Virtualization of Spectrum Resources for 5G Networks

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***Abstract*—The next generation of mobile networks, 5G, is currently under development by the industry, academia and international standard organizations. The key drivers of 5G are to provide incomparable more capacity (1000x), extremely lower latency (sub-millisecond) and to accommodate 'any' type of user (e.g. machines) in the network. Software-defined networking (SDN) and network function virtualization (NFV) technologies promise to bring an unprecedented level of flexibility in resource management. This paper presents a radio frequency spectrum management framework that is suitable to programmable 5G networks, under the overarching architecture of the 5G PPP COHERENT project. It also provides description of the recent advances and up-to-date initiatives for resource management in programmable 5G networks. The core contribution consists in the design of an SDN-enabled spectrum management application (SMA), and the related abstraction models that have been developed to enable flexible spectrum management. This paper demonstrates that suitable policy and topology abstraction models are key to spectrum management and sharing process.**

I. Introduction

It is well known that the global mobile traffic growth will soon reach an unprecedented level of exabytes per month [1]. Various strategies have been considered in recent years to find appropriate solutions that could be applied in 5G networks. The Shannon capacity equation provides an assessment of how this goal can be achieved - the observed capacity will grow linearly with the bandwidth, and logarithmically with the signal-to-noise-ratio (SNR). Thus, the easiest way will be to increase the spectrum together with improving the signal quality. The amount of spectrum that can be used for delivering specific services to the users is the result of complicated and rigid (inter-)national agreements and regulations. Such an observation has stimulated the development of advanced strategies for protecting information in the error-prone radio channel (e.g. LDPC codes), as well as the exploitation of various diversity techniques (e.g. multiple-input multiple-output, MIMO, schemes). At the same time, numerous spectrum measurement campaigns have emphasized the problem of spectrum scarcity and inefficient use. This work verges on more flexible approaches to spectrum management and control. The quest for new spectrum management schemes to support the trend of rapidly growing mobile data traffic can be satisfied by utilizing higher frequency bands (e.g. the millimeter wave region) and better usage of lower frequencies, e.g. below 6 GHz. According to the RSPG opinion on the pioneer bands for 5G [8], a set of bands from millimetre waves to below 1 GHz frequency bands are needed to support the wide range of envisaged 5G services, varying from multi-gigabit per second data rates to machine-type communications requiring ubiquitous coverage and low latency. In this context, research on spectrum deserves further inspection, as spectrum is a precious public resource with multiple players involved including products vendors, mobile (virtual) network operators, regulators and other legal bodies. This paper investigates the spectrum management and sharing issues in 5G networks in the context of network architecture and abstraction concepts developed in 5G PPP COHERENT project.

The rest of the paper is organized as follows. Section II provides an overview of the state of art on spectrum sharing and Section III provides an updated description of recent trends in spectrum management. Section IV shows the 5G-PPP COHERENT network architecture, and Section V provides the core contribution of the paper, which consists of the design of a Spectrum Management Application (SMA). Spectrum abstraction models and a graph based method are detailed that can enable flexible spectrum management in 5G networks. Finally, Section VI draws the conclusions of this work.

II. Related work on radio resource management in programmable 5G networks

5G promises to overcome the limitations of previous mobile technologies by adopting virtualized network architectures employing virtual network functions and supporting multi-tenancy. Additionally, the scarcity and economic considerations of spectrum i.e., the market value, makes for a more convincing case for spectrum sharing to meet the ambitious 5G network performance targets. With the new virtualized 5G network architecture, spectrum sharing has been investigated in several works to demonstrate its effectiveness for supporting more network services while addressing performance isolation concerns. Several works in the literature consider a model where the spectrum owner/infrastructure provider acts as the facilitator of spectrum sharing between several mobile virtual network operators (MVNO). Such a model is very relevant in the context of 5G networks which are being developed to provide dynamic control and management, and support multi-

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tenancy for disjoint services. In [2], the authors investigate the problem of obtaining maximum benefit (highest efficiency) for the spectrum owner when information of the tenant mobile virtual network operators is not available. They propose to use efficient trading of sub-carriers under incomplete information of MVNOs. Multiple services providers engage in a spectrum exchange relationship for a pre-defined price and the authors present an optimal trading contract to maximize the utility for the spectrum owner. In [4], the authors take a similar model but investigate the allocation of spatial streams to different MVNOs in a massive MIMO cell. Each MVNO is allowed to use its own scheduling policy and user priority scheme in the allocated streams. The authors also propose an auction scheme for the allocation of the spatial streams and demonstrate a close to optimal allocation. The issue of network slicing for MVNOs and the selection of most appropriate multiplexing technique (TDMA, FDMA or SDMA) has been investigated in [5]. The authors investigate the QoS aware, joint admission control problem and propose an algorithm that takes the QoS effects and stochastic traffic into consideration. The authors investigate the benefits of joint spatial-frequency multiplexing over static frequency slicing using simulations. An interesting approach to dynamic spectrum access is presented in [6] in which it is proposed to add a Spectrum Virtualization Layer (SVL). This layer receives the modulated baseband signals from the transmitter and maps them onto dynamically allocated physical frequency bands. A reverse mechanism is adopted at the receiver end. This mechanism can also be applied in the MVNO context where the services are mapped dynamically onto the shared spectrum. A collaborative spectrum sharing framework for LTE virtualization is presented in [7]. The authors take the context of using existing network infrastructure i.e., LTE, and they propose a framework for temporal and spatial reuse of spectrum by multiple operators using dynamic adjustments of network parameters.

III. Spectrum Management in 5G Networks

Recent trends in 5G spectrum research and standardization are looking at both below and above 6 GHz bands, including the millimeter wave region. The issue of millimeter waves is being specifically addressed in preparation for the World Radiocommunications Conference 2019 (WRC-19) of the International Telecommunication Union Radiocommunication Sector (ITU-R), in which the frequency range between 24-86 GHz is being considered [9]. Also, the use of lower frequencies is highly fragmented, as the frequencies are assigned to various stakeholders including aeronautical, radio navigation, fixed satellite and radio amateur services. Research indicates that not the entire spectrum is occupied by these services at all times and at all geographic locations [10]. The low occupancy together with growing pressure created by the rapid traffic increase has stimulated the development of new solutions for dynamic spectrum access. In order to improve the efficiency of spectrum use, administrations and regulatory authorities around the world are striving to develop frameworks for allowing different services to share and coexist in the same frequency bands. Considered approaches fall under the concept of hierarchical spectrum access as different services have different priorities in spectrum usage. In Europe, Licensed Shared Access (LSA) has been proposed by the European Commission (EC) as a general regulatory framework to introduce an additional usage on a band with existing incumbent usage in a controlled, license-based, manner [11]. The first use cases for LSA were those that enable mobile systems to access the bands allocated to them but currently having incumbent usage, namely, 2.3 GHz [12] and 3.6 GHz [13] bands. Another, approach for spectrum sharing gaining attention in Europe, and especially in UK, is the unlicensed use of TV white spaces (TVWS). Similar frameworks for the TV bands have been developed in other parts of the world as well, for example in Singapore and Canada. In the US, incentive auctions are being held on the TV band, allowing broadcasters to resell their licenses [14]. Additionally, a 3-tier model for Broadband Radio System (CBRS) is currently under standardization process for the 3.5 GHz band in the US [15]. This is part of the ambitious goal to protect services against spectrum usage, and not based on ownership in the future [16]. In Europe, the importance of unlocking spectrum assets and exploration of new methods for spectrum sharing has been highlighted as one of the pre-requisites for exploiting the full innovation potential of 5G both by the EC [17] and ECC [18].

IV. The COHERENT 5G Network Architecture

The COHERENT 5G network architecture (or simply COHERENT architecture), as shown in Fig. 1 is based on a few fundamental concepts for addressing network control and management that have materialized in the form of (i) data and control planes separation, (ii) network state abstraction models and (iii) network programmability for supporting heterogeneous radio access technologies and network services. Management functions i.e., Operations, Administration and Maintenance (OAM) and core network functions are shown on the left-hand side of the figure, indicative of the separation from radio access network management. The user plane in Fig. 1 is made of virtual and physical radio transmission points (R-TP). For network management and control, the COHERENT architecture uses a logically centralized controller and coordinator (C3) that maintains network information such as network topology and network state, and is decoupled from the data/user plane. Being a logically centralized entity, the C3 can have several instances that through the northbound interface (NBI) provide the entry point to network management and control applications. Also, multiple C3 instances overcome scalability concerns and individual C3 instances are responsible for disjoint network segments. Furthermore, radio resource management (RRM) functions such as scheduling impose stringent latency constraints, which are addressed in the COHERENT architecture by Real-Time Controllers (RTC) responsible for time-critical network control decisions. Network applications acquire different information about the underlying physical network, which are maintained at the C3 level through *abstractions*. The COHERENT architecture

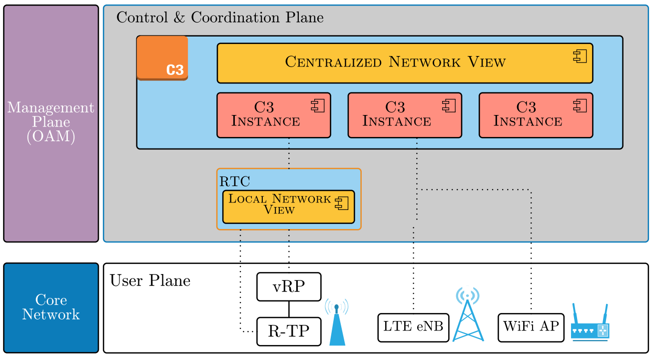

Fig. 1. COHERENT project wide architecture.

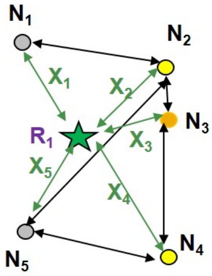

Fig. 2. Network graph example

enables collecting status reports at different layers of the communication protocol stack, and provides abstract network models. A fundamental abstraction used in this context is that of a COHERENT *network graph* [3].

An SDN-enabled 5G network will be built on top of a heterogeneous RAN substrate where different technologies can operate within proximity at the same time, and over the same frequency band. Such a heterogeneous network environment exacerbates problems of co-tier and cross-tier interference, and calls for efficient spectrum management. Not only more spectrum would be needed but also with improved quality i.e., better Signal-to-Interference-plus-Noise-Ratio (SINR). 5G technologies will have to address these challenges by developing accurate and efficient abstraction models to control and manage such complex radio environments. For example, information about the spatial configuration of interference at a given location or about the propagation environment between mobile users and other users/base stations can be utilized by advanced RRM algorithms that target joint optimization of frequency and power. Different parameters are required to describe the abstractions, which can be stored in a dedicated database in an appropriate format for (non)real-time processing. One approach is to represent information as a network graph (G), with a set of vertexes (V) and edges (E). An exemplary network graph is shown in Fig. 2, which contains access points/base stations (yellow circles), a UE (star), and the connections annotated with parameters (for the ith node X_i, in this example $i = 1, 2, ..., 5$). It is assumed that there is a portion of information associated with each node, e.g., the number of available channels on each access point, $N_i, i = 1, ..., 5$, or requested rates with minimum QoS, $R_j, j = 1$. Two sub-graphs can be distinguished: a) the one with black arrows shows the relations between nodes as an agreement among operators to fulfill a spectrum sharing policy (e.g. licensed shared access), and b) the one with green arrows, which defines the transmission opportunities between UE and each node. Such a network graph can be complemented with new sub-graphs that enrich the network information description. Based on the abstract network graph model, different algorithms can be developed, such as node coloring and edge pruning, as well as multi-dimensional optimization of scheduling, interference and resources. In the following section this highly-generic abstracted network graph will be exemplified while discussion on the spectrum graphs. Effectively, the graph shall be consumed by network applications and services as an abstract representation of the physical network that paves the way towards radio-access networks virtualization.

V. Abstractions for Spectrum Management and Sharing

Referring to Fig. 1, the physical network substrate is virtualized whereby a layer of virtualization (i.e. hypervisor) to create virtual radio resource pools is proposed, which could be managed by different physical or virtual operators. In other words, the same physical device can host different functions that belong to different virtual networks increasing separation from the underlying hardware. The physical network is made of TPs, and different radio access technologies (LTE, Wi-Fi, etc.) may coexists causing mutual interference since they can operate over the same spectral region. The pool of virtual resources includes not only different radio access technologies but spectrum as well. We propose the use of SMA, shown in Fig. 3, which exemplifies the capability of the control and coordination network to manage specifically the spectrum resource. The SMA can rely on different abstraction models representing the status of the underlying network, based on which different cognitive algorithms and predictive models can be applied in the decision making process enforced through the SDN controller. To complete this picture, we argue that the SMA will rely also on different databases. Specifically, the abstraction models shall expose, using suitable data formats, more volatile information to the SMA through the northbound interface. Moreover, we consider that the SMA will benefit from the processing of virtual resource blocks and spectrum graphs, which are described in the following subsections.

A. Virtual Resource Blocks

As the network graphs presented in the previous section can be treated as a specific form of abstraction of the real wireless network, it may be beneficial to introduce the concept of virtual resources instead of dealing directly with real assets that are tied to a particular technology. Such an approach will be a necessary step towards the creation of the radio access network abstraction layer. Then, the algorithms utilizing

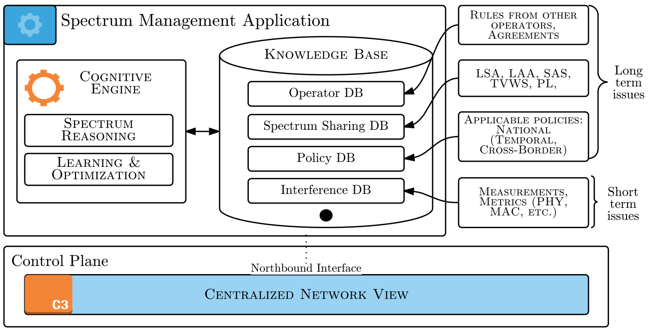

Fig. 3. Spectrum management application (SMA) detailed view

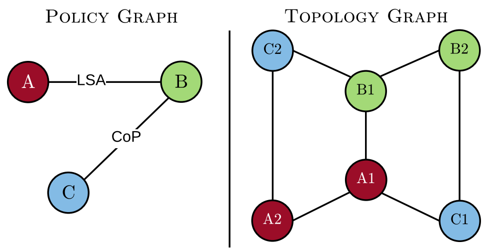

Fig. 4. Example policy and network topology graphs

the information stored in the network graph will not operate on the real radio resources (e.g. 20 MHz channels in Wi-Fi, physical resource blocks in LTE/LTE-A) but with the virtualized resource units called Virtualized Resource Blocks (VRBs). Such a block can be understood as a portion of spectrum that guarantees (statistically) certain level of QoS for applications (e.g. bit error rate, throughput, latency) in a given radio access technology. As a consequence, analogous to hardware drivers in computers, a dedicated mapping function between the virtual and the physical resources in a given technology has to be applied. Such an approach, will be the basis to enable efficient spectrum management in multi radio access technologies and support spectrum sharing at a higher abstraction level in virtualized wireless networks.

B. Spectrum Graphs

The COHERENT project approach to abstraction models and network graphs are also considered in the context of spectrum management and sharing among network operators. The SMA architecture in Fig. 3 highlights the different information that are needed in the management and sharing process. This information is also intended to be represented in the form of COHERENT network graphs representing the state of radio resource utilization in the network. In this section, we elaborate on how network graphs can be used by the SMA for deciding on spectrum allocation. This is done introducing first the policy graph ($\mathcal{P}$), and the topology graph ($\mathcal{T}$).

Policy Graph: Network operators that are engaged in a sharing agreement decide to comply with a sharing policy applicable to the network nodes deployed over a certain geographical area. Such a relational information is represented in an abstract manner through the graph $\mathcal{P}$. The same operators are allowed to subscribe to different policies at different geographical locations, provided that this is recognized eligible by the spectrum regulator. A policy not only lays down the general rules, but optionally the general technical constraints of the resource sharing process. Furthermore, each policy carries the information of whether the sharing is vertical or horizontal, i.e., in Licensed Shared Access (LSA) or CoPrimary (CoP). Referring to Fig. 3, this would be part of the SMA knowledge base, specifically the spectrum sharing database. Additionally, the policy graph is one fundamental input to managing the re-assignment of spectrum among the operators at run-time. An example of policy graph is shown in Fig. 4 among three network operators denoted by the vertexes A, B and C, which also identify the small cells that have been deployed (LTE, Wi-Fi, etc.). The relationships (edges) in $\mathcal{P}$ are derived directly from the policy in place, and therefore the graph can be used for identifying spectrum sharing opportunities. Moreover, Vertexes can be annotated with different technical attributes (e.g. center frequency, transmit power, cell type, cell ID, etc.), whereas edges with the features of the sharing model i.e., LSA or CoP, and optionally with other technical information (received signal strength, small cell load, etc.).

Topology Graph: Fig. 4 shows an example where multiple small cells (vertexes) are operating in the same geographical area, but belong to the three different network operators as in the policy graph $\mathcal{P}$. We shall denote with $\mathcal{S}$ the set of deployed small cells. The edge among two nodes respectively located at x and y is an expression of the geographical proximity (i.e. notion of distance $||x - y||$), and it can be correlated to the harmful interference in case of sharing the same frequency band. An edge in $\mathcal{T}$ is present iff the two vertexes lays within a maximum geographical distance (interference range). It is worth noticing that the vertexes in $\mathcal{P}$ have multiple correspondence in the set $\mathcal{S}$. For SMA, $\mathcal{P}$ and $\mathcal{T}$ are the fundamental inputs to identify candidate small cells (TP in Fig. 1) for spectrum management purpose. The information carried out in $\mathcal{P}$ and $\mathcal{T}$ are combined to identify potential conditions of interference, when spatial reuse is allowed and to identify eligible nodes for sharing. The SMA shall consider the priorities among eligible nodes (if any) and allocate spectrum to the eligible operators based on different criteria such as auctions, knapsack problems and sum-rate optimization. To provide evidence of the usefulness of these graphs, few examples are provided in which the SMA derives the spectrum sharing opportunities from combining $\mathcal{P}$ and $\mathcal{T}$.

1) Example 1: Fig. 5(A) shows a scenario where node B1 is offering a part of its radio spectrum (indicated by B1:O) to other small cells in the topology graph that are requesting additional spectrum (indicated by e.g. A1:R). After an initialization phase, we shall assume that small cells of different operators are allocated on different frequency bands. To simplify the explanation, we assume that at a time *t*, only one cell is offering resources (local traffic under-loading), while all other small cells are requesting additional spectrum (e.g. local traffic overloading). We propose here a two-step approach. In the first step, as node B1 offers spectrum, the

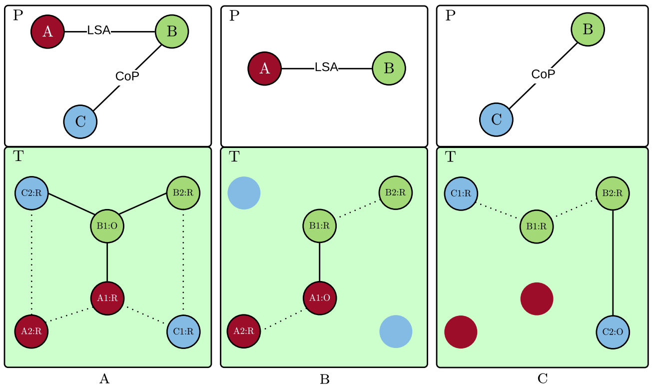

Fig. 5. Spectrum sharing example using P and T graphs

SMA can construct an induced policy sub-graph ($\hat{\mathcal{P}} \subset \mathcal{P}$) that involves the incidence to operator B. In this example, the full policy graph and the induced graph of node B do coincide. The SMA can hence prune the topology graph by removing edges that are not in $\hat{\mathcal{P}}$. In the second step, the SMA shall take into account also possible conflicting situations that might arise when sharing the spectrum of operator B. In Fig. 5(A), potential conflicts are denoted with dotted edges. It is important to notice that the sharing of the same frequency band can have the side effect of raising interference problems even in small cells that are spatially separated from B (e.g. node A2), and for which spatial reuse is allowed.

2) Example 2: Fig. 5(B) shows a scenario in $\mathcal{T}$ where only node A1 is offering spectrum to others and all other cells are requesting. In the first step, the induced policy sub-graph includes the incidence to operator A. The subsequent pruning of the topology graph is as in Example 1. As the policy sub-graph only allows the resources of operator A to be shared with operator B, the requesting nodes of C are not considered any more. In the second step, as no edge exists between B1:R and A2:R in the topology graph, the B's resource can be allocated to both small cells on an non-interfering basis. Potential conflicts would arise between small cells B1 and B2 but since they are part of the same operator's network, RRM techniques can be then used by this operator.

3) Example 3: Fig. 5(C) shows a scenario where node C1 is offering spectrum to all eligible requesting small cells. The SMA shall follow the same procedure as before to reduce the topology graph to the nodes and edges that are eligible per the policy graph. The induced graph $\hat{\mathcal{P}}$ allows the resources of network C to be allocated only to network B, and therefore small cells of operator A are not considered for spectrum allocation.

VI. Conclusion

This work studied spectrum sharing in the context of next generation mobile network. Particularly, we showed that dynamic spectrum sharing can take place within the 5G SDN-enabled architecture using abstract network graphs with COHERENT project as a use case. We gave an outlook of the radio resource management in 5G networks and the recent trends of spectrum management activities. The core contribution of this work has consisted in defining heterogeneous network abstraction models in the form of network graphs that can be used by a spectrum management application and acquired through a centralized SDN controller. Using specific examples, we have shown that such an application can identify eligible small cells that participate to the spectrum sharing process, and shed some light onto possible solutions to dynamically assign radio spectrum resource to the requesting network entities.

References

[1] "The Mobile Enconomy", whitepaper, GSMA, 2016.
[2] D. H. N. Nguyen, Y. Zhang and Z. Han, "A Contract-Theoretic Approach to Spectrum Resource Allocation in Wireless Virtualization", 2016 IEEE Global Communications Conference (GLOBECOM), Washington, DC, 2016, pp. 1-6.
[3] "System Architecture and Abstractions for Mobile Networks", COHERENT Project Deliverable D2.2, 2016
[4] H. Ahmadi, I. Macaluso, I. Gomez, L. DaSilva and L. Doyle, "Virtualization of Spatial Streams for Enhanced Spectrum Sharing", 2016 IEEE Global Communications Conference (GLOBECOM), Washington, DC, 2016, pp. 1-6.
[5] H. M. Soliman and A. Leon-Garcia, "QoS-Aware Frequency-Space Network Slicing and Admission Control for Virtual Wireless Networks", 2016 IEEE Global Communications Conference (GLOBECOM), Washington, DC, 2016, pp. 1-6.
[6] K. Tan, H. Shen, J. Zhang and Y. Zhang, "Enable Flexible Spectrum Access with Spectrum Virtualization", 2012 IEEE International Symposium on Dynamic Spectrum Access Networks, Bellevue, WA, 2012, pp. 47-58.
[7] X. Wang, P. Krishnamurthy and D. Tipper, "A Collaborative Spectrum-Sharing Framework for LTE Virtualization", IEEE Conference on Collaboration and Internet Computing (CIC), Hangzhou, 2015, pp. 260-269.
[8] RSPG (2016) "Strategic roadmap towards 5G for Europe", Radio Spectrum Policy Group. European Commission. RSPG16-032.
[9] ITU-R (2015) "Agenda for the 2019 World Radiocommunication Conference", International Telecommunication Union Radiocommunication sector. Resolution 809.
[10] M. Höyhtyä, A. Mämmelä, A. Eskola, M. Matinmikko, M. Kalliovaara, J. Ojaniemi, J. Suutala, J. Ekman, R. Bacchus, Roberson, "Spectrum Occupancy Measurements: A Survey and Use of Interference Maps", IEEE Communications Surveys & Tutorials, vol. 18, no. 4, p. 2386-2414.
[11] RSPG (2013) RSPG Opinion on Licensed Shared Access. European Commission, Radio Spectrum Policy Group. RSPG13-538. p.34
[12] ECC (2015) Technical sharing solutions for the shared use of the 2300-2400 MHz band for WBB and PMSE. European Conference of Postal and Telecommunications Administrations. CEPT Report 58. 21 p.
[13] ECC (2016) Operational guidelines for spectrum sharing to support the implementation of the current ECC framework in the 3.6 -3.8 GHz range. European Conference of Postal and Telecommunications Administrations. ECC Report 254. 63 p.
[14] FCC (2012) In the Matter of Expanding the Economic and Innovation Opportunities of Spectrum Through Incentive Auctions. Federal Communications Commission. FCC 12-118. 205 p.
[15] FCC (2016) Order on reconsideration and second report and order. Amendment of the Commissions Rules with Regard to Commercial Operations in the 3550-3650 MHz Band. Federal Communications Commission. FCC 16-55. 123 p.
[16] PCAST (2012) Report to the president: Realizing the full potential of government-held spectrum to spur economic growth. Presidents council of advisors on science and technology. 192 p. Available at https://www.broadinstitute.org/files/sections/about/PCAST/2012%20pcast-spectrum.pdf (Accessed April 2017).
[17] EC (2016) 5G action plan from EC. Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions. European Commission. COM(2016) 588 final. 11 p.
[18] ECC (2016) CEPT Roadmap for 5G. Electronic Communications Committee of European Conference of Postal and Telecommunications Administrations, Available at http://cept.org/ecc/topics/spectrum-for-wireless-broadband-5g (Accessed April 2017).