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Spectrum Availability Assessment Tool for TV White Space

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ABSTRACT OF THE MASTER'S THESIS

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The growth of wireless communication relies on the availability of radio frequency for new services. More efficient spectrum allocations are required to serve the increasing data per user. The major regulatory bodies are formulating new spectrum management techniques to forge the growing spectrum scarcity. Exclusive use of spectrum is proved to be inefficient in many spectrum occupancy measurement campaigns. As a result, spectrum sharing methods are being considered.

TV broadcasting is not using the allocated frequency in some geographic areas, creating coverage holes known as *TV white spaces*. Both the industry and the regulators are investigating the capability of TVWS, as a potential source of spectrum for emerging wireless services. The FCC, in the US, has already released the requirements for opportunistic access to the TV whites paces. In a similar fashion, ECC, the pan-European regulator is finalizing the work on the technical and operational requirements for the possible use of cognitive radio in this spectrum.

In this thesis work, an integrated web-based spectrum availability assessment tool is developed for Finland. The tool is a front-end visualization of a time intensive computational process to answer key technical questions related to TVWS - what secondary data rate can be supported in the available white space spectrum? The assessment involves estimation of the available TVWS and its capacity for cellular-type secondary systems. The relative effects of the secondary system parameters on the TV system is compared using appropriate signal to noise and interference ratio plots. The tool uses dynamic web technologies for a seamless and user-friendly visualization of the assessment.

Keywords: spectrum regulation, TV white space, cognitive radio, geolocation database, dynamic opportunistic access, unlicensed white space device

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Alemu,Tizazu Bayileyegn

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List of Abbreviations

AM	Amplitude Modulation
AMPS	Advanced Mobile Phone System
ADC	Analog-to- Digital Converter
ARNS	Aeronautical Radio-Navigation
ASK	Amplitude-Shift Keying
API	Application Package Interface
CDMA	Code Division Multiple Access
CEPT	European Conference of Postal and Telecommunications Administration
COFDM	Coded Orthogonal Frequency Division Multiplexing
CR	Cognitive Radio
CRS	Cognitive Radio System
CSS	Cascading Style Sheets
DAC	Digital-to-Analog Converter
DDC	Digital Down Conversion
DHTL	Dynamic Hypertext Markup Language
DOM	Document Object Model
DSP	Digital Signal Processing
DTT	Digital Terrestrial Television
DSO	Digital Switchover
DUC	Digital Up Conversion
DVB-T	Digital Video Broadcasting - Terrestrial
ECC	Electronic Communications Committee(of Europe)
EIRP	Effective Isotropic Radiated Power
ETSI	European Telecommunication Standards Institute
FCC	Federal Comminications Commission(of US)
FM	Frequency Modulation
FICORA	Finnish Communications Regulatory Authority
GSM	Global System for Mobile Communications
GUI	Graphical User Interfaces
HTML	HyperText Markup Language
HTTP	Hypertext Transfer Protocol
IMT	International Mobile Telecommunications
ISM	Industrial, Scientific and Medical
ITU-R	Radiocommunication Sector in International Telecommunications Union
JVM	Java Virtual Machine
LTE	Long Term Evolution
MINTC	Ministry of Transport and Communications
MPEG-TS	Moving Picture Experts Group - Transport Stream
NRA	National Regulatory Authority
NMT	Nordic Mobile Telephone
PMSE	Program Making and Special Event
PSK	Phase-Shift Keying

QAM	Quadrature Amplitude Modulation
QPSK	Quadrature Phase Shift Keying
RAS	Radio Astronomy
RF	Radio Frequency
SDR	software-defined radios
SINR	Signal to Interference and Noise Ratio
SRTM	The Shuttle Radar Topography Mission
TACS	Total Access Communication Systems
TDMA	Time Division Multiple Access
TVBD	TV band devices
TVWS	Television White Spaces
UHF	Ultra High Frequency
URL	Universal Resource Locator
VHF	Very High Frequency
WLAN	Wireless Local Area Network
WSD	White Space Devices
WRC	World Radiocommunication Conferences
WWW	World Wide Web
W3C	World Wide Web Consortium
3GPP	3^{rd} Generation Partnership Project

List of Symbols

$Pr\{z\}$	Probability of event z.
γ_t	Target SINR level for reception without errors.
P_{tv}	TV signal power at the receiver.
P_{su}	The allowed power emission level from secondary white space devices.
h_c	Radio channel impulse response.
$L(r)$	The path loss experienced by a signal at a distance r from its source.
α	Path loss exponent.
E	The electric field strength, in $(\mu V/m)$
T_U	The duration of the useful part of the OFDM symbols of a DVB-T signal.
$\triangle$	The guard interval duration of the OFDM symbols for a DVB-T signal.
P_{IB}^{WSD}	The in-band transmit power of the white space devices.

1 Introduction

1.1 Overview

Following the roll out of commercial mobile communication networks in many parts of the world, the radio frequency is becoming more valuable than ever. Individuals, businesses and governments rely on this natural resource for communication. The growth of Internet as a standard communication platform fueled the emergence of new services like wireless Internet access. As more devices are competing for wireless access, the the available radio spectrum is becoming congested. The reserve radio resource pool is also depleting. Hence, in the future new allocations will inevitably become impossible, risking the growth of the whole wireless ecosystem come to a halt. On the contrary, studies (from various measurement campaigns) have shown that the current spectrum shortage is created by the tight regulatory schemes, introduced long ago to protect exclusive spectrum users[1][2][3].

Recently regulators, at various levels, are starting to devise new spectrum management methods to resolve the forthcoming spectrum crisis. From sponsoring free radio channels as spectrum commons to allowing opportunistic access for unlicensed devices, the regulators are showing their willingness to change the status quo. The Industrial, Scientific and Medical (ISM) radio bands in the 2.4GHz frequency are allocated freely for public use as spectrum commons. These bands showed tremendous success for short-range low power communication in wireless local area netowrks(WLANs). Another spectrum sharing technique, named opportunistic access, enables the unlicensed use of the idle portions of a licensed radio spectrum without harming the primary licensee. Regulators have been giving permission for wireless microphones to work in the occupied TV channels in interleave basis. After the digital switchover, new spectrum allocations are expected to complete in the coming years. Studies have revealed that the TV broadcasting is not using the spectrum efficiently i.e. the TV channels are not being used in some geographical locations[28][33]. These TV coverage-free areas, named as *TV White Spaces(TVWS)*, are considered to be the next potential immediate solutions for spectrum scarcity.

Many countries are evaluating the technical alternatives to employ the underutilized TV band spectrum. *Cognitive radios*, first introduced by Mitola [7], are proposed to be the possible enabler technologies. *Cognitive radios* are radios aware of their location and the radio environment to change their transmitter parameters accordingly. Cognitive techniques like geo-location database and/or sensing methods are identified as optimal candidate technologies for dynamic opportunistic access to the TV band frequencies[12][26].

Commercializing spectrum, in the TV bands, for opportunistic secondary access must be preceded by refined quantitative availability assessment. There was a prevailing 'chicken and egg' problem on the successful use of this valuable resource:

regulators are not willing to draft new spectrum policies without working demonstrations from the industry. The industry, on the other hand, is lacking confidence to invest in new technology without regulatory insurance. The *QUASAR - FP7 targeted research project(STREP)*, under which this thesis is done tries to resolve this dilemma from the technical end of the problem, assessing the available secondary spectrum that could be used for opportunistic secondary access.

This quantitative assessment research work uses multiple parameters and models to estimate the amount and capacity of the available TVWS. From a techno-economics perspective, however, the basic key questions are:

- How much white space is available? Where is it located?
- How much data rate can it support?
- What performance metrics are suitable to utilize the spectrum?

To address these crucial technical questions, the need for a visualization tool is indispensable. A user-friendly visualization interface is required to eliminate the barriers for seamless understanding of the outputs of the research.

This thesis work develops an integrated web-based *Spectrum Availability Assessment Tool* for TV White Space. The tool is front-end visualization for a time-intensive computational assessment - the white space spectrum availability and secondary capacity estimation made for Finland on the digital TV(DTT) coverage. The assessment methodology for the whole process involves considering the radio environment models, the DTT coverage and appropriate secondary system models. The tool also includes visualization for primary system performance, that are subjected to secondary system scenarios. This helps to compare the impacts of different parameters on the existing primary system. The graphical user interface of the tool is developed using standard, user-friendly and dynamic features to shorten the learning time for new users.

1.2 Thesis Structure

The remainder of this thesis is organized as follows:
Chapter 2 gives overview of spectrum regulation. This section discusses the evolution of the radio communication through ages, the regulatory frameworks at different levels (national, regional and international) and the changing regulatory trends following spectrum needs. The proposed cognitive techniques for opportunistic spectrum access are also explained briefly in this chapter.

Chapter 3 discusses specifically the regulatory landscape about the TV Whitespace regulation. The Federal Communications Commission (FCC) and the Electronic Communications Committee(ECC) are the two major regional regulators in North

America and Europe, respectively, formally endorsing the the wireless industry's appeal to access TVWS on unlicensed basis. This chapter highlights the detail requirements set by FCC and ECC.

In *Chapter 4*, the TVWS spectrum availability assessment is throughly explained. The discussion of availability metrics, the analysis of the primary system and the secondary system models, the channel models for estimating the radio propagation characteristics are described. This section defines the overall spectrum availability assessment methodology and its implementation in detail.

Chapter 5 focuses on identifying the standard principles behind the design of a user-friendly graphical user interface. The enabler technologies for making the tool browser accessible, the architecture of *Spectrum Availability Assessment Tool* and its implementation are explained in more detail.

Chapter 6 is a case study section. The *Spectrum Availability Assessment Tool* for Finland case is demonstrated. While in *Chapter 7*, the conclusion of the thesis work is briefly summarized and the possible future dimensions of this work are recommended.

2 Spectrum Regulation and Television White Spaces

2.1 Background

Communication technologies are transforming our society by connecting multiple communities, governments, businesses etc. from different backgrounds. Wired communication technologies, which had high market share before wireless systems became economically feasible, did not penetrate well into many communities across the globe. The huge investment needed by costly copper connections was the main reason. Consequently, in many developing nations communication remained a luxury commodity until recent availability of wireless technologies for mass market.

The radio communication systems before World War II were mainly amplitude modulated (AM) and frequency modulated (FM) broadcasting stations. The main problem at that time was improving the quality of reception. In the 1950s the fields of communication theory and information theory gave a wider perspective to analyze the system performance. Eventually, advances in electronics and circuit technology helped the achievement of highly miniaturized and easily portable devices that would otherwise need much space and wiring installation efforts. The invention of transistors was also a remarkable breakthrough for creating very efficient integrated circuits that,eventually, revolutionized the mass production of cheap electronic devices.

In the past three decades, we have seen tremendous success in field of information communication technologies. The liberalization of spectrum for commercial use has brought the success of mobile communication technologies. As the technology was getting broad market acceptance, the exclusive assignment of frequency to large geographic area proved to be uneconomical and inefficient use of the rather limited radio resource —the concept of breaking-down the whole geographic area into small hexagonal cells that could enable reusing the same frequency was developed.

The first generation (1G) of mobile technologies were analogue. There were multiple incompatible parallel developments in different parts of the world, for instance in the U.S. - the Advanced Mobile Phone System (AMPS), in the Scandinavia - the Nordic Mobile Telephone (NMT) and U.K. - the Total Access Communications System (TACS). While transferring to the second generation (2G) all networks adopt digital technology, offering a significant improvement in spectral efficiency. The Global System for Mobile Communications (GSM), the Code Division Multiple Access (CDMA) and other Time Division Multiple Access (TDMA) technologies were developed. The International Telecommunications Union (ITU) tried to converge the different 2G technology paths for interoperability to third generation (3G) system under the auspices of its International Mobile Telecommunication (IMT-2000). A collaboration of telecommunication standards bodies combined to create the 3rd Generation Partnership Project (3GPP). 3GPP has been working to standardize radio access, core network and service architectures[8]. 3GPP has developed the specifications for Long Term Evolution (LTE). All these developments in mobile communications systems have given economically viable solutions to developing nations which resulted in an exploding growth of cellular networks worldwide. In fact, the number of mobile subscribers reached 4.6 billion subscriptions by the end of 2010[9].

The ever-increasing data volume, associated with mobile broadband, and the demand for seamless network connection are adding pressure for further spectrum assignment. Until recently, most cellular mobile technologies tried to maximize their network capacity by increasing the number of serving stations —by shrinking (or sectoring) the coverage area for each base station. However, as more traffic is inundating the networks in the future, it seems the Shannon limit is inevitably reached where no more capacity improvement is made, unless a new spectrum is acquired. The Shannon capacity formula relates the capacity, C, with the bandwidth, W, as[6]:

$$C = W \log_2 \left(1 + \frac{S}{N}\right), \tag{2.1}$$

where W is the bandwidth, S - average received signal power and N - average noise power. It is impossible to increase the signal power indefinitely, hence, capacity can only be increased via bandwidth adjustment.

FCC *Report on Trends in Wireless Devices* showed that in 2010 alone, the number of wireless transmitters(devices) which received license was close to 12,000—nearly fourfold the amount of a decade ago. The report also identified that new wireless devices tend to integrate more transmitters, such as Wi-Fi, Bluetooth etc., and with added technical capability as compared to the traditional phones[10].

These developments urged the whole wireless industry stakeholders to search for extra radio spectrum. The widely discussed *spectrum white spaces* were targeted as promising sources of spectrum. The *spectrum white spaces* are the unused frequencies in a certain geographical area for a reasonable amount of time.The European Communications Commission (ECC) defined a *white space* as:
"A label indicating a part of the spectrum, which is available for a radio communication application (service, system) at a given time in a given geographical area on a non-interfering / non-protected basis with regard to other services with a higher priority on a national basis" [12].

Contrary to the conventional static spectrum allocations, these frequencies are still needed by the Primary Users (PU) and they cannot be leased for full time. The new Secondary Users(SU) can use the spectrum only at times when there is no primary transmission. This dynamic access scheme needs new enabler technologies such as Cognitive Radio (CR) —a radio that changes its transmitter parameters based on the environment.

In more broad terms:
"Cognitive radio system (CRS): A radio system employing technology that allows the system to obtain knowledge of its operational and geographical environment, es-

tablished 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" [12].

So far, the *spectrum white spaces* are identified in Television(TV), Fixed Satellite Stations(FSS) and many radar systems. The implementation of CRS involves new technical challenges and decisive approval of the regulatory bodies.

2.2 Spectrum Regulation

With current trends of growth in wireless data, radio spectrum is becoming a more valuable natural resource that is worth regulating. Radio spectrum accounts for only a small portion (3kHz to 300GHz) of the available electromagnetic spectrum. The range of spectrum values below and above the radio frequency(RF) can not be used for radio communication purposes. Frequencies below 3kHz need uneconomically large antennas, while frequencies higher than 300GHz are highly affected by attenuation. In fact, currently only the radio frequencies between 9kHz and 275 GHz are allocated for terrestrial or space radio communication services.

Spectrum regulation has a profound socio-economic impact. Due to the pervasive nature of radio signals, governments have to make mutual decisions for optimal use of the available spectrum. Many sensitive applications like satellite radio communications need these international agreements. Telecom equipment manufacturers will be advantaged from the economy of scale only if there is a harmonized spectrum use - this has significant implications in narrowing the *Digital Divide* between advanced and under-developed economies.

The digitalization of formerly analogue services freed a substantial amount of high quality radio spectrum—known as the *digital dividend*. The upper part of the Ultra High Frequency (UHF) band in the digital dividend (790-862MHz) is already allocated to mobile services in many parts of the world [13][14]. For increasing harmonization of the digital dividend towards mobile services worldwide, the World Radiocommunication Conference 2012 (WRC-12) has decided to allocate the 700 MHz band for mobile services, with date of entry into force from the end of 2015[15].

Studies have shown, even in other existing licensed bands, for instance television broadcasting band(470-790 MHz), aeronautical band for DME(960-1215 MHz), radar band (2700-3100 MHz, 5250-5850MHz) and IMT band(790-960 MHz, 1710-2025MHz), there is significant possibility of using them for opportunistic access[16][19]. Although this ambitious demand needs a more matured technology, the regulatory decisions matter when it comes to its realization.

On top of the complexity of the direct and indirect socio-economic effects resulting from spectrum use, there are international, regional and national players - each with its own agenda. The decision making process often takes many years to establish rules accepted by all levels. There are multiple drivers, however, that force the sluggish chain of regulatory procedures to move ahead. Firstly, the fast pace of technological development is bringing more efficient devices having special technical capabilities, such as intelligent radio cognition which require a totally different set of regulatory rules. Secondly, the unquenchable user requirements are becoming more demanding, from ubiquitous mobility to high data access, from desiring to access all belongings online to connecting to many people the whole day etc. There is also a more significant trend of digital convergence towards connecting everything to the Internet. As more and more devices are connected to the Internet, in the future it is inevitable that there will be one giant global network of things. All these developments have a strong impact on the current regulatory landscape and all of them necessitate that there must be change on the *status quo*.

2.2.1 Spectrum Regulatory Frameworks

There are many international and regional governing bodies for radio spectrum management and each country has its own spectrum regulators. The main role of the international and regional regulators is standardizing the most optimal spectrum management techniques. A worldwide harmonized radio spectrum regulation eases technological challenges, wireless devices manufacturing gets market confidence from the economy of scale by mass production. Apart from mutual responsibilities by all parties, standardization eases global market access - good to make the whole sector highly competitive and more innovative. As the global economy is becoming more and more dependent on one another, there is an increasing trend of centralizing standardization efforts in the telecom sector as well. The international regulators are becoming more involved in drafting a more acceptable spectrum allocation schemes each time. The national regulators, however, have a reasonable freedom to identify the models that suit their national interests, given they are under their responsibilities.

International and Regional Regulators

The *International Telecommunications Union(ITU)*, a specialized agency of the United Nations(UN), has the regulatory mandate at the international level. The ITU, through its World Radiocommunication Conferences(WRC), deals with the allocation of the available frequency(9kHz to 275GHz) to different applications.The Radiocommunication Sector of the International Telecommunication Union(ITU-R) plays in a vital role in the harmonization of spectrum management worldwide.

The primary goals of the agency is to make sure that there is interference-free radio communication systems at the local, regional and international scale. It works to bring an all-benefiting agreement, in a time when there is a growing importance of radio frequency in fixed, mobile, broadcasting, global positioning systems, space research, emergency telecommunication, meteorology, environmental monitoring etc. To keep the pace of technological evolution on track, the ITU investigates the possibilities to ensure a more flexible regulatory structure for the future, such as conserving spectrum and spectrum-sharing based on geographical location. To foster future innovation, the ITU encourages spectrum allocations to maintain neutrality on any technology.

At the European level, the *Electronic Communications Committee(ECC)* of the European Conference of Postal and Telecommunications Administration(CEPT) plays the regional regulatory role, which in many ways reflect European interests in the ITU and other international organizations. The ECC also works to formulate mutually optimal spectrum policies and regulatory procedures across Europe. The ECC works in partnership with the European Telecommunication Standards Institute(ETSI)—an industry-led organization involved in developing European standardization of telecommunications services and devices, and the European Commission(EC). With its goal of maintaining the single EU market for wireless services and equipment, the ECC is one of the influential telecom policy makers at the international level.

ECC provides four relevant deliverables to the member states. The *ECC Decisions* give regulatory texts that outline optimal procedures to harmonization issues—although they are not mandatory prescriptions, most CEPT member administrations are highly encouraged to follow them. For national authorities, ECC develops *Recommendations* as a guidance to deal with harmonization matters. Reports of the harmonization measures are compiled by ECC based on studies as *ECC Reports*. Finally, *CEPT Reports* reveal the final results of studies which show responses to the EU authorities, helpful for future EC Decisions. All these CEPT deliverables are non-binding to give the national authorities a reasonable flexibility based on their national interests [19].

National Regulatory Authorities

The European member states have their own National Regulatory Authorities(NRA). To ensure effective liberalization of the telecommunication sector each member state should have a structurally independent and impartial NRA, not involved in any form of telecom business. *Article 3*, of the *Common Regulatory Framework Directive*[20] explains that:
"Member States shall guarantee the independence of national regulatory authorities by ensuring that they are legally distinct from and functionally independent of all organizations providing electronic communications networks, equipment or services."

The NRAs can exercise power at the national level based on the recommendations and guidelines from the EC. Normally, the EC identifies relevant markets and provides market definition recommendations to the NRAs. Based on those recommendations, the NRAs will analyze them at the national level,to check if there is a monopolistic practice on the recommended markets for regulatory intervention.

In the UK, the Office of Communications(Ofcom) regulates the broadcasting, telecommunications and postal industries. Particularly, Ofcom oversees the TV and radio sectors, fixed line telecoms, postal services and airwaves over which the wireless devices operate.

In Finland, there are two institutions responsible for spectrum management: the Ministry of Transport and Communications (MINTC) and the Finnish Communications Regulatory Authority (FICORA). MINTC is responsible to prepare the telecommunication acts and policies suitable for Finland. It also issues policy and regulation implementation guidelines and directions. Where as FICORA implements the policies and decisions made by MINTC —it takes direct responsibility to manage, issue and control the use of frequencies based on the policies. Its licensing considers the current and future trends of radio communication systems. Together with the Finnish Competition Authority, FICORA handles competition issues in the telecommunications sector.

2.2.2 General Trends in Telecommunications Regulation

The main goals of regulation are to achieve non-interfering systems and a purely competitive telecommunication services market. The early practices of regulation focused on avoiding interference among the different broadcasting stations. In its founding legislation, the Federal Communications Commission(FCC), the United States regulator of non-governmental spectrum use, it was given the power to act based on the *public interests.* This *command and rule* type philosophy of spectrum regulation, based on *public interest*, had at times prohibitive implications on the proliferation of new technologies. Studies have shown that even the most *premium and congested traffic* areas are not using the allocated spectrum mainly because of the *artificial spectrum shortages* created by tight regulatory rules[6][2].

A report by United States General Accounting Office(GAO)[25] showed that the current structure of spectrum management do not promote the arrival of spectrum efficient technologies. The categorization of spectrum by service types(such as aeronautical radio navigation) and users(federal,nonfederal, and shared) affects spectrum flexibility for emerging technologies. The regime excludes dynamic spectrum acquisition techniques by technologies like software-defined radios(SDR) - radios that adapt to the real-time spectrum environment and configure themselves accordingly. The spectrum *white spaces* - unused frequencies in the licensed spectrum - can not be utilized efficiently unless new regulatory measures are taken. With new spectrum usage rules, *gray spaces* - frequencies where emissions exist but could support additional traffic without affecting the incumbent users - may be used with SDR technologies.

In recent years, however, there is a growing trend to make spectrum regulation to be decided by the market. This has been done in the form of government auctioning. When unassigned spectrum is discovered, bidders are allowed to contest —the spectrum will be leased for the bidder who brings more money. The spectrum might have been obtained, for instance, from a retired application, such as when analogue television broadcasting is changing its technology to digital systems. The Finnish regulator, FICORA, made one of such auctions for the 2500-2690 MHz spectrum blocks in November, 2009[21]. This market-based approach is also offering the possibility to allow the secondary-marketing (reselling) of the spectrum. The spectrum-ownership will be transferred in long-term or temporal basis to those entities who value it most[6].

Regulators are now convinced how strict regulatory policy impairs innovation. The commercial success of the wireless devices and services in the license-exempt radio frequency, commonly referred to as ISM-band(Industrial, Scientific and Medicine) substantiates this fact. These radio frequencies are not licensed to any entity —available as *spectrum commons* for public use. These bands are found very valuable for many wireless devices such as WiFi, Bluetooth, radio tagging(RFID), and a variety of uses from remote garage openers to control of toys and baby alarm monitors. The power emissions from the multiple devices can create strong electromagnetic interference and disrupt communications using the same frequencies. To minimize such possibility, there are certain allowed power levels and the technologies allowed are *spread spectrum* ones. The most widely used of the ISM radio bands is the 2.4GHz, but large new chunks of spectrum from 5GHz to 6GHz are now available worldwide for similar applications.

2.2.3 Regulatory Measures for Opportunistic Spectrum Access

Based on the various studies on the existing spectrum occupancy, only less than 20% of the the spectral capacity is being used effectively, even in the busiest radio environments like New York and Chicago[6]. Another study in downtown Berkeley, US, identified similar problem (see Table 3 below). This one revealed typical utilization of roughly 30% below 30GHz, and 0.5% in the 3 to 6GHz frequency band. Due to these significant inefficiency, all stakeholders are urging the old regulatory regime to address the growing spectrum demand.

Freq (GHz)	$0 \sim 1$	$1 \sim 2$	$2 \sim 3$	$3 \sim 4$	$4 \sim 5$	$5 \sim 6$
Utilization (%)	54.4	35.1	7.6	0.25	0.128	4.6

Table 3: Measurement of spectrum utilization (0-6 GHz) in downtown Berkeley[3]

Recently, many regulators are showing their willingness to allow secondary opportunistic access to the licensed bands. The *dynamic spectrum access* scheme targets the unused spectrum holes, *white spaces*, for temporary(license-exempt) spectrum sharing, both in the spatial and temporal dimensions. The FCC has made one of the most significant regulatory amendments in nearly 20 years - allowing a license-exempt access in licensed bands. FCC has given the details on using the licensed TV channels for unlicensed use[26]. The details are mainly guidelines how to access spectrum opportunistically while avoiding any interference to the primary users - without adding any more technology enhancements to the primary system.

Other regulators are following similar steps. In Europe, the ECC has already developed requirements for protecting the licensed users in the 470-790MHz, in an effort to foster future cognitive radio access [12]. The new upcoming technologies benefiting from the spectrum white spaces in the 470-790MHz bands should consider the protection criteria for the following incumbent services:

- Broadcasting services including Digital Video Broadcasting - Terrestrial (DVB_T).
- Program Making and Special Event (PMSE) systems like radio microphones in particular.
- Radio Astronomy (RAS) services in the 608-614MHz bands.
- Aeronautical Radio-Navigation(ARNS) in the 645-790MHz bands.
- mobile/fixed services in the bands adjacent to 470-790MHz.

The *White Space Devices (WSD)* must guarantee critical attention to these protected primary services from harmful interferences. For the implementation phase, many parties are undergoing studies for optimal enabler technologies.

2.3 Television White Spaces

Television broadcasting services operate in the Very High Frequency (VHF) and Ultra High Frequency (UHF) portions of the radio frequency, on a licensed basis. Regulators prohibit the use of these bands for unlicensed devices. Most regulators, however, are necessitating the adoption of digital transmission by all TV stations that were using analogue transmission. The US has already completed this *Digital Switchover(DSO)* by June 2009, while UK is planning to complete by 2012. In Finland, over-the-air analog television transmissions were shut off in September of 2007, while the cable television networks analog transmissions were allowed to continue until February, 2008 [27]. Similar steps are in progress (or already finished) in the remaining Europe. This transition has freed up a significant amount of spectrum for other services.

The other major benefit of the DSO is the opportunity to use the licensed TV bands for unlicensed wireless devices when licensed users are not needing them. There are suitable geographical locations which could not be accessed by some channels without interfering with their adjacent/co-channels, but still these channels could be

used by low power devices without disturbing similar primary users. These secondary devices, also known as *White Space Devices(WSDs)*, should be equipped with state-of-the-art cognitive capabilities to avoid any harmful interference to the protected incumbent services. The name *Television White Space(TVWS)* came from the broadcast coverage color map, where different colors indicating different signal levels, while geographical areas without TV signals are left white. Thus TVWS can be defined as:
Geographical locations where there is no TV signal and the broadcasting frequency can be used for secondary purposes without causing any interference to the performance of the TV broadcasting in the remaining areas and other incumbent services anywhere.

In Europe, the TVWS is located in the 470-790MHz bands - which is traditionally stronger signal, far better than the 3G and WiFi bands, for its capability to travel long distances and penetrate shadowing walls. It is also very promising for many potential services such as last mile wireless broadband access in rural areas.

2.4 Introduction to Cognitive Radios

Conventional digital transceivers as depicted in Figure 1, includes the analog *RF front-end* module responsible for transmitting/receiving the Radio Frequency(RF) signal from the antenna and down-converting the signal from RF to Intermediate Frequency(IF) on receive path (or up-conversion of the IF signal into RF signal, in case of transmit path). The middle section includes the Analog-to-Digital/Digital-to-Analog Converter (ADC and DAC) block, the demodulating Digital Down Conversion(DDC) and modulating Digital Up Conversion(DUC) blocks. The baseband section performs baseband operations such as (connection setup, equalization, frequency hopping, coding/decoding and correlation) and implements link layer protocols.

The continuous evolution of wireless access schemes is demanding new hardware updates each time. Mobile users, on the other hand, need technology-neutral roaming capabilities. This technical requirement is bringing a new variant of radio systems which rely on software-reconfigurability running on generic hardware with Digital Signal Processors(DSPs) and general purpose microprocessors. *Software-Defined Radios(SDRs)* are radios whose functional modules, such as modulation/demodulation, signal generation, coding and link-layer functions, can be implemented in software. In other words, the coding, modulation type and frequency band can be modified solely by changing software. This capability of SDR devices enables upgrading the modules, and hence the devices, mainly by software updates whenever the wireless access protocol is changing.

SDR can be a key enabler of other important types of radios which are more adaptive and reconfigurable. *Cognitive Radios(CRs)* are radios more flexible and adaptable to any radio environment by cognitive learning. Although there are multiple defini-

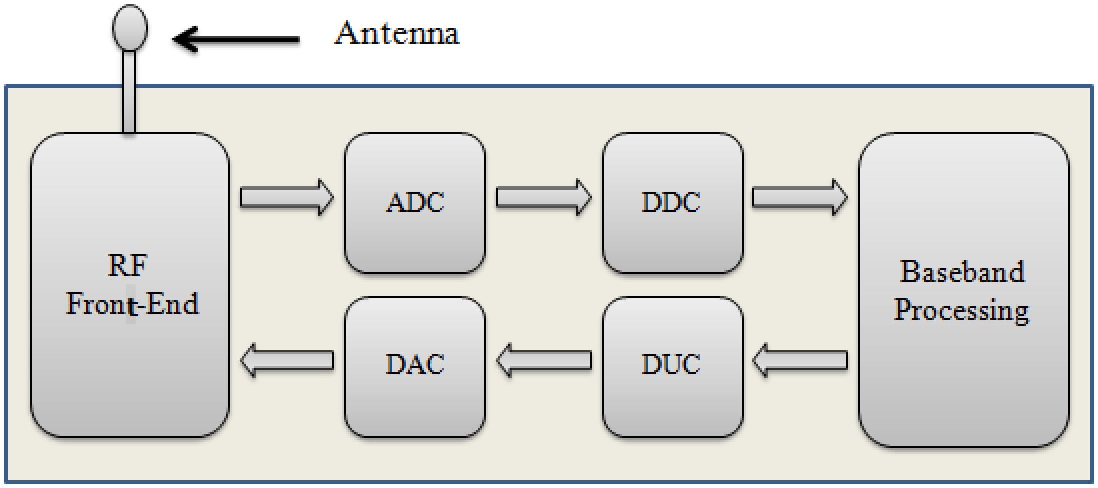

Figure 1: Generic digital transceiver

tions, the CR concept was first explained by Mitola and Maguire as:
"transforming radio nodes from blind executors of predefined protocols to radio-domain-aware intelligent agents that search out ways to deliver the services that the user wants even if that user does not know how to obtain them"[28].

CRs must have dynamic spectrum access support for wide range of frequencies, special intelligence for sensing and decision-making capabilities based on the radio environment as well as other functionalities like contacting database servers without the knowledge of the user. Ideal CRs change their internal operational behavior by learning from sensory inputs and recognizing patterns in a heterogeneous radio environment.

2.5 Cognitive Techniques to Access White Spaces

Cognitive secondary access to TVWS involves detection of the available spectrum holes in the TV-bands and to use the spectrum based on the regulatory requirements, which basically protect incumbent services from harmful interferences. Three cognitive techniques have been proposed by ECC to help WSDs find empty channels[12]:

1. Geo-location with databases
2. Spectrum sensing
3. Beacons

Currently, the geo-location assisted by database seems to be a more promising short-term solution for incumbent detection and interference avoidance.

2.5.1 Geo-location Databases

In this approach, the WSDs are required to consult a centralized (or regional mirror) *geo-location database* to determine if there are any TVWS (free channels) they can use without causing interference to other services. ECC needs that the WSDs have to recognize and indicate their current location before sending the query. There are few essential parameters yet to be decided in the future: the location precision, how often the devices should contact the database and the quality of the database itself. Too precise location requirement imposes unnecessary complexity to the WSDs, while contacting the server at short time intervals dries up the battery life of the devices.

With this scheme, WSDs are not allowed to transmit before they receive notifications from the database about the available white spaces, if any, in their position. This requires that the WSDs make initial connectivity to the database by some other way than the white space frequencies. Currently, the *master-slave* communication architecture is proposed to alleviate this problem. A *master* device, most likely an access point or a base station, having access to the location information will connect to the database via Internet. Then it in turn serves the inquiries of the *slave* WSDs at its vicinity.

The database scheme might work well for protecting services whose coverage plan

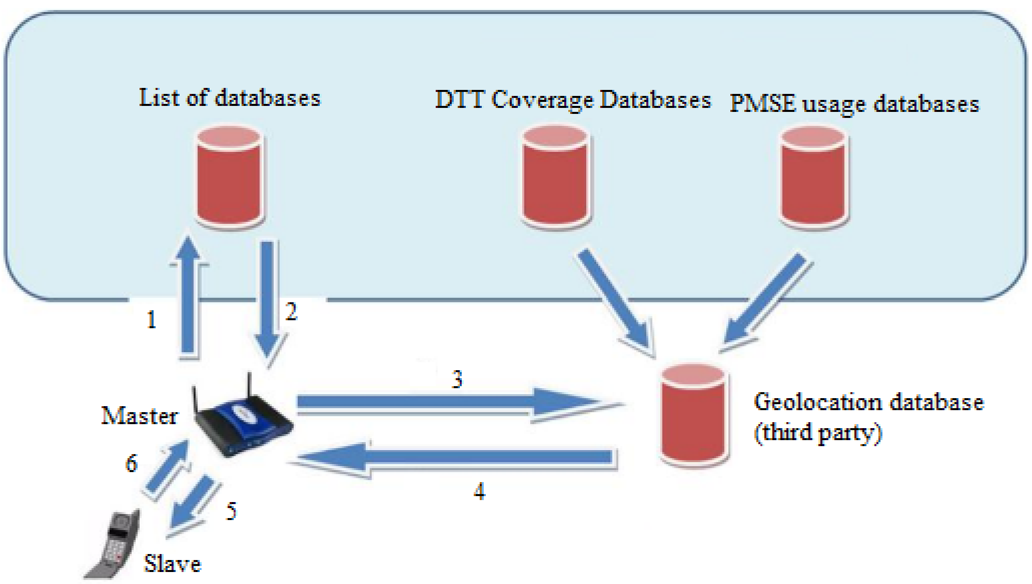

Figure 2: Possible geolocation database proposed by Ofcom[11].

is more or less fixed and deterministic, the protection of mobile incumbent services such as wireless-microphone, however, may need more sophisticated approaches.

2.5.2 Spectrum Sensing

Spectrum Sensing enables unlicensed devices detect the presence of any protected incumbent services in licensed channels, which appear to be white spaces. Spectrum sensing involves measuring the signal levels of the potential channel, based on the regulatory requirements. FCC, for instance, requires the *"TV bands devices [unlicensed WSDs] be capable of sensing analog TV signals, digital TV signals and wireless microphone signals at a level of -114dBm within defined receiver bandwidths"*. While this level is referenced to an omni-directional receive antenna of 0dBi gain, other approaches for sensing antenna are allowed as far as they maintain the same performance, with respect to the sensing threshold.

Up on finding a vacant channel, the WSDs may also be required to sense the adjacent channels to find out, if any, transmission power constraints. Certain services like radio astronomy in the band 608-614MHz, which are technically difficult to detect, might need special protection (or even exclusion) from these sensing procedures.

Spectrum sensing, if it is standalone, has very important advantage that it doesn't need connection to a centralized database server. This eliminates the need for extra communication infrastructures like the Internet. The down-side of this scheme, however, is that sensing signals may be vulnerable to what is called the *hidden terminal* problem shown in Figure 3.

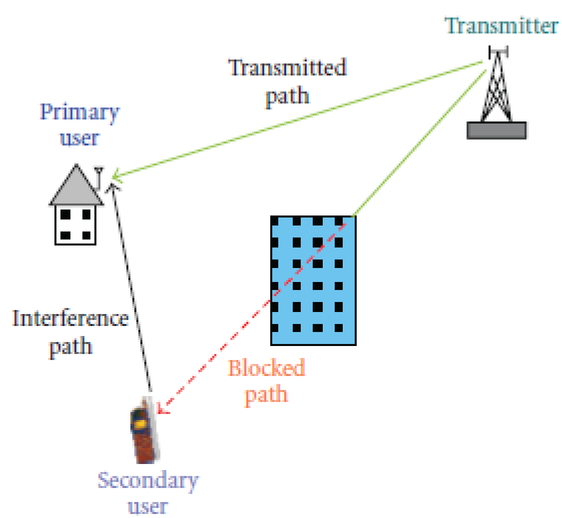

Figure 3: Hidden-terminal problem of sensing-based cognitive radio.[28]

While the unlicensed cognitive device is trying to sense the signal from the primary transmitter, which is located on the other side of the shadowing building, it may conclude that there is no primary transmitter nearby and may start transmitting on the same channel. In this scenario, the licensed users, which are still receiving from the transmitter and located at the vicinity of the WSD, will suffer from chronic interference.

2.5.3 Beacons

A third proposal for spectrum white space detection is using beacons. Unlicensed devices transmit only when they receive the beacons that carry information whether the channel is vacant or not. The beacons can be broadcasted by the TV stations, or a different unlicensed fixed transmitter using TV bands. Using beacons increases the probability of detection at lower threshold values, that would otherwise need more complex sensing systems.

This approach needs a dedicated infrastructure that broadcasts beacons and it should be operated depending on statistics from the licensed incumbent services. When beacons are lost probably due to shadow-fading, the hidden-terminal problem, explained above, may happen.

Regulators, such as FCC, have already decided to use geo-location database as a sole cognitive technique, sensing and the use of beacons to be optional ones. The reason behind such decisions is the less viability of these methods to detect white space spectrum. However, FCC, encourages the use of sensing with secondary devices for determining quality of channels and for the promotion of spectrum sharing among secondary devices[26].

2.6 The Problem of Aggregate Interference

Cognitive techniques such as spectrum sensing and beacon methods, have technical downsides related to secondary interference. When the number of secondary power emitters is increasing, their aggregate interference tends to increase beyond the tolerance level for the TV systems[16]. This demands the use of monitoring methods, which in effect help to control the density of secondary transmitters. Geo-location databases may well serve to solve such problems by controlling the density of WSDs.

3 TV Whitespace Regulation

In the United States there are two spectrum regulators: *National Telecommunications and Information Administration(NTIA)* regulates all federal government spectrum use, while FCC regulates all non-federal government spectrum use. All commercial broadcasting including television spectrum is regulated by FCC.

In June 2002, FCC established a *Spectrum Policy Task Force* to keep its pace with the current spectrum demands and revise its policies based on comments from all stakeholders including wireless equipment manufacturers, wireless service providers, academics, radio and TV service providers, etc. The Task Force held numerous meetings and workshops open for the public. After such efforts, the Task Force highlighted the need for more flexible spectrum policy for the following reasons[29].

- As technology is advancing, interference mitigation is becoming easier and wireless systems are becoming more tolerant to interference.
- In many cases the real problem is associated with the prevailing spectrum access policies than the physical scarcity of spectrum, which hampered potential spectrum users.
- More flexible and market-oriented regulatory models are imperative for the innovation of spectrum-efficient and more economical technologies.
- Fair spectrum regulation should have variety of models such as the granting of exclusive rights via market-based approach, increasing the "spectrum commons" and other means.

In recent years, the Commission has made significant improvement in its spectrum policies. In 2004, FCC proposed to allow opportunistic access to TV bands. After accepting petitions from all stakeholders and discussing the relevant topics, FCC released detail requirements for using the TVWS for unlicensed devices in 2008[26].

The pan-European ECC has also pursued similar steps to respond to the growing spectrum scarcity. In July 2008, ECC (in its CEPT Report 24)[33] started discussing the potentials of opportunistic access on TV white spaces and the associated risks for the existing radio systems. In January 2011, ECC released a detail technical and operational requirements for accessing the TVWS for unlicensed use [12].

The two institutions, FCC and ECC, used different approaches to protect the existing services while harvesting the available spectrum in TV white spaces. FCC requires protection based on distance, while ECC focuses on secondary power control. However, both of them are using similar secondary spectrum access technologies—geolocation with databases and/or sensing. The following two sections summarize the major decisions by FCC[26] and ECC[12] for realizing cognitive access to TV white spaces.

3.1 FCC

TV broadcasting in the US operates on 6 MHz channels designated from 2 to 51 in four bands of frequencies in the VHF and UHF regions of the electromagnetic spectrum (54-72MHz, 76-88MHz, 174-216MHz and 470-698MHz)[26].

In the US, TV *service contours* are used to estimate signal strength in the coverage area around the broadcasting station. Service contours are calculated using average terrain elevation from topographic data in eight specific directions and the principal community, if none of the eight directions point to it. The height of the electrical center of the antenna above this average terrain determines the effective height. This height and the effective radiated power are used to find out the distance to any specific field strength, such as the service contours. For instance Grade A and Grade B service contours are the most commonly used for FCC administrative purposes. The stations also use them for promotional and marketing purposes. Grade A contour covers all distances with field strength 68 dBu, while Grade B refers to 47 dBu. In addition to these specific field strength values for these two contours, a minimum field intensity named as *city grade contour,* is specified which must be provided for the entire principal community. it is 6-dB higher than the Grade A contour [18].

Besides the TV broadcasting, the channels are used for unlicensed services like medical telemetry (on any vacant TV channel from 7 - 46), remote controls(above channel 4 except for 37), and radio astronomy(in channel 37). The Commission requires these services must sense TV broadcasting and other devices to avoid harmful interference. To ensure this capability, the devices must be certified at FCC Laboratory.

FCC adopted protection criteria for the existing TV broadcasting systems based on the nature of their coverage. To avoid severe interference, techniques like using protection distance, gap between the intended service range and the interference range are used. Wireless devices must be located outside the coverage area by this protection distance, which depends on the height of their antenna and operating frequency (co-channel or adjacent channel).

Unlicensed devices must be located outside the inner contour signals of co-channel and adjacent stations by at least the minimum distances specified in Table 3.1. Portable WSDs, or TV band devices (TVBDs) in FCC terminology, with geo-location and databases access capability must respect the separation distances specified for unlicensed device with an antenna height of less than 3 meters.

After verifying with its own engineers and analyzing the responses from various stakeholders, FCC considered spectrum sensing as a less viable tool for white space detection. Consequently, devices with capability of locating themselves and access to database server are exempted from the spectrum sensing. For instance

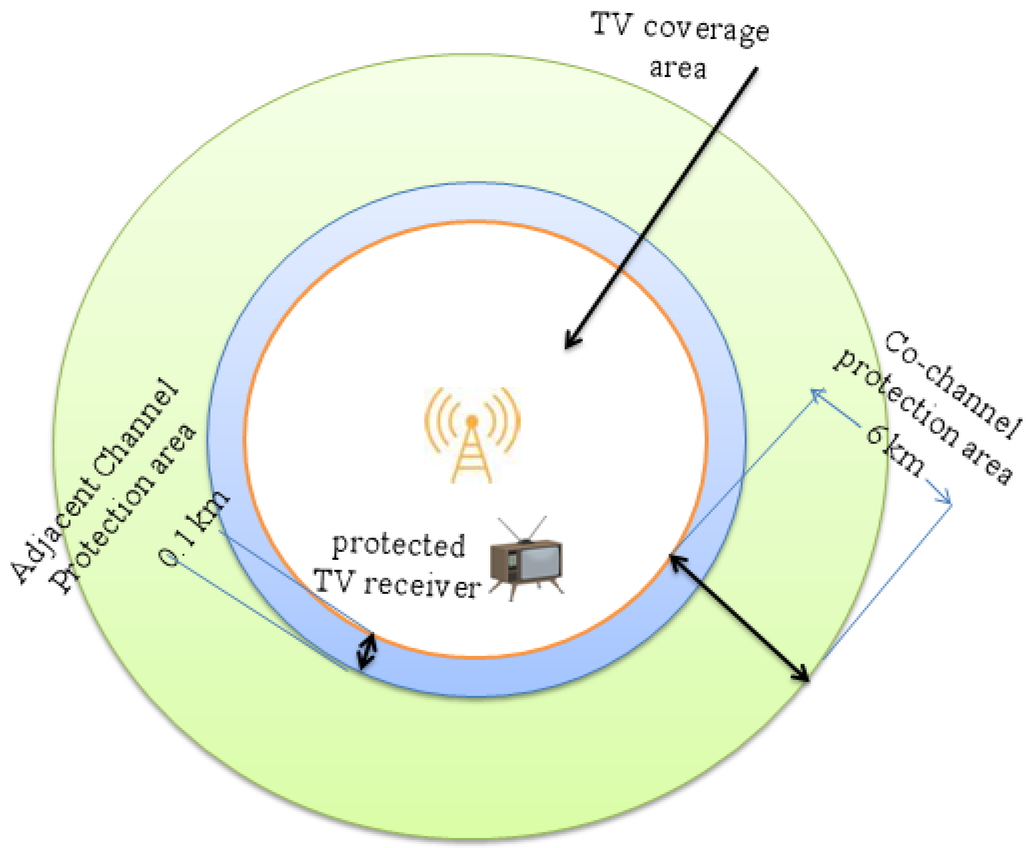

Figure 4: FCC protection distance, for a typical WSD antenna height≤ 3m. The position of the unlicensed device determines the frequency it is allowed to operate (adjacent or co-channel to the TV station) .

Antenna Height of Unlicensed Device	Required Separation (km) From Digital or Analog TV (Full Service or Low Power) Protected Contour	
	Co-channel	Adjacent Channel
less than 3 meters	6.0 km	0.1 km
3 —less than 10 meters	8.0 km	0.1 km
10 —30 meters	14.4 km	0.74 km

Table 4: FCC protection areas [26]

FCC admitted the inappropriateness of spectrum sensing to protect wireless microphones, which may be licensed or unlicensed, while it is possible to give protection to licensed ones via geo-location and database. Unlicensed wireless microphones, on the other hand, must tolerate significant level of interference by design. However, the Commission recommends the wireless device makers to include spectrum sensing to help them determine the relative channel quality and enhance spectrum sharing among unlicensed TV bands devices.

FCC put a limit on the EIRP power levels for personal/portable unlicensed devices to a maximum of 100mW. When the same device is operating closer to an occupied adjacent channel the maximum EIRP should be limited to 40mW. Sensing-only devices are allowed to emit up to 50mW EIRP. Fixed devices, however, are permitted to operate to a maximum 4W EIRP, but the Commission is quite strict for their operation adjacent to occupied channels. To reduce the out of band emissions, FCC requires that TVBDs power emission must be attenuated at least 72.85dB below the highest average power in the adjacent 6MHz bandwidth. Fixed TVBDs should locate their geographic coordinates to an accuracy of +/-50 meters. The same rule applies to portable unlicensed devices, on the condition that they check their location every 60 seconds.

3.2 ECC

In Europe the TV white spaces are located in the 470-790MHz contiguous frequency bands and unlike in the USA, each TV channel occupies 8MHz band. The presence of multiple autonomous national regulators becomes a challenge to impose very stringent white space usage rules.

ECC uses more detail signal propagation models to avoid secondary interference to different incumbent services (broadcasting TV stations, PMSE systems, radio astronomy, aeronautical, radionavigation systems, and border services at both ends of the 470-790MHz frequency). ECC proposed optimal secondary power emission equations and primary protection procedures by assessing the most common primary system settings. Unlike the FCC approach, the ECC document contains loose technical recommendations—that seem to offer a significant level of flexibility upon implementation in different member nations. ECC recommendation considers the geo-location database as a crucial tool to identify the TV white spaces, while sensing is left as an optional method. In fact ECC concluded autonomous sensing-only WSDs can not reliably detect the presence of primary systems even with more stringent sensing thresholds (for instance, -91dBm to -155dBm to detect TV signals). Moreover, ECC highly recommends geo-location databases to protect ARNS and portable PMSE services.

The ECC approach is targeted at maintaining a reasonable *location probability*, the probability with which a DTT receiver would operate correctly at a specific pixel —a receiver is considered to work correctly if the median of the wanted signal is greater than the minimum required value. Each pixel has 100m X 100m dimension. DTT networks use location probability to quantify the quality of their coverage. A typical coverage plan calculates the location probability for each pixel across the country. When a secondary wireless device is introduced, the interference naturally causes reduction in the DTT location probability. This reduction is used as a metric for imposing the regulatory in-block and out-of-block power emission limits for WSDs working in the DTT frequencies.

ECC suggests short-range WSDs to emit power levels of 10mW to 50mW and long-range ones between 1W and 10W. The autonomous operation of a WSD can be made safe by using a location specific maximum output power equations. For instance, the maximum permitted in-block power (EIRP) of a single WSD that can guarantee protection of the co- and adjacent channel TV channel reception is derived as follows[12][16].

The received TV signal quality is described by the signal to interference and noise ratio (SINR). ECC considers the TV outage, due to slow fading, is complementary to the location probability. The SINR distribution is related to the outage probability target(O_n):

$$O_n \leq Pr\{SINR \leq \gamma_t\} \tag{3.1}$$

where γ_t is the target SINR level.

The SINR is the ratio of the received useful signal, $P_{tv}g_{tv}$ and the noise added with interference

$$SINR = \frac{P_{tv}g_{tv}}{I_{tv} + I_{su} + P_n} = \frac{P_{tv}g_{tv}}{I_{su} + P_N} \tag{3.2}$$

where I_{su} is the interference from secondary users, I_{tv} is the interference from other TV stations, P_n is the noise power, $P_N = I_{tv} + P_n$ and g_{tv} is the TV signal attenuation.
The interference from other TV stations can be modeled as an increase of the noise floor. In slow fading channel the interference can be modeled with lognormal distribution.

$$I_{su} + P_N \approx 10^{\frac{\mu+z}{10}} \tag{3.3}$$

where μ(in dB) is the mean secondary interference added with the noise power, and z is the zero mean Gaussian random variable with standard deviation σ_{su}, which would be the slow fading standard deviation of the secondary signal.
By tuning the first two moments of the both sides of equation (3.3) to be equal and using (3.3) in (3.1), it is possible to derive the secondary power level that guarantees the outage limit.

$$P_{su} = \mu_{tv} - \mu_g - \gamma_r + q\sqrt{\sigma_{tv}^2 + \sigma_{su}^2} - MI - SM - M \tag{3.4}$$

where μ_{tv}, σ_{tv} are the mean and standard deviation respectively of the TV signal, μ_g is the mean secondary pathloss, γ_r is the protection ratio in dB due to frequency offset between the TV receiver and the secondary device, $q = Q^{-1}(1 - O_n)$ is the Gaussian confidence factor and the Q^{-1} is the inverse Q-function. MI accounts the margin for multiple secondary interference, SM is the safety margin and the margin M contains all the remaining parameters such as antenna gain, antenna directivity and polarization discrimination, feeder loss of the TV system, etc.

However, this approach requires the knowledge of a number of priori parameters such as the possible distance between the TV receiver and WSD(included in the calculation of M). The approach may not guarantee the protection of primary systems if, for instance, TV coverage has convolutions due to terrain irregularities. ECC concluded that the autonomous operation of WSDs should be compensated by taking a more conservative propagation characteristics. This has a direct impact on the utility of WSDs, which decreases when the detection requirements are very low.

The precise spatial separation between the WSD and a victim DTT receiver within the given pixel can not be known merely by geo-location database. To complement the SE43 methodology in determining the WSD transmission power limits, the concept of *Reference Geometry* is used. *Reference Geometry* refers to the minimum separation distance to be maintained between the WSD and the TV receiver in adjacent channel. Figure 5 shows the relevant reference geometry. This geometry helps for the calculation of optimal emission limits for mobile/fixed communication network terminal stations.

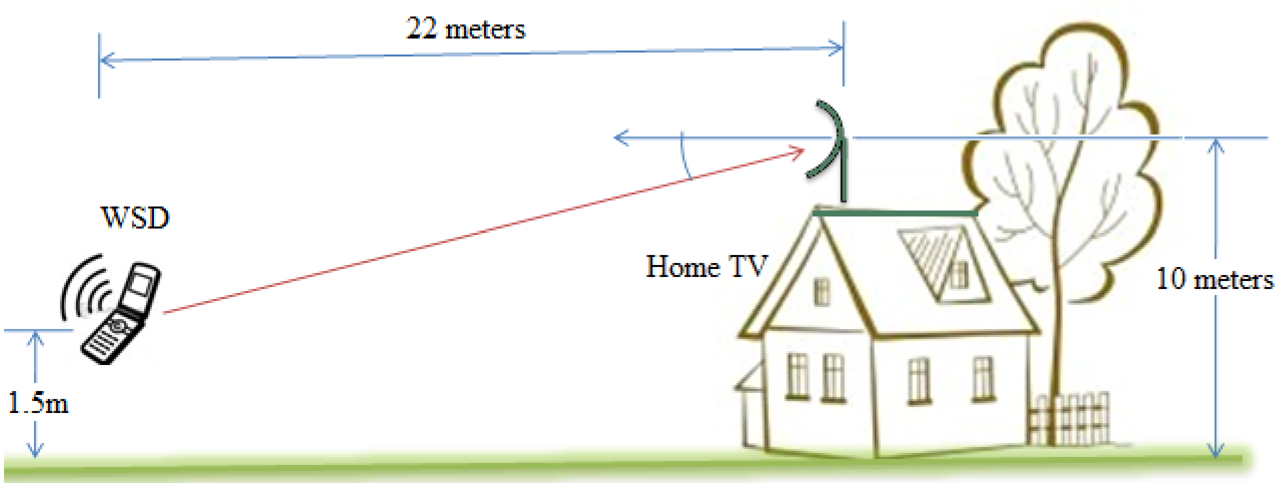

Figure 5: Reference geometry for adjacent channel options, assuming a portable WSD.

3.3 Protection of other systems in the TV spectrum

Wireless microphones are non-data devices which do not include geo-location technology—hence they are not required to be added to the database servers. FCC granted two channel reservations (in the range 14-51) for wireless microphones to safeguard them from potential interferences. Although there is no special protection scheme (as in contour mapping) applied for wireless microphones, most gathering venues and sites for major events will be registered to the geo-location database to limit the intrusion of unlicensed TVBDs in the area. If in any case, the number of wireless microphones is beyond the capacity the reserved channels could serve, the event organizer can register the details of the site beforehand for ensuring protection from unlicensed TV bands devices.

The ECC approach to protect program making and special event(PMSE) systems demands that WSDs should monitor their power emission. This requires the interference level from WSDs to remain well below -115dBm at the PMSE receivers. In some worst-case scenarios, the detection thresholds may drop from -120dBm to -155dBm. Generally, ECC recommends the need for a further study on combating temporal fading caused by multipath propagation, or using a geo-location databases and safe harbor channels dedicated for this specific service. Similarly, for the protection of radio astronomy(RAS) in channel 38, the ECC requirement suggests that this channel and its adjacent channels (37 and 39) be totally exempted for usage to autonomous WSDs, unless there is a centralized database at the European level or a multilaterally agreed management system that could secure the safety of this channel.

4 Spectrum Availability Assessment in the TV White Space

4.1 Introduction

Based on the QUASAR project definition[39],

"Spectrum is available for a certain set of secondary transmissions when it would not violate the regulatory rules if it were to be executed."

A number of possible metrics can be suggested for estimating the amount of the available spectrum, for instance, the number of unused TV channels per *pixel*[1] can be located for a geographic area. A channel is considered available for secondary usage at a pixel if the pixel doesn't fall within the coverage or the protection area of any transmitter using the same channel (see Figure 6).

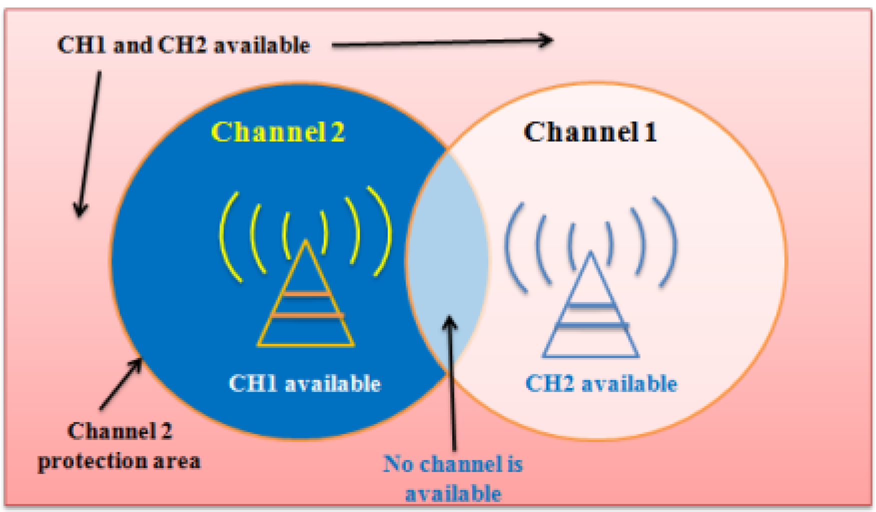

Figure 6: Channel availability for a two transmitter scenario.

Spectrum availability assessment is done as a back-end computation for *Spectrum Availability Assessment Tool*. In simulation environments, the process of estimating the amount of spectrum involves modeling the radio environment, considering the primary system network coverage and radio characteristics, devising measurement metrics and using appropriate secondary system scenarios for studying the feasibility of the assessment. This chapter discusses the propagation models, the measurement metrics and assessment methodology used in the spectrum availability assessment.

[1]A pixel may cover different area size depending on precision of the assessment. The location probability, which is used in DTT network planning, is typically calculated for every 100mx100m pixel across the country[12]. However, for this assessment we used a wider pixel size of 250mx250m. For the purpose of uniformity in this document, a pixel size refers to the 250mx250m dimension, unless it is related to location probability.

4.2 Radio Environment Channel Models

In wireless communication the transmission medium(channel) is shared by many radio systems. The characteristics of the radio signal changes as it travels from the transmitter to receiver antennas. The signal is affected mainly by the length of the path(s) taken by the signal and the transmission environment(trees, buildings,mountains,machineries,etc.). In general, the received signal,$r(t)$, can be obtained by the following equation where the transmitted signal, $x(t)$, and the channel's impulse response,h_c.

$$r(t) = h_c x(t) + n(t) \tag{4.1}$$

where $n(t)$ is noise signal.
The channel response has three main components; path loss, shadow and multipath fading.

i . Path Loss

A signal emitted by transmitter antennas is spread spherically. The signal gets weaker, the more it moves radially away from the transmitter. This attenuation due to the distance traveled by a signal is named as *path loss*. A most direct and easy approach for measuring the path loss is a line-of-sight propagation where there are no objects between (and around) the transmitter and the receiver. In free space, the received power can be described by the following equation.

$$P_R = P_T G_T G_R \left[\frac{\lambda}{4\pi r}\right]^2 \tag{4.2}$$

where P_R and P_T are the received and transmitted powers, G_T and G_R -antenna gains, r - path traveled and λ - wavelength of the carrier frequency.

In general, the path loss can be derived from the following empirical formula with P_0, power at a distance r_0 and α, the path loss exponent.

$$P_R = P_T P_0 (\frac{r_0}{r})^\alpha \tag{4.3}$$

And the path loss is written as:

$$L(r) = L_0 + 10 \cdot \alpha \cdot \log_{10}(r/r_0) \tag{4.4}$$

L_0 is the average path loss at reference distance r_0.

ii . Shadow Fading

Shadow fading occurs when there are big structures like buildings, mountains, trees, etc. between the transmitter and the receiver. Shadowing happens when the transmitted signal is lost through absorption,reflection, scattering and diffraction —see in Figure 7. The net path loss can be approximated by the equation:

$$L(r) = L_0 + 10 \cdot \alpha \cdot \log_{10}(r/r_0) + X_\sigma \tag{4.5}$$

Here X_σ, in dB, is a normally distributed(Gaussian) random variable with standard deviation σ.

iii . Multipath Fading

In a radio environment with multiple scatterers, the radio signal arrives at the receiver from different directions—with varying delays (phase) and signal strength (amplitude). Depending on their phase, the multiple signals may add or subtract each other upon arrival, yielding increased or decreased received power. There may be a line-of-sight between the transmitter and the receiver units, giving rise to one or more dominant signal components (if any). Figure 7 illustrates how the multipath effect works from signal reflections and the line-of-sight components. Moreover, multipath(fast) fading is characterized by its rapid fluctuation over small areas.

The relative effects of the three components the channel response can be compared in Figure 8. It is clearly shown that shadowing weakens the signal, next to path loss, while multipath fading varies rapidly in the range of the transmission path.

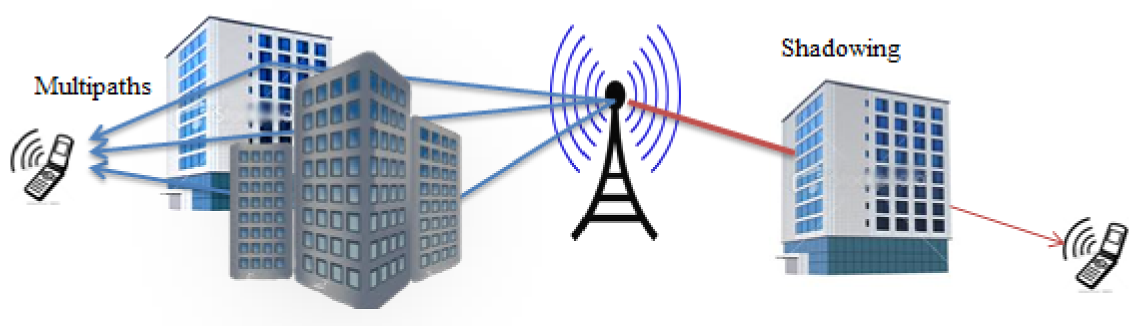

Figure 7: Multipath and shadow fading.

4.2.1. Statistical Models

To help better estimation of the signal strength in simulation environments, the radio channel is modeled based on the signal properties and the nature of its propagation environment. Empirical models that are developed based on measurements taken in various radio environments or statistical distributions that could approximate the real world scenarios are used to model the channel properties and the signal propagation characteristics.

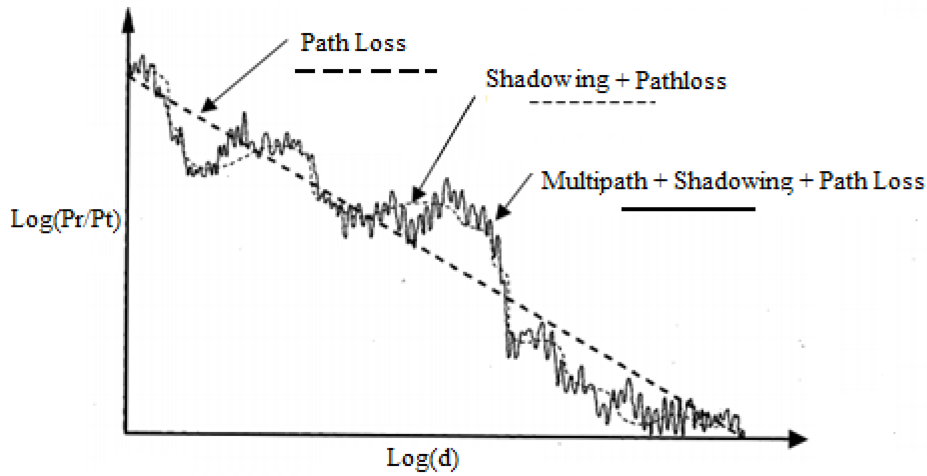

Figure 8: Comparing path loss, shadowing and multipath fading [38].

a. Okumura Hata Model

One of the famous statistical models of signal propagation in a multipath radio environment is *Okumura Hata Model*. The simplified mathematical path loss equations are derived from measurement results for limited set of parameters(antenna heights, frequency and distance). The model works well for medium range coverage areas, but may not be suitable propagation model for distances beyond 100km. The operating frequency falls in the range of 30MHz - 3GHz [39].

$$E = 69.82 - 6.16\log_{10}(f) + 13.82h_t + a(h_m, f) - (44.9 - 6.55\log_{10}(h_t)(\log_{10}(d))^b \tag{4.6}$$

where E is the field strength in dB(μV/m), f is the frequency in *MHz*, h_t (in meters) is the transmitter effective antenna height above ground in the range 30-200m, h_m is the mobile station antenna height above ground in the range $1 - 10$m, d is the distance in km. The value of the function $a(h_m,f)$ is:

$$a(h_m, f) = \{\ (1.1\log_{10}(f) - 0.7)h_m - (1.52\log_{10}(f) - 0.8)$$

Where as the parameter b can be computed as:

$$b = \begin{cases} 1 & d \leq 20\text{km} \\ 1 & +(0.14 + 0.000187f + 0.00107h^*)(\log_{10}(0.05d))^{0.8},\ d > 20\text{km} \end{cases}$$

where $h^* = \frac{h_t}{\sqrt{1+0.000007.h_t^2}}$

b. Point to Area Propagation Models

There are differences between point-to-point and point-to-area radio link modeling. They are distinguished by the amount of data required, point-to-point mode must provide details of the terrain profile of the link that the area prediction mode will estimate by using empirical medians. TV broadcasting needs a model that can predict the point to area propagation characteristics. The *ITU-R P.1546-3* recommendation predicts terrestrial point-to-area radio propagations for frequency values 30MHz - 3GHz. The model is aimed at tropospheric radio propagation covering long-range distances (1-1000km) and traveling over land, sea or mixed land-sea paths for effective transmitting antenna heights less than 3km. The ITU recommendation is an extrapolation of the measurement data under different geographical and climatic conditions. Field strength propagation curves for 1 kW effective radiated power at nominal frequencies of 100, 600 and 2000MHz are used to extrapolate(or interpolate) other propagation characteristics. The curves are based on measurement data mainly relating to mean climatic conditions in temperate regions containing land, cold and warm seas. Although propagation conditions may vary according to the weather conditions, the methods for interpolation and extrapolation between families of field-strength curves are general. Therefore, if families of curves exist for regions with different climate, accurate characterization of radio propagation in different regions may be attained using the methods found in the ITU recommendation[30].

Another model Irregular Terrain Model(ITM), also called Longley-Rice model, is used to estimate the propagation pattern of the TV broadcasting for both coverage area and point-to-point link predictions. The model predicts the median attenuation of the radio signal as a function of distance, antenna heights, and extra losses due to refractions caused by the intermediate (terrain) obstructions. It involves dozens of functions that implement numerical approximations to theory[31].

These models are used by many propagation prediction softwares for generating electric field strength coverage maps. Appropriate terrain models must be used to estimate the electric field propagation patterns. The Shuttle Radar Topography Mission(SRTM) terrain model is the most commonly used terrain model. SRTM is high-resolution global digital topographic database created by specially modified radar system[32].

4.3 DVB-T System Basics

DVB-T, Digital Video Broadcasting - Terrestrial, is a European-based digital terrestrial television, DTT, broadcasting technology. It enables the transmission of compressed digital video, audio and other data using an *MPEG transport stream (MPEG-TS)*.DVB-T standard offers various modes of network planning, giving rise to many flexible reception options from rooftop aerials to indoor receivers in buses and cars. To reduce the effect of multipath propagation conditions, DVB-T loads the data stream into large number of orthogonal narrow-band frequency carriers. This technique, is known as *Coded Orthogonal Frequency Division Multiplexing(COFDM)*.

The transmitted signal is organized into frames and four frames constitute a superframe. Each frame consists of 68 OFDM symbols while each symbol is constructed either by 6817 carriers, socalled *8K mode*, or 1705 carriers in *2K mode*. A symbol consists a useful part with duration T_U and a guard interval with duration $\triangle$ (see the tables below). The guard interval is used at the start of each symbol to fight multipath situation at the receiver. Guard interval may have durations of 1/4, 1/8,1/16 or 1/32 as compared to the useful part. For instance a guard interval of 1/4 means that each COFDM symbol is preceded by a guard symbol one-fourth of the useful symbol. Besides the guard bands, increasing the redundancy of bits is employed for correction of bit errors. DVB-T uses code rates of 1/2, 2/3, 3/4, 5/6 and 7/8.For instance, a code rate of 2/3 refers to a transmission where 2 units of data are non-redundant and useful while the remaining 1 unit is inserted for error correction.

Parameter	**Value**
Channel bandwidth	8 MHz
FFT size	8192 (8K)
Number of subcarriers	6817
Modulation	64-QAM
Code rate	2/3
Carrier spacing	1116 Hz
Useful symbol duration	896 μs
Guard interval	1/8

Table 5: DVB-T parameters, Finland [40].

Figure 9 shows the power spectral density of DVB-T signal. The overall spectral density of the modulated data cell carriers is the sum of the power spectral densities of individual carriers. For comparison of the 8K and 2K modes see Table 6.

Parameter	**8K mode**	**2K mode**
Number of carriers K	6817	1705
Duration T_U	896 μs	224 μs
Duration for guard interval of 1/8 ($\triangle$)	112 μs	28 μs
Symbol duration for guard interval of 1/8 ($\triangle + T_U$)	1008 μs	252 μs

Table 6: Comparison of 8K and 2K modes using 8MHz channels [37].

DVB-T can use any of the three modulation schemes such as *QPSK(Quadrature Phase Shift Keying),16QAM(Quadrature Amplitude Modulation) or 64QAM*. 64-QAM, for instance, is a modulation scheme that conveys data by changing both the phase of a reference signal(phase-shift keying, PSK) and/or the amplitude of the carrier wave(amplitude-shift keying, ASK) which carries $\log_2(64) = 6$ *bits per symbol*. It can also use hierarchical modulation, where two separate data streams are modulated onto a single DVB-T stream—a high priority stream embedded within a low priority one to allow a more flexible reception based on receiver quality. The two independent data streams can be transmitted in the same signal using different

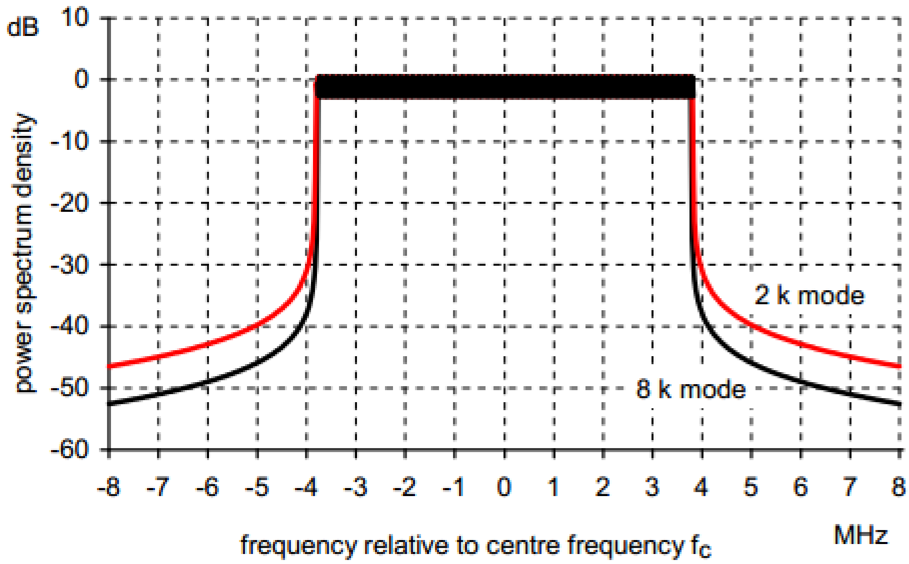

Figure 9: Theoretical DVB transmission signal spectrum for guard interval $\triangle = 1/4$ (for 8MHz channels)[37].

modulation techniques, for instance, QPSK for one (high priority) stream and 16-QAM for the low priority one. The high priority stream can be received in the case of relatively poor carrier-to-noise ratios but with low data rates, while the low priority ones can carry high data rate with high carrier-to-noise ratio but need good receiver quality. Moreover, it can operate in 6, 7 or 8MHz channel bandwidths, which gives a great deal of spectral flexibility.
The set of DVB-T parameters employed in Finland is shown in Table 5.

4.4 Assessment Methodology

Spectrum availability assessment for TVWS involves the following steps:

- **DVB-T system setup analysis** —This includes collecting the primary system transmitters across Finland and the neighboring countries, which will have direct impact(or may be victimized) to secondary system scenarios. This step identifies the location, transmit power and transmission patterns of primary transmitters.

- **Primary coverage area computation** —Using appropriate propagation and terrain models, the approximate coverage areas for DVB-T transmitters can be estimated. The coverage is calculated for each *pixel*(the smallest unit of geographical coverage for the assessment) across the whole country.

- **Computation of permitted secondary power**—Based on a specific regulatory requirement,for instance ECC requirements for working in TVWS[12], the permitted secondary power can be calculated for specific secondary system scenario. The secondary power emission level for a single secondary user is stated in equation (3.4).

- **Secondary system scenario**—The type of secondary system scenarios affect the computation, in our case we used cellular type secondary scenarios for analyzing the TVWS capacity. Both homogeneous cells, having similar size throughout the country, and variable cells which are dependent on the population are used.

- **Spectrum availability estimation and assessments related to secondary system scenario** —Spectrum availability can be quantified based on the availability metrics. Using the secondary system scenarios, the secondary spectrum capacity can be analyzed and the relative impacts of using different secondary parameters on the primary system can be compared using performance curves.

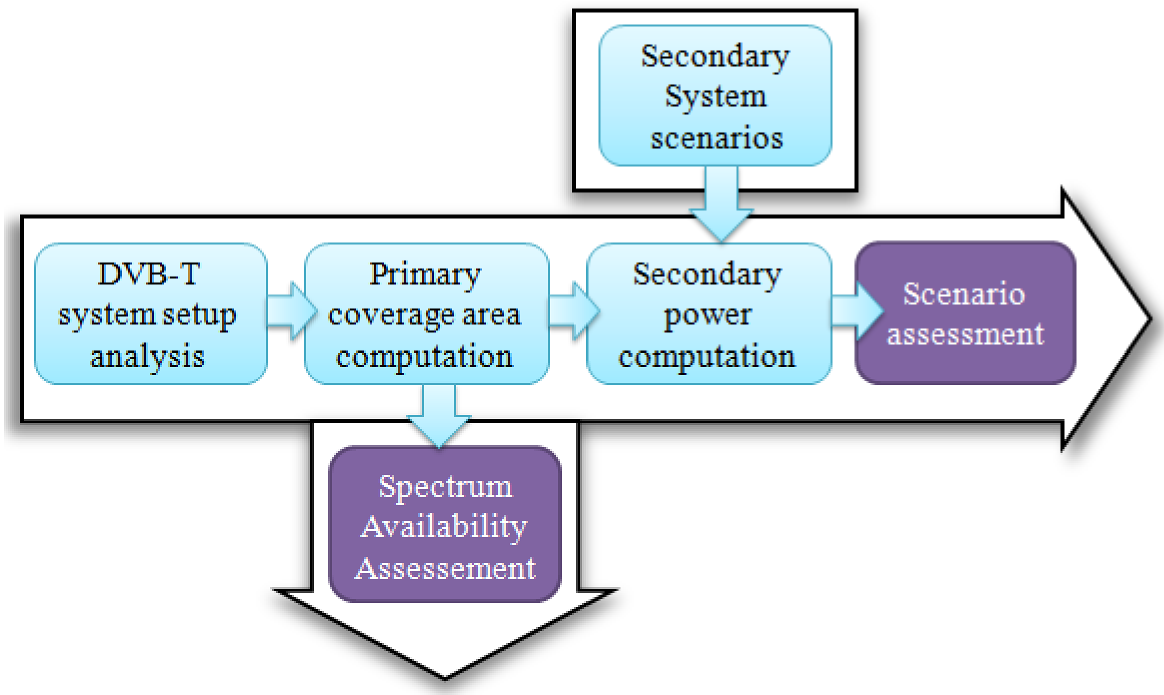

Figure 10: Assessment methodology flowchart.

4.5 Implementation of Assessment Methodology

4.5.1. System modeling and coverage area computation

The assessment includes all 620 DVB-T inside Finland and 1240 TV transmitters in the neighboring countries. Unlike cellular mobile networks like GSM, TV cells are relatively large. They have long co-channel reuse distance.The propagation model for the primary system is ITU-R P.1546. Assuming fixed reception over Ricean channel, the minimum field strength for 500MHz frequency is 52.5 dBuV/m. This minimum requirement is assumed to ensure successful reception for worst-case receivers at the edge of the coverage area.

The initial step for identifying the amount of available TVWS is to determine the area that is covered by each TV transmitter, using the above models. This process defines the TV channel protected contour at areas where the *location probability* is 95%. Location probability assumes the received signal from a TV transmitter in a given area (e.g. a pixel) varies with lognormal distribution when changing position in the area. A pixel has a *location probability* of $P\%$ if the $(1-P)^{th}$ percentile of the lognormal shadowing distribution is equal to or larger than the required signal level.

Mathematically, the location probability including TV self-interference, in the absence of WSDs is given by:

$$q_1 = Pr\left\{P_s \geq P_{s,min} + \sum_{i=1}^{K} r_{u,k}P_{u,k}\right\}, \tag{4.7}$$

where $Pr\{x\}$ is the probability of event x, P_s is the received wanted signal power at the TV receiver's antenna connector at the considered location, $P_{s,min}$ is the minimum TV receiver RF sensitivity in the presence of ambient noise, $r_{u,k}$ is the TV protection ratio for the k^{th} unwanted TV signal and $P_{u,k}$ is the received signal power from the k^{th} interfering TV tower. The presence of WSD decreases the location probability. Regulators need to limit the maximum amount of interference from WSD, such that the maximum probability degradation is limited to $\triangle q$. The new equation, denoted by $q_2 = q_1 - \triangle q$, becomes :

$$q_2 = Pr\left\{P_s \geq P_{s,min} + \sum_{i=1}^{K} r_{u,k}P_{u,k} + r(\triangle f)GP_{IB}^{WSD}\right\}, \tag{4.8}$$

with $r(\triangle f)$ being the TV-WSD protection ratio for frequency offset $\triangle f$, G is the path gain between the WSD location and the interfered TV receiver's location, and P_{IB}^{WSD} the in-band transmit power(EIRP) of the WSDs. All the power values are in linear domain(in Watts).

4.5.2. Secondary power computation

Using different regulatory requirements, FCC or ECC rules, primary protection areas and the operating secondary power levels can be calculated.

i. **FCC**
The FCC rule sets maximum fixed allowed maximum transmit power for WSDs —fixed WSDs with antenna height less than 30m maximum permitted EIRP of 36dBm (which corresponds to 4 watts) while mobile ones are limited to

20dBm(0.1W). Around each TV transmitter there is a radial distance limit, where no WSD is allowed to operate in the same channel. The WSDs are also not allowed to operate in the first adjacent channel to occupied DTV channel, only this time the protection distance is smaller. For instance, a WSD having antenna height 10m to 30m, the adjacent channel protection zone is 0.74km and the co-channel protection is 14.4km.

ii. **ECC**

The SE43 working group under CEPT, allows secondary transmitters to transmit at different power levels based on their distance to the coverage area. The scheme calculates the maximum permitted power for a WSD at a given location—the calculation is based on permitted degradation of location probability for TV reception.

Recalling equation (4.8):

$$q_2 = Pr\left\{P_s \geq P_{s,min} + \sum_{i=1}^{K} r_{u,k}P_{u,k} + r(\triangle f)GP_{IB}^{WSD}\right\}$$

Assuming $Z = P_s - P_{s,min} - \sum_{i=1}^{K} r_{u,k}P_{u,k}$, in the above location probability equation, it becomes:

$$q_2 = Pr\left\{r(\triangle f)GP_{IB}^{WSD} \leq Z\right\} \tag{4.9}$$

$$= Pr\left\{P_{IB}^{WSD} \leq \frac{1}{r(\triangle f)G}Z\right\} \tag{4.10}$$

The two possible conditions are $Z \geq 0$, in which case the signal can be easily detected, and $Z < 0$, signal is weaker than the receiver sensitivity level. Considering these two cases, the new location probability equation is derived as[34]:

$$\begin{aligned} q_2 =& Pr\left\{r(\triangle f)GP_{IB}^{WSD} \leq Z\right\} \\ =& Pr\left\{Z < 0\right\} Pr\left\{P_{IB}^{WSD} \leq Z \mid Z < 0\right\} + Pr\left\{Z \geq 0\right\} Pr\{P_{IB}^{WSD} \leq Z \mid Z \geq 0\} \end{aligned} \tag{4.11}$$

But according to the original assumption in equation(4.7),

$$Pr\left\{Z < 0\right\} = 1 - q_1,$$

$$Pr\left\{P_s \leq P_{s,min} + \sum_{i=1}^{K} r_{u,k}P_{u,k}\right\} = 1 - q_1 \tag{4.12}$$

This occurs during TV outage conditions due to shadow fading or self-interference from other TV stations.
P_{IB}^{WSD} must be non-negative. Therefore, when Z is negative, it follows that $Pr\left\{P_{IB}^{WSD} \leq Z \mid Z < 0\right\} = Pr\left\{P_{IB}^{WSD} < 0\right\} = 0$.

Therefore, equation (4.11) becomes:

$$q_2 = 0 + q_1 Pr\left\{P_{IB}^{WSD} \leq Z \mid Z \geq 0\right\} \tag{4.13}$$

Lets define $\mathcal{Z} = Z, for Z \geq 0$ and 0, for negative values of Z. The new expression for the q_2, in logarithmic domain:

$$q_2 = q_1 Pr\left\{P_{IB}^{WSD} \leq \mathcal{Z} - G - r(\triangle f)\right\} \tag{4.14}$$

where $\mathcal{Z}$ is in dBm, G and $r(\triangle f)$ are in dB. Finally, assuming G and Z are lognormally distributed random variables, the permitted WSD transmit power that safeguards the location probability of TV reception is[34]:

$$P_{IB}^{WSD} \leq m_{\mathcal{Z}} - m_G - r(\triangle f) - \sqrt{2} erf^{-1}(2(1 - \frac{q_2}{q_1}))\sqrt{\sigma_{\mathcal{Z}}^2 + \sigma_G^2} - IM, \tag{4.15}$$

where $m_{\mathcal{Z}}, \sigma_{\mathcal{Z}}, m_G, \sigma_G$ denote median and standard deviation of $\mathcal{Z}$ and G, respectively. erf^{-1} is the inverse complementary error function, IM - is interference margin that can be set by regulators for premium safety like aggregate interference protection[2].

The simplified illustration for FCC and ECC power allocation schemes across the radial distance from a TV broadcast station is shown in Figure 11. In the diagram the TV coverage is intended to reach protected receivers at R_{TV}. With FCC ruling additional radial protection distance, r_p must be added to allow unlicensed device. ECC rule, however, allows unlicensed WSDs even closer to R_{TV} but with tighter power control the more it gets nearer.

4.5.3. Secondary system scenarios

The secondary system may assume any of the possible configurations like cellular, point-to-point links, etc. We used square-shaped cellular secondary system design, for instance, to compare the number of available channels using the FCC and ECC rulings. The cells can have either fixed radius of 2km, 5km and 10km that is homogeneous regardless of the population gradient or a custom radius that is based

[2] The above equation (4.15) is a modified version of the original power equation suggested in ECC 159 report by SE43 working group. A close analysis in [34] revealed that the previous one overestimates the allowed secondary power, for failing to account for the TV outage.

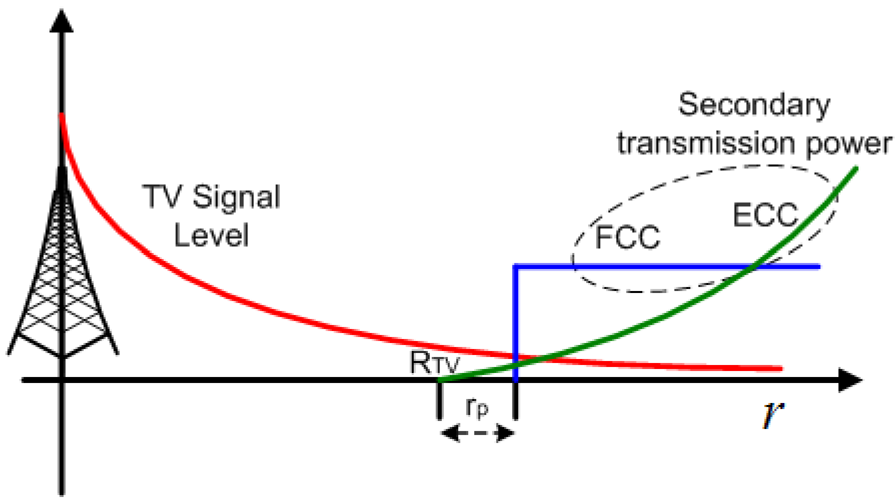

Figure 11: Power gradient of TV signal, and comparison of WSD signal power using FCC and ECC rules.

on population-density. Okumura-Hata propagation model is used for estimating the secondary system signal propagation characteristics. Secondary antenna height is fixed at 30m.

In the second case, when the secondary cell radius is based on population density, a hierarchical three-level cellular radius was used to accommodate only 10,000 users per cell i.e. first the whole country is covered by a 32km radius cell. Then if a cell has more than 10,000 users, it is divided into medium-sized cells. If any of the medium-sized cells contain more than 10,000 users, they are divided into small-sized cells. Using cellular-type analysis it is possible to account for the effect of the primary system on the usability TV spectrum in a pixel. When interference from the primary system is sufficiently high able to cause secondary outage, the same channel can be assumed non-available in that pixel.

Name	**Size**	**Coverage [km^2]**	**Number of cells**
small	1x1km	1	1744
medium	4x4km	16	5459
large	32x32km	1024	327

Table 7: Secondary cell sizes based on population density.

4.5.4. Spectrum availability and secondary system scenario assessments

The spectrum availability assessment can be summarized in three main outputs. *Availability assessment* estimates the amount of TV spectrum free to use for secondary access. By using cellular-type secondary system model, it is possible to evaluate the *secondary system performance* on the available spectrum. Finally, the assessment must evaluate the amount of interference the secondary system is causing to the primary system. The *primary performance curves* are used to show the

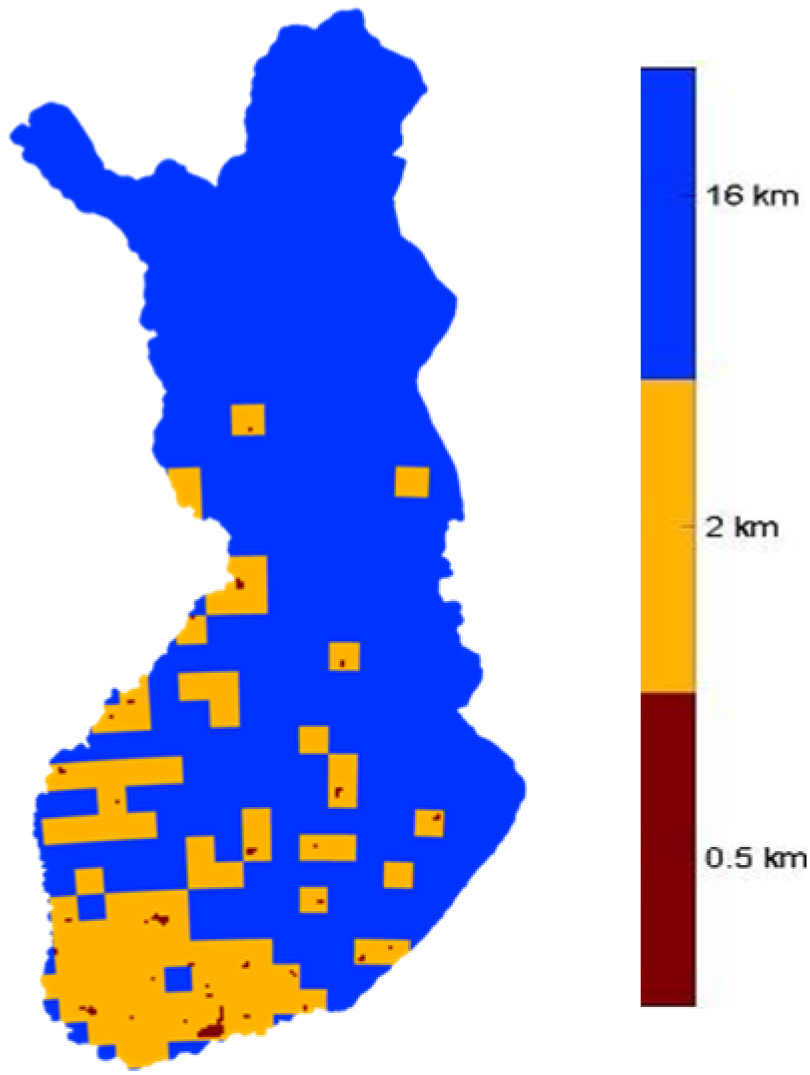

Figure 12: Cellular-type coverage layout for secondary system: 10km homogeneous radius(left) and radius based on user density(right)

relative impacts of the various secondary parameters to the TV system.

a. **Availability assessment**

Using the definitions for spectrum availability (see *Introduction* subsection 4.1), the amount of harvestable spectrum can be estimated.The spectrum availability maps can be presented as color-coded illustrations (see Figure 13) to visualize the geographical presence of the TVWS spectrum.

b. **Secondary system performance**

The outputs of this research give guidance to how cellular-type secondary systems could give different parameter-specific outputs. The parameters are population density, regulatory ruling(FCC or ECC), the primary system param-

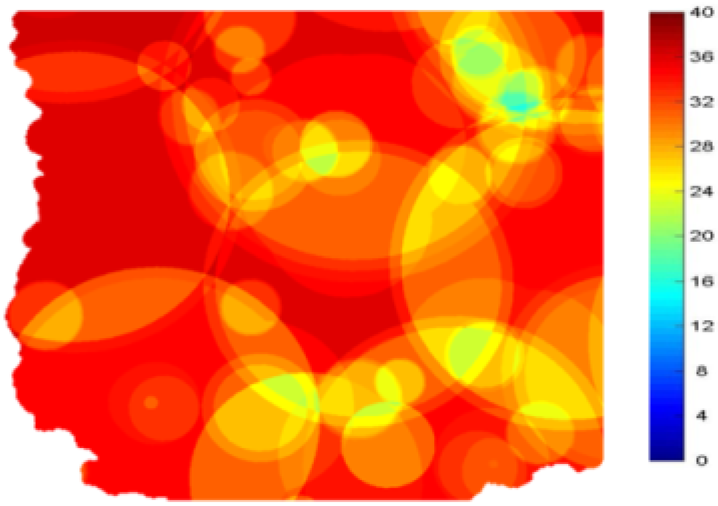

Figure 13: Color-coded availability map (number of free TV channels)

eters(reference geometry and allowed outage probability), secondary cell sizes (homogeneous or user-density based), and parameters that affect the signal propagation characteristics (antenna height and interference margin). These parameters are introduced to measure the capacity of the TVWS for a cellular-type secondary system model - *secondary capacity*. Figure (14) shows a color-coding method used to illustrate the secondary capacity of the TVWS for different areas.

c. **Primary system performance**

Signal to noise and interference ratio curves are used to know the approximate relative aggregate impacts of the secondary system on the TV coverage. If TV receivers at the border of the coverage area are receiving the minimum target signal to noise and interference ratio, the remaining users are assumed to be safe. Hence,the estimation of aggregate secondary interference on the primary system was tested on selected sample points along the TV coverage area cell borders. The plots in Figure 15 gives relative impacts of the different secondary system on the primary for different settings; for instance, reference geometry, homogeneous or population density-based cellular radius and interference margin. The secondary antenna height is set to 30m.

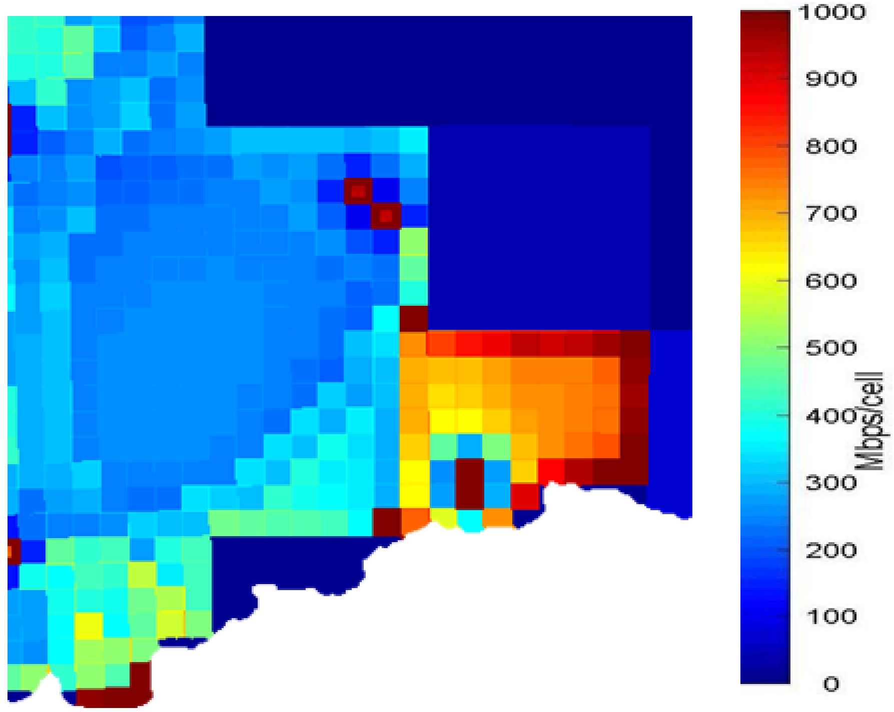

Figure 14: Color-coded map for secondary capacity (average capacity per cell, when secondary cell-size varies based on population density).

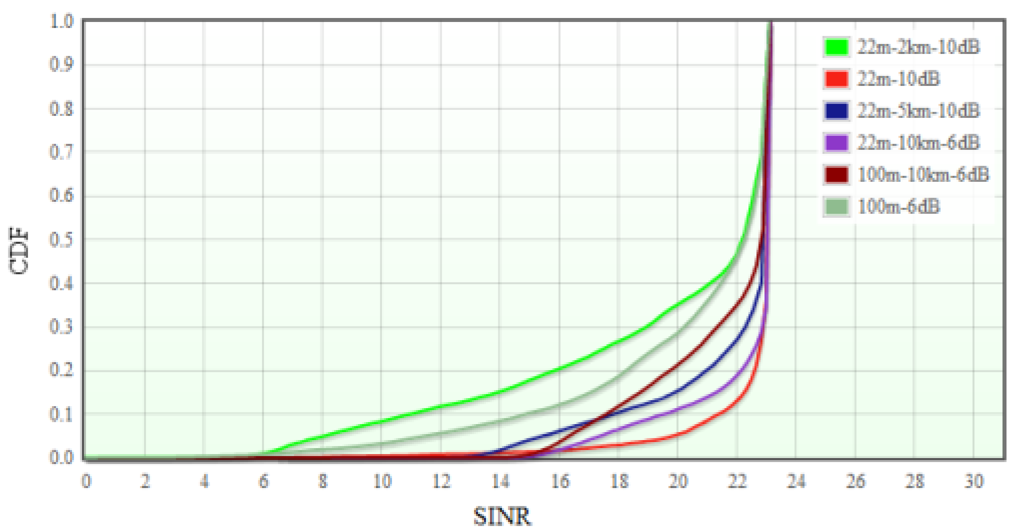

Figure 15: SINR distribution at the TV cell borders at the presence of aggregate secondary interference.

5 Front-End Visualization

5.1 Introduction

Data —which may be a byproduct of research, gathering, discovery or even creation, is a raw material for communication, but less adequate for a meaningful communication. Data must be organized and presented in some order to acquire informational value[44].

It is worthwhile to explain the famous DIKW(Digital, Information, Knowledge and Wisdom) hierarchy, shown in Figure 16, mostly used in the Knowledge Management and Information Science domains. Data is turned into information by presenting it in understandable arrangement, whether it is a visual or auditory one. Unless data is translated into information, the user finds it difficult to comprehend the meaning of the data at hand. Knowledge, however, is related to experience

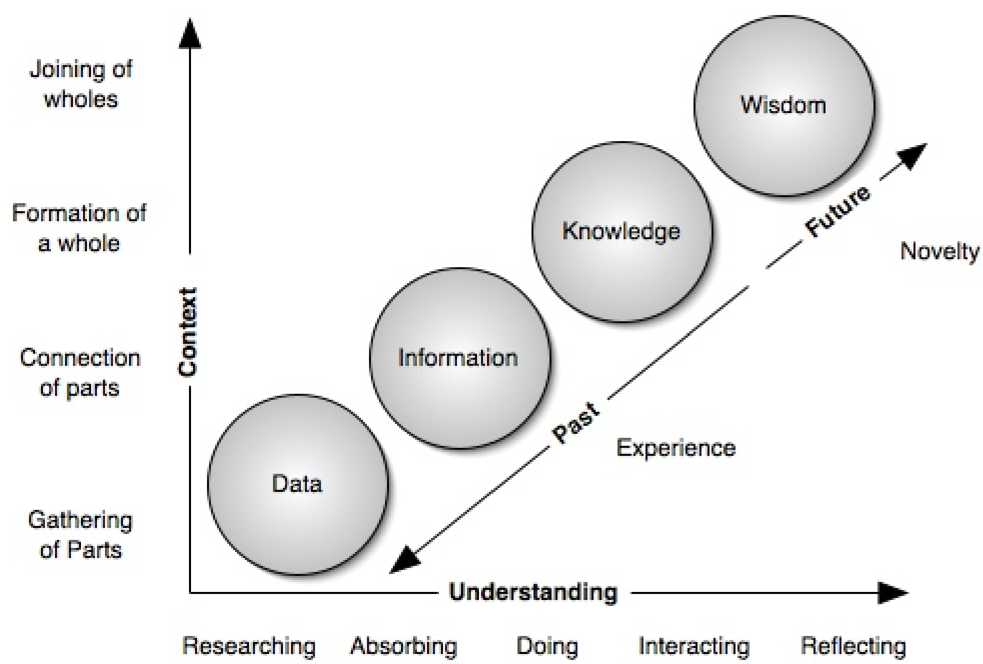

Figure 16: The Continuum of Understanding[46]

acquired from static information and it depends on the perspectives of the learner. Knowledge is obtained by interacting with others or with tools to acquire the patterns and the meanings included in their information. Variations of experiences give a learner different types of knowledge, which eventually affect the person's point of view or thought. Local knowledge can be acquired by a few people having similar experiences of the same thing, but general knowledge depends on high level shared experiences by many people of a certain discipline. The ultimate understanding of patterns or experiences created by organized data finally becomes wisdom. We can share those experiences that are the knowledge units to create wisdom —in other words, wisdom can be communicated with more contextual perspective and deep understanding[44][46].

When it comes to human-machine interaction, we have accumulated a set of common experiences with the conventional Graphical User Interfaces(GUIs). GUIs enable presentation of data by exposing the user to interact with graphic art forms and objects. Effective GUI delivers organized data (information) to users. It invites the users to new interactions with forms and structures that, eventually, will pile up on their existing experiences and become a new knowledge to edify their wisdom. Interactive GUI design is a narration design that is intended to replace the mechanical model with our linguistic model[44].

Computers are being used in most of our daily activities including communication. With the increasing connectivity of devices and services to the Internet, they are becoming more valuable than ever. The Internet is making information access more ubiquitous, more fast and cheaper. The creation and development of the World Wide Web (WWW) in the last three decades increased the pace of data sharing among users, regardless of the devices involved. The peripheral devices to access many services, whether it is in a remote server or a local machine, involve interaction with GUIs. To ensure that a GUI is full of meaningful and informative experience, it is highly recommended to comply with certain design standards.

5.2 Graphical User Interface Design Guidelines

The design of GUI involves the consideration of the perceptual and cognitive psychology of the users of a system. A user interface design should consider at least how people perceive, learn, remember and convert patterns into action. Most of these topics are, in fact, associated with human psychology.[47].

When it is our first time to perform an activity, we do it in very controlled and conscious way, but with training it becomes more and more automatic. Activities like riding a bicycle, typing with keyboard, writing,etc. are started as a more conscious and non-automatic and become less conscious and automatic ones when we are trained over time. The progression time from controlled to automatic has a significant implication for GUI designs —how can we design a user interface so that it takes less time to train users to become less-conscious automatic users? The goals of efficient user interface design is to enable faster understanding of the system functionalities by the users to the point of becoming automatic without taxing much cognitive energy.

When we are accustomed to a visual interface, we become less strained and more of context-free. Context-free recognition is a cognitive technique by our brain trying to identify visual graphics from simple to complex patterns. It may be line segments, buttons, graphic images or forms that can be combined to form a whole visual meaning. On the contrary, unskilled users prefer using context-based, top-down approach, a recognition which involves understanding based on context. The reader may start from whole paragraph down to objects, words and characters. This kind of visual system starts recognition from complex patterns or by knowing the meaning of the text (that may be the sequence of events in a user interface) in advance, it then uses that knowledge to identify or guess the contents of those patterns[47].

Poor information design impedes experienced users' automatic context-free recognition, compelling them to resort to a conscious and context-based usage i.e. increased burden, limited speed and comprehension. There are many rule of thumb tips for designing a user interface to make it more context-free recognizable. It is highly recommended to avoid using unfamiliar vocabulary and script typefaces —not common in the computer world, small fonts, noisy background, less organized text-alignment, too much unnecessary text or any additional features that may disrupt the automatic perception of a user interface [47]. If the user interface is web-based, it should also consider the loading time, the background color of the page and accessibility issues—too much background script codes may sometimes freeze browsers.

A user-centric interface design considers data organization and classification to make it easily understandable by its users. The information arrangement could be done based on data sources, relationships between each data, position and time. The organization of information affects the way it is understood[44]. This organization, however, should not challenge the users memory requirements. Most people don't keep detail information in memory, other than those their goals made them pay attention. In fact, many people prefer seeing and recognizing things to recalling them [47]. A User Interface should avoid requiring too much information memorization —it could provide some guidance to users, for instance, by adding some modes, listing alternatives in drop-down, auto-fill methods and other means.

Another method might be making the visualization tool task-focused, simple and consistent. It is good the designer perform task analysis and design task-focused conceptual model before actually designing the user interface and strictly follow those targets set in the conceptual model. The following issues may be very important to consider:

- What is the tool intended for?
- What goals may users expect?
- Who are the target users?
- Any guidance to main tasks without causing an error.
- Steps to do a task, comprehensible terminology, associated risks, etc.

This helps designers to eliminate the gap between the user goals and the actual features on the visual interface. If users perceive the visual tools are not directly

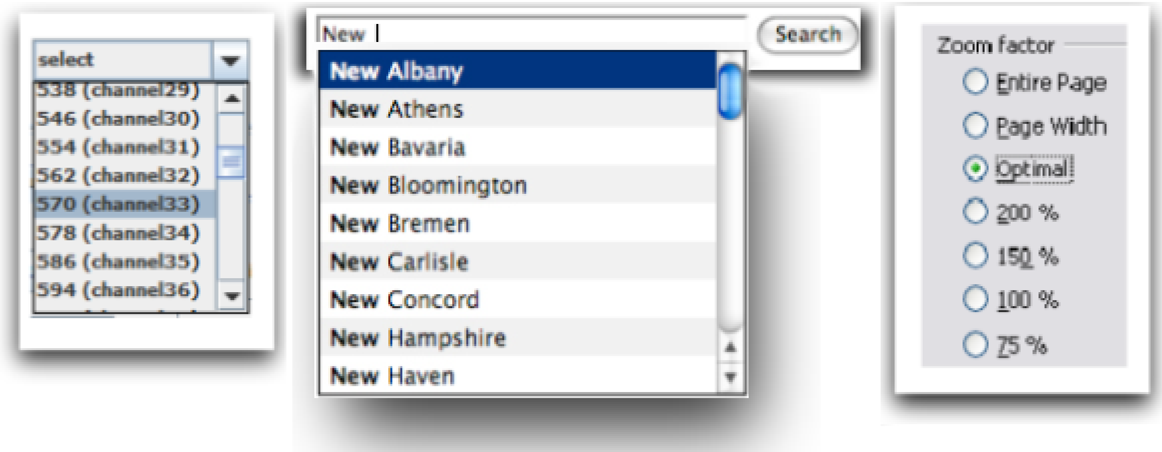

Figure 17: Visualization tools for assisting users to memorize(drop-down list, auto complete pop ups and radio buttons)

related their goals, they will pay less attention to them. The gap between the needs of the user and the functionalities of the tool determines the learning time. When the tool works their intended tasks easily without expending too much cognitive effort, automatic use can be achieved quickly.

In summary, a user interface design is recommended to be consistent and its terminology usage to comply with that of the day to day softwares. User-centric UIs challenge our recognition rather than our recalling capacity i.e. minimizing short-term memory load. The visual interface can use an online documentation and help for assisting users.

5.3 Requirements Analysis

There are many undergoing researches, including EU FP7 QUASAR project [19], doing quantitative assessment of the available white space for opportunistic secondary access. Oftentimes the academic community is required to provide direct answers to questions such as:

- How much TV white space is there?
- How much of it is harvestable?
- How much cumulative and average secondary data rate can be supported in the TV white space, across different geographical locations?
- What is the relative impact of the secondary usage on the primary system, under various parameters?

By using the ECC and FCC guidelines, we have analyzed the availability of TVWS in the existing DVB-T system, in the whole Finland. The outputs of our research are arrays of quantitative capacity maps(Figure 18) and signal to noise and interference ratio (SINR) values, obtained by varying multiple parameters —helpful for comparative analysis. It is required to make the capacity maps and SINR plots browser accessible. Technically, we need three fundamental features; map services, browser-based plotting technologies and the capability of comparative visualization.

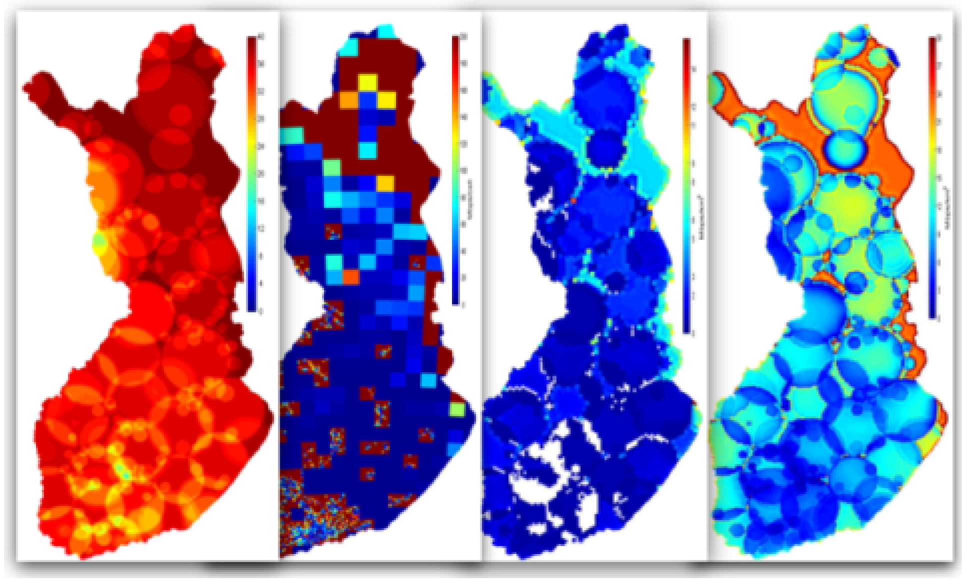

Figure 18: Examples of quantitative capacity maps*(available channels, user density based capacity per cell, capacity per area of 2km and 5km radius respectively)*.

5.3.1. Web-based Visualization Technologies

HyperText Markup Language(HTML) is markup language for creating content for information provided on the World Wide Web (the Web). Markup languages use their own syntax to differentiate content from annotation. HTML has limited capability to influence the appearance of the document on the browser, instead Cascading Style Sheets(CSS) can be used as a method for modifying presentation semantics (the look and feel) of HTML documents. CSS works by separating content from web page structure. It is used as a stylistic guideline to modify the format of the presentation.

There are various free map service providers to visualize the capacity plots; Google Maps, Bing Maps, OpenStreetMap, WikiMapia, Nokia Maps and others. We chose Google Maps for its customizable web-based visualization experience. Google Maps provides its own *Google Maps API(Application Package Interface)* that can be used to embed the mapping service on non-commercial third party websites.

Google Maps API uses *Javascript* technology, which is a scripting language (lightweight programming language) very well compatible for most browsers. Apart from becoming a scripting language of choice in Google Maps environment, Javascript is very popular tool in dynamic web-based applications. The World Wide Web Consortium(W3C) standard known as Document Object Model (DOM) is a language-neutral interface that allows scripting languages like Javascript to dynamically access and update the content, structure and style of HTML documents. Javascript uses an API for browsers, called *XMLHttpRequest*, to submit request to web-servers and to load server-side files to the browser. For the SINR plotting functionality, we can make use of XMLHttpRequest protocol and any of the Javascript plotting libraries, specifically we used a library named as *flot*. Moreover, Javascript is executed in the browsers without preliminary compilation, this has greatly eased its portability across different systems.

The combination of HTML, CSS and Javascript allows a very flexible web-based GUI visualization. An HTML document presented by the three technologies is named as Dynamic HTML (DHTML). DHTML enables faster content fetching from server without the need of refreshing the page. It is the main tool in dynamic web formatting and visualization.

One other alternative to DHTML is Java applet, which can offer a more dy-

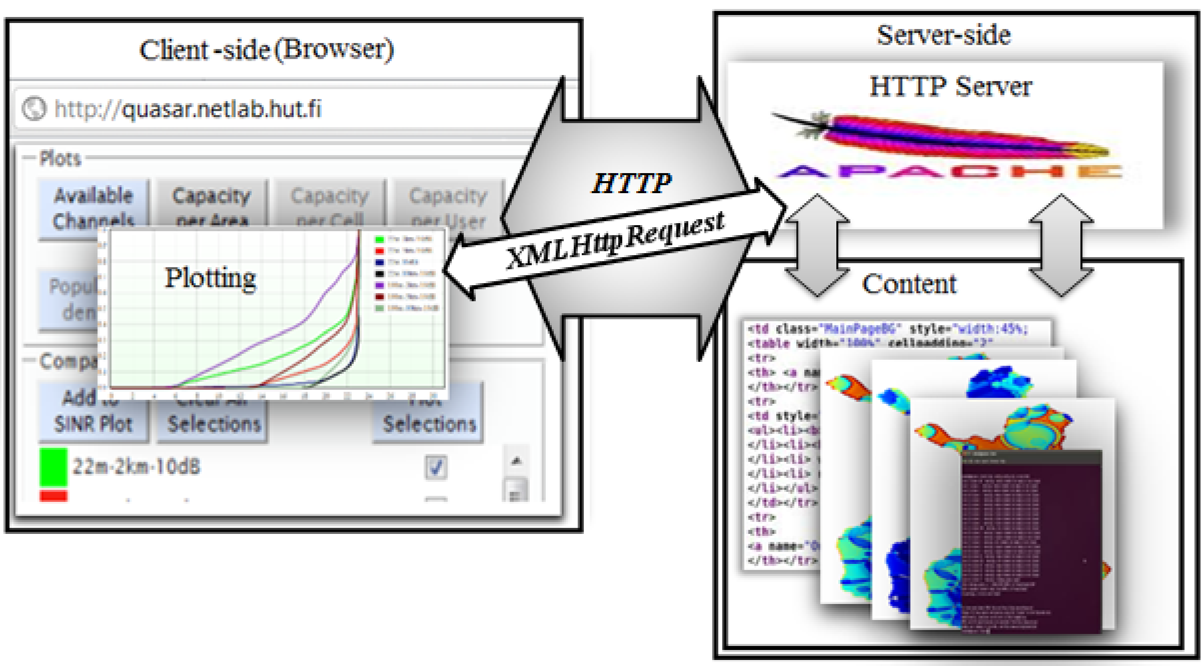

Figure 19: Client-server communication.

namic client-side GUI. They have an advantage of giving the programmer more control of the UI and with capability of handling computation intensive visualizations. Java applets run in a web browser using Java Virtual Machine(JVM), a platform-independent code execution component for Java codes. However, applets are with many limitations. Firstly, the user must have JVM enabled browser. Secondly, they are restricted by many security issues in the face of malicious intents using applets, they work under security sandbox model. Besides these, applets lack the flexibility of dealing with on-line map services.

5.4 Spectrum Availability Assessment Tool Architecture

As discussed in the above section,the main goal of the *Spectrum Availability Assessment Tool* is to visualize the findings of the undergoing research in TVWS, for Finland. The architecture shown in Figure 20, represents the theoretical model for realizing our technical requirements. The back-end computation takes population and TV broadcast data as inputs. By using the appropriate propagation models and relevant parameters, the computational outputs are stored in a web server. The web server can be accessed by any of the latest browsers; Mozilla Firefox®, Internet Explorer®, Google Chrome® and others.

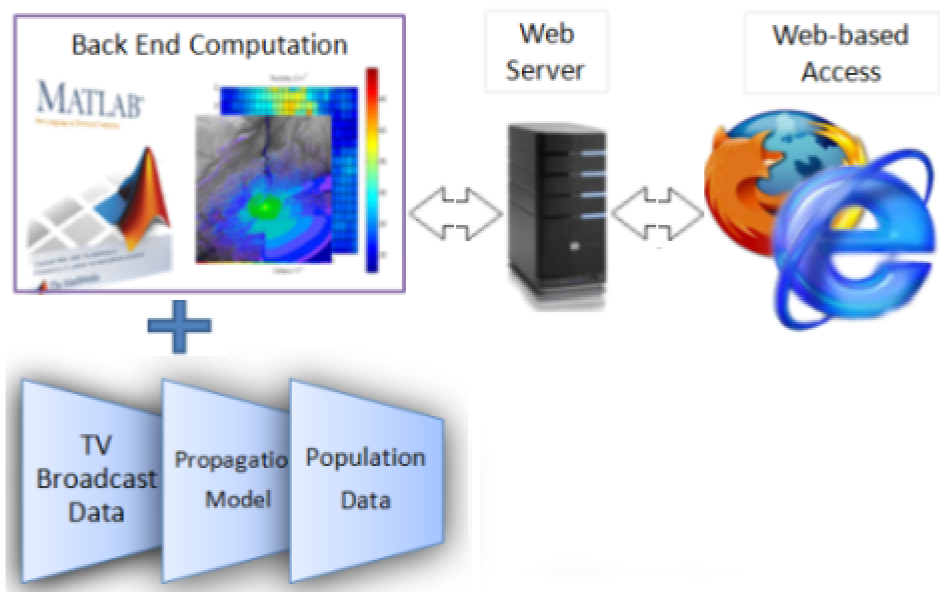

Figure 20: Theoretical model of spectrum assessment visualization tool architecture.

5.5 Implementation of Assessment Tool

There are few practical problems to implement the theoretical model. The major one being the time requirement, it takes too much time to generate any of the required outputs (roughly 0.5 - 3hrs), so that real time interaction is almost impossible. Normally, this is also a big hurdle to stand-alone applications. Secondly, it needs tougher bandwidth requirement that is able to transport many gigabytes of DVB-T broadcast and population data in only few minutes. The direct implication is that we can not make a timely browser-side computation. These limitations ultimately demand the computation to be server-side and can not be real-time one.

Consequently, a new model have to be implemented —shown in Figure 21. The new approach uses ready outputs that are pre-calculated and stored in a database server. Practically, the need of the database can be compromised based on the data size(number of generated values) and the features needed at the front end - browser based access. In this scheme, everything is calculated ahead. This gives a great level of flexibility to use either a server-side or browser-side mechanism to access the data. The model in Figure 21 uses browser-side scripting languages to fetch data from the web-server.

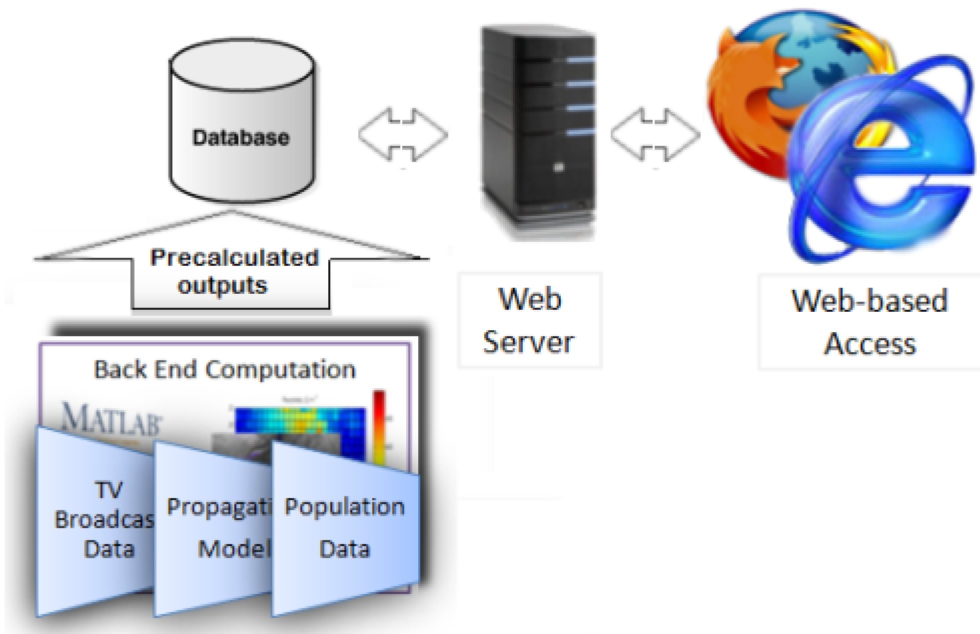

Figure 21: Spectrum assessment visualization tool architecture, practical model.

6 Spectrum Availability Assessment Tool : Finland Case Study

6.1 Introduction

Finland is located in 64N latitude and 26E longitude. Finland is a sparsely populated country with average population density of 17.7 per square km and a total area of 338,145 square km out of which more than 10% is covered with water. Finland has population exceeding 5.26 million (estimate for 2012). Most of the population lives in the southern part of the country (more than 1 million residents live in the Helsinki Metropolitan Area alone)[49].

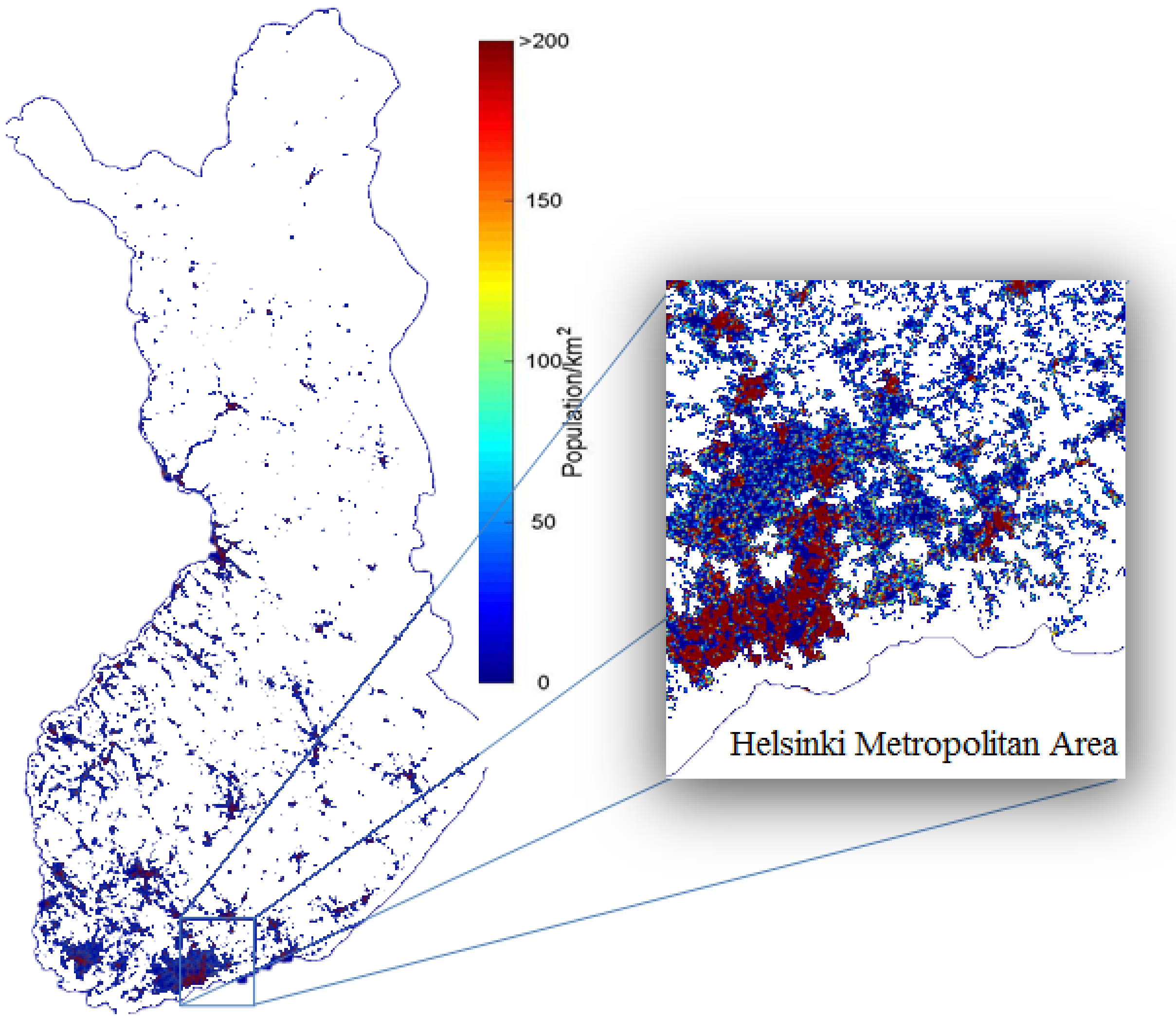

Figure 22: Population density of Finland.

As discussed in the previous two chapters, *Spectrum Availability Assessment Tool* is a web-based visualization tool for a time-intensive back-end computational process. The outputs of the computation are spectrum availability maps, capacity maps for cellular-type secondary system and TV SINR plots that show the relative impact of the different secondary system parameters on the primary system.

The tool can be accessed on the web by using a *universal resource locater (URL)* address. URL is a specific character string (in our case *http://quasar.netlab.hut.fi*) that constitutes a reference to web server. The content is hosted in *Apache HTTP Server*. Apache is an open source(allows access to the source code, modification and free redistribution) web server. Web servers are softwares that serve requests from browsers by organizing content residing in them—they only serve requests and hence they remain in listening mode until they receive them. The requests are sent from browsers to web servers using the URL addresses.

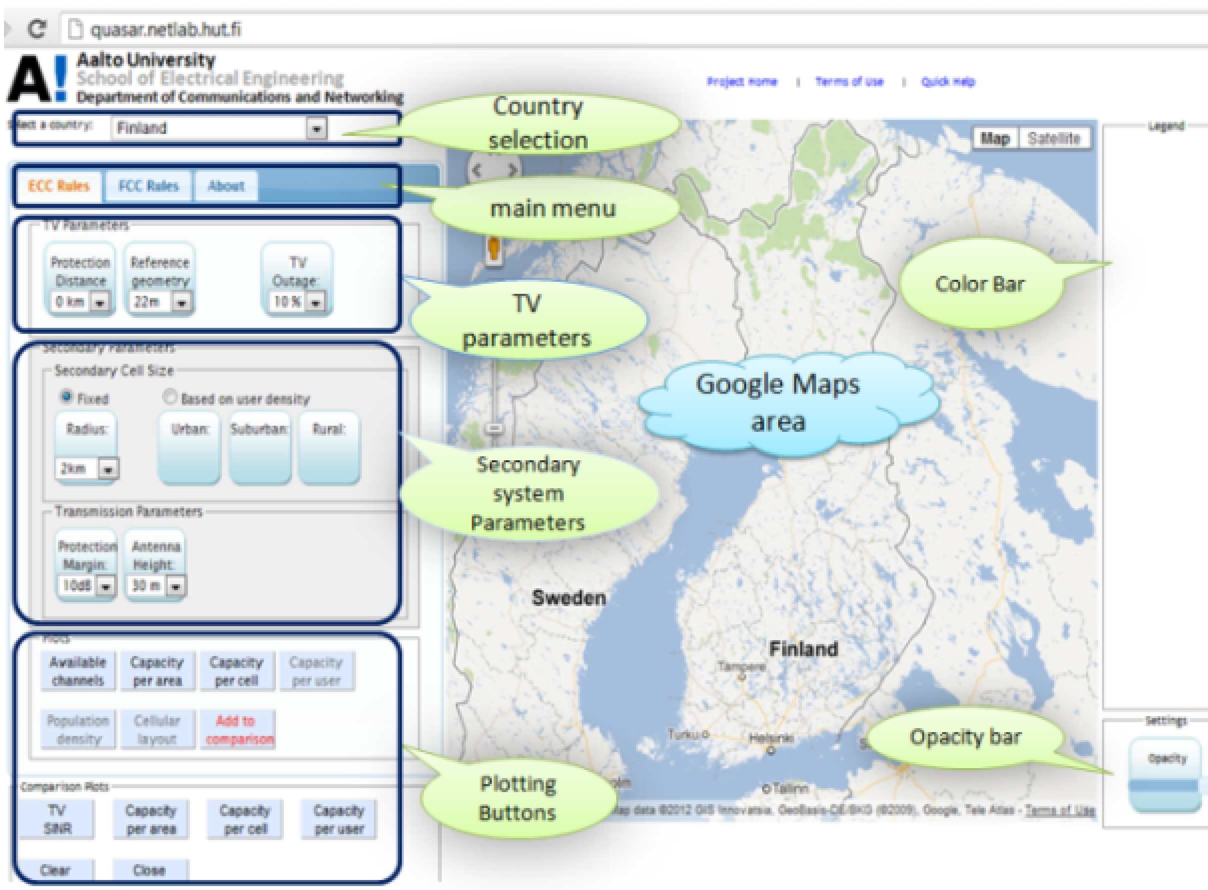

Figure 23: Graphical User Interface of *Spectrum Availability Assessment Tool*.

6.2 GUI Controls

The GUI controls are the tools to customize the visualization of *Spectrum Availability Assessment Tool*. The map zooming and panning (part of the Google maps module) are used to pinpoint into places with better resolution. The *Opacity* control enables identification of geographic places on the Google maps by adjusting the transparency of the capacity/availability maps on the Google maps.

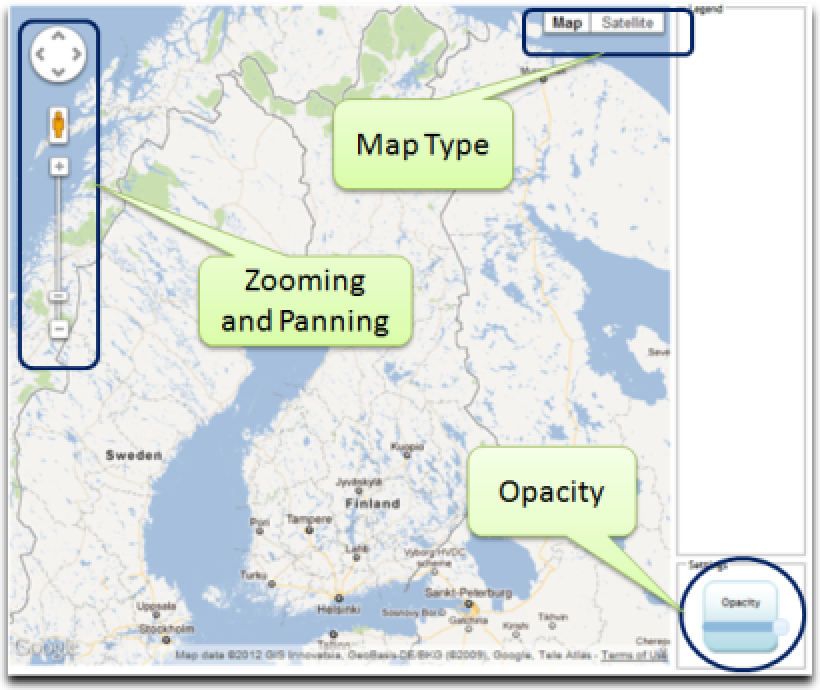

Figure 24: GUI controls.

6.3 Terminology and definitions

The definition of terms used in the GUI:

- *Protection Distance* - the minimum radial distance between a secondary transmitter and an intended TV receiver operating on the same channel.
- *Adjacent Channel* refers to the minimum separation between the primary receiver and the secondary transmitter working in adjacent channel, it is also known as *Reference Geometry*.
- *TV outage* - target outage probability at the TV coverage area border in the presence of secondary transmitter.
- *Fixed Radius* refers to the homogeneity of cellular radius of the secondary system across the country. It can have constant values of 2km, 5km or 10km.
- *Based on user density* - the cellular radius of the secondary system is dependent on population density. The secondary cells can have radius of 0.5km for densely populated urban areas, 2km for suburban areas having medium population density and 16km for sparsely populated rural areas.

- *Protection Margin* - the extra power margin added in the calculation of power emission level for a secondary device, for protecting the primary system from harmful interference. It includes the safety margin, SM, and the aggregate secondary system interference, MI. Refer equation (3.4).
- *Antenna Height* - the height of secondary device above average terrain level.
- *Available Channels* - the number of free TV channels, in a specific geographic location (on a map).
- *Capacity per Area* - the secondary capacity (data rate) on the available channels, when homogeneous cellular size is used across the country.
- *Capacity per Cell* - the average capacity in the TVWS available to the whole secondary cell, when the cell-size is based on population density.
- *Capacity per User* - the average capacity of the TVWS available to each user in a cell. It is obtained by dividing the *Capacity per Cell* to the average number of users in a cell.

6.4 Introducing the tool - brief demonstration

When the user requests the URL address *http://quasar.netlab.hut.fi*, the web-based graphical interface shown in Figure 23 appears. The graphical user interface contains mainly three areas(panels). The left-most panel includes the main menu(ECC Rules and FCC Rules) for selecting the analysis scheme. The middle area houses the Google maps,upon which the capacity and availability maps are overlying. The right panel includes the legend (color bars for referencing the capacity and availability maps).

In the *ECC Rules* sub-menu the user can set TV parameters like *Protection Distance, Adjacent Channel and TV Outage.* Since ECC ruling is based on power-level control the *Protection Distance* is 0km.
In the *Secondary Parameters* panel, the user can set the *Secondary Cell Sizes*—two options are the homogeneous *Fixed* radius scheme of 2km, 5km or 10km and the *Based on user density*, which relies on population density to resize the radius of the secondary cell. The *Protection Margin* and secondary *Antenna Height* are used to set the *Transmission Parameters.*

6.4.1. Visualization on the map

The *Plots* field contains the collection of buttons that are used to display the availability and capacity maps on the Google maps.

1. **Plotting available channels**
   To plot the available channels, the user should select the *Protection Distance* options and click the *Available Channels* button. See Figure (29).

2. **Capacity per area**
   The necessary settings for plotting the capacity per area are the *Adjacent Channel* option, the secondary cell size scheme should be set to be *Fixed* and the *Protection Margin*. As a result of the combinations of these parameters (Figure 25), the user can get many plots.

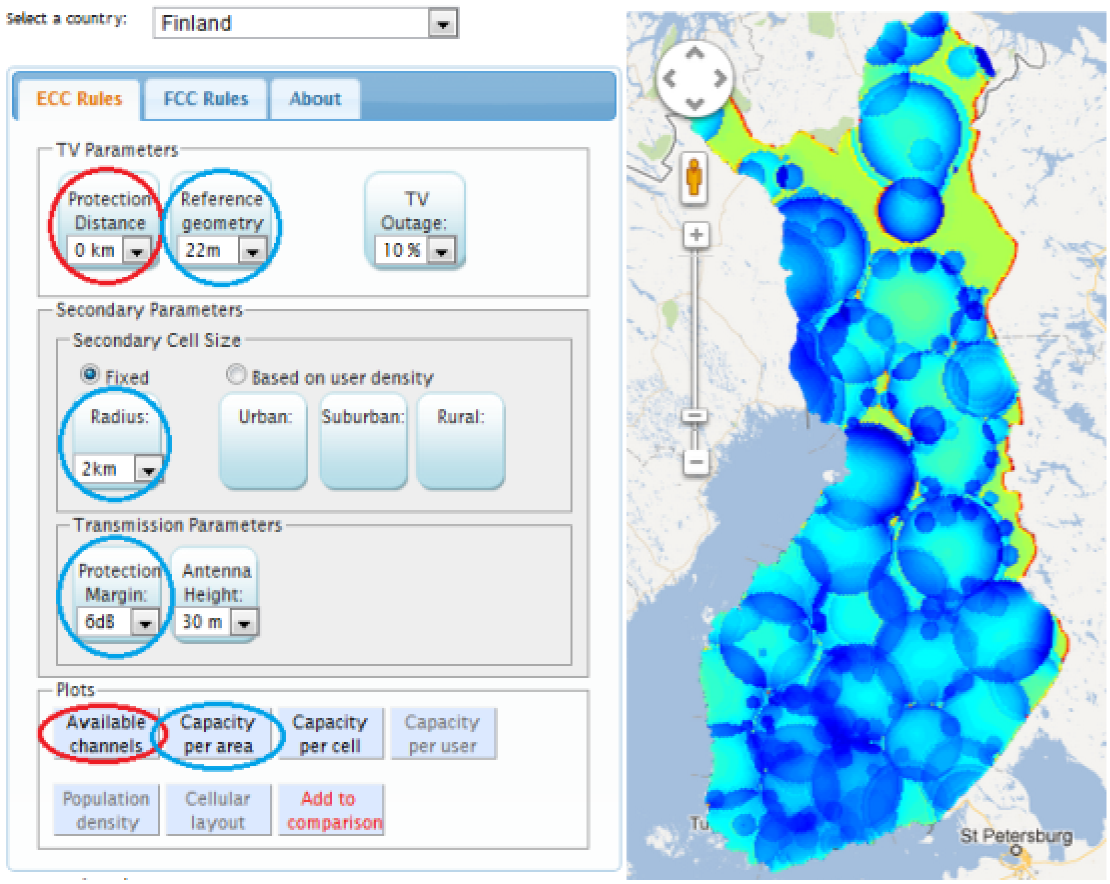

Figure 25: Plotting available channels and capacity per area.

3. **Capacity per Cell and Capacity per User**
   The *Capacity per cell* and *Capacity per user* are calculated for *Based on user density* option. When the *Based on user density* radio button is selected, the *Capacity per Cell* and *Capacity per User* buttons are highlighted. Therefore the user is automatically prompted about the button groups that refer to *Fixed* and the *Based on user density* secondary cell-size options.

6.4.2. SINR Comparison and Plotting Utilities

Spectrum Availability Assessment Tool gives comparative insight into the secondary parameters affecting the TV system. The user can select the secondary parameters for comparing the impact of the secondary system on selected boundary test points on the primary coverage, particularly, the SINR of the primary curves is plotted for comparison.

To plot multiple SINR parameters :

- Select the plotting parameters(*Adjacent Channel, Secondary Cell Size* and *Protection Margin*) shown in Figure 26.
- Click *Add to SINR Plot* to add the parameter combination to plotting list.
- Check the parameters combinations from the plotting list and click *Plot Selections*. *Clear All Selections* clears the plotting list. The plot appears in new window. as shown in Figure 28.

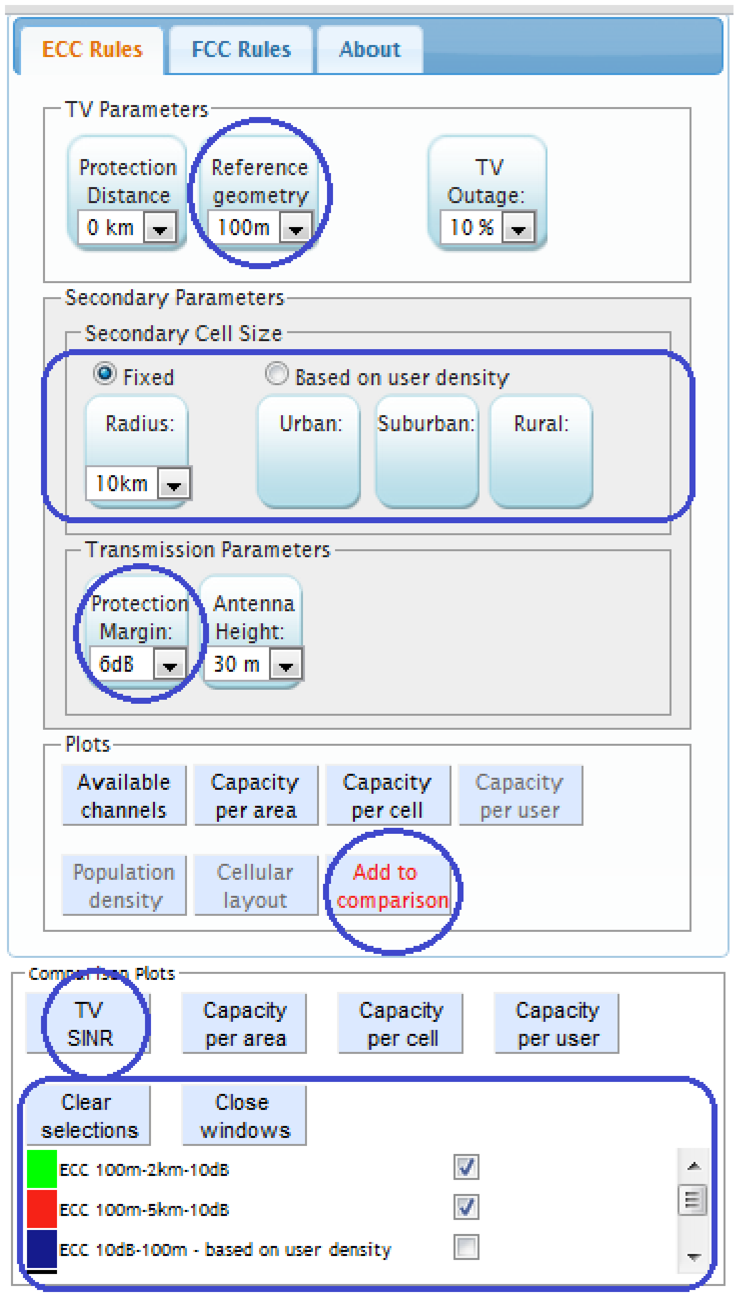

Figure 26: SINR plotting parameters.

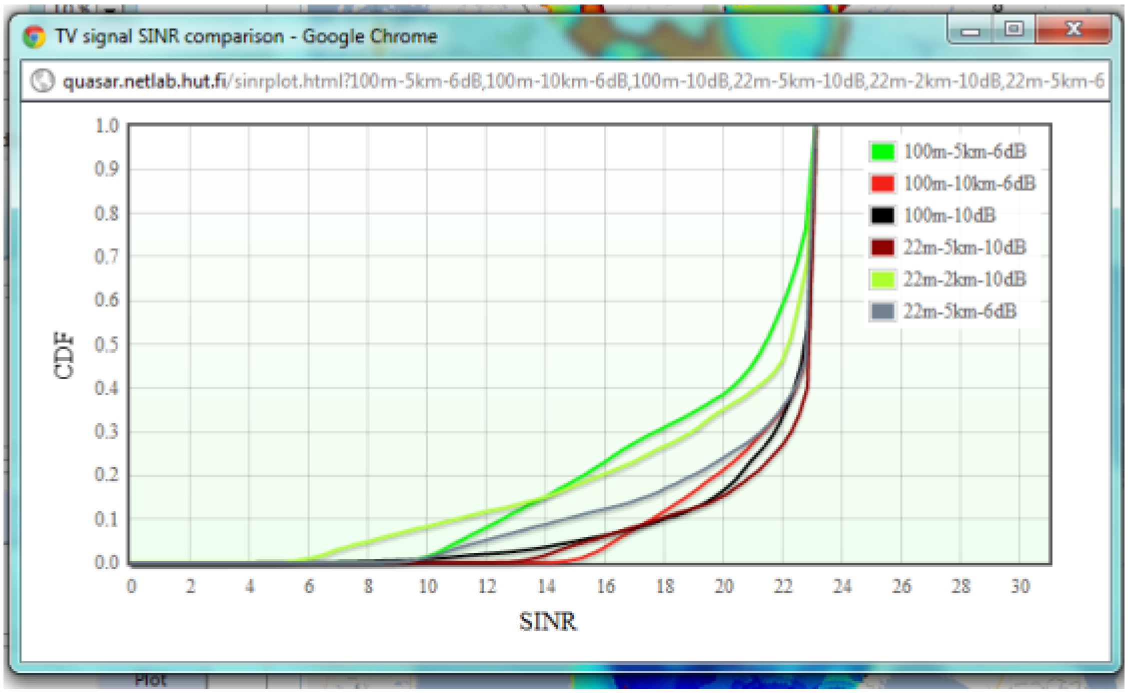

Figure 27: Comparison of primary performance under different parameters.

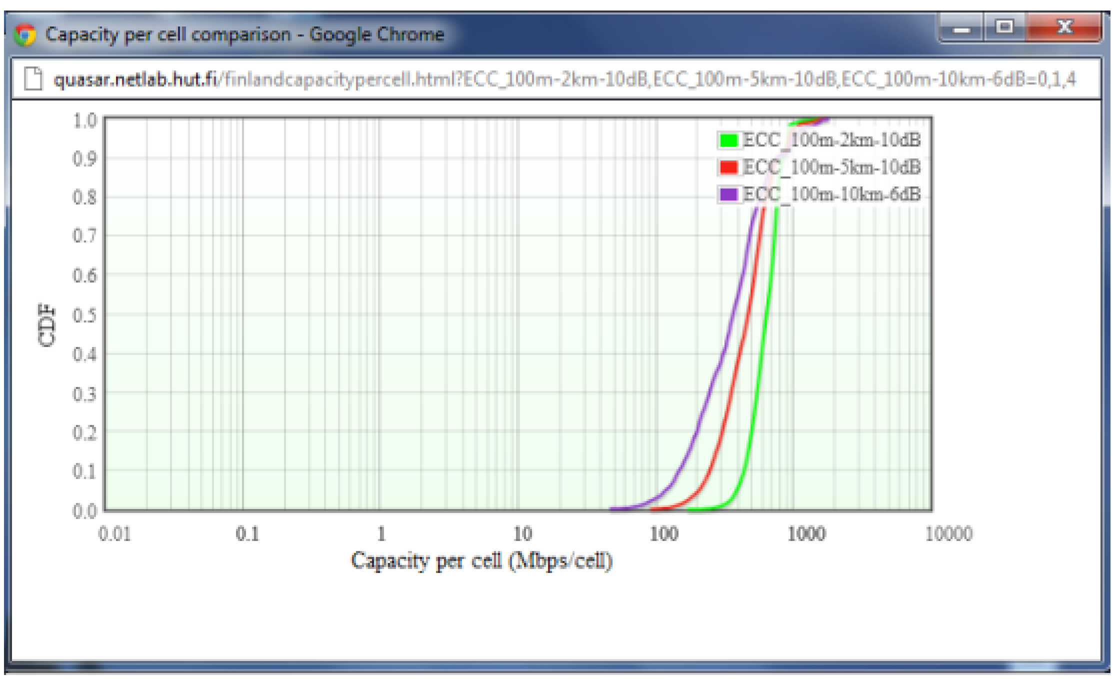

Figure 28: Secondary capacity under different parameters.

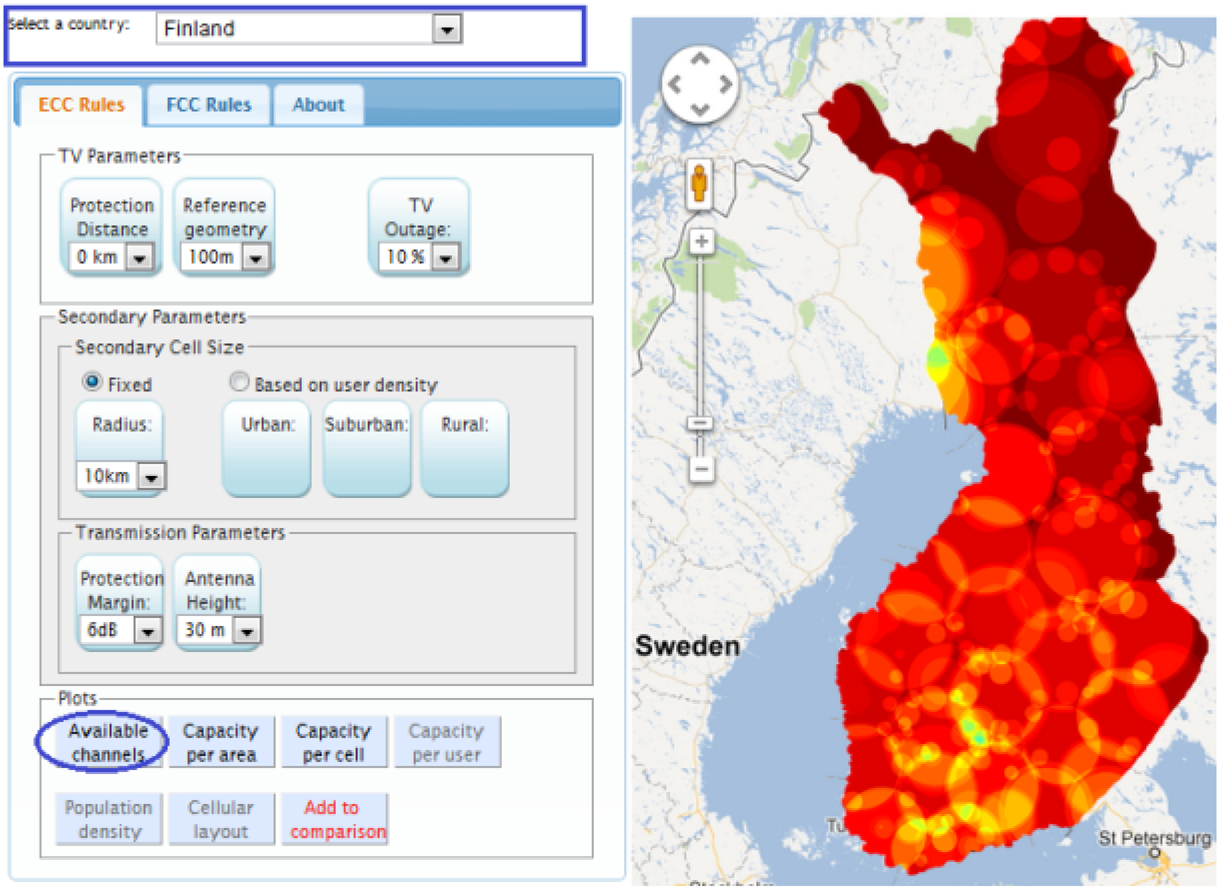

Figure 29: Available channels in Finland, using ECC rules.

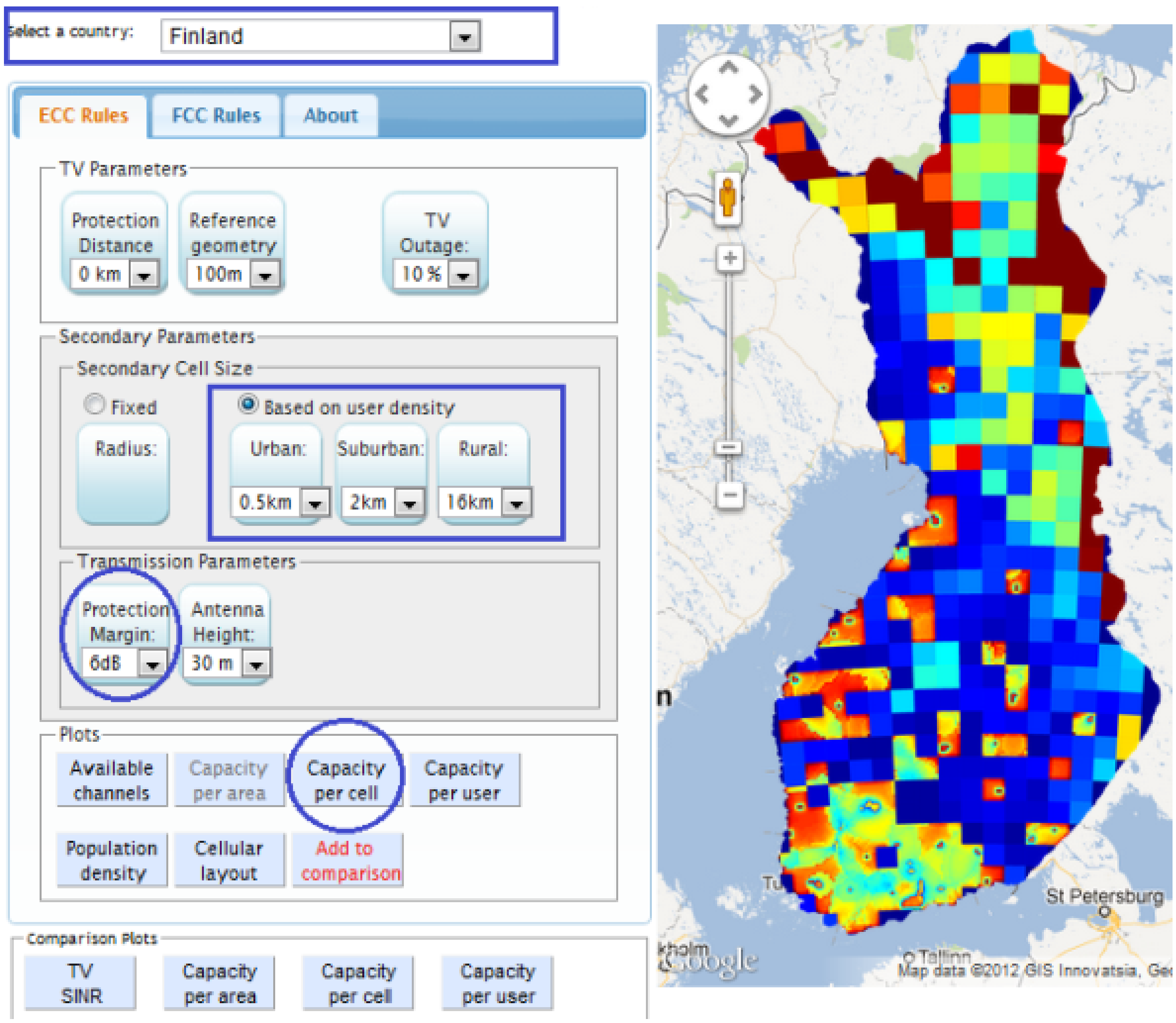

Figure 30: Capacity per cell for 100m reference geometry.

7 Conclusion

The increasing immensity of the data volume created everyday and the converging trend towards more ubiquitous network connectivity is posing new challenges to the wireless industry. Regulators are already introducing flexible methods of spectrum access to promote investment in new technologies that are spectrally efficient.

In this thesis, an integrated spectrum availability assessment tool for TVWS is developed, for Finland. The tool visualizes the outputs of the TVWS quantitative assessment research, which works for identifying the amount of spectrum that is usable for opportunistic secondary access. The *Spectrum Availability Assessment Tool* is browser-accessible interface for a back-end computational process. The tool is developed based on the philosophy of giving prompt and interactive reply to immediate questions related to TVWS such as the amount and the spatial distribution of available spectrum, and its capacity to support secondary services.

The pre-calculated dataset and graphic-contents are used to compare the availability of the TVWS for variety of parameters. The parameters include TVWS regulatory rules, protection margin, secondary antenna height, and cell radius for cellular-type secondary system model. By introducing these parameters the relative impact of the secondary network on the primary system is estimated .

Spectrum Availability Assessment Tool has a graphical user interface designed to minimize the learning-time for technical users. The tool enables selection of different technical parameters and it has user interface controls for customizing the visualization of capacity and availability maps for TVWS. The tool has plotting utilities for comparing the impacts of secondary parameters on primary system.

On account of the intensive time requirements of the back-end computation, this tool is developed using pre-calculated dataset. This made the tool more flexible, web-friendly as compared to the real-time processing.

Currently, *Spectrum Availability Assessment Tool* uses many single-tile capacity and availability maps. In the future, the tool can be extended to use multiple tiles per map, each having different geographic precision and displayable based on the zoom-level. When zoom-level is increasing different set of map-tiles, computed with more precise geographic information, can be loaded. This method makes it easy to visualize cities and localities, having special significance with respect to spectrum management. Although the assessment may require detail geographic and population data, it is possible to produce even more reliable TVWS spectrum analyzer using this method.

References

[1] D. Cabric, "Cognitive radios: System design perspective," Ph.D. dissertation, University of California, Berkeley, 2007.

[2] Staple Gregory and Kevin Werbach. "The End of Spectrum Scarcity - IEEE Spectrum.*" IEEE Spectrum: Technology, Engineering, and Science News.* Web. 23 Dec. 2011. <http://spectrum.ieee.org/telecom/wireless/the-end-of-spectrum-scarcity>

[3] J. Yang, "Spatial channel characterization for cognitive radios," Masterś thesis, University of California, Berkeley, 2004

[4] Mischa Schwartz,HISTORY OF COMMUNICATIONS: *IMPROVING THE NOISE PERFORMANCE OF COMMUNICATION SYSTEMS: RADIO AND TELEPHONY DEVELOPMENTS OF THE 1920S*, IEEE Communications Magazine, December 2009.

[5] C. Santivanez, R. Ramanathan, C. Partridge,R. Krishnan, M. Condell, S. Polit. "Opportunistic Spectrum Access: Challenges, Architecture, Protocols", *Proceedings of the 2nd Annual International Wireless Internet Conference (WICON)*, August 2006, Boston, MA. <http://www.ir.bbn.com/~ramanath/pdf/osa-wicon06.pdf>

[6] Alexander M. Wyglinski, Maziar Nekovee, and Y. Thomas. Hou. *Cognitive Radio Communications and Networks: Principles and Practice.* Burlington, MA: Academic, 2010.

[7] I. Mitola, J., and J. Maguire, G.Q., "Cognitive radio: making software radios more personal," IEEE Commun. Mag., vol. 6, no. 4, pp. 13-18, 1999.

[8] 3GPP, "*3GPP - About 3GPP*". Web. 10 July 2012. <http://www.3gpp.org/About-3GPP>

[9] "Robust Demand for Mobile Phone Services Will Continue, UN Agency Predicts." *Welcome to the United Nations: It's Your World.* 10 Feb. 2010. Web. 28 Nov. 2011.<http://www.un.org/apps/news/story.asp?NewsID=33770>

[10] FCC, "From the FCC Lab:*Report On Trends in Wireless Devices*",January 2011.<http://transition.fcc.gov/oet/info/documents/reports/wirelessdevices.pdf>

[11] Ofcom, "Implementing geolocation: ", November 2009. <http://stakeholders.ofcom.org.uk/binaries/consultations/geolocation/summary/geolocation.pdf>

[12] ECC, "Report 159: *Technical and Operational Requirements for the Possible Operation of Cognitive Radio Systems in the 'White Spaces' of the Frequency Band 470-790 MHz*",September 2010.

[13] ITU, *The Digital Dividend* Web. 12 July 2012. <http://www.itu.int/net/itunews/issues/2010/01/27.aspx>.

[14] *Australian Communications and Media Authority: Register of Radiocommunication Licences.* Web. 12 July 2012. <http://web.acma.gov.au/pls/radcom/spectrum_auction.results?pCAT=520>.

[15] Cristian Gomez,*spectrum and mobile broadband: the progress of global harmonisation* May 2012, Web. 12 July 2012. <http://www.itu.int/ITU-D/tech/events/2012/Broadcasting_CTU_CBU_Barbados_May12/Presentations/15_BroadbandMobileServicesAdd_FRancy.pdf>.

[16] R.Jäntti, J. Kerttula, K. Koufos, K. Ruttik. Aggregate interference with FCC and ECC white space usage rules: case study in Finland. *IEEE International Symposium on New Frontiers in Dynamic Spectrum Access Networks, DySPAN 2011*, April 2010.

[17] Joseph W. Mwangoka, Paulo Marques,Jonathan Rodriguez. Exploiting TV White Spaces in Europe: The COGEU Approach. *IEEE International Symposium on Dynamic Spectrum Access Networks, DySPAN 2011*, May 2011.

[18] O'Connor, R.A.; , "Understanding television's grade A and grade B service contours," *Broadcasting, IEEE Transactions on* , vol.47, no.3, pp.309-314, Sep 2001.

[19] QUASAR, *ICT-248303: Regulatory Feasibility Assessment,*December 2010. Web. 26 Dec. 2011. <http://www.quasarspectrum.eu/images/stories/Documents/deliverables/QUASAR-D1.2.pdf>

[20] European Commission, *"DIRECTIVE OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL on a common regulatory framework for electronic communications networks and service"* , August 2000. <http://ec.europa.eu/archives/ISPO/infosoc/telecompolicy/review99/com2000-393en.pdf>

[21] FICORA,*"EXPLANATORY MEMORANDUM: REGULATION ON 2500-2690MHZ SPECTRUM AUCTION"* ,September 2009. <http://www.ficora.fi/attachments/englantiav/5jXIir75t/MPS60english.pdf>

[22] Nekovee, M.; , "Current Trends in Regulation of Secondary Access to TV White Spaces Using Cognitive Radio", *Global Telecommunications Conference*, Dec. 2011.

[23] Harrison, K.; Mishra, S.M. and Sahai, A. "How Much White-Space Capacity Is There?", *New Frontiers in Dynamic Spectrum, 2010 IEEE Symposium on (DySPAN 2010)*, April 2010.

[24] J. G. Proakis, Digital Communications, 3rd ed. New York: McGrawHill, 199

[25] United States. General Accounting Office. Report to Congressional Requester *SPECTRUM MANAGEMENT Better Knowledge Needed to Take Advantage of Technologies That May Improve Spectrum Efficiency.* May 2004. Web. 20 Dec. 2011. <http://www.gao.gov/new.items/d04666.pdf>

[26] FCC-10-174, In the Matter of Unlicensed Operation in the TV Broadcast Bands:*SECOND MEMORANDUM OPINION AND ORDER* ,September 2010.<http://transition.fcc.gov/Daily_Releases/Daily_Business/2010/db0923/FCC-10-174A1.pdf >

[27] Finnish Ministry of Transport and Communications *Switchover to All-Digital Television Final Report of Monitoring Group*, Helsinki, 2008. <http://ec.europa.eu/information_society/policy/ecomm/doc/current/broadcasting/switchover/fi_fin_rep_monit_grp.pdf >

[28] Maziar Nekovee,*A Survey of Cognitive Radio Access to TV White Spaces*, International Journal of Digital Multimedia Broadcasting, Volume 2010. <http://www.quasarspectrum.eu/images/stories/Documents/publications/Nekovee_journal2010.pdf>

[29] FCC,Spectrum Policy Task Force - Report,November 2002. <http://hraunfoss.fcc.gov/edocs_public/attachmatch/DOC-228542A1.pdf>

[30] ITU, *RECOMMENDATION ITU-R P.1546-3*, Method for point-to-area predictions for terrestrial services in the frequency range 30 MHz to 3000MHz, 2001-2007.

[31] NTIA, *The ITS Irregular Terrain Model, Version 1.2.2, The Algorithm*. <http://flattop.its.bldrdoc.gov/itm/itm_alg.pdf>

[32] Shuttle radar topograph mission (SRTM), <http://www2.jpl.nasa.gov/srtm/>

[33] CEPT Report 24, *Technical considerations regarding harmonisation options for the Digital Dividend: A preliminary assessment of the feasibility of fitting new/future applications/services into non-harmonised spectrum of the digital dividend (namely the so-called "white spaces" between allotments)* <http://www.erodocdb.dk/docs/doc98/official/pdf/CEPTRep024.pdf>

[34] Lei Shi, Ki Won Sung, and Jens Zander *On the Permissible Transmit Power for Secondary User in TV White Spaces*, in Proc. IEEE CrownCom 2012.

[35] Uwe Ladebusche, Claudia A. Liss,*Terrestrial DVB (DVB-T): A Broadcast Technology for Stationary Portable and Mobile Use*, Proceedings of the IEEE, Vol.94, NO.1, Jan 2006. <http://www.erodocdb.dk/docs/doc98/official/pdf/CEPTRep024.pdf>

[36] H. A. Harms, L. M. Davis, and J. Palmer, *Understanding the signal structure in DVB-T signals for passive radar detection*, in Proc. of 2010 IEEE Radar Conference, Washington, DC, USA, May 2010 <http://www.princeton.edu/~hharms/passive_radar_harms.pdf>

[37] ETSI, *Digital Video Broadcasting (DVB); Framing structure, channel coding and modulation for digital terrestrial television,* 2009. <http://www.etsi.org/deliver/etsi_en/300700_300799/300744/01.06.01_60/en_300744v010601p.pdf>

[38] Andrea Goldsmith, Wireless Communication (p.25), Cambridge University Press, 2005. Web. 1 Mar. 2012. <http://faculties.sbu.ac.ir/~m_hosseini/files/WIRELESS%20COMMUNICATIONS[2].pdf> <http://www.etsi.org/deliver/etsi_en/300700_300799/300744/01.06.01_60/en_300744v010601p.pdf>

[39] QUASAR, *ICT-248303: Methodology for assessing secondary spectrum usage opportunities - final report,* December 2010. Web. 1 Mar. 2012. <http://quasarspectrum.eu/images/stories/Documents/deliverables/QUASAR_D2.2.pdf>

[40] QUASAR, *ICT-248303: Initial report on the tolerance of legacy systems to transmissions of secondary users based on legacy specifications,* December 2010. Web. 1 Mar. 2012. <http://quasarspectrum.eu/images/stories/Documents/deliverables/QUASAR_D3.1.pdf>

[41] Kate Harrison, *Cognitive radios in the TV whitespaces: challenges and opportunities*, EECS Department, University of California, Berkeley, Dec 16, 2011. <http://www.eecs.berkeley.edu/Pubs/TechRpts/2011/EECS-2011-151.pdf>

[42] Hamid Reza Karimi.Geolocation databases for white space devices in the UHF TV bands: Specification of maximum permitted emission levels. *IEEE International Symposium on Dynamic Spectrum Access Networks (DySPAN)*, 2011.

[43] QUASAR, *ICT-248303: Model integration and spectrum assessment methodology,* March 2011. Web. 1 Mar. 2012. <http://quasarspectrum.eu/images/stories/Documents/deliverables/QUASAR_D5.1.pdf>

[44] Fei Hu; Lixia Ji;,"GUI design: From information architecture to interactive experience," *Computer-Aided Industrial Design and Conceptual Design, 2008. CAID/CD 2008. 9th International Conference, pp.913-917, Nov. 2008.*

[45] Jonathan Hey, The Data, Information, Knowledge, Wisdom Chain: *The Metaphorical link*, December 2004.

[46] Clark D.,"Understanding and Performance" *Talent & Performance*. 2004. Web. 06 Feb. 2012. <http://www.nwlink.com/~donclark/performance/understanding.html>.

[47] Jeff Johnson, Designing with the Mind in Mind: *Simple Guide to Understanding User Interface Design Rules.* Burlington: Morgan Kaufmann Publishers, 2010.

[48] Apache Software Foundation, *Apache HTTP Server Documentation Version 2.2,* October 2009. <http://www.apache.org/dist/httpd/docs/httpd-docs-2.2.14.en.pdf>

[49] CIA - The World Factbook Feb. 2012. Web. 07 Mar. 2012.<https://www.cia.gov/library/publications/the-world-factbook/geos/fi.html>