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ENVIRAN: Energy Efficient Virtual Radio Access Networks

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Abstract— **ENVIRAN is a new research project aiming at the research, design and deployment of new architectural solutions for network virtualization and cognitive radio networks. The project is about developing and testing a new network architecture, to enable innovation through programmability and control of network functions and protocols. For doing this, we solve different technical challenges. These are about network virtualization, open architecture, reconfigurable software suite, virtual base station and decision support system. Another important part of the project is regarding the development of a cognitive virtualization platform, to test the new developed solutions.**

It is well known that cognitive radio technology is a key concept suggested to use the radio frequency spectrum in a more efficient manner than previous mobile networks. The difference in our case is that the cognition is used not only to provide better resource use for bandwidth but also for other categories of resources like energy/power consumption (by using, e.g., green routing, cooperative/relay networking), hardware utilization (in form of, e.g., virtual Base Stations, cognitive/reconfigurable wireless devices), reduce the cost of supporting the required QoS/QoE, new business models.

Cognition and virtualization concepts are used to increase the efficiency of network management and resource utilization as well as to reduce the power consumption and the cost of supporting the expected QoS/QoE for communication. The expected research results will be tested, among others, in the world-wide virtual network PlanetLab.

I. Introduction

Research on green cognitive wireless radio networks has been a hot topic over the last years, with the consequence of more investments in research programs. Today, the current state of the art in Dynamic Spectrum Access (DSA) and Cognitive Wireless Networks (CRN) research is that it is not yet sufficient mature to get CRN technologies accepted by the telecommunications industry. There is hence an imperious need for further research and new testbeds. In particular, future research must consider multiple deployment scenarios and business directions.

On the other hand, the research on Cognitive Wireless Cloud (CWC) is not as mature as the research on DSA and CRN, as this research is in its early stage. That means there is strong need for new research activities and results to solve the above-mentioned research questions and to develop new technologies accepted by industry.

An intensive activity of standardization of Cognitive Radio Networks and Green Communications is done nowadays, which is driven by standardization authorities like 3GPP, European Telecommunications Standard Institute (ETSI), Institute of Electrical and Electronics Engineers (IEEE), US Department of Energy (DOE), Ministry of Economy, Trade and Industry of Japan (METI). Other important authorities are national administrative agencies like the Federal Communications Commission (FCC) in the USA, the Office of Communications (OFCOM) in the UK and the Swedish Post and Telecom Agency (PTS) in Sweden. Generally, these associations focus on harmonization of terminology and definition of reference models, analysis of trade-offs and potential risks and benefits of the new technologies as well as monitoring contributions to relevant standardization bodies.

ENVIRAN is a research project proposal submitted to EU FP7 with the goal to develop an ambitious and innovative approach to public safety communications and deliver a proof-of-concept [1]. LTE will be used for these purposes. For doing this, a consortium with ten EU partners has been created: VTT (Finland), BTH (Sweden), Tecnalia (Spain), University of Genoa (Italy), Teletel (Greece), Indra (Spain), Thales (France), Fraunhofer (Germany), TeamNet (Romania) and Abertis Telecom (Spain).

ENVIRAN will deliver an integral solution for more efficient resource usage of radio resources like energy, radio spectrum and existing infrastructures, which are not fully used today. The particular goal is to provide solution for situations when the safety communication is most critical, which demands for greater interoperability and enhanced inter-agency cooperation, broadband capabilities, cost effectiveness and high reliability and security. For doing this, ENVIRAN will use the concepts of virtualization and cognition to provide better resource usage to improve energy consumption, to improve the bandwidth and the hardware utilization as well as to reduce the associated cost to support the expected applications and the associated Quality of Service/Quality of Experience (QoS/QoE).

The ENVIRAN solution contains, among others, terrestrial segment, satellite segment, reconfigurable resource management, dynamic spectrum access and policy, facilities for green operations and policies as well as performance provisioning.

The rest of the paper is as follows. Section II presents the basic concepts behind ENVIRAN. Section III contains a short description of the ENVIRAN network architecture. The main research activities are presented in Section IV and Section V concludes the paper.

II. Basic Concepts

ENVIRAN is a combination of cognitive mobile communication technologies and green cloud computing for supporting mobile applications in a more efficient way with reference to flexibility, bandwidth, energy consumption, hardware utilization and cost.

A green cognitive virtualization platform will be developed and deployed, for end-to-end slicing. A slice is defined to be an isolated set of computational and network resources allocated and deployed across the entire network, for a particular task. The virtual networks will be extended from wired networks to wireless networks as well.

The main advantages of such an architecture are the possibility to define, develop and deploy a so-called meta-architecture to concurrently accommodate multiple architectures as well as to develop testbeds to experiment with different disruptive network and service architectures, without interference among experiments.

The users have no knowledge about the existing resources of different categories (e.g., computation, bandwidth, data access, storage, energy) but they have access to resources on-demand. Data storage and processing are moved out of the mobile devices and base stations to powerful computing platforms located in clouds. Green operations are provided as well. The efficiency of network management (in terms of, e.g., reconfigurability facilities, dynamic resource provisioning, quick and reliable decisions, better spectrum utilization, energy savings, reduced cost of supporting the expected

QoS/QoE levels) is increased. Another important advantage is in form of possibility for concurrent deployment of multiple network technologies on a shared network. The so-called multi-tenancy facility is provided in this case, which means that service providers of different categories (network operators, service operators, data center owners) can share the existing resources as well as the costs. Other advantage is in form of easy of integration of multiple services from different service providers, to meet the demands of users.

At the same time, network virtualization demands for solving questions related to, e.g., resource isolation, provision of expected performance, scalability (how many slices can be supported in a particular meta-architecture), flexibility, network management, context awareness, application development. Also, mobile network virtualization further complicates things because of the need to solve questions related to developing virtual Base Stations (vBS), cross-network signaling and operation, security issues, new business models.

All together, it is expected that this will open up the possibility of developing new advanced services like mobile healthcare, mobile commerce, mobile gaming, mobile learning.

III. Network Architecture

ENVIRAN is composed by several elements. These are (figure 1):

- ENVIRAN Access Service, which is about system for the provisioning of access to the ENVIRAN services. The objectives of ENVIRAN Access Services are to provide the access to system resources with improved efficiency in utilization of existing resources like energy, spectrum, hardware. There are two categories of Access Services, which are for terrestrial segment and for satellite segment.
  - ENVIRAN terrestrial segment, which is based on using Long Term Evolution (LTE) for public safety. LTE offers important advantages in terms of unified communication infrastructure, standardized interfaces and protocols, greater interoperability and enhanced facilities for interagency cooperation, much increased broadband capabilities, increased reliability and security facilities as well as cost effectiveness. An important element of the ENVIRAN terrestrial segment is the use of the so-called virtual Base Station (vBS). This means that several functions traditionally done at the Base Stations (BSs) or Access Points (APs) or User Equipment (UE) are now moved into the green cloud. Examples of functions are user management, resource allocation, cooperation enforcement and routing decisions.
  - ENVIRAN satellite segment, which is based on using satellite communication for places with no terrestrial access, or with difficult geographic conditions and with no preinstalled or damaged infrastructure. Generally, the satellite segment is requested to provide performance similar to the performance provided by the terrestrial segment. The price in this case is in form of high cost for the satellite communication.
- ENVIRAN cloud service, which is basically a solution used to significantly increase the efficiency and awareness of the whole system. The main targets are to provide the system management in an efficient way, to increase the system flexibility through centralized management and to reduce the sustainable operational expenditures. Elements like information collection, service-aware and management-aware functions, virtualization functions, radio resource management, decision making, energy savings policies, safety policies and business policies are considered here.

Altogether, these elements provide the ENVIRAN service for public safety communications. Furthermore, the ENVIRAN Access Network will be built up as an open architecture, which is composed by virtual Base Stations (terrestrial segment) and virtual Gateways (satellite segment). The open architecture is designed to support some functions of LTE for public safety, e.g., vertical handover, joint resource allocation, cooperative communications. These functions will improve LTE for public safety.

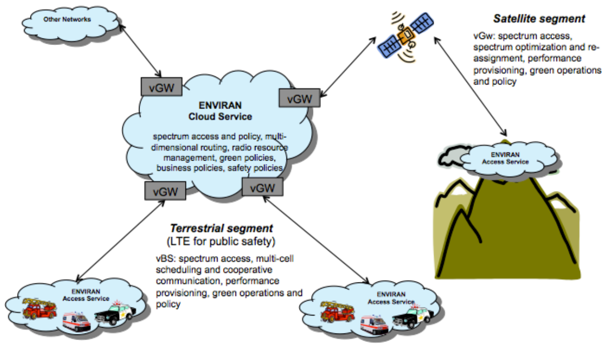

Fig. 1. ENVIRAN architecture

The suggested network architecture is based on the concepts advanced in [2]. This architecture is of type Cognitive Wireless Network over Multiple Operators (CWNMO), also known as Cognitive Wireless Cloud (CWC).

A so-called Cognitive Network Manager (CNM) is used to control the multi-domain network. This is an entity that collects information about the existent resources in multiple networks/domains and, based on some particular decision making algorithm, takes decisions needed for the particular situations. In a similar way, a so-called Cognitive Terminal Manager (CTM) is used for similar purposes in terminals. Furthermore, a so-called Common Control Channel (CCC) is used for control purposes, to provide the signaling needs among the diverse participating entities in different networks (cross-network signaling). To avoid interference with the licensed bands, CCC is placed in out-of-band frequencies like, e.g., the unused parts of the UHF band recently released by the discontinuation of analog TV [3]. The main advantage is that the control data is separated from the user data transmission, and the synchronization problems are eliminated.

A reconfigurable software suite with three layers is used in CNM and CTM. These are the overlays (service- and management-aware functions, also used for the interconnection with the applications/services), the middleware and the underlays (Software Defined Radio underlay, virtualization functions, for interconnection with the networking elements). The convergence between wired and wireless networks as well as among heterogeneous wireless access technologies is provided. User-centric communication is offered for a multitude of services with the associated elements (network selection, seamless mobility, application and session management as well as guaranteed QoS/QoE). Other elements are in form of cognitive network operation and management (CNOM) as well as provision of advanced services, e.g., energy efficient. Cognitive networking means that the networking entities (Base Stations, Mobile Terminals) have the ability to operate in a carrier independent way and to optimally take decisions regarding the selection of, e.g., appropriate radio interfaces, transmit power level, MAC, routing protocol, e2e route as well as to organize into resource-optimized ad-hoc network. Furthermore, the Cognitive Wireless Cloud facility offers scalability advantages like the possibility for link aggregation and radio selection over multiple operators.

The wireless network cloud functionality means that several functions traditionally done at the Access Points (APs) or Base Stations (BSs) or even Mobile Terminals (MTs) are now moved into the green cloud. Examples of such functions are network and user management, greening, resource allocation, cooperation enforcement, medium access, routing, data flow scheduling, handover management. Software Defined Radio (SDR) is used to carry the data exchange.

A so-called Wireless Networking Functionality as a Service (WNFaaS) layer is added in the four layers virtualization protocol stack, to enable the provision of wireless network cloud functionalities. This is a concept initially suggested in [4]. This means that all control, configuration, optimization and mobility control functionalities are moved from the APs or BSs controllers to the green cloud, and provided as a service to customers.

Practically, this means that now the radio antennas are physically decoupled from the BSs, where BSs exist virtually within general-purpose green Data Centers (DCs) at distant locations. An important advantage of this concept is cost savings. Network upgrades are easily done through installation of new software at DCs. Another important advantage is that the network can now be managed in a more centralized way, with the raw signals being relayed to/from multiple antennas via, e.g., optical fibers. Finally, it is also important to highlight the efficiency aspects of this concept, which now become better. Pooling the software radio resources within a DC makes the network much more adaptive to user demands, as the resources can now be easily reallocated across different BS cells.

There are several difficulties related to the problem of extending the virtual networking to wireless networks, which need a particular attention. Some of the most important ones are regarding [5], [6]:

- Abstraction of heterogeneous wireless access networks (for emulating multiple BSs) for seamless connection with the wired virtual network.
- Programmability, for control purposes.
- Isolation of wireless resources such as radio frequencies, throughput or name spaces for accommodating multiple virtual networks on a single wireless access network, for ensuring performance guarantees.

Another important element in the suggested architecture is the so-called green cloud. By this, we mean cloud architectures where the data transfer and computation is energy efficient. The goal, in this case, is to develop advanced topology, techniques and schemes that reduce energy consumption in the data transfer and computation while achieving higher data rates. This is particularly important for Mobile Terminals (MTs), with limited storage and computing capacity, due to limited size and battery. MTs of type Cognitive Radios (CRs) will be able to shift data and functions to the cloud by using their communication and networking capabilities. A green cloud can be used in this case to perform resource/energy demanding operations like, e.g., related to video processing and transfer, and feed back the results of the computation.

Information about the available resources is collected and a multi-dimensional knowledge database is used to represent the data collected in the heterogeneous networks. Different categories of resources can be considered for data representation like Radio Access Technology (RAT), Cell_Id, frequency band, transmission power, modulation scheme, domain, geographic location, built-in resources (processing power, battery level). A decision maker unit is used for the computation of, e.g., end-to-end (e2e) route and a predefined objective function is used for decision making. The goal is to exploit the under-utilized spectrum portions for green-friendly communication. Continuous and dynamic optimization of the system performance must be provided as well as efficient use of the system resources (spectrum, energy). These mechanisms are acting at different layers in the TCP/IP protocol stack. The effects of the taken decisions are evaluated and the future actions are improved thereby providing self-adaptive operations and control. Service and business driven management is done in a transparent and independent way with reference to the existing underlying elements (network infrastructure, domains and resources).

For instance, in the case of IP layer, the decisions may refer to routing, which is expected to be of type multi-dimensional ad-hoc. By "multi-dimensional" it is meant that the end-to-end (e2e) route is expected to cross several dimensions like space, domain, frequency, power, time. A number of difficult questions need to be answered regarding opportunistic spectrum access, spectrum and network heterogeneity, demand for energy saving as well as the demand to provide diverse Quality of Service (QoS) / Quality of Experience (QoE) levels for different applications (multi-dimensional optimization problem).

Furthermore, the advent of cognitive radio devices and networks with elements like femtocells provide an enabler for green systems and services as well. For instance, given a CRN, there are several methods that can be used to save power, like [7]:

- Moving subscribers from one particular band to other active band allowing so the first band be switched-off.
- Using dynamic spectrum sharing and reducing so the necessary transmission power by increasing the channel bandwidth.
- Using dynamic spectrum sharing to better take advantage of favorable propagation bands and reducing so the transmission power.
- Using of cooperative communication techniques (relay, distributed antennas system, multicell coordination, group cell).

Theoretical studies reported in littterature indicate that there is a significant potential for reducing the power consumption for the operator by using spectrum management solutions based on CRN. Power reductions by more than 50% are reported, e.g., in [7].

IV. Research Issues

The research and development activity is partitioned in several distinct activities. These are as follows:

- Cognitive Virtualization Platform.
- Protocols and Software Suite.
- Cognitive Network Operation and Management.
- Performance Modeling and Analysis.

Details on these activities are as follows.

A. *Cognitive Virtualization Platform*

Basically, this is about research and development of a so-called Cognitive Virtualization Platform (CVP), which is a virtual network with cognitive radio networks facilities and other facilities. The tasks of this platform are to provide cooperative resource management over wired and heterogeneous wireless networks as well as to provide virtualization of cognitive Base Stations, with cognitive radio functionalities. By this, we mean Dynamic Spectrum Access (DSA), reconfigurable software suite and decision support system for cooperative network operation and management. The virtual cognitive Base Station is implemented as a virtual machine.

There are three functional elements in the CVP:

- Heterogeneous wireless access networks, which are accommodated in one virtual network by sensing the radio environment, making decisions on optimized selection of wireless access and reconfiguring the radio functions.
- Integrated resource management, for wired and wireless networks. This is about virtual network reconfiguration, protocol selection on virtual networks and resource allocation to virtual networks. A number of parameters (both individual and system) are made programable and used for purposes like, e.g., operation frequency, bandwidth, MAC parameters, routing parameters.
- Data Center, used for management purposes. As mentioned above, a fifth layer (WNFaaS) will be developed for these purposes in the four layers virtualization protocol stack.

A solution similar to the one advanced in [8] will be developed. This is based on using three entities: service provider, infrastructure provider and radio terminal.

With the help of these entities, different services can be developed, which are relevant for different scenarios. Both slice user and administrator perspectives will be considered in the service development. All together, this creates a so-called Mobile Virtual Network Operator (MVNO). Connected with this, we will also study economic models regarding the sharing of resources and services among teleoperators, service operators as well as other aspects regarding energy-efficient cognitive radio networks.

B. Protocols and Software Suite

This research activity is about exploring different architectural options and, based on that, to suggest a comprehensive solution covering heterogeneity, legacy and security issues. Both network operator and user requirements are considered in this work.

Some of the most important parts of this work are:

- Development of new cooperative algorithms and network policies for heterogeneous networks, which will be combined with green CRN techniques. The goal is to provide broadband services to small cell users with high spectral utilization. Key technical challenges are on interference mitigation, handover, self-organization, radio resource allocation, backhauling and cooperative Multiple Input Multiple Output (MIMO).
- The software suite will take routing and optimization decisions for efficient communication with reference to parameters like best energy efficiency, highest possible bandwidth, lowest price, best security level. Related to this, we will investigate the definition of appropriate QoS metrics for e2e routing, path selection algorithms and routing algorithms. The challenge is to compute e2e paths to satisfy the particular e2e QoS/QoE constraints. For doing this, local state information and/or global state information can be used. A particular difficulty is because an e2e route may involve crossing different IP domains and different spaces, e.g., geographical space, frequency and power. The path selection problem is treated as an optimization problem. The goal is to investigate and to compare different routing solutions together with the associated optimization algorithms, and to finally design routing and optimization algorithms able to cope with realistic traffic and networking conditions.
- Decision making, where the primary goal is to develop an uniform decision making system for communication under energy, spectrum and domain constraints. Routing decisions can be characterized in terms of input information (characteristics of spectrum opportunities), energy characteristics, output selected channels and the internal process of decision making. Elements like spectrum access and policy, energy constraints, self-organization in heterogeneous networks and security will be considered. The target is to combine together different decision making methods to take intelligent decisions based upon partial characterizations of CRNs. Different possible techniques will be evaluated such as neural networks, genetic algorithms, game theory and/or heuristic algorithms such as fuzzy logic.
- Wireless Networking Functionality as a Service (WNFaaS) is an architecture where all control, configuration, optimization and mobility control functionalities are moved from the APs or BSs controllers to the green cloud. Basically, the main function is to emulate an isolated private BS transceiver for every slice. In other words, this means that the virtual Base Station (vBS) is emulated outside the physical BS and provides so portability facilities. Key elements of WNFaaS are the so-called orchestration model and the orchestration engine. The orchestration model is acting like a driver for the orchestration engine, whereas the orchestration engine is acting as a functionality provider. Different constraints must be considered for the orchestration engine regarding, e.g., time sensitiveness, robustness, frequentness, security.
- Green cloud, which is basically about research and development of methods and algorithms for energy savings in data centers but without sacrificing service level agreements [9]. These solutions are important as they represent excellent economic incentive for data centers- and tele-operators. This activity is basically about the development of better solutions for cloud architectures with high networking performance and efficient energy usage. Solutions like energy-efficient hardware, energy-aware scheduling in multiprocessor and grid systems, power minimization in clusters of servers and power minimization in wired and wireless networks will be investigated. A particular focus will be given to networking, where solutions based on re-engineering, dynamic adaptation (power-aware routing, provision of sleeping state), network and topology control will be considered.

Alltogether, the expected new solutions will give us the opportunity to provide new architectural solutions for green cognitive mobile communications and computing architecture and protocols.

C. Cognitive Network Operation and Management

This is about the development and implementation of a reconfigurable software suite needed for Cognitive Network Operation and Management (CNOM) and the decision support system. Basically, this is about combining cognitive algorithms, cooperative networking anf cross-layer design, with the goal of provisioning of real-time optimization of the system. For doing this, the scalability and fault tolerance capabilities of Peer-to-Per (P2P) will be used.

This activity contains:

- Design and development of a dedicated middleware platform.
- Specification of external and internal interfaces for the middleware.
- Specification and development of software overlays, e.g., knowledge database, decision maker, spectrum access and policy, green enabler.
- Design and development of a platform for data representation, for collection and analysis of data in multiple dimensions and hierarchical levels.
- Design and development of a decision making system, to support, e.g., selection of an e2e green communication channel for a particular communication.
- Development of green routing and optimization algorithms, also for inter-routing support among different CRNs.
- Determination of the theoretical limits of the suggested architecture and algorithms.

The architectural and protocol solutions are parts of the cognitive virtualization platform and they will be tested in this platform.

D. Performance Modeling and Analysis

The goal of this research activity is to develop theoretical models that enable us to predict the system performance and capacity in a real target environment consisting of a mix of cognitive virtualization platform, public and/or private cloud and local servers. For doing this, we will develop a framework for quantitative performance analysis of the system. The framework must be able to generate and submit real and synthetic workloads, to gather the measurement results and to extract different statistics relevant for the particular experiment.

This activity contains:

- Data representation and analysis. Data will be collected and presented in a multi-dimensional view, also called data cube. Example of parameters are frequency band, bandwidth, transmission power, energy efficiency, geographic location, domain. An important challenge is to enhance the visual representation of the data cube and to facilitate the interpretation, analysis and decision. Particular focus will be given to the problems of lower-dimensional data representation, data analysis as well as the assesement of the impact of heterogeneous traffic flows on the associated queuing systems and networks.

- Energy efficiency metrics. A difficult research question is regarding the definition and measurement of appropriate energy efficiency metrics for green cognitive cellular networks and the associated framework [6], [10]. The goal is to allow a comprehensive evaluation of energy performance and savings in a practical system of type Cognitive Wireless Network over Multiple Operators (CWNMO). The energy efficiency metrics are expected to provide information in such a way to allow for a direct comparison and assessment of the energy consumption of different components, systems and overall network. The problem in this case is because of the need to develop neutral energy efficiency metrics, which are not dependent on other parameters like spectrum efficiency, power reduction, deployment efficiency, network performance. This is because of the existent dependency (trade-offs) among these parameters, as mentioned above [11]. We will develop solutions that reduce or even eliminate the impact of the trade-offs on network performance and cost.
- Modeling, simulation and analysis of cognitive virtualization platform, including virtual Base Station and green cloud. The goal is to develop theoretical and simulation models to allow us that, based on measurements in a virtual cloud environment, to predict the performance and capacity in a real target environment. For doing this, we will develop an appropriate framework for quantitative performance analysis of cognitive virtualization platform, also including virtual Base Station and green cloud. The framework must be able to generate and submit real and synthetic workloads, to gather the measurement results as well as to extract different statistics specific to these entities. The performance and capacity tests must be related to the associated business process as well. All together, the performance and capacity tests are expected to enable, among others, the development of adequate migration strategies to right-size the investments in developing cognitive virtualization platforms and the associated elements.

All together, these results will provide us with powerful tools for performance evaluation and prediction to help us improve the design and development of the protocols and software suite.

V. Conclusions

A project proposal for research, design and deployment of a new architectural solution for green cognitive mobile system has been suggested. The main questions to be answered are about cognitive virtualization platform, protocols and software suite as well as system for cognitive network operation and management.

The benefits of such a system are huge with reference to energy savings, spectrum increase, hardware utilization, cost savings, new business models. We believe that the industry will show interest in our project as well as the expected scientific results.

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