Future Network & MobileSummit 2011 Conference Proceedings
Paul Cunningham and Miriam Cunningham (Eds)
IIMC International Information Management Corporation, 2011
ISBN: 978-1-905824-25-0

Testbed Federation: An Approach for Experimentation-Driven Research in Cognitive Radios and Cognitive Networking

Alejandro SANCHEZ[1], Ingrid MOERMAN[2], Stefan BOUCKAERT[3], Daniel WILLKOMM[4], Jan HAUER[5], Nicola MICHAILOW[6], Gerhard FETTWEIS[7], Luiz DASILVA[8], Justin TALLON[9], SofiePOLLIN[10]

[1]*Thales Communications SA, 146, Boulevard de Valmy, Colombes, 92704, France*
Tel: +33 (0) 146 13 26 16, Email:Alejandro.sanchez@fr.thaleshroup.com
[2,3]*Ghent University - IBBT, Gaston Crommenlaan 8 Bus 201, Ghent, B-9050, Belgium*
[2]*Tel: +32 9 33 14900, Fax: +32 9 33 14899 r, Email:Ingrid.moerman@intec.ugent.be*
[3]*Email:Stefan.Bouckaert@intec.ugent.be*
[4,5]*Tel. Network Group, Technische Universität, Einsteinufer 25, 10587 Berlin, Germany*
[4]*Tel: + 49 (0)30 31421980, Fax: +49 (0)30 314 23818, Email: willkomm@tkn.tu-berlin.de*
[5]*Tel: + 49 (0)30 31423827, Fax: +49 (0)30 314 23818, Email: hauer@tkn.tu-berlin.de*
[6,7]*Vodafone Chair Mobile Communication Systems,*
Dresden University of Technology, Dresden, Germany,
[6]*Tel: +49 (0)351 463 41047 Email: nicola.michailow@ifn.et.tu-dresden.de*
[7]*Tel: +49 (0)351 463 41047 Email: fettweis@ifn.et.tu-dresden.de*
[8,9] *CTVR, Trinity College, College Green, Dublin, 2, Ireland*
[8]*Tel: +353-1-8963660, Fax: + 353-1-6772204, Email: dasilval@tcd.ie*
[9]*Tel: +353-1-8968441, Fax: + 353-1-6772204, Email: tallonj@tcd.ie*
[10] *IMEC, Kapeldreef 75 3001 Leuven, Belgium*
Tel: +32 16 28 8750, Email: sofie.pollin@imec.be

Abstract: The sub-optimal exploitation of radio spectrum is widely accepted. Cognitive radio is a technology that aims to address this issue and improve the overall efficiency of radio spectrum utilization. However, this promising technology is far from being mature at present. In addition to theoretical research, experimentally-driven research is needed to convince industry and regulators of the benefits of cognitive radio. Several initiatives in this direction are taking place or are currently operational in both Europe and the United States. Most of them feature testbeds devoted to a specific radio access technology, network topology or application. A "federation" of testbeds, addressing different applications or technologies each, can offer a richer and more powerful framework to tackle the large variety of challenges of experimentally-driven research in cognitive radio. The approach proposed in this paper combines the existing capabilities of several testbeds to build a "federation". Through intelligent combination of hardware and software components originating from different testbeds and linking them together via standardized interfaces, new components with enhanced capabilities are created. Another key feature of the "federation" is the establishment of a benchmarking framework, enabling repeatable and reproducible results in a controlled wireless environment and allowing a fair comparison between experiments.

Keywords: Cognitive Radio, Cognitive Networking, Experimental Research, Software Defined Radio, Testbed, Federation, Interfaces, Benchmarking.

1. Introduction

Many studies across Europe and the United States have shown that vast amounts of the licensed spectrum are under-utilized, when time and geographical location are taken into account [1]. In this context, dynamic spectrum access is considered by the scientific community as one of the key solutions towards more efficient utilization of this limited physical resource and thus models for spectrum access with varying degrees of freedom are studied. Among those, one promising approach is represented by the concept of cognitive radio (CR), which falls into the category of hierarchical spectrum access. It can be further classified as a method for spectrum overlay [2].

Cognitive radio and cognitive networking (CN) involve several aspects that exceed the scope of traditional wireless communications systems. Novel features from the technical side include software-defined radio (SDR) capability, frequency agility and spectrum sensing functionality, while components for observing the wireless environment, adapting to given conditions and learning from past decisions are brought along by the cognitive aspect.

Typical cognitive radio scenarios involve wireless communication systems that operate in the Industrial, Scientific and Medical (ISM) band, because of its internationally accepted open sharing model, as well as in the frequencies that are being freed up in the switchover from analogue to digital TV broadcast, also known as the Digital Dividend. In cognitive radio, challenges arise from the large diversity of existing wireless standards that operate in these frequencies and the unpredictable behavior in terms of channel access and traffic load when different wireless systems coexist. Further, a question of interest to mobile operators is whether and how cognitive radio can be brought to coexist with established cellular networks of 2G, 3G and 4G.Therefore other cognitive radio scenarios are also addressing cooperative and collaborative dynamic spectrum access in licensed bands.

The cognitive radio paradigm was first proposed by [3] more than a decade ago. However, the technology is still in an early stage of development. Hence, research in the cognitive radio and cognitive networking domains appears as a necessity. As introduced above, the complexity of this endeavour is huge and thus it calls for advanced approaches. An experimental-driven research based on an infrastructure of federated testbeds is the approach this paper will present.

The research leading to these results has received funding from the European Union's Seventh Framework Programme FP7/2007-2013 under grant agreement n° 258301 (CREW project).

2. Overview of Salient Cognitive Radio Testbeds

There are a number of cognitive radio testbeds in various phases of planning or operation by research labs around the world.

CORNET, at Virginia Tech, is a heterogeneous wireless communication network testbed based on cognitive radios. This network consists of 48 radio nodes spread over four floors and is focused on cognitive engine design, self organizing networking algorithms and network security. It is designed to serve as a resource for cognitive radio research and education, adopting open source software and a component-based modelling structure [4].

Rutgers in New Jersey has a project called ORBIT which includes a two-tier laboratory emulator/field trial network testbed designed to achieve reproducibility of experimentation, while also supporting evaluation of protocols and applications in real-world settings. It uses a large two-dimensional grid of 400 IEEE 802.11 radio nodes which can be dynamically interconnected into specified topologies with reproducible wireless channel models. Their testbed has been used to evaluate coexistence among different hardware platforms in shared spectrum bands [5].

RWTH Aachen in Germany has what is called a DES (Distributed Embedded Systems) testbed, which is a hybrid wireless multi-transceiver network. It consists of a wireless mesh network (WMN) and a wireless sensor network (WSN). The testbed consists of 95 wireless mesh routers equipped with three or more IEEE 802.11a/b/g network adapters and the same number of wireless sensor nodes of type MSB-A2. The research focus of this group is on network architectures, protocols on ISO/OSI layers 2-7, and applications for next generation wireless networks.

Unlike these testbeds, each of which is operated by a single research group, a federation such as the one proposed by the CREW project [6], brings together testbed capabilities in several academic institutions and industrial research labs.

The idea of federated network testbeds has been explored by research programs funded by the European Commission and the National Science Foundation, in the US. There are several European initiatives like OneLab, PII and WISEBED [7]. The GENI project, in the US, is a virtual laboratory for at-scale networking experimentation. The objective is to provide an experimentation environment for exploring innovations in network science, security, and network services and applications. All of these are large research efforts targeted at general network architecture and protocol design and experimentation, while CREW focuses on the specific needs and challenges of cognitive network and dynamic spectrum access research.

3. Challenges for Experimental Validation of Cognitive Radio and Cognitive Networking Solutions

A cognitive radio is a radio that adapts its operation intelligently to the dynamic environment. In that short definition, the major challenges for cognitive radio experimentation are already visible: the need for reconfigurable or adaptive hardware and software and the need for a well-defined dynamic environment. Furthermore, since in a federation of testbeds each of them contributes with their own hardware and specific environment, it becomes extremely challenging to define an experimentation framework that can be applied to all, and more importantly, to allow a fair comparison between experiments on different testbeds or in different environments. The three major challenges that are identified in this approach are briefly discussed below.

3.1 – Adaptive Hardware

Most experimental testbeds are, for cost reasons, based on off-the-shelf hardware. While these off-the-shelf solutions offer certain levels of adaptability, this adaptation is typically limited to a small set of configuration parameters such as setting the transmission power of the communication channel. In addition, it is often difficult to get access to the low level physical layer parameters, which are needed for instance for monitoring the dynamic environment or sensing. As an alternative, many researchers use Software Defined Radio (SDR) solutions such as the USRP [8] or WARP [9]. These solutions are much more adaptive or reconfigurable, but more expensive and, more importantly, more difficult to employ in large networks because of their limitations in data-rates or software support.

Single research institutions nowadays rarely have the resources and knowledge to bring the plethora of different wireless technologies together to perform large-scale experimental cognitive radio; instead, experiments are often conducted at a single location with particular equipment available. Effective experimentation for cognitive solutions will require merging off-the-shelf solutions with fully flexible SDR solutions.

Emulation of wireless conditions that may be experienced by a cognitive radio offers an alternative and complementary approach to pure testbed experiments, by enhancing the repeatability of experiments while preserving the realistic channel conditions encountered by the radios. Emulation has been used in wireless network research, as discussed in [10] and references therein. The recording of wireless environment parameters measured in one of the federated testbeds for use in experiments run in a different testbed can enable a form of emulation, and is an important component of CREW's approach.

3.2 – Well-defined Environment

Every testbed is defined in a specific environment, city or office building. Cognitive solutions can be compared by how well they adapt to a given environment or situation. This can be achieved by performing a single experiment in many testbeds, or by emulating different environments in a given testbed. For both approaches, it becomes necessary to be able to define and specify a dynamic channel environment as well as to reproduce (replay) the environmental characteristics in a controlled way for a fair comparison among competing protocols. Furthermore, it is also desirable to monitor the environment during the experiment for validation purposes: the test facilities should provide the experimenter with information about the actual environmental conditions during the experiment for real-time or post factum/offline analysis in the process of verifying the comparability of experiments.

One of the biggest challenges in cognitive radio research is the reliable detection and protection of primary communication. While reliable primary user detection is one main reason why experimental validation is needed, it is also a great challenge, because it requires the generation of realistic primary user signals. Using real "production" primary signals is often not possible for two reasons: first, primary user communication may in reality be influenced by the cognitive experiment (and thus simple non-adaptive reproduction of primary signal may be insufficient); second, it is hard to evaluate the performance of the cognitive system, i.e. verifying whether the primary user communication was influenced by the cognitive radio system-under-test. Artificial primary signals are also hard to produce (due to a lack of spectrum licenses and the complexity of the signals) and simplified versions might not give realistic results. Furthermore, reproducing realistic propagation environments that are characteristic to the particular primary user systems will often be difficult. This is, in fact, related to a more fundamental challenge: it is typically impossible to reproduce wireless conditions exactly, because small differences in the environment may lead to large variations in the quality of the signal (e.g., due to small-scale/multipath fading [11]). Therefore, usually multiple replications of the same experiment must be carried out to achieve a certain level of statistical confidence and to realize "comparability".

3.3 – Experimentation Framework

As mentioned before, cognitive solutions can be compared according to how well they adapt to a given environment. They can also be compared according to how much interference they create to an existing user. Therefore a framework is needed to compare different cognitive solutions that are applied to the same environment, as well as in different testbeds/environments.

Dedicated support for repeatability of experiments, that is, to test and evaluate cognitive radio concepts and algorithms under "comparable" external (environmental) conditions in order to allow a fair comparison between different approaches, remains another major challenge. One reason is that the definition of comparability or reproducibility is often dependent on the system/concept under investigation and has to be well-understood by the experimenter: for example, a communication protocol that realizes cooperative, distributed spectrum sensing might be evaluated with the help of a process that generates stochastic primary user traffic (following a certain distribution). On the other hand an algorithm that, for example, relies on certain temporal characteristics of the primary user (e.g. to detect a primary user by its specific beacon interval discovered in the energy profile) may require more deterministic traffic conditions. Although ultimately it is the user/experimenter that has to understand this aspect, the testing environment should allow different granularities of "repeatability" and increase the experimenter's awareness of possible problems. An experimentation framework can, e.g., support the user by providing automatic repetitions of experiment-sets with the possibility of adding suitable termination conditions.

The definition of experimental facilities or a federated testbed and methodologies introduced in the next section address the above challenges for experimental validation of cognitive radio and cognitive networking solutions.

The specific characteristics of each testbed that belongs to a federation, and the experiments enabled by these testbeds, are widely different. An uniform control framework for experimentation is hence not a primary concern of the CREW project. However, we envision the definition of a set of benchmarks that can be used across multiple testbeds and multiple realizations of a given type of experiment (e.g., a cooperative sensing experiment, or a distributed dynamic channel selection experiment). We are also defining guidelines for the collection and storage of data sets that result from cognitive radio experiments, with the objective of allowing reusability and comparison of results.

4. Technical Approach

4.1 – Federation

There are many challenges involved in bringing together mature wireless (cognitive) testbeds and cognitive components, as explained above. Each testbed and cognitive radio component has its own history and user group, which results in valuable complementary expertise within the federation consortium. However, there is also a certain overlap in functionality: multiple tools and techniques are available to describe experiments, run experiments, and to collect data. Furthermore, the different testbeds and cognitive components to be integrated in the federation are very diverse, ranging from flexible software architectures [12] deployed on top of cognitive radio platforms such as the USRP [13], to large-scale wireless sensor and Wi-Fi based testbeds with over 200 nodes [14,15].

The most common approach found in the literature to federate different testbeds is to define an interface on top of each testbed, to allow remote access and configuration from a single control point. In contrast, the main research efforts of the proposed approach are not invested in creating a single uniform tool to reserve resources, but in optimally combining the available expertise and resources in a pragmatic way: federation is not seen as the goal, but as a means to facilitate advanced experiments in the field of cognitive radio and cognitive networks. Moreover, running simultaneous experiments on multiple interconnected wireless testbeds which are outside of each other's interference range (e.g. in different countries) is different from interconnecting wired testbeds: while the location of wired servers is not necessarily important, wireless interference domains are completely separated when remotely interconnecting wireless networks. As a result, two remotely interconnected wireless networks cannot represent a single wireless domain. Since spectrum use is an important aspect of cognitive radio research, simultaneous use of different testbeds is not considered a priority.

To this end, a three-step federation roadmap is followed. In a first step, a common portal website is created that holds a comprehensive and uniform description of the functionality and characteristics of each testbed and cognitive radio component, access information and usage guidelines. In this initial federation mode, access to individual testbeds –initially by all partners, later by the broader public- is enabled.

The second step is to physically relocate hardware and tools. For example, a software architecture for cognitive radio research developed at one location can be installed on top of sensing hardware currently developed at a second location, and then deployed in a controlled wireless experimentation environment at a third location. In this second federation mode, the individual partner sites remain operational, while the combined expertise and equipment now also allows more complete and more controlled experiments. For example we can envision a three-testbed hardware/software combination where every single part of the CR node (radio, network and system stack, testbed control) is fully under control of the experimenters.

In a third step, solutions will be developed that allow recording wireless traces in one test environment, and replaying them, possibly in other test environments. The possibility to record and replay wireless traces is an enabler for repeatable tests, and allows re-creating interference patterns in a first test location that were recorded in a second test location. The recorded traces might contain interference patterns generated by equipment only available in the second testbed, but of interest to the experimenters using the facilities available at the first location. As such, the emulation of testbed components is possible, avoiding the necessity to physically collocated equipment. To enable this type of emulation and to allow performance results obtained in one experimental wireless environment to be compared with results in other environments, open data sets are created. These open data sets are used to describe spectrum sensing data, packet traces, but also general wireless conditions in which experiments take place.

Figure 1 depicts the three steps or federation modes.

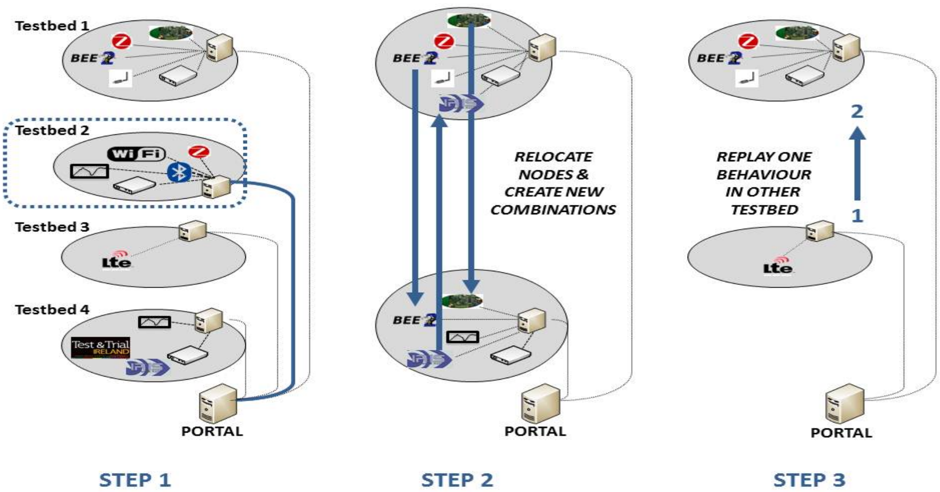

Figure 1: Federation modes

4.2 – Component Models and Virtual Components

As envisioned by Joe Mitola by the introduction of the “Cognitive Cycle” concept [3], cognitive radio relies on the reconfiguration capability of its constituents to adapt itself in the best way (depending on user input, performance criteria, spectrum constraints) to the context in which it operates. Today this reconfiguration capability is provided by SDR. The more the physical layer processing is moved to the software domain, the more the reconfiguration properties of the cognitive radio are enhanced. One of the multiple issues this reconfiguration capability has to deal with is the interfaces definition, both in terms of “location”, or level in the signal processing stacks, software/hardware partitioning, radio access technology or cognitive enabler decomposition and in terms of accurate parameters set.

When working with several, heterogeneous testbeds, each aiming at a particular scenario and technology, a wise combination of distributed components belonging to separated testbeds might enable the creation of new elements, also called virtual components, with new properties, unlocking new potential advanced experiments. However, this interesting situation could only be possible if the right interfaces are available to let the remote or heterogeneous items act together. These interfaces would allow the establishment and implementation of the so-called virtual components. SDR approaches can offer a solution to tackle these issues.

Component models thus analyse this problem, by taking one by one the testbeds' components, and looking at the way of combining them in case this makes sense and brings an added value, e.g. virtual components with new properties and enhanced capabilities. Then a second step targets interface design. A plethora of questions may arise at this stage: What kind of data should the interface convey? What control parameters are required to allow the interface to operate and be adjusted? What is the right location of the interface in the processing or data flow? The number of elements available in a federation of testbeds and thereby the number of combination use cases is enormous, thus the opportunities for interfaces definition that this overall framework offers is significant.

One of the foreseen combinations is the mix of available hardware radio platforms with sensing agents. The federation features a high number of radio platforms for different radio bands and cognitive elements to perform sensing. An immediate virtual component arises from the combination of hardware and software. Currently, in the SDR landscape, more specifically within the Wireless Innovation Forum, an interface is being specified to enable a complete separation of radio access technology or "waveform" elements from any potential target platform on which the waveform is planned to be implemented. This interface is the "Transceiver Facility Specification" [16]. Version one was released in the beginning of 2009 and a new version is currently under development. The basic foundation of this interface is the separation of the physical layer into two parts: the transceiver, which belongs to the platform, and the modem, which contains the waveform processing.

This approach offers a pragmatic solution to the issue of multimode devices. Those devices should be able to deal with many Radio Access Technologies with very different media access control or physical layer characteristics (WiMAX, LTE, WiFi, GSM, WCDMA). A single platform that supports many waveforms and that is able to reconfigure to any of them enables multi-sensing capabilities including demodulation and feature detection. However, the current state-of-the-art of these powerful devices is still struggling to offer competitive solutions in terms of cost or energy consumption. The current solutions are often only affordable for military equipment or fixed telecom infrastructure equipment.

4.3 – Benchmarking

In order to experimentally evaluate the performance of wireless (cognitive) networking solutions, typically a large number of experiments are required. The analysis of these experiments can be tedious and error-prone, as a large amount of data is to be processed, and the conditions of the wireless medium during the test are not always fully known. If other wireless devices or RF equipment (e.g. operational WLAN, microwave oven) are used in the environment during an experiment, the results might easily be affected. Furthermore, performance results based on ad-hoc created experiments are difficult to compare with experimental results gathered in different wireless testbeds, and experiments are difficult to repeat.

To overcome these difficulties, a benchmarking framework must be implemented which makes it possible to evaluate solutions relative to a baseline evaluation. To this end, the traffic and interference characteristics of reference scenarios (e.g. home, office, public buildings) and different wireless technologies (e.g. Wi-Fi, Bluetooth, LTE) are determined. When running experiments, a reproducible background reference scenario can be chosen. Simultaneously, the benchmarking framework is used to collect and process spectrum information and network level data, both from the devices under test, as well as from dedicated observation devices. During and after the experiments, the framework may be used to capture the performance of the solution using one or more metrics, making it possible to fairly compare the performance of different cognitive radio and cognitive networking solutions, or to compare the performance of different iterations of a single solution. Based on the collected input, the benchmarking framework should indicate whenever the collected results cannot be trusted, for example when an unexpected rise in externally caused RF interference is observed.

Eventually, this benchmarking framework is extended with automated evaluation methods based on design of experiment principles [17]. Based on a parameter input range, the benchmarking framework will then schedule multiple tests and continuously monitor benchmark results. For those input parameters leading to the most interesting outcome, additional, more fine-grained experiments can be scheduled. The duration of the experiments may also be dynamically adjusted by monitoring the variance of the outcome parameter(s), and experiments can be rescheduled when errors in the testbed infrastructure –such as a failing node or external interference- are detected. As an expected result, the time needed to reliably determine the performance of a cognitive radio solution should be significantly reduced, while the comparability and reproducibility of the experiments is enhanced and testbed occupation and user effort is minimized.

5. Conclusions, Benefits of Experimental Research with Testbeds

The concept "federation of testbeds" has been presented in this paper. It offers an advanced framework consisting of an infrastructure enabling advanced experiments otherwise hard to perform in separated testbeds dedicated to a specific technology or application.

While it might be difficult to grasp the characteristics of a cognitive system's wireless environment in an accurate model, testbeds can profit from scientific/research licenses [18] [19] for spectrum use and allow researchers to gather real-life data. This enables experimenters to verify the feasibility of principles and concepts that derive from theoretical research.

The different challenges any experimentation-based research has to cope with arise from the variety of experimentation hardware and software available. The definition of standardized interfaces together with benchmarking can be employed to address issues such as the calibration of individual components to a common scale, the repeatability of experiments through reproducible conditions, as well as the compatibility of multiple elements to build "virtual" components. Through the comparison of different sensing algorithms and by employing different sensing hardware in an experimental setup, it can be revealed how certain approaches perform under real-life conditions. This leads to conclusions about how heterogeneous systems can coexist reliably, which in turn can serve as an incentive for further cognitive radio research and support the related regulatory and business processes. Similarly, demonstrations that cognitive devices are able to maintain a certain level of quality of service will certainly make the cognitive radio concept more appealing for future communication systems. Moreover, studies on operational reliability are especially relevant when cognitive radios are considered an option for safety critical systems. In the same way, before spectrum sharing in licensed bands can be established as a mean to increase spectral efficiency, the impact of a secondary system on primary user needs to be quantified in order to convince network operators and regulatory bodies.

References

[1] M. A. McHenry, “NSF spectrum occupancy measurements - project summary.” Shared Spectrum Company, Aug. 2005.

[2] Qing Zhao and Brian M. Sadler, “A Survey of Dynamic Spectrum Access,” IEEE Signal Processing Magazine, May 2007.

[3] J. Mitola, “Cognitive Radio: An Integrated Agent Architecture for Software Defined Radio”, Dissertation, Royal Institute of Technology (KTH), Sweden, 1998.

[4] T. Newman et al., “Virginia Tech Cognitive Radio Network Testbed and Open Source Cognitive Radio Framework,” 5th Intl. Conf. on testbeds and Research Infrastructures for the Development of Networks and Communities (TRIDENTCOM), 2009.

[5] X. Jing et al., “Distributed Coordination Schemes for Multi-radio Coexistence in Dense Spectrum Environments: An Experimental Study on the ORBIT testbed,” 3rd IEEE Symposium on New Frontiers in Dynamic Spectrum Access Networks (DySPAN), 2008.

[6] http://www.crew-project.eu/

[7] http://www.ict-fire.eu/home/fire-projects.html

[8] USRP2 manual, “http://www.ettus.com/downloads/ettus_ds_usrp2_v5.pdf”

[9] P. Murphy and A. Sabharwal and B. Aazhang, “Design of WARP: A Flexible Wireless Open-Access Research Platform,” Proceedings of EUSIPCO, 2006.

[10] G. Judd and P. Steenkiste, “Using Emulation to Understand and Improve Wireless Networks and Applications,” Symp. on Network Systems Design and Implementation (NSDI), 2005.

[11] Theodore S. Rappaport, “Wireless Communication: Principles and Practice ", Prentice-Hall, 2002.

[12] P. Sutton et al., “Iris: An architecture for Cognitive Radio Networking testbeds”, IEEE Communication Magazine, pp. 114-121, 2010.

[13] Ettus Research LLC,http://www.ettus.com/

[14] S. Bouckaert, W. Vandenberghe, B. Jooris, I. Moerman, and P. Demeester, "The w-iLab.t testbed ", Proceedings of TRIDENTCOM, May 2010

[15] V. Handziski, A. Köpke, A. Willig, and A. Wolisz, “TWIST: A scalable and reconfigurable testbed for wireless indoor experiments with sensor networks,” Proceedings of RealMAN 2006.

[16] SDR Forum Transceiver Facility Specification v1.0.0, http://www.sdrforum.org/pages/documentLibrary/documents/SDRF-08-S-0008 V1_0_0_Transceiver_Facility_Specification.pdf

[17] D.C. Montgomery, “Design and Analysis of Experiments”, John Wiley and Sons. 2004.

[18] www.testandtrial.ie

[19] http://www.easy-c.de/index_en.html