of functionalities and requirements presented in that standard is comprehensive and it covers most of the important aspects from the LSA perspective. Below, we first generalize these LSA functionalities and requirements to any potential spectrum sharing scheme considered in 5G networks. Finally, we present a dedicated importance matrix that indicates the levels of importance of each functionality for the considered spectrum sharing strategies. These identified functionalities and requirements characterize the COHERENT spectrum management, coordination and control system.
General Functional Requirements (GFR):

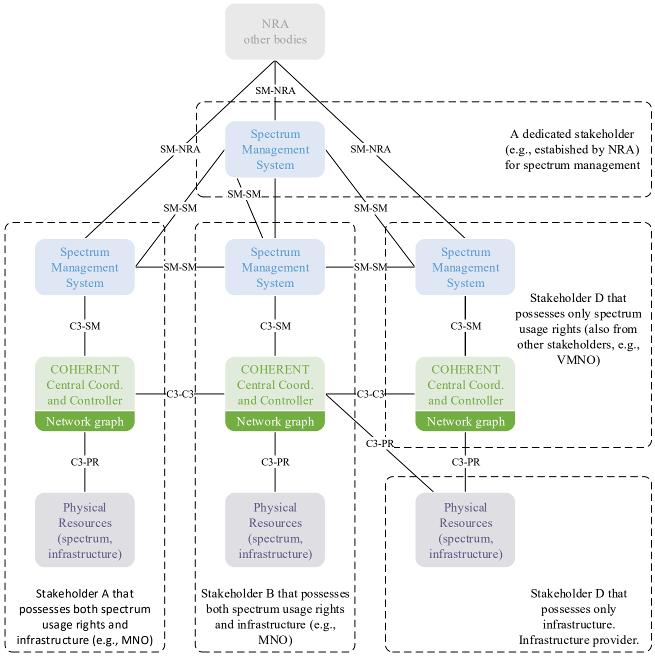

Fig. 2. Interfaces for COHERENT Spectrum Management, Coordination and Control System .

- Spectrum Resource Sharing (GFR1)
  The Spectrum Management System shall support flexible spectrum management and spectrum/infrastructure sharing in various cases (horizontal, vertical, mix etc.). Various stakeholders can be involved in the spectrum sharing. For example, in LSA case, there are incumbents and LSA licensees whereas co-primary sharing involves two mobile network operators.
- Quality of Service (GFR2)
  The system shall support provision of agreed Quality of Service (or even Service Level Agreement) to each involved stakeholder.
- Information Exchange between Stakeholders (GFR3)
  Involved stakeholders shall be facilitated to exchange information among themselves in order to effectively manage the radio spectrum (e.g., via monitoring of the current status of the spectrum utilization etc.)
- Multiple Stakeholders Support (GFR4)
  The system shall support the co-existence of many stakeholders (e.g., incumbents, licensees, equal-right MNOs etc.)
- Sharing Framework Support (GFR5)
  The overall system shall support the national solutions and regulations related to radio spectrum.
- Confidentiality of Spectrum Resource Information (GFR6)
  Various mechanisms shall be implemented to ensure required level of confidentiality between the stakeholders. These will be different for various spectrum sharing strategies.
- Provision of Failure Indication (GFR7)
  Practical implementation of a flexible spectrum management system relies on immediate and accurate detection of any potential failures in the spectrum usage as this will lead to interference issues. The spectrum sharing system has to support this functionality.
- System Data Storage Function (GFR8)
  The whole spectrum management system should support access to the information required for efficient implementation of the agreed spectrum sharing strategy between the interested stakeholders. Such access will be granted by supporting entry, storage and modification of the above-mentioned information.
- System Reporting Function (GFR9)
  Monitoring of the spectrum resource utilization among various stakeholders should lead to periodic (or in broader aspect scheduled) or on-demand report generation. Various forms of these reports generation shall be possible, i.e., prepared in a human-understandable form, or tailored to the needs of specific entities of the system.
- Support of Scheduled Operation (GFR10)
  The spectrum sharing system shall support realization of any scheduled actions among interested stakeholders.
- Support of On-Demand Operation (GFR11)
  The spectrum sharing system shall support realization of any allowed on-demand actions.
- Support for Pre-Configuration (GFR12)
  The Spectrum Management System shall support the pre-configuration of the spectrum resource usage among stakeholders based on the limited set of predefined protection requirements for each interested stakeholder. Such pre-configuration can be applied to the whole or part of specified spectrum band or can be defined only for a specific geographical area.
- Verification of Inputs to the Spectrum Management System (GFR13)
  The system for flexible spectrum management shall be equipped with a tool for verification of any possible input delivered to the system, e.g., the requirements delivered by one stakeholder can be rejected if they violate other agreements and guidelines.
- System Availability to Stakeholders (GFR14)
  Information about the available system shall be accurate and reliable. The system has to guarantee the preventing mechanisms against any malicious attacks or various failures or accidents.
- System Operation in case of Change of Sharing Arrangement or Sharing Framework (GFR15)
  The system will be fully flexible if it will allow the (scheduled or immediate) changes of sharing arrangements.

Stakeholder Protection Requirements (SPR)

- Protection of Information of the Stakeholder (SPR1)
  The spectrum management system shall protect the sensitive information of the interested stakeholder. Following the system shall allow the stakeholder to store a descrip-

tion of the spectrum resources and its availability.

- General Protection of the Stakeholder (SPR2)
  The system shall support various mechanisms to ensure the fulfilment of the spectrum usage and protection requirements of any stakeholder by other stakeholders; this is particularly important in the hierarchical spectrum sharing schemes
- Variation of Stakeholders Usage and Protection Requirements(SPR3)
  Stakeholders shall be allowed to change their requirements on spectrum resource usage and protection. The system shall provide this information to any other affected stakeholder. An example could be the change of the requirements by incumbents which influence the licensees, or the change of the spectrum usage plans in co-primary sharing.
- End-to-end Acknowledgment of Operational Changes (SPR4)
  In general, the system shall support the opportunity to prove that one of the stakeholders (e.g., the licensee) has implemented required changes in response to the changes initiated by other stakeholder (e.g., incumbent).
- Support of Constraints on Stakeholders Transmissions (SPR5)
  Interested stakeholder shall be allowed to provide the spectrum usage in the form of a set of constraints that have to be fulfilled by other stakeholders interested in the usage of the spectrum resources. These constraints can be, for example, the constraints on the transmit power or radio characteristics, or interference limits observed by interested stakeholder.

Security Requirements (SR)

- Data Integrity (SR1) The spectrum management system shall provide mechanisms to ensure the integrity of the data stored in the system and the data exchanged between any of the interested stakeholders.
- Data Authenticity (SR2) The spectrum management system shall provide mechanisms to ensure the authenticity of the data and information stored in the system and the data exchanged between any of the interested stakeholders.
- Data Confidentiality (SR3) The spectrum management system shall provide mechanisms to protect the data and information stored in the system from unauthorized access.
- Identity management and authentication (SR4) The spectrum management system shall provide mechanisms to provide identity management and authentication of any interested stakeholder.
- Support of Authorization Profiles (SR5) The system shall support the creation of dedicated authorization profiles assigned to defined groups or types of stakeholders.

TABLE I
IMPORTANCE OF IDENTIFIED FUNCTIONALITIES WITH THE REFERENCE TO SELECTED SPECTRUM SHARING STRATEGIES (LEGEND: IMPORTANCE LEVEL: H HIGH, L LOW)

Functionality	Sharing Policy						
	LE	LSA	SAS	LAA	PL	TVWS	CoP
GFR1	L	H	H	H	H	H	H
GFR2	H	H	H	H	H	H	H
GFR3	L	H	H	L	H	H	H
GFR4	L	H	H	H	H	H	H
GFR5	H	H	H	H	H	H	H
GFR6	H	H	H	H	H	H	H
GFR7	L	H	H	H	H	H	H
GFR8	L	H	H	H	H	H	H
GFR9	L	H	H	H	H	H	H
GFR10	L	H	H	L	H	H	H
GFR11	L	H	H	L	H	H	H
GFR12	L	H	H	L	H	H	H
GFR13	L	H	H	L	H	H	L
GFR14	H	H	H	H	H	H	H
GFR15	L	H	H	L	H	H	H
SPR1	H	H	H	L	H	H	H
SPR2	L	H	H	L	H	H	H
SPR3	H	H	H	L	H	H	H
SPR4	L	H	H	L	H	H	H
SPR5	L	H	H	L	H	H	H
SR1	H	H	H	H	H	H	H
SR2	H	H	H	H	H	H	H
SR3	H	H	H	H	H	H	H
SR4	L	H	H	L	H	H	H
SR5	L	H	H	L	H	H	H

Abbreviations: Licensed Exempt (LE), Licensed Shared Access (LSA), Spectrum Access System (SAS), Licensed Assisted Access (LAA), Plularistic Licensing (PL), Tv White Space Systems (TVWS), Co-Primary Shared Access (CoP)

V. CONCLUSION

Heterogeneous networks with virtualized elements and sophisticated spectrum management and sharing requirements have to be controlled in a coordinated and autonomous manner. In this paper, we presented a new architecture for spectrum management and sharing pursued within the scope of COHERENT project that focuses on such coordinated control. The architecture is based on the provision of an abstraction of the underlying network through network graphs. These graphs not only capture the physical resources of the network but also represent the network state and the state of the radio resources. We presented how these graphs together with the coordinated control layer provided by COHERENT C3 entity help in realizing many of the spectrum management and sharing objectives. We also presented a generalization of the main functionalities and requirements for spectrum sharing in 5G networks.

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