2016 23rd International Conference on Telecommunications (ICT)

REM: Revisiting a Cognitive Tool for Virtualized 5G Networks

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***Abstract*—The evidence that mobile data traffic is enormously increasing is forcing the whole telecommunications industry to rethink most of the paradigms which have driven until now the design of mobile networks, traditionally very efficient for voice and limited data communications. It is foreseen that 5G technology will introduce disruptive changes with respect to how radio resources are managed and consumed. In past years cognitive radio made its way to enable more intelligent and autonomous wireless networks but it has encountered several practical problems which have slowed down the massive adoption of this technology. Recently, an apparent turnaround has risen from the adoption of Software-Defined Network (SDN) and Network Functions Virtualization (NFV) principles. In this work we shall restart from known cognitive radio concepts which have been innovative in terms spectrum management in past years, paying particular attention to the concept of Radio Environment Maps (REMs). The main contribution of this work is hence to propose a high-level architecture in which SDN and NFV are the enablers that will facilitate the adoption of REM as the tool for spectrum management, since 5G will exhibit unprecedented levels of flexibility in managing different types of resources.**

I. Introduction

It is widely foreseen that the global mobile traffic in the future will continue to grow reaching the impressive level of exabytes per month (as indicated by Cisco [1]). Various strategies have been considered in recent years to find appropriate solutions that could be applied in the next generation of mobile network, referred to as 5G. Going back to fundamentals the channel capacity equation of Shannon provides us good 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 improving the SNR (e.g. advanced coding schemes) or the exploitation of various diversity opportunities (e.g., multiple-input multiple-output, MIMO, schemes) for many years. On the other hand, however, numerous spectrum measurement campaigns all over the world have emphasized the problem of high spectrum scarcity and inefficient use of the resource. These arguments have triggered the discussion on more flexible approaches to spectrum management and control.

The work presented in this paper has been funded by the EU H2020 project COHERENT (contract no. 671639).

Nearly twenty years ago the idea of cognitive radio was proposed for the first time by Mitola in his seminal work [2]. The idea can be summarized by saying that artificial intelligence can be applied also to telecommunications (both mobile devices and network), leading to more flexible and more efficient utilization of available resources. Cognitive networks are capable of analyzing previously observed data, learn from this analysis, find the best decisions and enforce them. Despite that the idea is an essential step forward it cannot be argued that it is close to practical deployment, since many important problems that blocks its implementation have to be solved still. One of them is an efficient and flexible spectrum management.

In cognitive radio, sensors provide information about spectrum utilization to detect the presence or absence of licensed users (incumbents). A cognitive engine can be designed to identify and exploit vacant frequency bands. Numerous spectrum sensing algorithms have been proposed in the literature [3]. The performance of single sensing device solutions, measured by the reliability of incumbent licensed users detection, showed to provide insufficient incumbent protection by the main regulatory bodies such as the Federal Communications Commission (FCC), Ofcom and the Electronic Communications Committee (ECC). In this context, cooperative sensing schemes have gained consensus as a promising approach to raise spectrum occupancy awareness [4]. However, in perspective of massive deployment of cognitive radio systems, the concept of REM made its way to become one of the pillar of cognitive systems [5]–[8]. Various research efforts done in recent years have greatly accelerated the development of this new technology and REM is the enabler of the Radio Environment Awareness (REA) idea. If combined with advanced spectrum sensing and monitoring techniques, REMs may become pivotal in future wireless networks in general.

A. The REM Concept

A REM is in principle the ensemble of advanced database and storage devices administered by a dedicated management

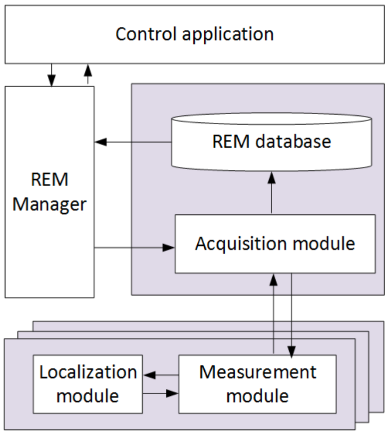

Fig. 1. The REM concept

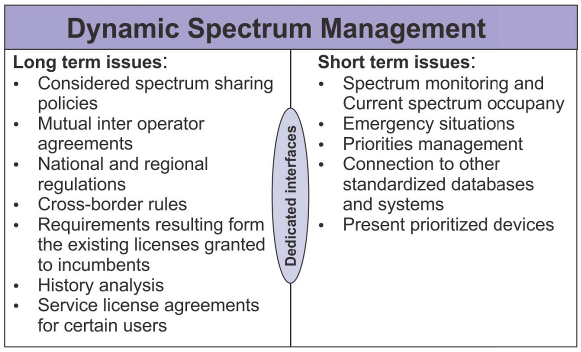

Fig. 2. Conceptual split of key aspects to be resolved in the context of dynamic spectrum management.

system (e.g., REM manager [7]). The functional architecture of the REM concept is shown in Fig. 1. It has four basic building blocks. The distributed *measurement module* periodically collects radio signal statistics from the geographical region covered by the REM. The *REM database* is a knowledge-based repository that stores spectrum occupancy information in a geographical region, where the granularity depends on the implementation of the measurement module. The *REM manager* generates and maintains the REM. The *control application* utilizes the REM information for spectrum management.

The REM approach is aligned with the recent concept of Radio Access Network (RAN) virtualization, in which network functions are decoupled from the underlying proprietary hardware [9]. Successful implementation of wireless networks virtualization relies on the orchestration of storage, database and hardware resources. In this paper, we shall argument the role of REM in the virtualized 5G network to enable efficient spectrum management.

The rest of the paper is structured as follows. Section II overviews the functional and implementation requirements for flexible spectrum management systems. Section III proposes the generic REM-based architecture for multiple stakeholders, whereas Section IV discusses how the proposed model relies on virtualization. Conclusions are provided in Section V.

II. Considerations on Spectrum Management in the Context of 5G

Finding accrued spectrum management and control schemes has become an evident need for more efficient utilization of the available spectrum resources for the next generation of mobile networks. Alternatively, more spectrum is needed but this can be satisfied only through either utilizing higher frequency bands (as this is considered in, e.g., millimeter wave systems) or better utilization of lower frequencies, e.g. below 6 GHz. However the utilization of lower frequencies is in general highly fragmented, statically and exclusively assigned to various stakeholders (aeronautical, radionavigation, fixed satellite and radio amateur services), which in turn results in a static licensing policy. On the other hand, one may observe that the spectrum is not occupied by incumbents all the time and at all geographic locations. This situation entails the problem of inefficient usage of the radio spectrum which, together with the anticipated traffic increase, has stimulated the development of new solutions for dynamic spectrum access. In the context of the next generation of mobile networks, this statement deserves further inspection, as spectrum is a *precious* public good with multiple players involved, such as products vendors, mobile (or virtual) network operators, regulators and other legal bodies. The problem to solve can be divided in two parts: long-term and short-term spectrum usage (see Fig. 2), which are discussed below.

1) Long-Term Spectrum Usage:

- *Considered spectrum sharing policies* include the change from static to dynamic approach to spectrum access, which has led to the development of various, advanced spectrum sharing schemes. Beside the traditional exclusive use of spectrum (also referred to as command and control) and license-exempt usage (in which any system is allowed to use the spectrum provided that it complies with technical specifications), solutions such as Licensed Shared Access (LSA) [10], Spectrum Access System (SAS) [11], License Assisted Access (LAA) [12] and Pluralistic Licensing (PL) [13] have been proposed, just to mention a few. Once the operator decides which spectrum sharing policy is the most convenient, it entails several requirements on its practical implementation. For example, the selection of the LSA approach means that involved operators need to agree on the rules, and how this policy can be applied (in terms of prices, chunks of leased spectrum, specification of power spectral density, etc). The rules and policy need to be stored and updated on demand in a dedicated database.
- *Mutual inter-operator agreements* can be used to reduce hardware costs. Network operators can decide to share the infrastructure, and mobile virtual network operators can offer services to mobile users without having any base station physically deployed. This trend can be extended to spectrum sharing agreements, where two or more operators define the rules on common usage of selected spectrum bands. Clearly, agreements are strictly related to

the applied spectrum sharing policies but they require the definition of some key long-term decisions, such as the amount of spectrum which is leased by one stakeholder to another, or the maximum allowed transmitted power. Long-term detailed agreements, stored in a dedicated repository, pave the way also for short-term coexistence rules.

- *National and regional regulations* are based on the prerequisite that an operator is obliged to follow the laws of national and/or regional regulators. This set of rules is fundamental for the identification of possible transmission schemes, but also for the definition of spectrum sharing policies and inter-operator agreements. These rules are rather inflexible and do not usually change over a short-time scale. However, since the approach for exclusive spectrum use is somehow depreciated, and more flexible solutions are allowed, the long-term rules might become more generic or adaptive to real-time monitoring of spectrum utilization and occupancy. An illustrative example would be the implementation of SAS or any other hierarchical approach.
- *Cross-border rules* have to consider the differences between different countries and national regulations, thus cross-border dependencies have to be further evaluated. This includes not only the consideration of rules coming from regulators, but also the mutual agreements between foreign operators and service providers.
- *Requirements from existing licenses granted to incumbents* should reflect the fact that if the proposed spectrum sharing policy is hierarchical and assumes incumbent protection, secondary operators will need to ensure seamless coexistence on the same geographical region. This requires to comply with long-term agreements (for full protection of incumbents in certain areas) but also real-time monitoring of the current spectrum occupancy is required. The former can be realized whereby dedicated repositories which can even be static, whereas the latter requires real time access to advanced databases.
- *History analysis* shall follow traffic behavior in geographical locations with a time granularity assumed to be daily, weekly, or in general to keep track of periodic cycles. In this case, it is beneficial to rely on the spectrum sharing decisions already made in the past in similar circumstances. Such an approach would require the presence of a dedicated cognitive engine for the analysis of data logs, as well as of databases and possibly large storage capacity. It can also be imagined that persons responsible for maintenance and traffic control would also be interested in data mining, thus dedicated interfaces serving the purpose should be developed.
- *Service license agreements (SLA) for certain users* is different from what discussed above since the definition of service license agreements assumes a user-centric approach. Service providers will be mandated to define SLAs which need to be enforced. Adequate human and machine interfaces are required in this case.

2) Short-Term Aspects Spectrum Usage:

- *Spectrum monitoring and occupancy* of different wireless systems deployed over the same space require permanent real-time monitoring of the spectrum resource. This is crucial to verify that the generic, long and short time rules are fulfilled and that constraints are not violated. The parameters measured at Layer-1 could include values of the received power and interference levels, whereas at higher layers other metrics could be used to estimate spectrum occupancy. In the context of 5G the development of a monitoring function is necessary, which requires careful database design for efficient (big) data mining. In this case, specific machine-to-machine communication is required, as the controller (engine) will query and update the database automatically without human intervention.
- *Emergency situations* require that the monitoring function must be complemented with the strict rules characterizing emergency situations. Once an emergency starts, immediate actions have to be performed to adapt network behavior in order to fulfill the rules set in place during a specific crisis. These rules are derived from the long-term databases described previously but need also to be continuously updated and maintained. Human intervention should be limited in this case.
- *Requirements resulting from existing licenses granted to incumbents* implies that once the long-term rules for incumbent protection are set in place, they have to be monitored in real time. It may happen that under an existing licensing scheme a new service specific of a protected system will be initiated, and the whole network needs to be reconfigured and adapted. Interaction between the databases and monitoring function is foreseen.
- *Management of priorities* depends on the spectrum sharing strategies enforced in a specific geographical region. Different priorities can be defined, and the presence of high-priority users has to be detected, such information stored and service quality ought to be guaranteed. Hence, permanent monitoring of different metrics that pertain to different layers is needed.
- *Connection to other standardized databases and systems* is essential for future wireless networks based on the integration of different technologies. A good example is the mutual coexistence between cellular and WiFi networks (we could indeed refer to advanced 3GPP Access Network Discovery and Selection Function (ANDSF), and to the WiFi Passpoint concept). The role of the database would be to continuously exchange information between coexisting wireless systems for better spectrum utilization similar to the LAA approach.
- *Equipment databases* could also be envisaged since the presence of databases containing information on the registered or currently operating devices could be beneficial for spectrum management. For example, incumbents or prioritized users could register their devices and request full protection at the expense of some additional cost.

TABLE I
DATABASES TYPES FOR SPECTRUM MANAGEMENT SYSTEM; S/L - STANDS FOR SHORT- AND LONG-TIME SCALE, RESPECTIVELY; H/M STANDS FOR HUMAN AND MACHINE UNDERSTANDABLE INTERFACE, ACCORDINGLY.

Database Name	Time scale	Content	Interfaces
Spectrum Sharing	L	Applied spectrum sharing policies	H/M
Inter-operator Agreements	L	Details from the legal and technical agreements	H/M
Policy	L	National transmit policy definitions	H/M
Cross-border Policy	L	Cross-border agreements	H/M
Incumbents Protection	L/S	Incumbent protection rules	H/M
Experience	L	Past decisions and data	H/M
SLA	L/S	Detailed definition of SLAs	H/M
Spectrum Monitoring	L/S	Real-time data on spectrum	M
Occupancy	L/S	Spectrum occupancy metrics	M
Emergency	L/S	Technical guidelines for emergency cases	M
Priority	L/S	Priority rules	H/M
External System	L/S	Allowed external systems	H/M

The above discussion allow us to summarize the list of prospective databases in Table I, where their functions are presented in brief. Furthermore, we may notice that there is the need for the definition of interfaces (or information exchange protocols) between the short- and long-term databases.

III. REM AS A TOOL FOR LONG- AND SHORT-TERM SPECTRUM MANAGEMENT

One of the key conclusions that can be drawn from the above discussion is that there is a strong need for accurate radio environment awareness. Long- and short-term data have to be stored for further processing by dedicated entities. In the context of cognitive radio, the REM concept was proposed as a tool for advanced spectrum management. The classical REM system consists of four key functional entities as described in Section I-A. This generic model is however object of further modifications and improvements. For example, a hierarchical, layered structure of REMs is considered in [7]. Numerous papers addressed potential applications of REMs in future wireless networks such as 5G [14]–[16].

In the context of advanced spectrum management system for the 5G ecosystem, we propose the multi-stakeholder approach, where various players can be present at the same time. REM databases could belong to a telecommunication operator, or fully or partially to a third party (e.g. a company offering solutions for enterprises). This concept is shown in Fig. 3. This approach does not assume any constraint on the structure of the databases in the sense that they can be fully distributed with hierarchical or even non-hierarchical arrangement. Moreover, there are no strict rules on how the database management has to be implemented. The management entities (engines) can create a specific hierarchical structure or can be the federation of autonomous modules. In this last case, the key problem consists in proprietary definition of standardized interfaces between the autonomous spectrum management systems (or specific sub-modules).

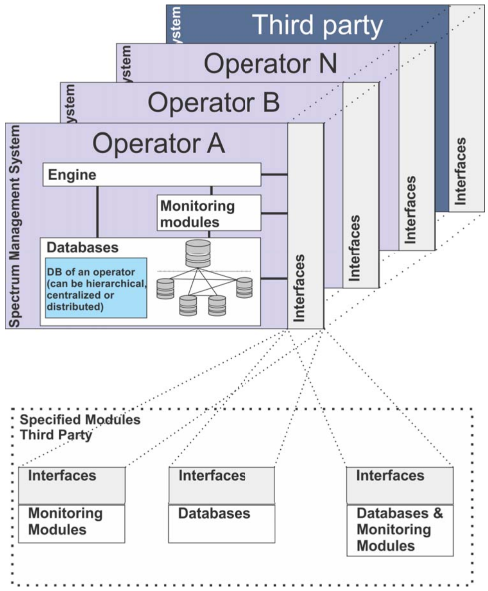

Fig. 3. REM based spectrum management

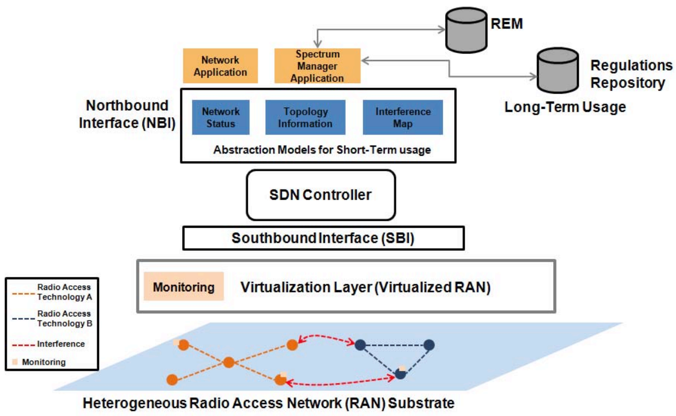

Fig. 4. SDN enabled long- and short-term spectrum management framework

IV. REM AS PART OF THE ECOSYSTEM IN VIRTUALIZED 5G NETWORK

Since 5G networks will strongly rely on new management and orchestration paradigms, the concepts behind the different databases presented above can be revisited in view of this approach. Indeed, 5G networks shall take advantage of SDN and NFV principles as the enablers for advanced network management. An SDN-enabled 5G network is built on top of an heterogeneous RAN substrate where different radio access technologies are operated within the same geographical region and at the same time. Such a spatial configuration makes interference very complex and harmful. As mentioned, not only more ample spectrum chunks are needed but also improved spectrum quality. This implies that in wireless systems the signal-to-interference-plus-noise-ratio (SINR) is more crucial than just SNR.

The simplified SDN-enabled architecture proposed in this work is shown in Fig. 4. The simplification consists in the fact that we do not detail how the virtual and physical infrastructure is managed due to lack of space. The physical network substrate is virtualized whereby a layer of virtualization (i.e. hypervisor) to create virtual radio resource pools, 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 (i.e. increased separation from the underlying hardware). The physical network is made of generic transmission points, and different technologies (LTE-U, WiFi, etc) may coexists causing mutual interference since they operate by assumption over the same spectral region and are deployed within the same space. The pool of virtual resources does not include only different radio access technologies but spectrum as well. The SDN controller enforces decisions on the underlying network through the southbound interface (SBI) and communicates with applications through the northbound interface (NBI).

The new application we propose is the *Spectrum Manager Application* (SMA), which exemplifies the cognitive engine previously discussed. The SMA can rely on different abstraction models representing the status of the underlying network, based on which cognitive algorithms and predictive models are executed. Decisions are then enforced by the SDN controller. A particular abstraction model is the interference map, which utilizes the SINR measurement reports. The reports are obtained from monitoring physical and virtual devices. The concept of interference in virtualized networks was already presented in [17]. To complete this picture, we argument that the SMA will rely also on different databases, including the REM and a repository where national and international regulations are stored and maintained. The abstraction models are used for short-term spectrum management, whereas the REM and the repository of regulations for long-term usage. In specific, the abstraction models shall expose, using suitable machine readable format, more volatile information to the SMA, which are successively passed to the REM, where they are stored and made accessible on demand. Thus, we enable two different REMs which operate over different time scales and that together become the enabler for efficient spectrum management.

V. Conclusion

In this work we have revisited several well-known and cutting edge research concepts which shall enable more efficient use of spectrum resources. The goal is to obtain larger bandwidths and higher spectrum quality. In this regard, advanced spectrum management which borrows from network virtualization principles can play an important role in 5G technology. We discussed that this will not only allow a more flexible utilization of spectrum and the adoption of more flexible license schemes, but also for cost reduction since radio resources can be shared and separated from the underlying hardware. The proposed high-level architecture exemplifies how these two aspects can be treated jointly. The core concept highlighted by this work is to utilize radio environment maps, a well-known concept in cognitive radio, since REM is still a fundamental tool for long- and short-term spectrum management in virtualized networks.

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