OULUN YLIOPISTO
UNIVERSITY of OULU

DEGREE PROGRAMME IN ELECTRICAL ENGINEERING

MASTER'S THESIS

INTERFACE FOR RESOURCE SHARING AND CO-OPERATIVE DECISION MAKING IN COGNITIVE RADIO SYSTEMS

Author	Miika Lahti
Supervisor	Marcos Katz
Second Examiner	Jari Iinatti

November 2013

Lahti M. (2013) Interface for Resource Sharing and Co-operative Decision Making in Cognitive Radio Systems. University of Oulu, Department of electrical engineering. Master's Thesis, 52 p.

ABSTRACT

As smart phones, tablets, and wireless devices in general grow more and more popular, the demand for wireless connectivity keeps rising. At the same time, applications and services require more data to be transmitted for single users, which puts even more stress on service providers to increase capacity. One option is to build new base stations and provide different ways to connect - especially in the areas of dense usage. However, this is expensive and requires end-user devices to be able to use different wireless techniques and to switch between them according to position and data usage. On the other hand, the variance of wireless technologies and specific spectrum allocation has caused another phenomenon: in certain areas, the spectrum allocated to one user group is heavily utilized but the spectrum usage might otherwise be minimal.

To answer these rising problems on capacity and spectrum utilization, developing and researching of new solutions is required. A prominent area of research that can make a difference is cognitive technology: it provides ways to use spectrum and existing technology more efficiently than in their current state. Meanwhile it can also optimize the use of radio and operator resources when building new equipment and systems.

The goal of this master's thesis work is to implement an interface between a cognitive trial environment and a separately functioning cognitive radio network. The cognitive trial environment is built around a cognitive engine, which is an entity that manages network resources according to the information it receives from the environment. The outside network consists of cognitive radio devices called Wireless Open-access Research Platforms and a cognitive engine of its own. They are able to provide information and management capabilities that are beneficial for the environment. The interface will be a solution for the environment's cognitive engine to gain knowledge of the outside network and manage the resources of the cognitive radio devices residing in it.

This thesis work will also discuss the meaning and the development of cognitive radio and network techniques. The discussion takes a look at the underlying reasons to develop cognitive solutions and how the cognition could be implemented in the future.

Keywords: cognitive networks, cognitive radio, cognitive engine, wireless communications.

Lahti M. (2013) Käyttöliittymä kognitiivisessa radiojärjestelmässä resurssienjakoa ja yhteistoiminnallista päätöksentekoa varten. Oulun yliopisto, Sähkötekniikan osasto. Diplomityö, 52 s.

TIIVISTELMÄ

Älypuhelinten, tablettien ja muiden langattomien laitteiden suosion kasvaessa myös langattomien yhteyksien kysyntä nousee yhä suuremmaksi. Uudet sovellukset ja palvelut vaativat yhtä suurempien tietomäärien siirtämistä, mikä entisestään vaatii kapasiteetin lisäämistä ja lisää painetta palveluntarjoajien suuntaan. Erityisesti alueilla, joilla käyttöä on paljon, tarvetta voidaan helpottaa rakentamalla uusia tukiasemia ja tarjoamalla muita liitäntätapoja. Tämä on kuitenkin kallista ja vaatii käyttäjien laitteilta kykyä käyttää eri tekniikoita ja kykyä vaihdella niiden välillä sijainnin ja tiedonsiirtomäärien mukaan. Langattomien teknologioiden laaja kirjo ja tarkat spektrimääritykset ovat toisaalta aiheuttaneet toisen ilmiön: joillain alueilla yhdelle taholle määritetty spektri voi olla hyvin raskaalla käytöllä vaikka spektri muuten olisikin lähes tyhjä.

Näihin ongelmiin vastaaminen vaatii kehittämistä ja tutkimustyötä uusien ratkaisujen parissa. Kognitiivinen teknologia on yksi tällainen lupaava tutkimusalue, joka saattaa tuoda ratkaisun: sen avulla spektriä ja nykyistä teknologiaa voidaan käyttää entistä tehokkaammin, samalla kun uutta laitteistoa voidaan rakentaa entistä optimoidummin palveluntarjoajien resursseja ajatellen.

Tämän diplomityön tavoitteena on luoda käyttöliittymä kognitiivisen testiympäristön ja erillisen kognitiiviradioverkon välille. Kognitiivinen testiympäristö rakentuu verkkoresursseja ympäristöltä saadun tiedon mukaan muokkaavan kognitiivikoneen ympärille. Ulkopuolinen verkko, jolla on oma kognitiivikoneensa, taas koostuu WARP:ksi (Wireless Open-access Research Platform) kutsutuista kognitiiviradioista, jotka kykenevät antamaan tietoa itsestään ja ympäristöstään sekä samalla muuntamaan omia toimintojaan tarpeen ja vaatimusten mukaan. Käyttöliittymä tulee olemaan ratkaisu, jolla kognitiivinen ympäristö saa tietoa ulkoisesta verkota ja jonka avulla se voi vaikuttaa ulkopuolisen verkon kognitiiviradioresursseihin.

Tämä diplomityö käsittelee myös kognitiiviradion ja –verkon tarkoitusta, hyötyä ja vaatimuksia. Samalla se tutustuu myös syihin, joiden takia kognitiivisia ratkaisuja tarvitaan ja miten niitä voitaisiin tulevaisuudessa hyödyntää.

Avainsanat: kognitiiviverkko, kognitiiviradio, kognitiivikone, langaton tiedonsiirto.

TABLE OF CONTENTS

PREFACE

This master's thesis was conducted at the Communication Networks knowledge centre of the VTT Technical Research Centre of Finland and the measurements part at the Centre for Wireless Communications at the University of Oulu. The thesis is part of the publications of Cognitive Radio Trial Environment (CORE) project, which is a joint project between several Finnish companies and institutes and also funded by the Finnish Funding Agency for Technology and Innovation (Tekes).

I want to thank my advisor at VTT Marko Palola, my team leader Jyrki Huusko and CORE project manager Marja Matinmikko for the guidance and the instructions as well as for reviewing this master's thesis. Thanks also go to my colleagues at VTT for their advices on the issues during the work. Finally I want to thank Marcos Katz from University of Oulu for supervising the thesis.

Also, special thanks to my family for the support throughout my studies—especially to Anni.

Oulu, October 8th 2013.

Miika Lahti

LIST OF SYMBOLS AND ABBREVIATIONS

AI	Artificial Intelligence
ASA	Authorized Shared Access
BS	Base Station
BSO	Beneficial Sharing Opportunity
CC	Core Client
CE	Cognitive Engine
CM	Cognitive Manager
CRS	Cognitive Radio System
CSL	Cognitive Specification Language
CWC	Centre for Wireless Communications
DSA	Dynamic Spectrum Access
FPGA	Field-programmable gate array
GQoSM	Generic Quality of Service Measure
GUI	Graphical User Interface
HTTP	Hypertext Transfer Protocol
IEEE	Institute of Electrical and Electronics Engineers
IMT-Advaced	International Mobile Telecommunication-Advanced
ITU	International Telecommunication Union
ITU-R	ITU Radio Communication Sector
ISM	Industrial, Scientific and Medical
LSA	Licensed Shared Access
LTE	Long-Term Evolution
MAC	Medium Access Control
MNO	Mobile Network Operator
PHY	Physical (layer)
QCC	Qosmet Core Client
QMCP	Quality of Service Measurement Protocol
QoE	Quality of Experience
QoS	Quality of Service
RKRL	Radio Knowledge Representation Language
SDR	Software Defined Radio
SSAR	Shared Spectrum Access Rights
SW	Software
Tekes	The Finnish Funding Agency for Technology and Innovation
UDP	User Datagram Protocol
UE	User Equipment
UI	User Interface
WARP	Wireless Open-access Research Platform
WARP-CE	Cognitive engine of CWC’s WARP environment
WCC	WARP Core Client
WLAN	Wireless Local Area Network
VTT	VTT Technical Research Centre of Finland

1. INTRODUCTION

Since the introduction of mobile phones in the turn of 1990's, the use of mobile and wireless communication systems has been continuously growing. First it was because of the rising popularity of mobile phones but soon laptops and other wireless devices began to have wireless connectivity too. Today it is expected that any laptop has a wireless local area network (WLAN) interface incorporated. Cheaper technology has brought wireless gadgets to everyone's disposition. It is estimated that the number of mobile-connected devices will exceed the number of people on earth in 2013 [1]. Mobile devices have also been turning into a more multimedia oriented direction—like smartphones and tablets—where the traffic generated by them is much higher than that by a basic phone; the same estimation says that smartphones will overtake laptops as the most mobile traffic producing device type in 2013. New applications, video and music streaming and machine-to-machine communication are a few examples of the new kinds of services that are taking the use of wireless radio communication to a new level. While the current situation in itself calls for action, the telecommunication market is also expected to keep growing strongly in the future. The mobile data traffic growth has during the recent years been more than forecasts have projected and the newest estimate that by 2017 the traffic will be 12 times what it was in 2012 [1]. Therefore it is important that new technologies and solutions are under constant research and the ever higher need for fast and reliable transmission is met.

During recent years, the wireless network capacities have increased with new technological advancements. Long term evolution (LTE) technology, for example, provides the theoretical maximum peak data rate of 300 Mbps downlink and 75 Mbps uplink [2] and in the future the data rates can be only expected to rise since even LTE does not yet meet the international mobile telecommunications-advanced (IMT-advanced, also marketed as 4G) requirements set by International Telecommunication Union's radio communication sector (ITU-R) [3]. This progress has had its part in the increasing popularity of wireless devices but a very fundamental problems lie on the availability of free frequencies [4] and the increasing complexity of the data transmission system in general [5].

Even though the amount of physical spectrum is not a problem in itself regulation prohibits the flexible use of most frequencies: On one side, due to the current regulation the spectrum access is heavily controlled and usage remains under-utilized in some parts. In addition to free bands and those allocated to mobile network operators (MNOs), many parts of the spectrum are reserved for government, military or some specialized user group who may not continuously use the bands efficiently. Thus, depending on time and geographical location, the bands dedicated MNOs and—for example—WLAN can be under heavy use while the others may not have any traffic at all since there are no primary users nearby. Basically, the use of spectrum can be divided into three groups: unoccupied most of the time, only partially occupied and heavily used frequencies. [4][6]

There are multiple ways to respond to these problems related to inefficient spectrum utilization: One would be to concentrate on building completely new base station sites with higher density. This answers the problem partially as it allows the increase in capacity but it adds to the complexity of the whole transmission system and can end up being an expensive solution. A more profitable and elegant solution would be to optimize resources—such as spectrum usage—and use the technology that already exists more efficiently while taking the flexibility into account when researching and developing new solutions.

In reality, optimization cannot be fully executed only with current technology but also regulatory limits define how efficiently the spectrum can be used. Therefore complete optimization requires both regulatory and technological work in order to accomplish what is needed. The technological needs of the spectrum (and system) optimization could be reached with cognitive radio systems (CRSs), which have capabilities to obtain knowledge, learn and dynamically adjust to its surroundings. CRS makes it possible to make better use of the frequencies locally but also improve spectrum sharing in a wider scale. In addition, CRSs affect more than just the wireless data link; the effect ranges all the way to network management. One example of a shared spectrum access concept that would benefit from CRS is authorized shared access (ASA). The concept sets a framework for an idea where the access to “limited” radio resources can be allowed to someone else under an ASA license.

When considering the scope of this thesis work, some of the main considerations with CRS are resource sharing and communication between the components of a transmission path in general. In order for the whole network to be cognitive it is required that the decision making entity has knowledge about the available resources. While a CRS might include several of these decision making entities it is also of importance to have these communicate and operate in unison. Co-operation and resource sharing in return require an interface between the entities to enhance the communication, which is the main area of discussion in this thesis. The research is executed using VTT Technical Research Centre of Finland’s (VTT) Core trial environment and a cognitive radio network created by Centre for Wireless Communications (CWC). The CWC trial environment uses wireless open-access research platforms (WARPs) as manageable radio links. Both of these environments include a decision making entities called cognitive engines (CE) and they are further introduced in Chapters 3 and 4.

The contribution of this master’s thesis lies on the execution of the interface between the two environments and the results and knowledge gained from it. These will be used in the CORE-project (introduced in Chapter 3) when designing further components for the environments and researching the usability and requirements of future CRSs.

The rest of the thesis is structured as follows. Chapter 2 goes through the basic concepts behind CRS, including technologies, regulatory work and spectrum sharing concepts and explains cognitive radio and cognitive networks (CN) in somewhat more detail. VTT’s core trial environment and CWC trial environment that are used in the project at hand and in this thesis work are introduced in Chapter 3. Chapter 4 introduces the designed interface that enables the co-operative decision making and resource sharing while also goes through the acquired measurement results with the introduced solution and setup. Finally, Chapters 5 and 6 will go through what has been learned from previous chapters, sum together the content of this thesis work and briefly discuss the future of cognitive radio systems and networking in general.

2. COGNITIVE RADIO SYSTEMS

As mentioned in the first chapter, CRS could be an efficient solution to optimize radio spectrum usage and to increase the performance of any network. The concept of CRS involves several parts of communication systems and the used methods range from cognitive radio base stations to intelligent network management. A common aspect to all of these is that they are able to respond autonomously or "intelligently" to changes in their environment and in the intelligent system itself. In other words, they are cognitive.

Traditionally, the word 'cognition' has been used to describe a human mental processes but it has also been quite popular word in technology during recent years with a few other similar words: Cognitive, smart and intelligent - for a few - all describe a device's (or a human in that matter) capability to be aware of its surroundings and somehow react to changes by adjusting and learning. With humans, the term 'cognition' includes processes like the transformation, reduction, elaboration, storage, recovery and usage of sensory information [7] or—more simply—attention, memory, understanding language, solving problems and making decisions. Similarly, many of these processes also apply to cognitive systems in technology. In order to meet the set goals, a cognitive system needs to constantly be aware of its surroundings, remember previous situations, adjustments and outcomes, understand input from measurements and users and most importantly solve problems and make decisions that match the criteria. It should be noted that mere adaptive response (acting according to preset criteria) does not meet the definition of cognitive system.

This thesis work concentrates on cognitive radio systems and considering the topic, ITU-R has defined CRS as follows: "A radio system employing technology that allows the system to obtain knowledge of its operational and geographical environment, established policies and its internal state; to dynamically and autonomously adjust its operational parameters and protocols according to its obtained knowledge in order to achieve predefined objectives; and to learn from the results obtained [8]." So, for a radio system to match the criteria of cognition it needs to include the processes to gain knowledge, adjust parameters dynamically and learn from previous decisions—the three main capabilities of a cognitive system.

First of the key elements of cognition is knowledge. According to Mitola [9], the term 'cognition' means a mix of declarative and procedural knowledge in a self-aware learning system. Although Mitola's work concentrated on cognitive radios (CR) rather than CRS, the postulation about cognition and knowledge remains very alike. While declarative knowledge is verbally transferrable knowledge of how things are (know-that) and procedural is knowledge about how to do things (know-how) [10] it is easy to see that cognitive systems need to incorporate both: Declarative part is the knowledge about the state of the system, components included in it and information about the environment of the system. Like mentioned, procedural knowledge is more difficult to interpret in language and it is, after all, knowledge of how to improve system performance and affect functionality—in other words, knowledge of what kind of effects the changes will have.

It has been more than ten years since Mitola introduced the idea of cognitive radio [11] and even less has passed since cognitive networks and radio systems came to discussion. It was already 2006 when Thomas et al. [12] postulated with the idea of cognitive network. In technology, such times are short for a commercial breakthrough and therefore the technology is still only on the level of research. Of course, aforementioned factors, such as support from business, are also relevant. While there has been lots of progress and prototypes already exist on various topics of CRS the commercial emergence is yet to be seen. All the research projects include topics like dynamic spectrum access (DSA), spectrum sensing or autonomic management, which provide capabilities that benefit towards the realization of cognitive products. Even though recent projects have also seen progress in regulation, it is still an obstacle towards reality that would make CRS business flourish. [13]

While cognitive radio systems have been under research for years there is still confusion with the related terms. The term ‘cognitive radio system’ is often used interchangeably with cognitive networks. Both operate around the same concepts and ideas but basically the difference is that where cognitive networks consider the whole transmission path including wireless radio environments and wired links and protocols [12], cognitive radio systems concentrate on the phenomena around the wireless communication systems [8]. In addition, a cognitive network doesn’t need to include any wireless radio links as cognitive radio systems infer. It should also be noted that CRS differs from CR, which is basically just an intelligent radio transceiver whereas CRS can include several CRs and other wireless network elements.

This chapter enlightens the background behind cognitive technologies beginning from the concept of software defined radio and the cognitive radio built atop of it. After that the picture is broadened by taking into account larger systems and even networks consisting of cognitive components. The topics discussed include the requirements and benefits of CRS and CN. Finally the chapter goes through some of the central concepts in cognitive communication technologies—shared spectrum access methods and decision making in cognitive systems.

2.1. Software defined radio and cognitive radio

Even before cognitive radio systems there has been a need for new radio capabilities that push the functionality of traditional radio transmitters and receivers beyond their hardware-based stiffness. Physical layer functionality has been very inflexible since it was (and still is) realized mainly with hardware and only controlled by software. Modifiable hardware components are usually expensive and they have a limited range of scalability. Since field-programmable gate arrays (FPGAs) and other programmable processing technologies have become less expensive, it has now become possible to move physical layer functionality to these components where they are easily adjustable and re-programmable. This technological progress has led to a new generation of radio devices that are called software defined radios (SDRs).

While being an important step towards cognitive radios, SDRs themselves are not necessarily cognitive - the definition of SDR [8] is already met when they provide only the core functionality that cognitive devices require: their operating parameters are altered by software. This difference between SDR and CR is why there has been a lot of confusion about the terminology of cognitive radios: the term “cognitive radio” is frequently mixed with “software defined radio”. Partially the reason is that cognitive radio may often be built on top of a SDR: where a SDR is simply a radio that has some or all of its physical layer functionality done in the digital domain rather than the analogue [14], a cognitive radio implements an intelligent system that has access on the capabilities of SDR [9].

Wireless Innovation Forum [15] defines cognitive radio as one of the three types of SDRs. The two others are adaptive radio and intelligent radio. These types differ in the level of cognition and intelligence they have: Adaptive radios have capabilities to monitor their own performance and fine-tune their operating parameters while cognitive radio can also monitor its environment. The intelligent radio has an additional ability of learning when compared with the definition of cognitive radio. In a broad sense, all of these definitions have some level of cognitive capabilities included but compared with ITU-R's definition [8] of CRSs learning is also included as one of the main capabilities of a CRS (and CR).

Although cognition and intelligence had been subject to study before Mitola introduced the idea of cognitive radio, they had not been applied to radio technology in the same sense. Partially this was due to the restrictions in technology and especially computing capabilities: for a radio to be genuinely cognitive it needs to be able to adjust radio parameters that are traditionally executed in the analogue domain. The values of these components are usually fixed and are impossible or at least hard to change dynamically. Even while many components had been moving to digital and had increased flexibility, they lacked the means to distribute the provided capabilities and knowledge. Not to mention the lack of intelligence that could use these. The main idea of the cognitive radio concept is to make radio self-aware in a sense that it is aware of the components the radio consists of and of the capabilities these components provide. [9][11]

Just providing capabilities to acquire knowledge do not make a radio cognitive, though. If executed with SDR, cognitive radio lies on top of the functionality provided by SDR and is basically the intelligence controlling the radio. The definition of cognitive radio [6] follows the definition of CRS: it is a wireless communication system that is aware of its environment and is capable of learning, making autonomous decisions and adjusting operational parameters according to gathered information. In its simplest form, the awareness of the environment can be just the ability to sense which frequencies are currently being used and which ones are free. In that sort of case the cognition would then switch the used frequency according to what brings the best performance and fulfils the pre-set goals.

An important role of a cognitive system is played by the way it connects with the outside world. Radio knowledge representation language (RKRL) introduced by in [9] makes it possible for the intelligent part of the cognitive radio to firstly be aware of what capabilities the radio holds inside but also of the environment it operates in. RKRL represents outside stimulus (be it measurement information or policies set by users) in a way that the cognitive intelligence is able to understand it. The same goes with the capabilities of the cognitive radio: RKRL makes it possible for the radio to understand the hardware and software components of the system and the extent they can be adjusted.

RKRL is heavily tied with the idea of cognition cycle, which is an improved version of the simple OODA loop (observer - orient - decide - act) [9]. This loop can be seen in its simplified form in Figure 1.

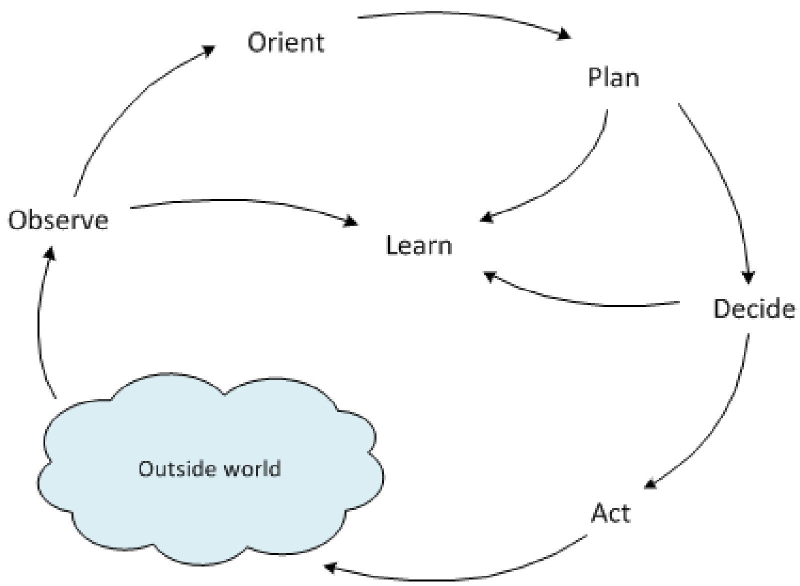

Figure 1. A simplified picture of the cognition cycle based on [9].

Any stimulus received from the sensors of a cognitive radio initiates a new cognition cycle where the outside world is observed in the first phase. After this, the cognitive radio orients itself and may skip next phases if the observations require more immediate actions. In a normal situation, however, the cognition plans how to respond to the received stimuli and then decides the apparently most optimal actions. A crucial part of the cognition cycle is learning where new and prior states are taken into account and the future planning and decisions are based on the observations about the past actions. [9]

2.2. Cognition in a network

Whereas a cognitive radio is aware of its surroundings and is able to adapt according to them, it is not aware of other components or cognitive devices in the network other than through indirect ways (such as scanning the radio spectrum or "spectrum sensing"). Spectrum sensing in itself is not straightforward and easy task and it has its own issues: Many radio environments have many undetectable signals and the systems incorporating a CR usually require that no interference is caused for the main user who has the primary rights over the used frequency [16]. Radio spectrum environment is also only a single aspect of a network that can include multiple technologies and standards that all have a significant role in the transmission but are oblivious to the data they transmit and the other components around them [17].

Thomas et al. [12] suggest a definition for a cognitive network in as follows: "A cognitive network has cognitive process that can perceive current network conditions. The network can learn from these adaptations and use them to make future decisions, all while taking in to account end-to-end goals." Similar kind of idea of 'a knowledge plane' has also been proposed before [17]. It is obvious that cognitive network is defined in a very similar way with cognitive radio (as is cognitive radio system in general). A crucial difference is that in a cognitive network a weight is set on the end-to-end goals that define the performance of the complete system. This difference separates cognitive network from other cognitive communication technologies and makes the system all-covering instead of just being an intelligent layer. [12]

The difference between CR and CN (or more accurately CRS) is demonstrated in Figure 2. The advantage of CRS is in the way it is able to use the information over the whole network rather than just on one node. Also, the further the CRS reaches the better its view of the whole network performance is. For example, if both end-devices of communication are included in the cognitive radio system it is possible to measure detailed end-to-end performance over the whole network.

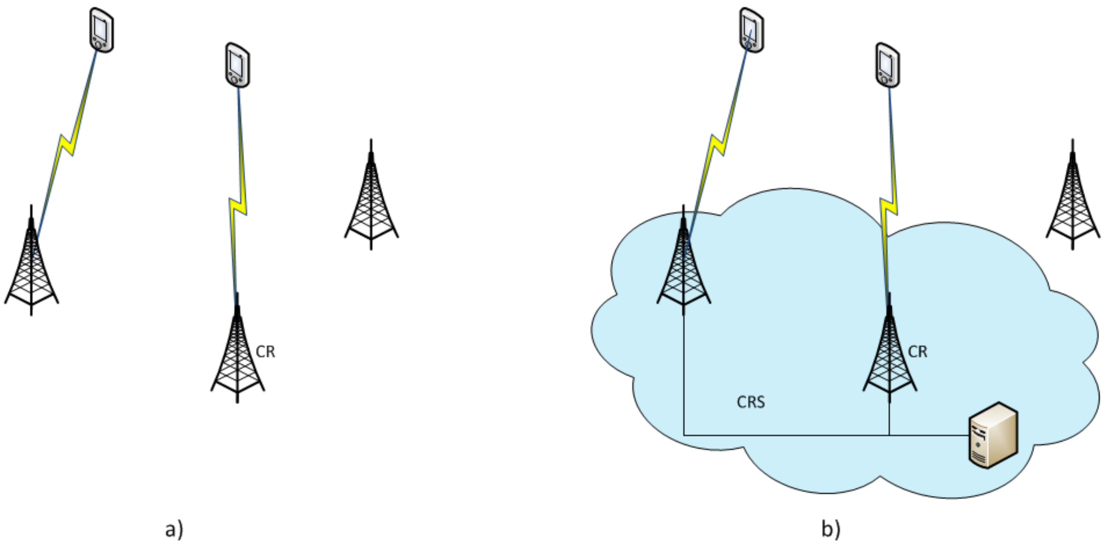

Figure 2. Difference between cognitive radio and cognitive radio system. a) Cognitive radio is aware of its radio environment and can adapt to it. b) A cognitive radio system is aware of the whole network (all network components belonging to it that are able to provide information or capabilities) and can adapt more easily and use the information from a CR more extensibly.

While considering end-to-end goals, the system denoted as cognitive network includes all the network elements along the transmission path. CN needs to receive information about the status of each of these network elements and capabilities to make changes on them that will affect the overall performance. It is important to remember that cognitive networks are not limited to only wireless networks and they do not necessarily even include a wireless medium. As stated before, a CN including wireless medium is basically a CRS.

Although cognitive radio systems may consist of just cognitive radios it should be expected that many components will still be the so-called ordinary network equipment for years. These components are unintelligent and only work with their pre-set radio parameters. Bringing the cognition into a network can enhance the use of these elements too. For example, offloading a mobile device from a service provider's heavily loaded network to a close-by WLAN network seamlessly requires certain amount of cognition on the user's device and on the network level but the WLAN base station itself may be an ordinary "dump" WLAN router.

As stated earlier, one of the problems that have caused consideration with cognitive radios is the fact that they positively affect the performance on only one node of a network. They lack the ability to measure and adapt to a larger scale. A change of parameters at a cognitive node that has a positive local effect might still have a negative effect when the whole network is considered. Nevertheless, cognitive radios are an important part of a cognitive network in providing functionality and information. It is common that the biggest bottlenecks in a transmission path are the wireless links: they are the most prone to interference and are the most limited at data transmission rate; where wired transmission lines can use the full bandwidth without restrictions, wireless links must take into account neighbouring channels and other users in the region. Therefore wireless radio spectrum regulation is required to provide a certain level of usability.

2.2.1. Benefits of cognitive networks

As said, one of the biggest concerns when considering the future of wireless networking is how most of the radio spectrum resources cannot be accessed due to insufficient technology and stiff regulation. The cognitive radio is partially an answer to this problem but it has limitations with having the bigger picture of the effect of the changes; a cognitive radio can easily make a change that increases the performance of a single node but it does not see the problem it causes to other components in the network - or the effect on end-to-end performance. To be able to completely answer the problem of spectrum usage the system needs to have knowledge of the complete spectrum usage in the area. This can be only done with a system that is more aware than a radio; a cognitive network can overcome that obstacle.

Having the cognition covering the whole network has also other benefits when compared with only local cognition. Obviously, another apparent advantage is to have the view of the performance of the complete network instead of just a node-to-node level view. In addition, this view makes the disarray of different protocols and technologies more transparent. Therefore cognitive network is able to learn and act according to higher level goals (e.g. end-to-end transmission efficiency) but also takes into account lower level goals (e.g. the energy efficiency of a single node). Bigger picture matters in communications and it is another huge benefit of cognitive networks: a single node would be oblivious to overall throughput even while improving performance locally.

The advantages of cognitive network should be even more obvious in a longer run: when compared with an ordinary network, cognitive networks could also enhance resource management, quality of service (QoS), security and access control for a few examples [12]. The only limiting factors here are the flexibility of network components that provide the functionality and the extensibility of the interface between cognition and network components. The example improvement targets also tell that the effect of cognitive network is not tied just in wireless communications but the effect can be seen in wired parts of the systems too.

A big difference between an ordinary network and a cognitive network is seen when facing problems. While obviously cognitive network is able to acquire knowledge of network status and is aware of the problems unlike an ordinary network it is also able to make changes to solve the problems and increase performance; something that requires a certain level of intelligence. This intelligence should also be forward-looking and pre-emptive in its decision making, i.e., in the ideal case a user is not even aware of the occurring problem since it is addressed beforehand. An example of this kind of forward-looking acting is a case where a cognitive intelligence knows when rush hours increase the amount of wireless traffic in certain regions at a certain time and the intelligence reacts to this knowledge. It is still possible to act reactively and in some cases it is not even possible to foresee problems but forward-looking decision making should have a distinctively better effect. [12]

Forward-looking intelligence does not have to rely on mere statistics about human traffic behaviour either. The amount of data traffic generated by the user depends heavily on the type of media he is using. Just text messages and phone calls are a small part of traffic compared with watching video streams - some might even use video chats. All these produce different types of need from the network: Video stream requires mainly a good downlink connection where buffering can help with the quality of video. Two-way video chat in the other hand requires both uplink and downlink to work efficiently and real time functionality is essential. To take all this into account, a cognitive network (or a subsystem like radio) should be context aware. The end-to-end goals of different content are also different and should not be left unattended.

Network structure mentioned above does not consider only the physical level of data transmission. The current structure of networks is based on a multi-layered protocol stack where the physical link is only the bottom layer of transmission. Cognitive network could easily be left only to manage physical connections where it could optimize transmission power, modulation and where to connect. This would only be half-done though. By making changes in only one layer might cause problems with the other layers and therefore a cognitive network should implement cross-layer design where it can view and control each layer separately and still maintain the awareness of the whole picture. [12]

How big of a difference there is between situations where the nodes of a network work individually compared with one where network is governed with an all-managing intelligence, is an important question related to cognitive networks.

While the previous benefits have mainly concerned the commercial sides of the communications, yet another problem can be seen with the public sector. Regulation already ensures enough spectrum and connectivity, so they are not the main problem here. Rather the benefit of cognitive networks could be seen when dramatic disturbances caused by catastrophes occur; these occurrences could be for example quakes, floods or military actions. Cognition in the network could overcome or bypass these problems and ensure reliable and predicted communication channels. This aspect has been becoming more and more important in the society of today, which is increasingly dependent on communication.

In the current state, wireless communications business is built around the stiff regulation and except for ISM (Industrial, Scientific and Medical) bands spectrum usage is reserved for certain users. Cognitive technologies could also have a strong impact on this side of wireless communications: While making more flexible use of spectrum possible cognitive technologies could benefit the current spectrum users while creating completely new business opportunities. This business point of view also works as a push for the new technology. While the current business ecosystems probably will not disappear suddenly (but rather benefit from being able to provide more reliable and flexible services), the scene will see some changes as regulation allows more room for different kinds of business opportunities that become possible with cognitive networks. Like when considering spectrum usage in general, with business opportunities the highest potential lies on how the spectrum is accessed. [18]

2.2.2. Requirements for CN

The aforementioned benefits set the goals that require some technical and regulatory problems to be solved before they are met. A cognitive network is only as good as the underlying network elements let it be. Other limiting factors are the flexibility of the complete cognitive system and how all its hardware and software components connect together in this cognitive framework. Meanwhile, the implementation of new components and how much of these new technological advancements are allowed to be used in practice add to these limitations. As a summary, the requirements can be divided under different topics that answer the questions: How the network performance is affected? How and what information about the network is provided? How is the information used to enhance the performance of the network? In which ways is it allowed to adjust the network?

Many components already provide some functionality and scalability to affect the performance of communication systems and there are also ways to measure local and end-to-end performance. Still, improvements are required throughout the field as more options mean more flexibility and adaptability for the system. When looking into the key points of research with CR [19] refers to three main functions of simplified cognitive cycle presented in Figure 1. They are spectrum sensing, decision making and learning and adaptation in the sense of reconfigurable hardware. These are also of importance with CRSs but with some difference: whereas one of the main areas for CR research is the adaptability for the hardware, CRS and CN require the same kind of adaptability from the software and hardware included in the network—not just the hardware related to spectrum. This thesis work mostly considers the topics around spectrum sensing (or rather spectrum awareness) and requirements for the network systems to apply cognition. While decision making and learning are an important aspect with cognitive technologies they are not in an essential role here.

With cognitive radio systems, spectrum awareness is in an essential role when either enhancing or decreasing the system performance. The way it is done and how the knowledge is used can have multiple effects. As noted earlier, the necessity of spectrum sensing (or at least having knowledge of local spectrum usage) comes into important consideration especially with spectrum sharing concepts. According to [20] the sensing itself should be done in several nodes as individual sensing is not enough for a reliable result.

While current networks already differ drastically in their structure, we do not even know what the future direction of the networks is going to be. In addition to ever-improving technology, the regulation of wireless spectrum is also due to change in the future. This all makes the technology of the future networks hard to foresee. Therefore it is important to develop the cognitive networks in a way that they are extensible with network components we cannot even imagine yet. Taking into account the current variation between networks, the future networks require a lot of flexibility.

To be fully functional in tying together the user set goals, cognition and the network, even in the future, cognitive network also needs a fully functional software framework. This kind of cognitive network framework is illustrated in Figure 3. First, that network needs an interface and a language between user (a human or an application) and the cognition. This is very much alike with RKRL proposed by Mitola but for cognitive network. In [12] Thomas et al. propose a cognitive specification language (CSL) that would be able to adapt to new network elements, application and goals – even those that do not exist yet. The second side of the cognitive network framework is the interfaces between cognition and network elements: cognition needs an application programming interface (API) to be able to manage the elements and network elements need ways to measure and provide information about the network status. [12]

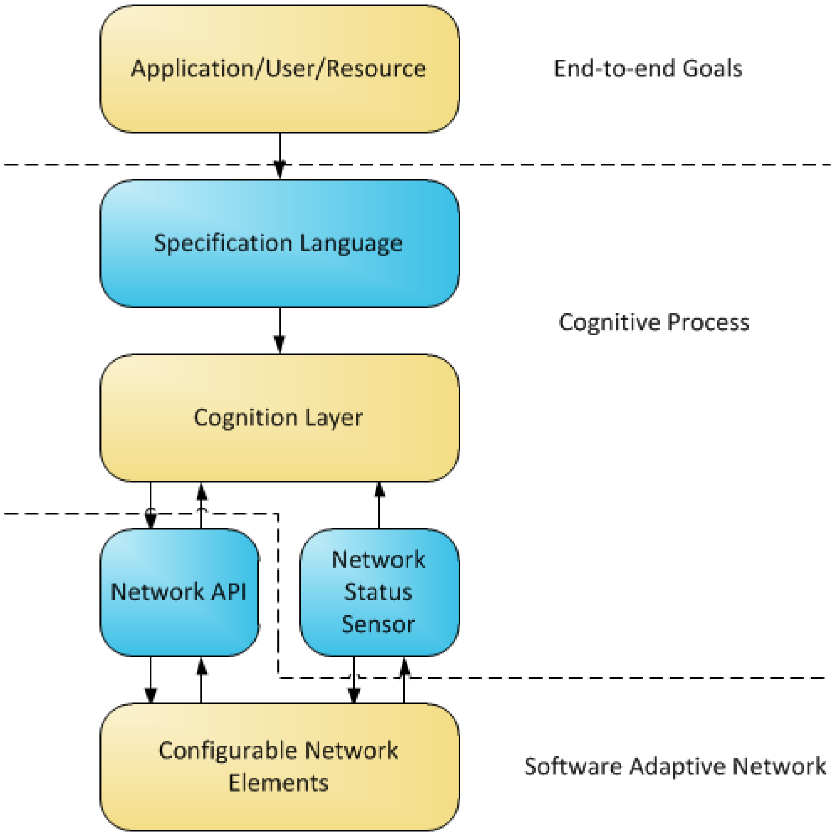

Figure 3. The cognitive network framework.

Whereas cognitive radio can often be the intelligence built on top of SDR, cognitive network should have a similar software-definable element. Software adaptable network (SAN) suggested in [12] is an example of how to provide the functionality of the underlying network nodes in which cognitive network depends on: SAN connects the intelligence of a cognitive network with the tuneable elements of the network. This kind of software adaptability makes it possible to take into account also the future capabilities of the network as well as the current ones not yet implemented in cognitive networks. SAN itself consists of modifiable or configurable network elements that work as an interface between cognitive network intelligence and the actual network components. [12]

Basically, SAN provides control over the network nodes but taking into account the vast differences of information that could be used by cognitive network SAN could work as an interface to the other direction too. The idea of software adaptable network works well as a starting point to take the functionality of cognitive network even further. While the SAN could be a universal interface applied by the developers, it will only be a future view. At this point tying together the network components and central cognition is relied on the developers of cognitive networks who include new components in the system.

Even without any future components the transmission of information and decisions brings up a concern: In addition to the original load of the network comes the load of the cognitive network communication. Even while much lower scale than the expected high traffic that calls out for CRS solutions, the management traffic should be taken into account. As the amount of devices that connect to cognition increases, the amount of traffic increases too. Therefore one essential point of consideration is to decide what data is required and transmitted. In addition, how the data is transmitted is important, too, since CN cannot manage the network if the components are out of reach. In order to avoid this, the device needs multiple connections or some local cognition of the network status and available alternate means of connection.

While the components that provide and transfer the information and capabilities need improvement as well, there are currently no intelligent components that would make use of the provided resources. It is obvious that the benefits of a cognitive network are achieved only with proper intelligence. The cognitive entity of a cognitive network does not have to differ much from what is used with a cognitive radio; basically it just has to has the knowledge about what components are included in the network as well as what capabilities the components have, i.e., the cognitive network has to also be aware of itself like a cognitive radio in the previous chapter.

Like any cognitive device, cognitive network also needs a feedback loop similar to cognitive radio's cognition cycle in Figure 1. After the information is gathered and transferred to the cognitive entity the data has to be processed according to the current knowledge of the environment and provided capabilities. In an even more simplified manner the main capabilities of a CRS (or any cognitive network or device) are obtaining knowledge, learning and ability to make decisions and adjustments [21]. One of the most important parts of the cycle is decision making, which in itself is a huge topic and has been under research and development for years, and many forms of solutions could be used with cognitive systems [22]. Taking a previous version of artificial intelligence (AI) and applying it to a cognitive network does not work though: AI is not yet on the stage where it could take over and learn to use all the possible components by itself. Some amount of learning is still already applied and simulations have shown improvements after familiarising the decision making entity with the adjustable parameters [23].

It is also expected that every environment a cognitive system is used in is either unique or is expected to have changes happen sometime in the future. Therefore it is important that the decision making part of the cognitive cycle is able to learn or at least adapt to situations of a new kind. Without learning the system would end on the same response every time with a certain state no matter what the outcomes of the earlier responses were. Learning would also lead towards pre-emptive decision making, where the problems do not even arise before they are addressed. This approach would in theory be much more beneficial and worth striving for than a reactive way of addressing the problems. Reacting to problems rather than foreseeing them causes unnecessary error and a decrease of quality while in many cases the provided information could be used for a pre-emptive solution. A simple example would be two radio systems beginning to overlap each other: if a CN was aware of both of them it could change the operating parameters of the systems before the actual overlapping happens. This kind of situation is discussed in more detail in Chapters 3 and 4.

As a whole, independent of the used method of decision making part, the part of cognitive cycle making the decision is called cognitive engine. CE generates decision based on input values and knowledge based in previous system states and results. In case of cognitive devices it can be said that a CE also has at least some machine learning elements since it is obvious that the definition itself requires the system to learn from previous situations and decisions. [23][24]

In the end, all these different elements that build up a cognitive network and its framework need to be applied in real. In order to test and showcase the cognitive radio systems there have been several testbeds of cognitive technologies. They all seem to address only single parts of a communication system and only a few of them have included a framework addressing multiple parts of a cognitive network at the same time. This is an important factor when the whole range of a network is considered and the end-to-end performance is kept in high importance. In [25] it is suggested that a federation of testbeds is required to fully benchmark the framework for cognitive radio systems. This makes it possible to combine different testbeds in a process that, for example, includes interface standardization and results in an environment where cognitive radio systems can be tested and compared equally. [25]

2.2.3. Co-operation of cognitive entities

Another important factor with cognitive networks is the teamwork and collective behaviour of the system. In [26] it is weighted that teamwork is important when considering the future of cognitive networks; the teamwork of several nodes can highly enhance the performance of the system when all take part in searching for a solution instead of just one entity. Especially in cases where the cognition is distributed and possibly consisting of several cognitive radios collaboration is important in order to achieve end-to-end goals.

The effect of team work and cooperation is also acknowledged in earlier research efforts at VTT [27]: Increasing amounts of cognitive nodes would increase the amount of processing to amounts where the cooperative and shared use of knowledge would be much more beneficial and save resources. A radio device with unfavourable connectivity could access a network through the air interface of a neighbouring device, for example, or with the help of knowledge gained from other devices. Even several CRs would benefit from the cooperation [28].

In the end, the resources of a network device are much more varied than just spectrum. They can be divided into five categories: radio resources (e.g. time, frequency, space, power), built-in resources (e.g. mass storage, batteries, processing), user interface resources (e.g. sensors, speakers, microphones), social resources (e.g. individual and groups behind devices) and connectivity resources (e.g. different air interfaces and other possible connections). This diversity of resources offers great potential for the co-operation and shared use of resources. A driving force in this thinking is that when introducing co-operation to a node it should offer a clear benefit in return to sharing the resources. [27]

The intelligence in cognitive network can be executed in many different ways: In the other extreme there exists only one entity that controls the entire network from the end devices to network management. While moving away from that, the network is divided into smaller systems that each have some level of decision making intelligence to make individual decisions. In this distributed form, end-to-end goals cannot be met without having some control (or at least view) over the whole transmission system. The individual entities could message between each other and base the decisions on distributed knowledge or there could be one entity that covers the whole system but leaves the small level decision making to low-level entities.

Basically the two forms of end-to-end covering solution with distributed cognition are the same thing and can be seen as an all-covering intelligence with just different amount of intelligence and control. The simplest form just distributes the knowledge to the decision making entities without providing any decisions. This way all of the entities would have to make decisions of the same kind and end to the same conclusions regarding the end-to-end goals and the needed modifications they should do. This adds the unnecessary need to be aware of the whole system in every node, which in return increases the amount of local processing and traffic generated by the cognitive network as is already pointed out in [27].

When comparing with the single cognition situation, similar problems can be seen. The single cognition needs to gather all the information and at the same time needs to process it all. This generates lots of lag in the decision making process, which is an essential factor in many cases. It was also noted in [28] that losing a connection to one network element could paralyze sizeable portions of the network.

In the end, it is only intuitive to think that some centralized decision making would be required but the distribution of smaller level decisions should also exist. The centralized decision maker would have the end-to-end view while making sure no overlapping and conflicting decisions are made. The individual nodes could in return maintain the connection and take care of local concerns. Distribution could also work with parallel systems where one is aware of the whole system and distributes either the required information or just the decisions. As stated in [27] defining the resources and their importance and relevancy remains an important research issue. In addition, their synchronicity and the accuracy of the information are something that should not be overlooked [28]. These sum up towards delays caused by the CRS decision making and the importance of the delay depends heavily on the applications relying on the system [4].

2.3. Shared access concepts and regulation

While technological advancements with cognitive radio systems could soon make it possible to efficiently manage and share spectrum resources, a big obstacle still remains from making it reality. While radio spectrum is a finite resource the amount of it would still be sufficient to provide all the currently needed bandwidth. Due to regulation, most of it is unavailable to more flexible access though. Therefore, on many locations big parts of spectrum are left without use. These “white spaces” are a very interesting opportunity that can be accessed with CRS technology and proper regulation. Since regulation discusses the spectrum access rules and conditions it is more relevant to consider regulation from the CRS point of view rather than cognitive networks in wider sense.

There are different ways to increase the capacity of the networks: It could be seen as a triangle where CRS is in one corner but it is not enough in itself. It requires either expansion of radio networks or making use of the old frequencies. Cleaning up “old frequencies” and applying them to new use can often be very expensive and it would therefore be easier to regulate the usage in a way where it is possible to lease or use frequencies in a cooperative manner. Regulation is essential here since it guarantees an undisturbed connection and the completely free usage of spectrum would soon lead to problems. The goal is essentially to provide an interference free environment for the primary user while giving more possibilities for secondary users.

There will always be a need for new frequencies and it is acknowledged that in the future spectrum will be made accessible for new users. In addition to technological progress, this kind of scenario also requires a regulatory change to allow more flexible spectrum access. For example, EU supports all actions towards a flexible sharing and cooperative use of spectrum while keeping the authorisation system as simple as possible. [29]

Basically, spectrum sharing and shared spectrum access refer to a situation where several systems operate in the same frequency but the spectrum access is based on regulated rules. The rules define which (if any) of the systems have the priority for the access and if other systems are allowed to access the same spectrum and in which manner. This manner can range from a part of the frequency range during a certain time window to a longer term leasing of the whole frequency range or even opportunistic open access [28].

First step towards shared spectrum access is identifying Beneficial Sharing Opportunities (BSO). BSOs can be identified on licensed or unlicensed bands where it is more suitable and beneficial to have multiple users or applications use the same channel when compared with just one user. The costs resulting from BSO should be taken into account when identifying the possibilities. Identifying these bands is a necessary and important step in the standardization process. Another useful tool would be identifying Shared Spectrum Access Rights (SSAR) to guarantee some level of protection against interference. [29]

From a technological point of view, many shared access concepts already exist and they make good use of the cognitive technologies. However, regulation for these concepts needs to be in order before real-life implementations can be realized as also recognized by ITU-R [30]. Two examples of the recently emerged concepts that are currently under standardization work and could implement SSAR are authorized shared access (ASA) and licensed shared access (LSA). Based on the concepts, the frequencies at hand could be accessed under the supervision of the regulator by parties who have made an agreement on the rules of access with the original license-owner.

One of the core philosophies with all shared access concepts is that there will not be any restrictions or interference for the original user; the unused frequencies are used by the loaners only when incumbent users are not affected or do not exist in the current location. The minimization of interference is also stressed by EU [29]. Basically this requires capabilities—such as databases or sensing—to obtain knowledge of spectrum availability; it could be realized with a CR or with knowledge of the spectrum usage around the area where a CRS would be useful [21]. In a simple case, this is required only from the secondary users who ensure that no interference is caused to primary user who should be able to continue to work as before.

2.4. Licensed shared access and authorized shared access

As with every new area of discussion and research, terminology with shared access concepts is confusing and has not yet settled. While there are currently numerous different shared and cooperative access concepts under study and research, the two—LSA and ASA—are the ones most tied with this thesis work. While EU supports all kinds of steps taken towards flexible and efficient spectrum usage, it all falls under the concept of licensed shared access. Basically authorised shared access is part of LSA, too, but only considers mobile networks and the frequencies used by them.

ASA is a framework for sharing spectrum between limited amounts of users. Like with the general idea of spectrum sharing, under ASA concept the original spectrum user, known as "the incumbent", would share the spectrum allocated to him with others using the ASA license. These "ASA licensees" could access the spectrum under pre-defined conditions. These conditions can be of different types: they can be static and tied to a certain location or time or more dynamic where authorisation or restriction could be made in on-demand fashion. Especially these dynamic implementations could take advantage of the recent CRS advances. Of course the importance of the incumbents' rights to the spectrum should be taken into consideration first. The ASA licensees also have the obligation not to cause any harm or interference for the incumbent. [31]

According to [31], a typical setting up of ASA arrangement usually involves the following steps:

1. The incumbent reports the conditions under which the ASA bands can be accessed.
2. Administration assesses the conditions and sets a framework according to them.
3. The administration sets up an ASA licensing process and ASA licensees apply for authorisation.
4. According to the nature of the spectrum access (dynamic or static) ASA licensees might have to connect to a database that provides the information on the times and areas of available spectrum.
5. When the incumbent needs to have access to the spectrum at hand, ASA licensees need to be informed about it and they make the required changes to free ASA spectrum.

With these steps in mind it is easy to see that the flexible use of spectrum would require cognitive radio system capabilities of some sort. Without the flexibility of an SDR the system would have to consist of several different radio units. A cognitive radio system in the other hand would provide the database and overall functionality that could realize all of the steps required for ASA concept. End-to-end performance knowledge and interference awareness are extra advantages that could benefit ASA concept.

A crucial point with the concept can be seen with the last point of the above list. While ASA licensees are more flexible with the delays in decision making the incumbents may need much quicker changes in order to keep up with the required changes. This is where the delay of the whole CRS system comes into consideration. The delays are caused in several parts of the system starting from the where and how the knowledge is acquired. The decision making and transportation of the information are another cause and finally the ASA licensee's CR device will have an effect too. This master's thesis considers this generation of delay when CR and CRS are working together in a system that uses them like an ASA system would.

3. COGNITIVE RADIO TRIAL ENVIRONMENT

This master's thesis is tightly connected to CORE-project, funded by the Finnish Funding Agency for Technology and Innovation (Tekes). The project introduced a trial environment where different CRS technologies can be tested and showcased. It allows researchers to run experiments and measurements on cognitive decision making in different network setups. The creation of the trial environment also includes the development of cognitive decision making techniques and scenarios and business models for the future CRS business ecosystem. [32]

This chapter goes through the trial environment structure and basic principles behind it. The thesis concentrates on the core environment created at VTT and a cognitive radio network created by CWC. The most crucial point being the interface or a "Core Client" (CC) implemented between them to enable information and resource sharing. In this case, information can be any measured local or end-to-end statistic of the data usage and connection performance or just the status of a network node. Resources in the other hand include information about types of available connectivity and used frequencies.

3.1. Configuration of trial environments

The configuration of the trial environments of the project includes several wireless networks that mostly work on WLAN frequencies but also include other radio standards like LTE. The most centric environment is the VTT CORE trial environment, which is designed to have the most top level cognitive decision making entity. In addition to this entity—called Cognitive Engine—the environment includes components for collecting information from other environments and different parts of the system as well as providing the means to control and manage them. These components are called core clients and they can be included in an internal or external part of the environment. In addition to internal parts—like servers—the complete system includes external parts that may be servers, computers, mobile phones, network elements or other environments. An example of how the VTT trial environment locates with the other environments and components is introduced in Figure 4. [32]

While this thesis works concentrates on VTT CORE trial environment and CWC CORE trial environment only the components relevant to this cooperation are introduced.

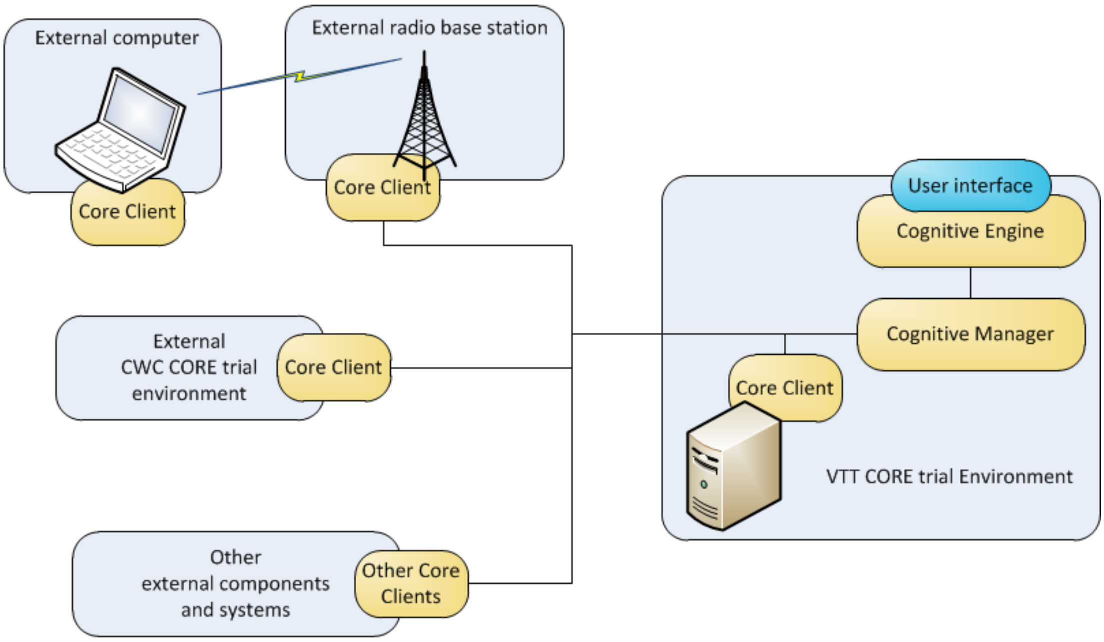

Figure 4. An example of how other CORE trial environments and external components connect with VTT trial environment. The structure of VTT trial environment is also visible.

3.1.1. VTT CORE trial environment

The heart of the VTT CORE trial environment is cognitive engine. It is the decision making component of the environment that bases the decisions on user set requirements, policies and settings. It may be operating on a local computer or a distant server but it connects and controls other components of the environment using hypertext transfer protocol (HTTP) based messaging protocol. Users can control the CE via a web based user interface that can be accessed from anywhere with only a web browser. In its current state, CE can be configured with only simple clauses so that it makes the certain decision if its conditions are filled. This does not fully comply with the definition of cognition but enables the testing and measurement of the environment and components that are required for a cognitive network.

Since the project involves the co-operation of several different external environments, devices and programs, they need to be integrated into the trial environment somehow. This is done with core clients. They provide information about the state of the component or environment they are integrated into and offer capabilities regarding the adjustments and reconfiguration. A CC can be modified to match every use case separately but it has the same basic structure for all instances. The modified parts include the functional capabilities and provided information of the end-entity where the CC is added. The CCs can—for example—also provide information about the quality of the connection if it is integrated with proper software. The basic structure has the means to communicate with the other parts of trial environment and other typical functionality (e.g. logging) that are independent of the system where the CC is operating.

The modifiability of cognitive engine and core clients is basically limited only by the needs and imagination of the users. This makes it easy to include completely new systems in the environment without drastic changes to other components. This works well along the lines of how a cognitive network should be extensible for new network elements. After creating a necessary instance of core client, the only need is to have CE aware of the information and capabilities of the new client. Of course, having this kind of functionality automated would be very beneficial.

Core clients do not communicate with CE directly but the information and commands are managed by cognitive manager (CM). It works as a server between core clients and core engine as can be seen from Figure 4. CM eliminates multiple simultaneous connections and therefore eases the logging and functionality of cognitive engine. Cognitive manager, cognitive engine and core clients may be running on the same or different locations because of the HTTP based messaging system between these components. Multiple core clients can connect to single cognitive manager but only one cognitive engine is allowed.

3.1.2. CWC CORE trial environment

The CWC trial environment consists of several Wireless Open-access Research Platform (WARP) radio units, forming a network of users and base stations. WARP is a scalable and extensible programmable wireless radio platform operating on ISM bands and it is developed by Rice University. It is designed to prototype advanced wireless networks and is used by many organisations in cognitive radio testing since it allows cross-layer design between medium access control (MAC) and physical (PHY) layers and flexibility over typical off-the-shelf platforms relying on IEEE standards. A WARP board is built around an FPGA, which handles most of the radio functionality. Therefore it may be considered as a software defined radio. [33]

With the basic setup, a WARP board has physical and medium access control layer functionality executed with the FPGA but in this trial environment CWC has made some changes into the MAC layer and included Linux operating system to enhance the functionality of a WARP board with network level capabilities. Therefore it is possible to manage the parameters of a WARP board with specific messaging protocol working on top of user datagram protocol (UDP) and need for manual adjustment or local computing is unnecessary. [34]

In the CWC trial environment some of the WARP boards work as base stations (BS) and the rest as user equipment (UE) connecting to the base stations—forming a wireless radio network. In addition to the WARP boards, the environment also includes a server and a database for data storage and an environment-specific cognitive engine (to make a difference from the cognitive engine of VTT CORE trial environment's cognitive engine, CWC trial environment's cognitive engine will be referred to as WARP-CE). WARP-CE receives information from WARP units periodically and stores them into the database. The received information can be accessed afterwards and the local decisions are made according to it. The information is mostly related to status of the boards (used channel, modulation etc.) but some performance metrics are also available (for example throughput). WARP-CE also incorporates a graphical user interface (GUI) to enable a real-time viewing of environment's status and some amount of control over the used parameters. [35]

A typical WARP setup in CWC trial environment is able to connect multiple WARPs working as base stations with multiple users as shown in Figure 5. Like stated, the UEs connect to BSs with wireless radio link working on ISM frequencies (either 2.4 GHz or 5 GHz bands). These frequencies are divided into 14 channels according to WLAN standard and WARP-CE controls which ones of these are used by WARP units. Therefore multiple wireless connections can be easily managed in the same location without interference. The BSs have a wired connection to a router that also connects to the server, which includes WARP-CE, database and GUI. [34][35]

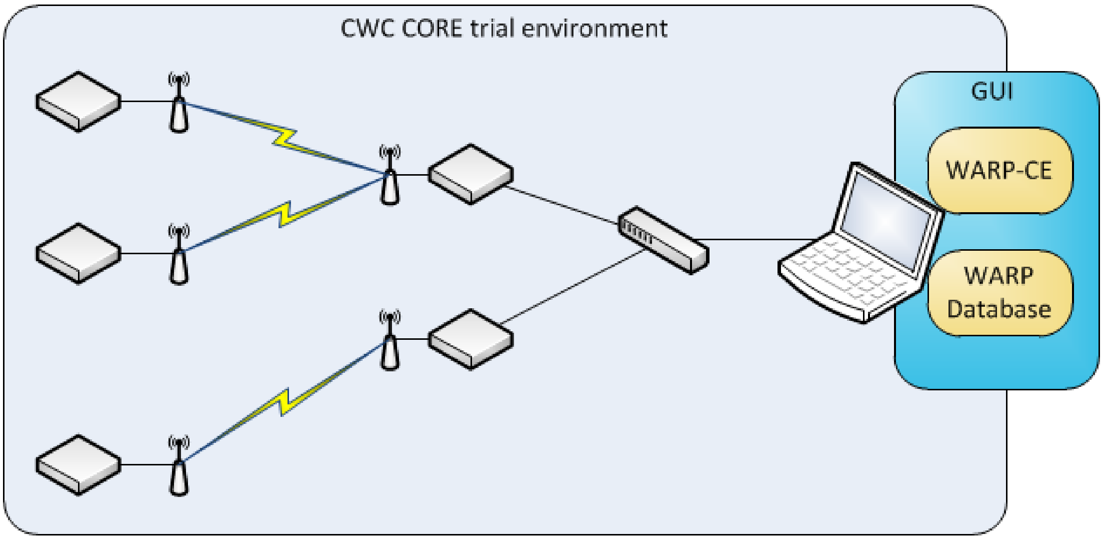

Figure 5. A typical setup in CWC trial environment includes multiple base stations and user-end-devices connecting wirelessly and being managed by WARP-CE.

At this point, the core idea of the CWC trial environment is to research and experiment with load balancing between base stations. The functionality of the WARP network supports an easy switching of frequencies and UEs can change the connection to a different BS dynamically. This thesis takes advantage of this ability to change frequencies flexibly and of the access to detailed information about the network's status.

3.2. Interface between environments

The goal of this master's thesis is to design and create a solution for these two environments—VTT trial environment and CWC trial environment—to share resources and apply co-operative decision making between them. Avoidance of mismatching decisions is another important advantage that is gained from the co-operation. In order to get the two environments work properly together an interface is required to filter, translate and deliver information and commands or decisions between WARP-CE and CE. One of the goals of CORE trials is to get different environments incorporating cognition to work together in a co-operative manner.

In the case with CWC and VTT trial environments, CE would be the top decision maker as it has the view of the complete network whereas WARP-CE is only aware of the WARP network. WARP-CE would still mostly maintain its independence but CE could make a decision that overrides others in order to increase end-to-end performance or achieve a user-set goal. It is important to have lower level decisions in order to react quickly to changes and needs of local radio connections.

There are a few different ways to approach the design of the interface: the component that connects the two environments could be placed in different parts of the system and there could be multiple instances of it. Since the GUI and connection to the database are programmed in Java an apparent choice is to make an implementation of the core client that works alongside GUI. Since the components in the VTT trial environment are already programmed in JAVA too it is reasonable to create a CC that matches the needed functionality. This also matches the primary idea of the CC that it can be recreated for different locations and uses depending on the local requirements and capabilities.

The approach has other benefits also in addition to being the simplest course of action: Since the client is implemented alongside GUI there is no need to create more than one instance of CC. The client can easily access all relevant information about all of the WARP units in the database. Even older data as the database stores data over a longer span of time, labels it with timestamps and keeps it until manual deletion. Running alongside the WARP GUI (and of course WARP-CE) also makes it possible to communicate directly with the decision making entity of the CWC trial environment. Therefore this approach provides more management capabilities over the whole WARP network.

The implemented WARP Core Client (WCC) is executed in the GUI/WARP-CE program. Therefore it basically works as a part of the program and it can be switched on and off from the GUI menu. The actual interfacing between WCC and WARP-CE was realized by taking advantage of the already existing database of the GUI program. Like mentioned above, the WCC is able to read information from that database. The WCC uses the same database connection as the GUI but is basically otherwise independent of the GUI. While the original sections of the database consist of WARP status information tables, the database did not work as a way to provide information and decisions to WARP-CE as it was. Therefore another portion was created into the database to store information based on decisions made by CE. While the CE has information from both the CWC trial environment and the networks outside it, CE has the authority over WARP-CE. With the approach of having a new table implemented into the database, the WARP-CE polls it periodically and makes decisions and modifications to the CWC trial environment based on the acquired information.

3.3. Alternative approaches

As the CWC trial environment consists of several boards that have sufficient processing capabilities, an alternative solution would have been to create several instances of core clients (basically at least every base station would need one). They would have been able to work completely separate from the CWC trial environment and its cognitive functionality but in return any control would have been difficult to execute. Since WARP-CE already communicates with the control programs of the WARP boards any outside adjustments would only lead to conflict and problems if not done in unison. The need for synchronicity regarding to WARP management leads back to having the need for another interface towards WARP-CE. Another obstacle with this approach would have been the required work as the WARP boards are Linux enriched and would have required a new type of core client implemented in C.

The problem of multiple instances could have been avoided with another approach that would have used the same messaging protocol that the WARP environment already uses. This realization could have been done with a different type of implementation of the JAVA based core client. It would have only been required that the CC was located in the same network as the CWC trial environment. Again, this alternative solution has the same problem as the earlier one: the messaging protocol in itself is not flexible and sufficient enough as it is to be able to provide information from CE to WARP-CE and a new core client would have been needed to communicate between them.

An advantage of these methods would have been the faster access to the CWC trial environment status information as it would not have had to circulate through the database of the environment. The advantage of having faster response time to decision could have been accessed too but it would have required the CWC trial environment components to be aware that an outside system might have modified the parameters. This in turn would have led to a more complex design and the original components would have required much more alteration than in the solution where a core client is integrated into the GUI.

3.4. A solution for measurements

Having a clear view of the end-to-end performance of any network is a significant point of interest. Especially important it is with a cognitive network that bases the decisions on the picture of the whole network and its performance. Acquiring this view is most easily done with end-to-end measurements that directly show the performance parameters of the transmission system.

In order to acquire measurement results in this master's thesis, a measurement tool called Qosmet was used. It is designed and developed by VTT to measure quality of service performance from the application point of view. Qosmet is designed so that the performance can be evaluated real-time and the measuring or monitoring itself is passive and adds a minimal amount of load to the network since there is no additional test traffic. The measured parameters include delay, jitter, packet loss, connection break statistics, load, the volume of data, packet sizes and estimation of subjective perceived quality. The measuring can be done on one point but more accurate information can be acquired with two-point measurement. Qosmet is based on measurement agents that run at the desired measurement points. These agents are light-weight software components called Qosmet Service that follow the internet protocol based traffic on the desired network interface. Qosmet itself uses Quality of Service Measurement Communications Protocol (QMCP) that allows full remote control over measurements. The monitoring of measurements can be done with Qosmet UI or any other software that is capable of using QMCP. The basic idea and structure of Qosmet are introduced in Figure 6. [36]

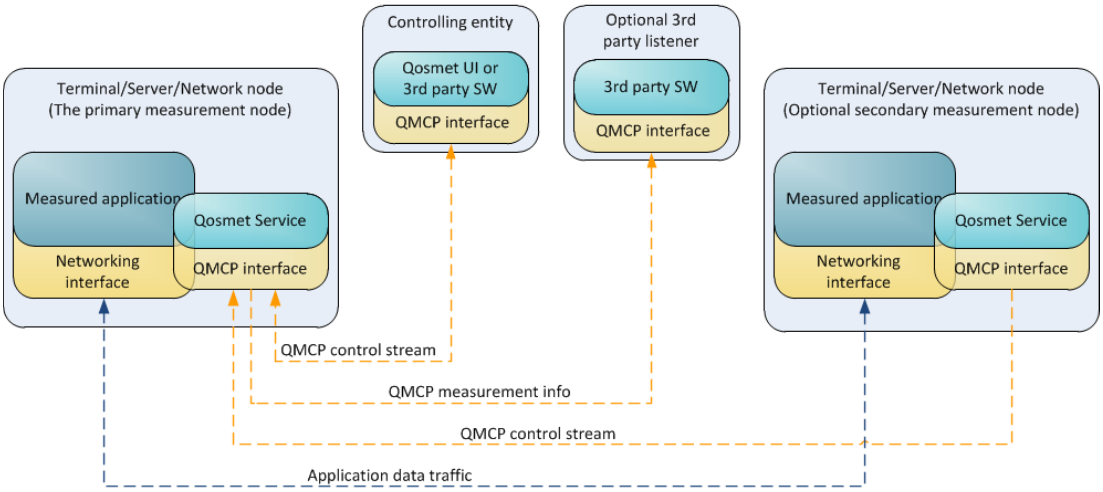

Figure 6. Basic structure of Qosmet measurement. Qosmet Services communicate through QMCP protocol while the measurement itself is passive and the measured application is undisturbed and unaware of it. The measured data can be monitored through Qosmet UI or a 3rd party listener or software.

Qosmet is also used with the VTT trial environment and one implementation of core client uses Qosmet Service and QMCP to provide measurement information and estimated Quality of Experience (QoE) to cognitive engine. This core client is called Qosmet Core Client (QCC). It uses the normal measurement structure of Qosmet but adds the QCC as 3rd party software that reads the measurement data and sends it to CE using VTT trial environment's messaging protocol. More exactly, the decisions are based on Quality of Experience value that is calculated in the Qosmet Service agent. The QoE value is an estimation of the perceived experience of the user that is based on Generic Quality of Service Measure (GQoSM) algorithm, which estimates the subjective experience of the media at hand by taking into account the various measured values. The algorithm—like Qosmet—is developed at VTT but the details are delimited outside this thesis. Nonetheless, the approach with QoE gives a better image of the performance of the system than what just a throughput or packet loss would since the actual subjective experience is heavily related to transmitted media. For example, low throughput and even higher amount of packet loss can be endured with single images or text but a video or audio stream gets disturbed relatively quickly by small amounts of transmission errors.

4. RESOURCE SHARING MEASUREMENTS

As explained in the previous chapter, the VTT CORE trial environment is composed of multiple network components and external systems under the management of cognitive engine. The main test scenario of this thesis work is based on one of these situations - more exactly the co-operation and resource sharing with the CWC trial environment, using a core client modified for this purpose.

This chapter goes through the test setup, equipment and scenarios which are used to experiment with the functionality and effectiveness of used solutions. Even though the measurements include the disturbance of wireless links, they are not the actual point of interest here. This thesis work looks into the effectiveness of cognitive solutions in preventing the effects of disturbance, whatever the source or type of disturbance is. Disturbance is only considered as an obstacle in the optimal transmission of information. The measurements are meant to test what kind of benefits can be achieved from cognitive radio systems communicating with each other and to postulate what kind of steps would be wise in the future.

4.1. Test setup and equipment

The measurements were carried out in the office laboratory space of CWC at the University of Oulu. The measurement setup was a simplified version of the CWC trial environment setup introduced in Section 3.1.2 consisting of one WARP unit as a base station and another unit as user equipment. These units were set to work and communicate together on 5 GHz WLAN frequencies. 5 GHz frequencies were chosen since they have less outside traffic than more commonly used 2,4 GHz frequencies. A short scan in the space showed that there was basically no traffic at all on the 5 GHz frequencies. The WARP unit operating as a base station had a wired connection to a router, which in return had a wired connection to a Unix computer and a measurement PC. The user-end-WARP unit was used for providing a connection for another measurement PC wirelessly over the WARP link. While it would have been possible to include more base stations and user equipment to the setup it was not necessary, taken into account the goals of these measurements: the extra base stations would have occupied unused channels and would not have had any significant effect on the operation of the channels used in the measurements. The measurement setup and equipment for cases without sending measurement data to CE are presented in detail in Figure 7.

The outside source of disturbance was carried out with an ordinary WLAN base station of which parameters could be altered from another computer. The transmitting power was set at maximum and the amount of interference was controlled with time between beacon signals -value. The WARP core client works as a part of the GUI and WARP-CE on the Unix computer where the database is also located. WCC connects to cognitive manager and cognitive engine with a WLAN connectivity of the Unix computer over the internet. CM and CE themselves are located on the Willab-server at VTT.

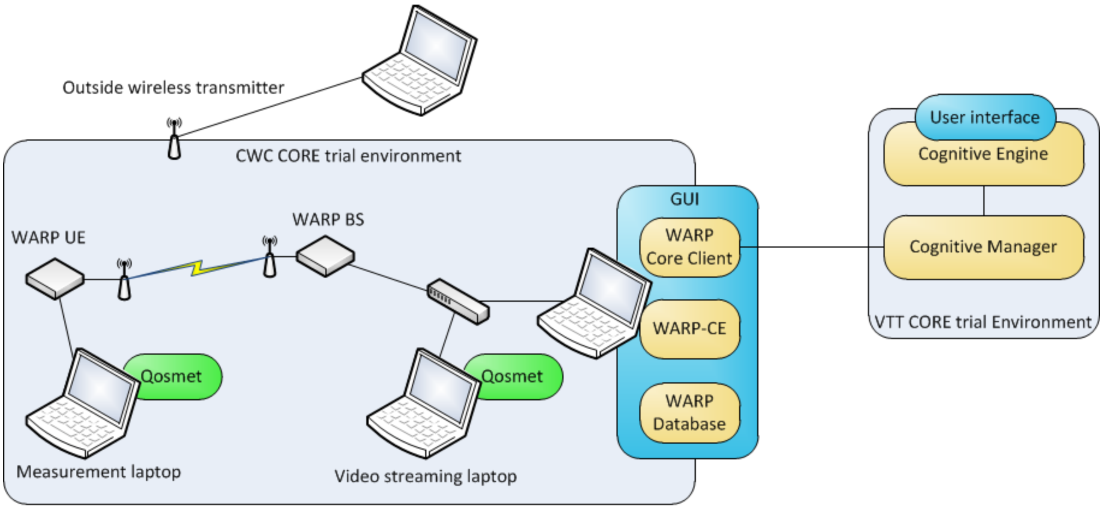

Figure 7. The measurement setup used in this thesis work for scenarios that did not require end-to-end quality data to be sent to cognitive engine.

Some of the test scenarios required the transmitting of measurement data from measurement laptop to cognitive engine of the VTT trial environment. In these scenarios, the measurement setup was altered to one shown in Figure 8: another core client was added to the measurement laptop in order to deliver measurement data from it.

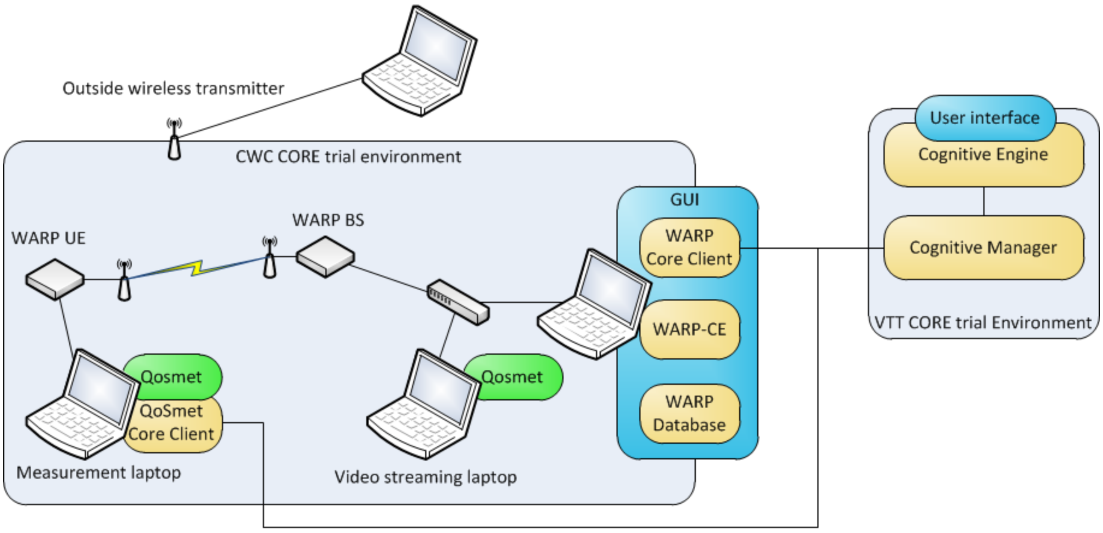

Figure 8. The measurement setup with the additional Qosmet core client for delivering measurement data to cognitive engine.

The actual measurements were carried out on the two measurement computers (as seen in Figure 7 and Figure 8) using Qosmet measurement tool. The tool was used to measure traffic between the computers using two-point measurement that, for example, enables the viewing of actual packet loss and throughput of the desired connection. The data collected with Qosmet was also used to form the decisions in the scenarios that included the transmission of measurement data to CE. As seen in

Figure 8 Qosmet has its own core client that provides information about the network status to CE.

The traffic between the measurement computers was a standard definition video stream between two VLC media players. A video stream works as a good indicator of effectiveness as packet loss affects the quality almost instantly and it requires a lossless connection to be considered as satisfying quality. At the same time it is a commonly transmitted media that makes the visualisation of the transmission quality easy. The video lasts for five minutes and if the interference appears after one minute of running and disappears at the point where the video has ran for four minutes. In the cases where the interference gradually increases, the increase happens between one and two minute point and decreases between three and four minutes.

4.2. Test scenario and test cases

The measurements are done with two test scenarios. In the first one, an outside wireless network using the same channel as WARP units starts to interfere suddenly with the wireless WARP link that is used for video streaming. This mimics a static base station that is suddenly turned on in the same location and in the same frequency band as the network of interest. WARP-CE is aware of the frequency used by the WARP network but it is oblivious of the outside source of interference and has no means to know if the used channel is occupied by some system outside its vicinity. The second scenario is similar to the first one but the disturbance simulates a non-static network that starts to slowly interfere with the link between WARP units. This simulates a situation where the networks move related to each other and don’t affect each other at first. These both scenarios are repeated with three different test cases.

In the first test case, CWC trial environment is working without any outside decisions from CE—as it is currently doing. In reality this means that the WARP link just stays on the allocated channel when another network starts to interfere with it suddenly. This should have a noticeable effect on the video quality at least on the peak interference and the disturbance should last until the interference disappears or decreases low enough for the signal to be transmitted without effect.

The second test case includes the core client working with the graphical user interface of the WARP-CE. This way the CE can inform WARP-CE if some channels are occupied by an outside network as stated before. In this case CE learns about the outside network and its location close to WARP network. It informs the CWC trial environment about the occupied channel by sending a message to WCC that sets the channel status to “occupied” in the database table allocated for WCC. WARP-CE will then move the base stations and users from that channel to free ones.

The third test case is similar to the second one with the exception that CE is not aware of the outside network directly. Another difference is that the user watching the video stream measures the performance with Qosmet measurement tool and this information is provided to CE with the Qosmet core client. In this case it is also assumed that if the quality of the stream drops notably CE decides that there must be something interfering with the channel. The quality of the stream is estimated with QoE value that is a combination of several measured values. Since the QoE value is ranked between 1 (the worst quality) and 5 (the best quality) the level of 3 is chosen as the trigger for the CE to notice that something is wrong. Values above 3 may be caused by random errors and are usually very short-lived and do not therefore affect the perceived experience of the user that much.

The last two cases are done in order to compare different ways of decision making: The second case performs a pre-emptive decision that attempts to avoid the disturbance as soon as there is knowledge about the other network being in close proximity and possibly causing problems. The third case is more reactive and the decision is based on the perceived effect of the interference rather than the knowledge of the other network itself.

The three cases are repeated for both scenarios. In addition, one measurement is performed without any kind of interference for comparison and there will eventually be 7 different measurement cases. They are summed up in Table 1.

Table 1. Different test cases and scenarios summed up for comparison and easy reference

	Scenario 1	Scenario 2
Baseline	**Baseline measurement** without any kind of disturbance or frequency management.	
Case 1	**Sudden interference without outside management** of CE.	**Gradually increasing interference without outside management** of CE.
Case 2	The cause of **sudden interference** is **known by CE as soon as it appears** and CE manages the frequency used by WARPs immediately.	The cause of **gradually increasing interference** is **known by CE as soon as it appears** and CE manages the frequency used by WARPs immediately.
Case 3	The disturbance caused by the **sudden interference** is detected with Qosmet and **CE uses the measurement information for decision**.	The disturbance caused by the **gradually increasing interference** is detected with Qosmet and **CE uses the measurement information for decision**.

4.3. Results

The results from the introduced test cases are divided into three sections: first section is the baseline measurement and the last two sections are divided into sudden interference and gradually increasing interference. Each of the cases was run 5 times (except for the baseline).

4.3.1. Baseline

In order to have a clear idea of the overall results, the first measurement is one of the setup with no outside interference. For a case of video streaming, the values under most interest are throughput and packet loss. Throughput shows the amount of data transmitted while packet loss is an effective measure for the quality of transmission. For the measurement with no interference, these are shown in Figure 9. It can be seen that even without any disturbance 100% packet loss is detected at 98 seconds into the video (due to scale of the figure the momentary loss can be seen only as a spike in

Figure 9). The WARP link can transmit only certain amount of data (approximately 1600 bits/s at maximum) and some packets are lost due to this. Locations of the antennas cause a slight variation to this maximum value but the distances were kept constant through all of the measurements.

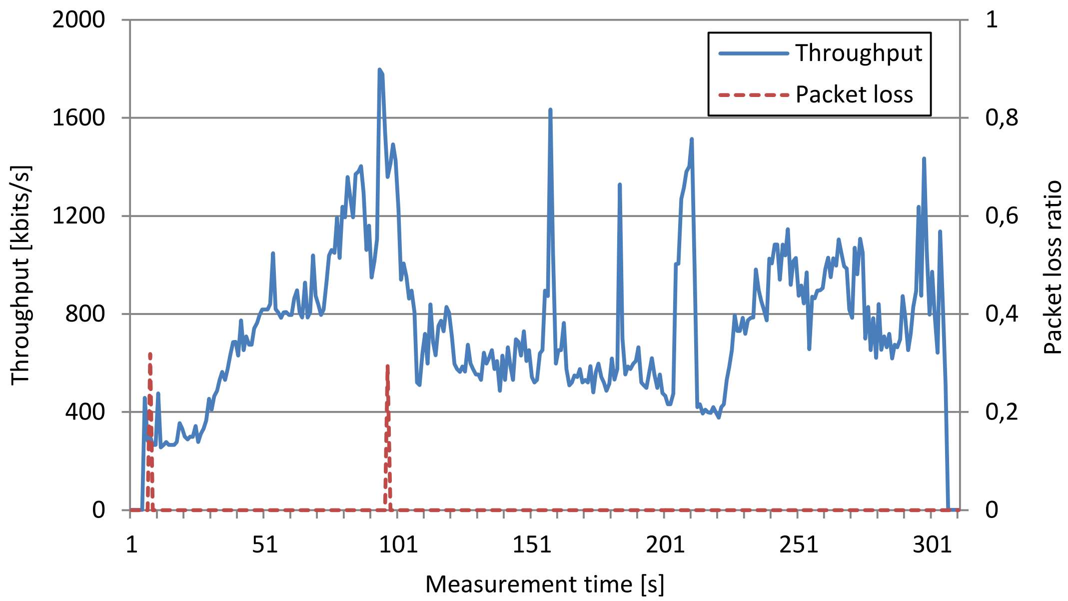

Figure 9. Throughput and packet loss values of a single stream of five-minute video without interference.

This single points of low quality caused by the limitation of the link and beginning of the stream are very brief and do not have much effect when compared with a longer run of undisturbed video stream. The average packet loss ratio for the baseline measurements is 0.0025 and peaks at 0.8 at the worst. The peak is again at 98 seconds in to the video and caused by the momentary high transmission rate. The results can be viewed from Table 2 at the end of this chapter along with the other results measured in this chapter. Although just about over 2% packet loss produces blocking and other disturbance it does not last long and is easily endured by the viewer if it is not frequent. With this in mind we can have a better indicator for the viewing experience (and of the transmission quality in a longer run). This is done by acquiring the QoE value from Qosmet. The GQoSM algorithm takes into account measurements over a longer period of time of a few seconds. The longer the disturbance persists the lower the QoE value drops. The acquired value varies between 5 and 1 where 5 is perfect quality and 1 very poor (basically no information is transmitted). A short drop in transmission quality drops the QoE value slightly for a short period of time as can be seen from Figure 10 but not so much that it could be interpreted as annoying disturbance.

These results can be used as a baseline when comparing the difference between later test cases.

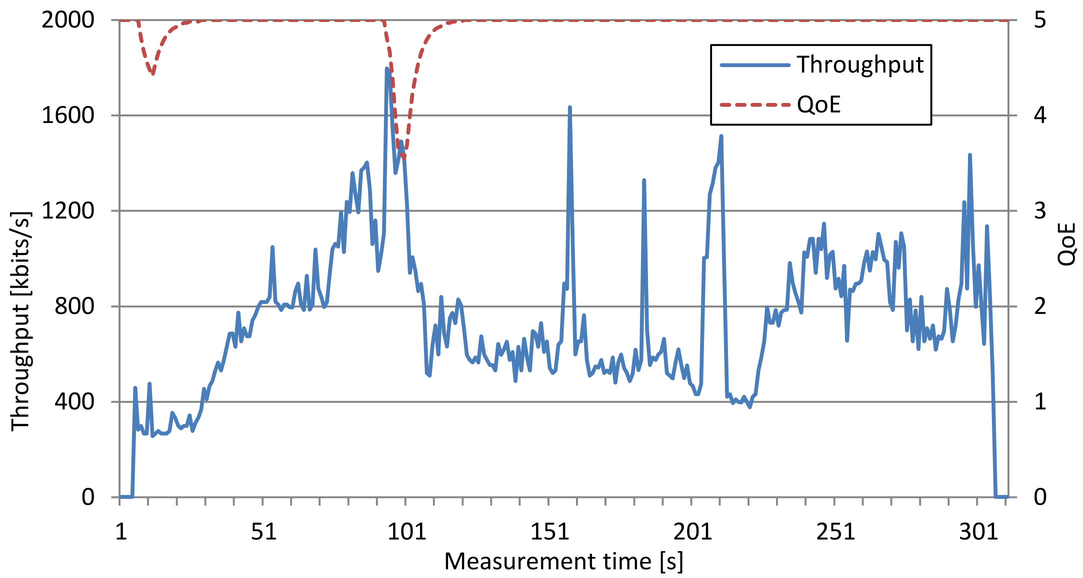

Figure 10. Throughput and quality of experience value for a single run of video stream lasting for five minutes.

4.3.2. Sudden interference

As stated previously in this chapter, the first test scenario experiments with the idea of sudden interference caused by an outside network. The kind of disturbance inflicted in this kind of situation is visualised in Figure 11. While we can still see the small spike in the packet loss ratio at the beginning of the video the source of disturbance is the lower rippling caused by the interference from 60 seconds to 240 seconds.

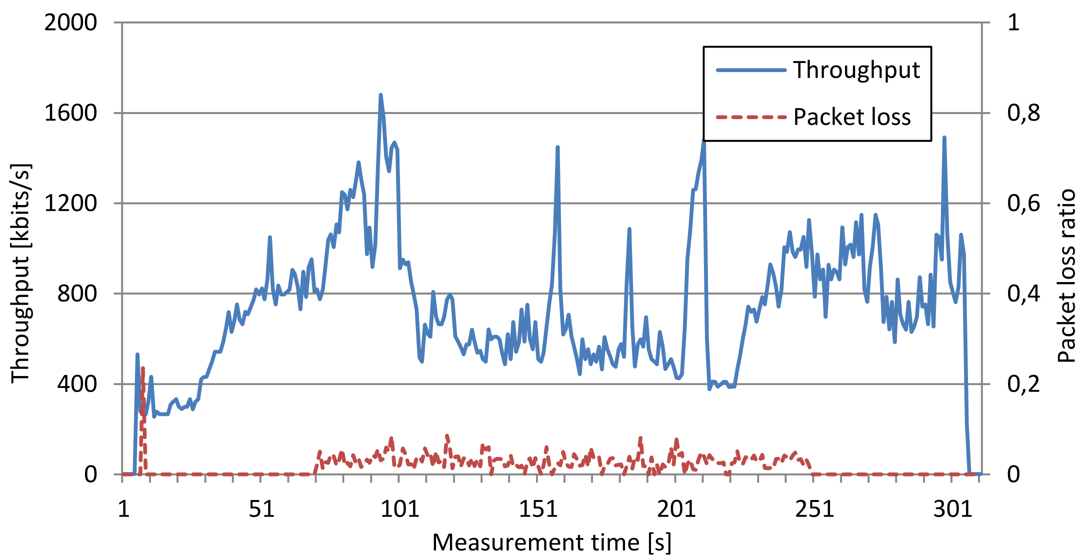

Figure 11. Throughput and packet loss ratio in the case of sudden interference.

Even though the rippling does not rise over 0.1 during the interference the effect is drastic in comparison with the small spikes measured with the baseline. A better indication, again, is the QoE value in Figure 12.

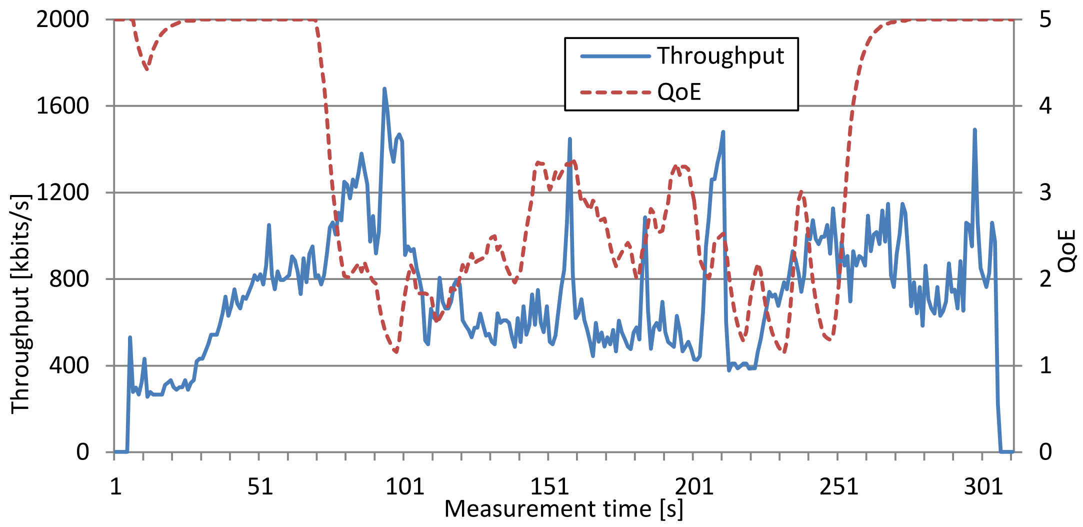

Figure 12. Throughput and QoE value in the case of sudden disturbance.

It can be seen that the quality of experience value drops below 2 at the worst and is generally below 3. Both of the values are unacceptable with streaming video where a value below 4 would cause the viewer to get annoyed in a longer run.

With cognitive radio systems there is a way to make the system aware of the disturbance and try to act in order to change the situation to better. In the second measurement case, this is done with the pre-emptive recognition of the problem and the changes to the system are made as soon as the outside network causing the problem is recognized. The effect on the packet loss can be seen clearly in Figure 13.

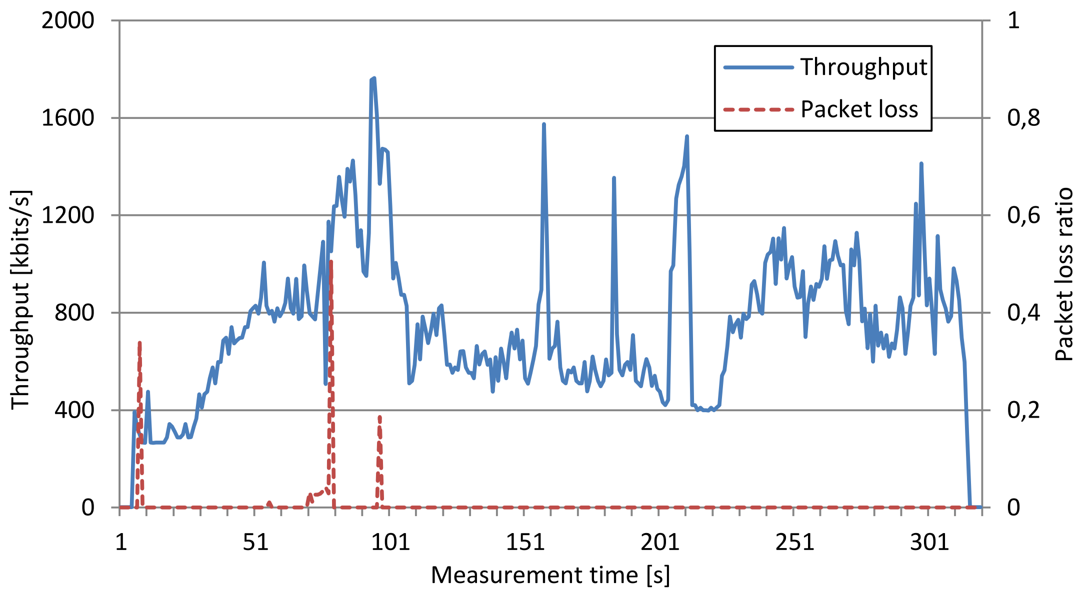

Figure 13. Throughput and packet loss with sudden interference and pre-emptive avoidance.

While the beginning and peak of the video still cause spikes in packet loss the disturbance caused by outside interference is clearly obsolete after the changes to the system take effect after a few seconds. The spike at the end of the low disturbance is caused by the WARPs changing frequency but like with the other packet loss spikes the effect is very brief and doesn't have much effect on the user's experience in the long run. Once again, the effect can be seen in the QoE value in Figure 14.

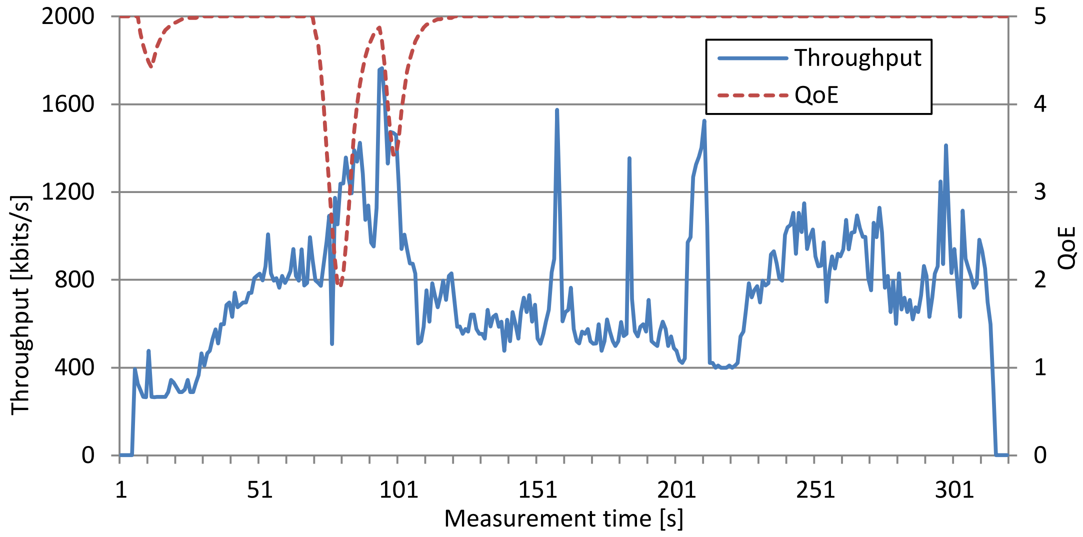

Figure 14. Throughput and QoE value with the sudden interference and pre-emptive avoidance.

Although the QoE value drops all the way to 2 it happens only for a short period of time and quality of the video stream stays good for most of the time. The outside network stays on the channel where it was originally interfering with the WARP link but obviously has no effect on the new channel where the WARPs were moved.

In the third case, the interference is detected only vicariously through the effect on the packet loss ratio (and therefore also on the QoE value which the decision is based on). As seen from Figure 15 the reactive way to try to affect the problem works basically as well as in the earlier case but with somewhat more delay.

The delay in the packet loss in this case varies between 23 and 37 seconds while with pre-emptive decision making the same values were 7 and 14 seconds. These can be seen in Table 4 at the end of this chapter. The MOS value in Figure 16 tells the same thing as the packet loss ratio previously; the disturbance lasts for a longer period of time but mostly the quality stays good.

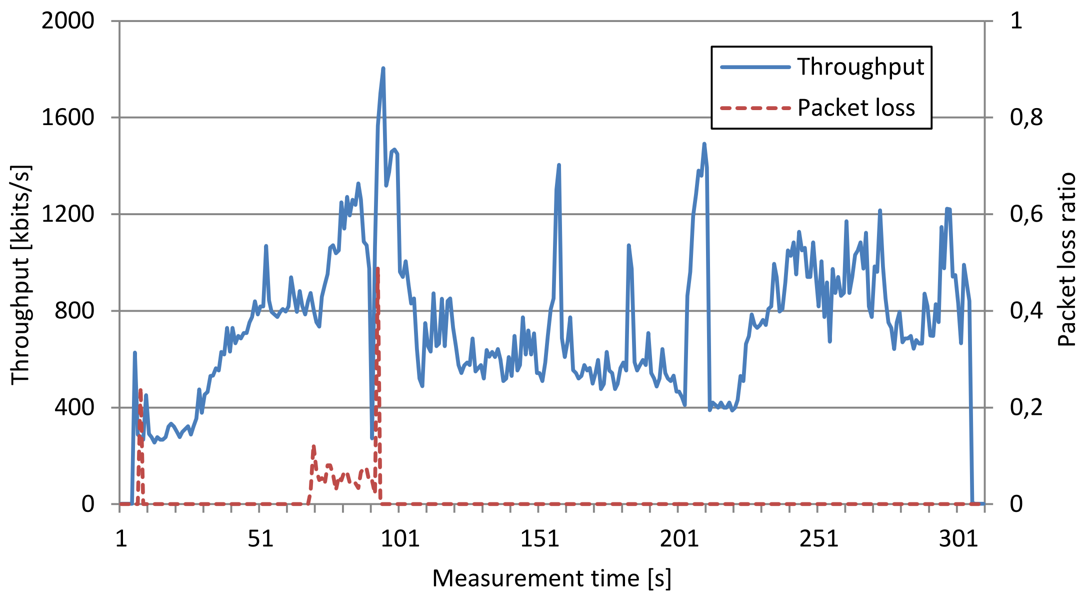

Figure 15. Throughput and packet loss ratio with sudden disturbance and reactive avoidance.

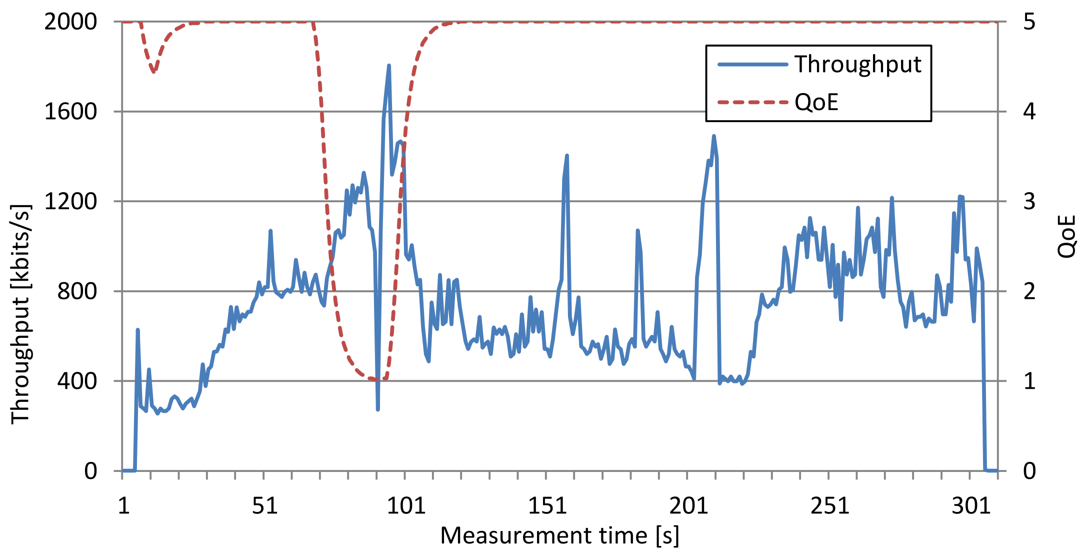

Figure 16. Throughput and QoE value with sudden disturbance and reactive avoidance.

4.3.3. Gradual interference

Sudden disturbance is a very straightforward way to measure interference but in today's situations the interference can often be more dynamic: gradually increasing and decreasing according to distance and transmission power. When comparing the sudden interference to the gradual in Figure 17 and Figure 18 the increasing and decreasing nature of the interference is clearly visible.

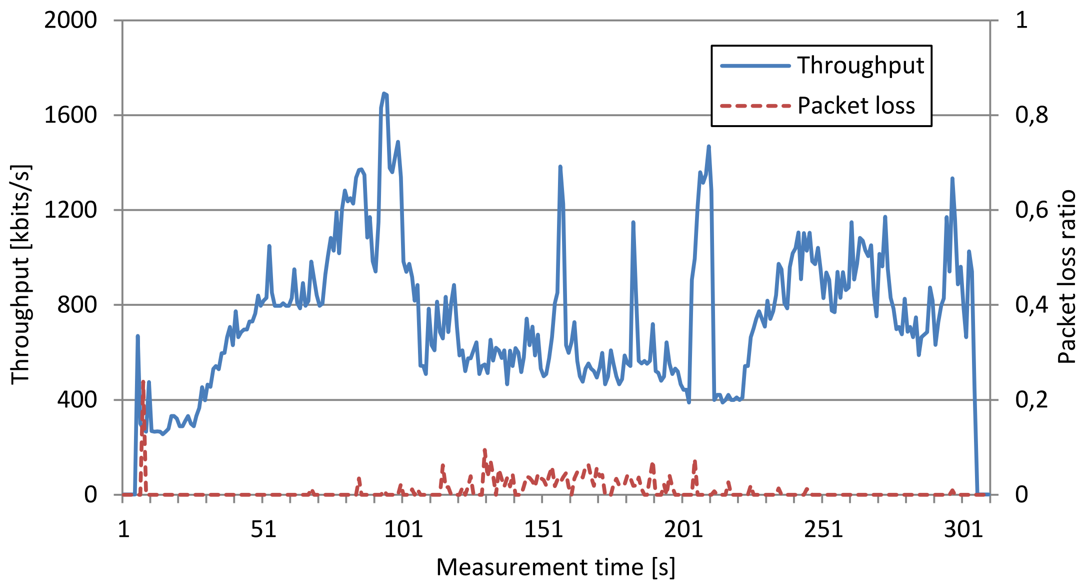

Figure 17. Throughput and packet loss ratio in the case of gradual interference.

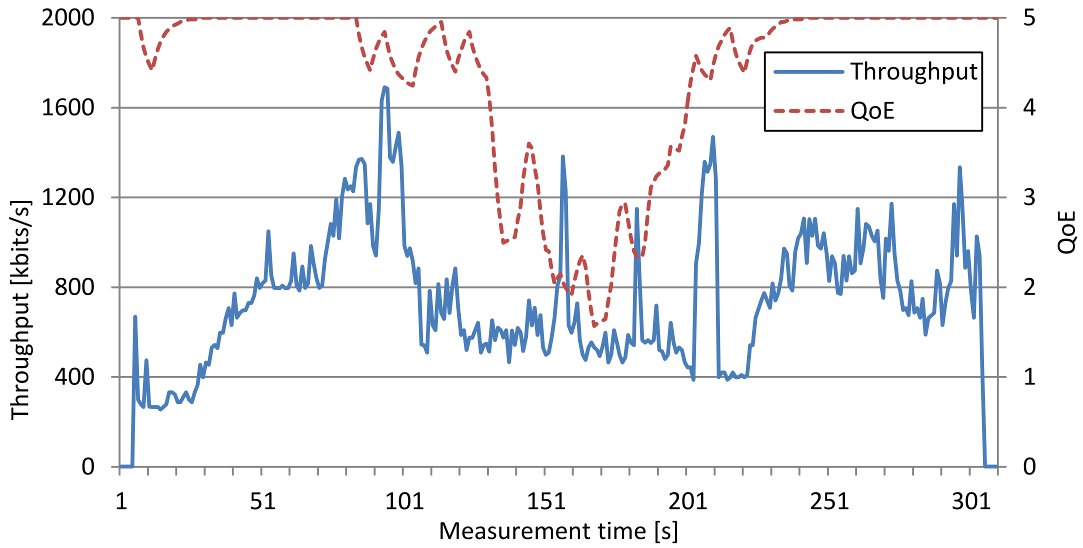

Figure 18. Throughput and QoE value with gradual interference.

In the case of the pre-emptive avoiding of disturbance, the cognitive engine gets the knowledge about the outside network at the same time as in the earlier case and the delay forms from the same elements. The disturbance does not show much in the packet loss ratio since it is avoided before it has time to have any significant effect on the transmission. Only the spike caused by the changing of the channel can be seen in Figure 19.

This is very close to what was measured with the baseline earlier in this chapter and results of the same kind can be seen with QoE value in Figure 20.

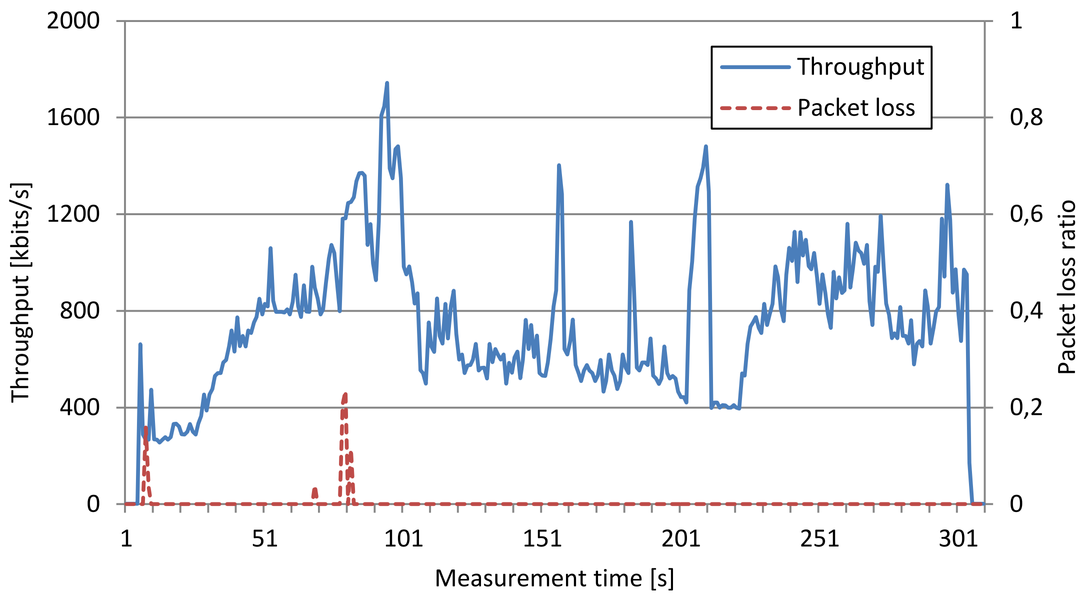

Figure 19. Throughput and packet loss ratio with gradual interference and pre-emptive avoidance.

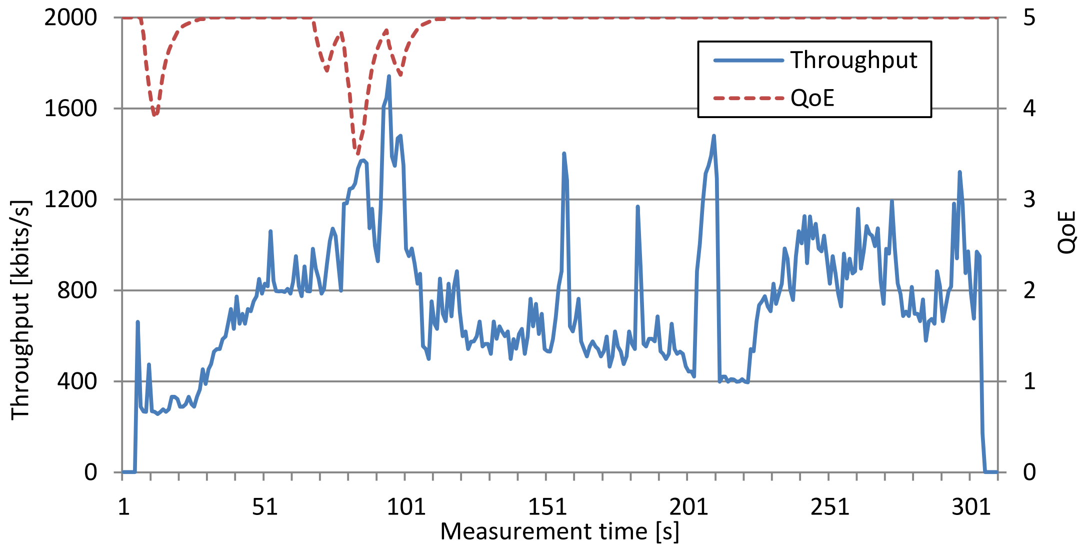

Figure 20. Throughput and QoE value with gradual interference and pre-emptive avoidance.

The story is very different with a reactive avoiding of disturbance where the system has to wait for a stimulus from the measurement software until it can make the decision to change frequency. It can be seen from Figure 21 that the delay compared with the pre-emptive case is significantly longer than in the previous scenario.

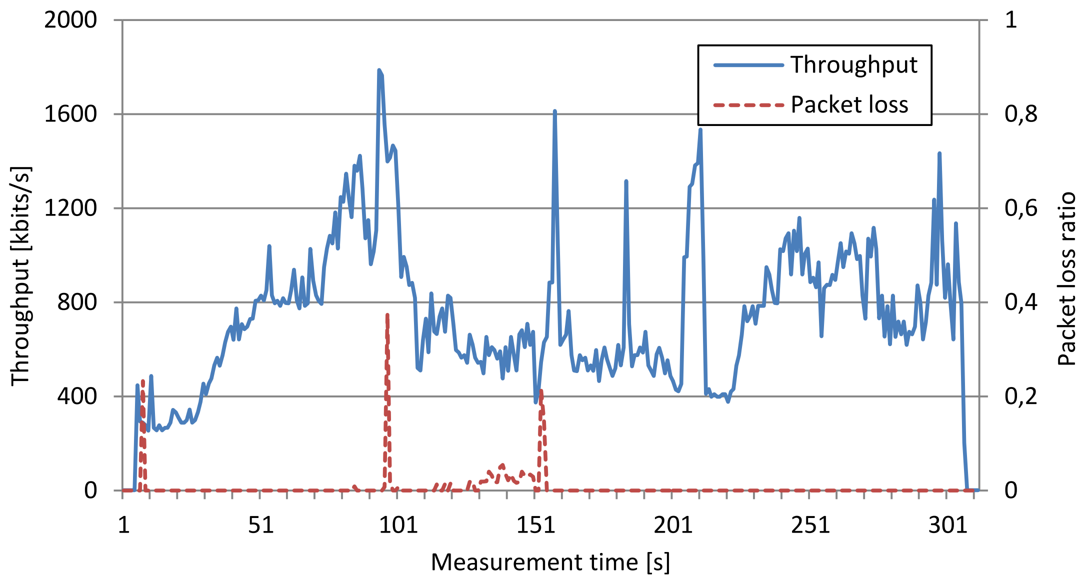

Figure 21. Throughput and packet loss ratio with gradual interference and reactive avoidance.

The delay mostly consists of waiting until the criteria for the decision to change frequency is met. Since the decision is made when QoE value drops below 3, it can clearly be seen in Figure 22 that it takes a while until it happens. At this point, there has already been clearly more packet loss than with the pre-emptive case.

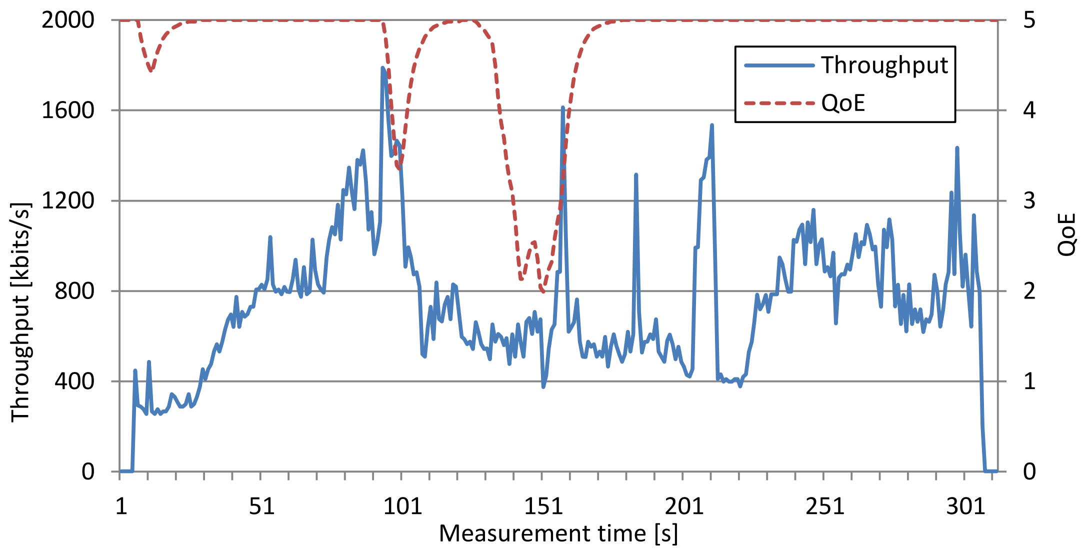

Figure 22. Throughput and QoE value with gradual interference and reactive avoidance.

Even while the decision switch channel comes at late point the effect on QoE value stays relatively low. The effect is of course much higher than with the pre-emptive case but it is close to what was measured with sudden interference in the same case.

4.4. Summary of results

The comparison of throughput and packet loss in all the cases is below on Table 2: since the five-minute video was the same every time there was basically no difference in throughput—only the packets that were lost do not count towards throughput. The minimum packet loss ratio in all cases was 0 since there were always undisturbed parts during the test runs.

QoE values are compared in Table 3. The first column is the grade for the user's perceived quality of experience based on GQoSM algorithm and the second column it the time below certain levels of QoE value. Again, QoE value of 5 is the maximum and denotes perfect quality. In case 3, a level of QoE below 3 triggered the decision to change the channel. It is seen that while three minutes of the five-minute video (60%) is spent under the interference around 75% of the time the quality is less than perfect. This is due to slight disturbance in the transmission and lingering nature of the errors that cause about 15% extra time being less than perfect. This can be seen straight from the baseline measurement as well as from case 1 of scenario 1 where about exactly 60% of time is spent under QoE value of 4.

Table 4 presents the delays from the beginning of the interference to the point where decision was received at the WARP core client (delay of decision) and to the point where the effect of the disturbance on packet loss disappeared (delay on disturbance). It should be noted that due to the varying nature of the interference and variation in the measurements, the delay in the perceived increase of quality was occasionally shorter than the delay of the decision. While the error in the delay values can be several seconds, the measurements still show a clear trend: basing the decision on measurement data can cause a significant difference in the response time.

Table 2. Comparison of downlink throughput and packet loss ratio between undisturbed video stream and different cases of interference

		Throughput			Packet loss ratio		
		min	average	max	average	median	max
Baseline		255,8	759,3	1829,6	0,00255	0	0,8
Scenario 1	Case 1	223,7	738,5	1718,2	0,02529	0,01389	1
	Case 2	85,5	754,8	1794,0	0,00562	0	1
	Case 3	91,0	750,4	1855,4	0,01169	0	1
Scenario 2	Case 1	23,8	747,5	1753,9	0,01612	0	1
	Case 2	171,3	756,3	1799,8	0,00335	0	0,55055
	Case 3	202,3	754,2	1832,6	0,00597	0	0,55318

Table 3. Comparison between cases on Quality of Experience (QoE)

		QoE			QoE, % of time			
		min	average	median	< 2	< 3	< 4	< 5
Baseline		3,44	4,96	5,00	0,0	0,0	1,2	14,7
Scenario 1	Case 1	1,00	3,38	3,02	18,9	49,5	59,1	73,8
	Case 2	1,08	4,83	5,00	1,1	2,6	9,5	26,4
	Case 3	1,00	4,54	5,00	8,8	11,2	13,4	32,5
Scenario 2	Case 1	1,00	3,91	4,59	14,1	25,4	33,5	76,5
	Case 2	1,94	4,87	5,00	0,1	0,5	3,9	30,2
	Case 3	1,63	4,69	5,00	1,8	7,7	10,8	38,3

Table 4. Comparison between the delays in decision making and in affecting the interference during measurements

		Delay of decision [s]			Delay on interference [s]		
		min	average	max	min	average	max
Baseline		-	-	-	-	-	-
Scenario 1	Case 1	-	-	-	-	-	-
	Case 2	8,60	11,38	14,10	7,00	11,29	14,00
	Case 3	17,20	24,47	30,80	23,00	31,50	37,00
Scenario 2	Case 1	-	-	-	-	-	-
	Case 2	7,70	10,95	16,50	7,00	10,60	18,00
	Case 3	41,20	78,22	109,10	48,00	91,33	117,00

5. DISCUSSION

This master's thesis provided a glimpse to cognitive technologies that could work as a more effective solution, concentrating on one of the biggest bottle necks: radio communications. While cognitive technologies are a promising way to enhance the wireless connectivity the research is still on-going and the advantages of cognitive radio systems are something that need to be shown true and need work to be achieved. CRSs can efficiently increase the performance of a network including radio links. At the moment, technology is reaching the point where CRSs are becoming a reality but other obstacles remain in standardization and regulation fronts too.

In order to showcase, experiment and measure a CRS system consisting of wireless links and different parts of the network controlled by cognitive engines in this thesis, an interface between a cognitive environment (VTT trial environment) and a cognitive radio network (CWC trial environment) was created. The interface is an implementation of a software component called core client and it provides a mean to cooperate and share resources between the CWC trial environment and VTT trial environment (more exactly the CEs in them).

The previous chapter introduced the measurement setup, measurements themselves and the acquired results. These results will be analysed in this chapter while also taking into account some other measurement made earlier with the same environment.

5.1. Measurement results analysis

With the first view of the results, an obvious presupposition can be noted as correct: an outside network in the same frequency band (even without heavy traffic) can have a notable effect on packet loss sensitive media like a video stream. Even a few per cent loss can cause an irritable amount of disturbance that makes the media unusable for the user.

The second notion follows the expected as well: the interference in a certain frequency can be easily avoided by switching to another—interference-free—channel. Even while a simple solution, this is not easily done by all the systems, not to mention that the disturbance itself is not detected by many systems. A cognitive radio introduced in Chapter 2 could do at least the switching to a free frequency and a full-scale CR would also be able to detect the disturbance or the other device accessing the spectrum in some measure. As previously stated, done with only one CR spectrum sensing is not a simple or reliable task [16].

The measurements clearly showed that both kinds of introduced cognitive methods had a clear impact on the quality of transmission: The interference was eventually avoided and at the best the user would not even have noticed anything happening. In the case of sudden disturbance and without any correcting measures, half of the time was spent under the QoE level of 3, which already is intolerably low quality (Table 3). With pre-emptive knowledge of the outside source of interference, this time could be lowered to only couple per cent and the reactive method did a little worse with 11 per cent. Both of these are a great increase in performance and with pre-emptive knowledge the disturbance was barely noticeable.

The gradually increasing interference of the second scenario did not cause as drastic of a drop on the quality as sudden interference (Table 3) as the time below QoE value 3 was 33 per cent. While the disturbance was still clearly notable the main difference in this scenario could be seen in the way the problem was addressed. As seen in Figure 21 the interference affected for a notably longer period of time with reactive avoidance. Again, it is not surprising that acquiring knowledge directly rather than indirectly gives a notable benefit; in Table 2 case 2—the pre-emptive method—has half the average packet loss when compared with case 3—the reactive method. Even bigger difference is on the reaction time (Table 4): with the reactive method, gradually increasing interference did not cross the threshold for the decision to change the channel until tens of seconds had passed.

However, while CRS systems clearly have a notable effect on end-to-end performance with small adjustments the delays raise a serious concern. While the media used by the secondary spectrum users can be durable against brief periods of interference lasting for several seconds, there are often situations (like video streaming) that show problems quickly. Even when leaving the used media out of the picture the significance of delays becomes apparent when considering concepts like ASA introduced in Section 2.3; the spectrum sharing concepts stress that the incumbents should endure as little interference from the concept as possible. Therefore it is essential that the delay from cognitive engine is as little as possible. Since ASA and other shared spectrum concepts usually consider situations where both spectrum users are known to the cognitive engine the delays in Table 4 that can be seen as relevant are those with pre-emptive decisions. While the delay there was quite notable it is still the only reasonable way to provide ASA functionality; using the channel opportunistically when there is no measured interference would harm the incumbent's right to the channel drastically. Delay of a few seconds can still be tolerable in many cases but if there is a need for a quicker clearing of spectrum, some other means should be used.

5.2. Discussion of the future of CRS

It is quite clear that cognitive radio systems are emerging to use in the future as they address the problem of limited spectrum access faced in the areas of dense population. The operators need to satisfy ever increasing demand for higher traffic and the data traffic moving to more wireless-driven systems are only a couple of the forces pushing the regulation and technology towards more flexible spectrum usage. While other solutions like smaller cell sizes and new technology with higher data rates exist cognitive radio systems could enable the use of existing hardware resources alongside with the new. Even the current resources could be set in better use by software upgrades.

The results of this thesis work point in a direction that there is huge potential in optimizing the wireless technology with CRS: Not only does it make better use of the available frequencies but it also guarantees better quality as active measurements could provide important information about the changing state of the system—especially with time sensitive media like video or music streaming and video conferences. With all the possible information that could be provided comes the problem of choosing what is relevant: all cannot be transmitted since that would, first, use the same capacity that is required by the users themselves. Second defect is the amount of delays that is caused by the abundant information: all the data needs to be processed and it all adds towards increasing feedback time from the cognitive engine. Many systems require a swift response, which can be gained with less information that is important. Finding and using more usable information (like direct knowledge of an interfering system rather than using indirect ways such as spectrum sensing or performance measurements) highly increases the performance of a CRS.

6. SUMMARY

It is commonly admitted that the increasing popularity of wireless connections sets new requirements for the radio systems and networks in the future. Not only does the increasing amount of information cause problems but the change to more mobile-oriented direction causes even more challenges. Combined with the fact that people with wirelessly connected devices gather in big cities, new ways to connect are required. The solution to shrink cell sizes could be a partial answer but it adds complexity and is expensive at the best.

This thesis introduced and discussed technologies (and related terminology) that will very likely be one way or another part of the future telecommunications. Software definable radios and cognitive radios make the single nodes of a communication system more intelligent and adaptable to varying requirements. At the same time, they are steps towards cognitive radio systems that enable intelligent communications among several nodes. Even further in to the idea lies cognitive network, where the whole communication system is harnessed under the cognitive functionality. In addition to gains in throughput, cognitive solutions provide stability and a general view of the system.

The discussion also included some of the applications that are already emerging from CRS research: shared access concepts—like authorized shared access—make use of cognitive radio systems to expand the amount of usable frequencies. This also involves the topic of regulation, since current legislation doesn’t automatically grant as flexible usage as would be required.

The contribution of this thesis was to create and research a method in order to enable resource sharing and co-operative between a cognitive radio system and a cognitive radio network. In practice this was realized with an interface that provided information for the cognitive engine working in the cognitive radio system and respectively passed the commands to the cognitive radio network. While the cognitive radio network was capable of switching between frequencies, it did not have means to acquire knowledge of the state of the used channel. Basically, no data could be coming through and the network was not aware of it. On the other hand, the decision making entity, cognitive engine, working in the cognitive radio system could be applied to acquire information about interference like the one blocking the used frequencies. The interface tied the functionalities of these environments together.

The used test cases indicated that sharing the information has a clear impact on the performance of a communication system. It was also seen that the type of information provided for the decision making entity has significance. The earlier the decision can be made the sooner the performance degrading issue can be countered. This is important when the excess traffic caused by a cognitive system is required to stay at the minimum.

7. REFERENCES

[1] Cisco Visual Networking Index: Global Mobile Data Traffic Forecast Update, 2012 - 2017 (accessed 6.3.2013). Cisco, URL: http://www.cisco.com/en/US/solutions/collateral/ns341/ns525/ns537/ns705/ns827/white_paper_c11-520862.html

[2] Akter R., Islam M. & Song J. (2010) PAPR in 3rd Generation Partnership Project Long Term Evolution: An Overview to Fine the Impact. IETE Technical Review, Vol. 27, Issue 6, pp. 493–502. Kyung Hee University, Korea & National University, Bangladesh.

[3] Akan A. & Edemen C. (2010) Path to 4G Wireless Networks. In: IEEE 21st International Symposium on Personal, Indoor and Mobile Radio Communications Workshops, September 26-30, Istanbul, Turkey, pp. 405–407.

[4] Cordeiro C., Challapali K., Birru D. & Sai Shankar N. (2005) IEEE 802.22: The First Worldwide Wireless Standard based on Cognitive Radios. In: First IEEE International Symposium on New Frontiers in Dynamic Spectrum Access Networks, November 8-11, Baltimore, USA, pp. 328–337, New York.

[5] Strassner J. (2007) The Role of Autonomic Networking in Cognitive Networks. In Mahmud Q.H. (ed.) Cognitive Networks: Towards Self-Aware Networks. John Wiley & Sons Ltd, Chichester, West Sussex, pp. 23–52.

[6] Haykin S. (2005) Cognitive Radio: Brain-Empowered Wireless Communications. In: IEEE Journal on Selected Areas in Communications, Vol. 23, No. 2, pp. 201–220.

[7] Binder M.D., Hirokawa N. & Windhorst U. (eds.) (2009) Encyclopedia of Neuroscience. Springer-Verlag GmbH, Berlin, pp. 779.

[8] Definitions of Software Defined Radio (SDR) and Cognitive Radio System (CRS) (2009). Report ITU-R SM.2152, SM Series.

[9] Mitola J. (2000) Cognitive Radio: An Integrated Agent Architecture for Software Defined Radio. Doctor of Technology Dissertation. Royal Institute of Technology, Teleinformatics, Stockholm.

[10] Bishop M. (2013) Knowledge. In: Lanzer P. (ed.) Catheter-Based Cardiovascular Interventions. Springer-Verlag GmbH, Berlin, pp. 45–48.

[11] Mitola J. & Maguire G. (1999) Cognitive Radio: Making Software Radio More Personal. IEEE Personal Communications 6, pp. 13–18.

[12] Thomas R., DaSilva L. & MacKenzie A. (2005) Cognitive Networks. In: First IEEE International Symposium on New Frontiers in Dynamic

Spectrum Access Networks, November 8-11, Baltimore, USA, pp. 352–360, New York.

[13] Sayrac B. (2012) Introduction to Cognitive Radio. In: Venkataraman H. & Muntean G-M. (eds.) Cognitive Radio and its Applications for Next Generation Cellular and Wireless Networks. Lecture Notes in Electrical Engineering, Vol. 116, pp. 3–26.

[14] What is Software Defined Radio (accessed 6.2.2013). Wireless Innovation Forum, URL: http://www.wirelessinnovation.org/introduction_to_sdr

[15] Defining Cognitive Radio (CR) and Dynamic Spectrum Access (DSA) (accessed 6.2.2013). Wireless Innovation Forum, URL: http://www.wirelessinnovation.org/defining_cr_and_dsa

[16] Sahai A., Hoven N. & Tandra R. (2004) Some Fundamental Limits on Cognitive Radio. In: 42nd Annual Allerton Conference on Communication, Control and Computing, September 29 – October 1, Monticello, Illinois, USA, 11 p.

[17] Clark D., Partridge C., Ramming J. & Wroclawski J. (2003) A Knowledge Plane for the Internet. In: Proceedings of the 2003 Conference on Applications, Technologies, Architectures and Protocols for Computer Communications, August 25-29, Karlsruhe, Germany, pp 3–10.

[18] Ahokangas P., Matinmikko M., Myllykoski J. & Okkonen H. (2012) Future Scenarios, Ecosystems and Business Models for Cognitive Radio Systems. VTT technology 55. VTT Technical Research Centre of Finland, Espoo, 54 p.

[19] Palicot J., Mitola J., Lei Z. & Jondral F. (2012) Special Issue on 10 Years of Cognitive Radio: State-of-the-art and Perspectives (Editorial). In: EURASIP Journal on Wireless Communications and Networking 2012. Springer International Publishing AG, 4 p.

[20] Cabric D., Mishra S. & Brodersen R. (2004) Implementation Issues in Spectrum Sensing for Cognitive Radios. In: Conference Record of the Thirty-Eighth Asilomar Conference on Signals, Systems and Computers, November 7-10, Pacific Grove, California, USA, pp. 772–776.

[21] Matinmikko M. (2012) Spectrum Sharing Using Cognitive Radio System Capabilities. Methods to Obtain and Exploit Knowledge of Spectrum Availability. Doctor's Thesis. VTT science 20. VTT Technical Research Centre of Finland, Espoo, 77 p.

[22] He A., Bae K., Newman T., Gaeddert J., Kim K., Menon R., Morales-Tirado L., Neel J., Zhao Y., Reed J. & Tranter W. (2010) A Survey of Artificial Intelligence for Cognitive Radios. IEEE Transactions on Vehicular Technology 59, pp. 1578–1592.

[23] He A., Gaeddert J., Bae K., Newman T., Reed J., Morales L. & Park C. (2009) Development of a Case-Based Reasoning Cognitive Engine for IEEE 802.22 WRAN Applications. SIGMOBILE Computing and Communications Review 13, pp. 37–48.

[24] Höyhtyä M. Palola M., Matinmikko M. & Katz M. (2011) Cognitive Engine: Design Aspects for Mobile Clouds. In: Proceedings of the 4th International Conference on Cognitive Radio and Advanced Spectrum Management, October 26-29, Barcelona, Spain, 5 p.

[25] Sanchez A., Moerman I., Bouckaert S., Willkomm D., Hauer J., Michailow N., Fettweis G., DaSilva L.,Tallon J. & Pollin S. (2011) Testbed Federation: An Approach for Experimentation-Driven Research in Cognitive Radios and Cognitive Networking. In: Cunningham P. & Cunningham M. (eds.) Future Network & Mobile summit 2011 Conference Proceedings. IIMC International Information Management Corporation, 9 p.

[26] Nolan K. & Doyle L. (2007) Teamwork and Collaboration in Cognitive Wireless Networks. IEEE Wireless Communications 14, pp. 22–27.

[27] Matinmikko M. & Bräysy T. (eds.) (2011) Towards Cognitive Radio Systems. Main Findings from the COGNAG Project. VTT tietotteita – Research Notes 2575. VTT Technical Research Centre of Finland, Espoo, 80 p.

[28] Lu L., Zhou X., Onunkwo U. & Li G. (2012) Ten Years of Research in Spectrum Sensing and Sharing in Cognitive Radio. EURASIP Journal on Wireless Communications and Networking 2012, 16p.

[29] Promoting the Shared Use of Radio Spectrum Resources in the Internal Market (2012). Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions, COM(2012) 478, European Commission, Brussels, 12 p.

[30] Studies on the Implementation and Use of Cognitive Radio Systems (2012). Resolution ITU-R 58. URL: http://www.itu.int/pub/R-RES-R.58-2012

[31] Report on Authorized Shared Access Concept (2012) Doc. FM(12)084, Annex 47. Electronic Communications Committee, Working Group Frequency Management.

[32] Matinmikko M., Palola M., Saarnisaari H., Heikkilä M., Prokkola J., Tuomivaara H., Kippola T., Jokinen M. & Hänninen T. (2013) CORE – Cognitive Radio Trial Environment. In: Wireless World Research Forum Meeting 30, April 23-25, Oulu, Finland, 5 p.

[33] Khattab, A., Camp, J., Hunter, C., Murphy, P., Sabharwal, A., & Knightly, E. W. (2008) WARP: A Flexible Platform for Clean-Slate Wireless

Medium Access Protocol Design. SIGMOBILE Mobile Computing and Communications Review 12, pp. 56-58.

[34] Jokinen M. & Tuomivaara H. (2011) LE-WARP: Linux Enriched Design for Wireless Open-access Research Platform. In: Proceedings of the 4th International Conference on Cognitive Radio and Advanced Spectrum Management, October 26-29, Barcelona, Spain, 5 p.

[35] Tuomivaara H., Raustia M. & Jokinen M. (2009) Demonstration of Distributed TDMA MAC Protocol Implementation with OLSR on Linux Enriched WARP. In: Proceedings of the 4th ACM International Workshop on Experimental Evaluation and Characterization, September 21, Beijing, China, pp. 85–86.

[36] Qosmet – Enabling Passive QoS Measurements (accessed 25.4.2013). VTT Technical Research Centre of Finland, URL: http://www.cnl.fi/qosmet.html