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Understanding the Challenges of TV White Space Databases for Mobile Usage

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Transition to the Digital Television (DTV) has freed up large spectrum bands, known as a *digital dividend*. These frequencies are now available for opportunistic use and referred to as Television White Space (TVWS). The usage of the TVWS is regulated by licensing, and there are primary users, mostly TV broadcasters, that have bought the license to use certain channels, and secondary users, who can use channels that primary users are not currently utilizing. The coexistence can be facilitated either by spectrum sensing or White Space Databases (WSDBs) and in this thesis, we are concentrating on the latter. Technically, WSDB is a geolocational database that stores location and other relevant transmitter characteristics of primary users, such as antenna height and transmission power. WSDB calculates safety zone of the primary user by applying radio wave propagation model to the stored information. The secondary user sends a request to WSDB containing its location and receives a list of available channels.

The main problem we are going to concentrate on is specific challenges that mobile devices face in using WSDBs. Current regulations demand that after moving each 100 meters, the mobile device has to query WSDB, consequently increasing device's energy consumption and network load. Fast moving devices confront the even more severe problem: there is always some delay in communications with WSDB, and it is possible that while waiting for the response the device moves another 100 meters. In that case, instead of using the reply the device has to query the WSDB again. For fast moving devices (e.g. contained inside vehicles) the vicious loop can continue indefinitely long, resulting in an inability to use TVWS at all. A. Majid has proposed predictive optimization algorithm called Nuna to deal with the problem. Our approach is different, we investigate spatiotemporal variations of the spectrum and basing on over than six months of observations we suggest the *spectrum caching* technique. According to our data, there are minimal temporal variations in TVWS spectrum, and that makes caching very appealing. We also sketch technical details for a possible spectrum caching solution.

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1 Introduction

Transition to the Digital Television (DTV) has brought to us what is known as a *digital dividend*: broad spectrum bands that are now available for opportunistic use and referred to as Television White Space (TVWS)[1]. The release of TVWS came at the right moment since frequencies allocated for mobile cellular networks and ISM[2] band became highly overcrowded while demand for mobility and wireless communication keeps on growing at an exponential rate [Jia14]. As Palicot et al. note, when we look at the spectrum allocation charts, all spectrum is already assigned, and there is nothing left to alleviate the increasing demand. On the other hand, when we investigate actual usage, a quite small fraction of allocated spectrum is really in use [Pal13]. One way to get more spectrum would be a fundamental revision of the regulations, which is not a feasible task. Another is to open access to licensed spectrum for other users, as long as they do not create harmful interference to incumbent license owners. The latter approach is known as Dynamic Spectrum Access (DSA), and it provides a set of spectrum access techniques enabling mutual coexistence in the opportunistic environment. DSA was a natural choice for TVWS regulatory framework.

Due to the lack of spectrum resources, the problem of efficient utilization of newly available TVWS has attracted much of interest as from the high political establishment as well as from the top-level academic researchers. In March 2009, U.S. Senator John Kerry introduced a bill titled Radio Spectrum Inventory Act requiring a study of the efficient use of the spectrum [Ker09]. Webb et al. estimate that "use of spectrum adds something like 3-4% to the Gross Domestic Product (GPD) of a country." [Web13]. There is a large variety of applications suggested for TVWS: network offloading, serving as a backhaul, rapidly growing Internet of Things (IoT) using Machine-to-Machine (M2M) communications and many others we overview in Section 2.2. In this section, we shall explore the concepts of DSA and White Space Database (WSDB) briefly, formulate our research goals and provide an outlook of the thesis.

DSA is the paradigm that defines the pragmatic aspects of the TVWS, and there are Primary Users (PUs), mostly TV broadcasters, which have bought

[1] In the USA the TVWS frequency band is between 50 MHz and 700 MHz, in Europe between 470 MHz and 790 MHz.

[2] Industrial, Scientific and Medical band is utilized among others by Wi-Fi technology.

the license to use certain channels, and Secondary Users (SUs), who can use channels that primary users are not currently utilizing. WSDBs were devised to solve the coexistence problem between PUs and SUs. Technically, WSDB is a geolocational database that stores location and other notable transmitter characteristics of primary users, such as antenna parameters and transmission power. WSDB applies radio wave propagation model to that information and calculates safety zone of the PU. The secondary user sends a request to WSDB containing its location and receives list of available channels. Cognitive Radio (CR) provides other approaches to facilitate the coexistence, e.g. spectrum sensing and beacons, but the gain of central management that WSDBs offer appears to be the winning solution from the regulatory point of view and technical feasibility.

1.1 Problem Statement and Contribution

In this thesis, we shall examine the practical usage of WSDB by Mobile White Space Devices (MWSDs) and collect TVWS spectrum availability data (practically the responses of WSDB) during the period of over six months. The collected data will comprise the basis for investigation of the spatiotemporal variance of TVWS spectrum. Observing spectrum variability, we aim to envision possible technology improvements to optimize the mobile usage of WSDBs.

Considering temporal perspective, we are interested how likely the availability of TVWS channels in certain locations will change during some time interval, e.g. day, week or several months. For example, if a person is going to work by the same route every day approximately at the same time and uses MWSD on the trip, how likely it is that the availability of the TVWS along the way will change from day to day? For such a user, is it reasonable to cache the results of previous queries to save the energy and reduce WSDB payload? From existing research, Madhavan et al. [Mad14] point out that they find interesting that TVWS availability did not change during the 10-day span of the measurements. We extend this by providing much larger scale temporal perspective with over six months of collected TVWS availability information.

To analyze spatial variance of TVWS, we shall model situations where the user is moving through various areas with diverse population densities and spectrum resources to see how the availability of TVWS changes along the way. We are questioning how reasonable it is to query the WSDB every 100 meters in sparsely populated regions, e.g. such as Alaska, as regulations require. We design our measurement routes to mimic real life like situations as much as possible. Popular tourist routes and sometimes stories about the people have provided the basis for selection of locations chosen for TVWS availability querying.

We plan to measure the delay that is required to send spectrum availability request to the WSDB and process the response. The delay is critical for fast moving MWSDs, since if the delay is long enough, the change of location will invalidate the received information. In certain cases when the velocity is high, and the delay is unacceptably long, the MWSD will not be able to use TVWS at all because changes of location will continuously invalidate all the spectrum responses. Such requests will only increase WSDB and network payload, along with the MWSD energy consumption. Our technology improvement is aiming at avoiding such conditions.

Another important metric we will pay attention to is the period for which the response of WSDB is valid. We refer to such a period as a *spectrum lease time*. WSDB response contains the spectrum lease time along with other information, and it provides the basis for developing the caching solution for mobile devices.

1.2 Limitations

There are no countrywide WSDB providers currently operating in Finland[3], and for that reason, we study spectrum environment in the United States of America (USA) using data provided by Google WSDB. In this choice, we are motivated by the pioneering status of Federal Communications Commission (FCC) in the field of TVWS regulation and convenient Application Programming Interface (API) provided by Google[4]. One may see using Google WSDB as a personal preference, and there are many WSDB providers like Microsoft,

[3]The only exception is WSDB service covering 40 square kilometers area surrounding city of Turku, provided by Finnish company Fairspectrum [Kok12].

[4]See the real time graphical tool Google provides to browse available TVWS spectrum on the map: https://www.google.com/get/spectrumdatabase/channel/. Google API description can be found here: https://www.google.com/get/spectrumdatabase/business/.

NICT, Spectrum Bridge Incorporated among others. However, due to the FCC regulations requirement stating that all commercial WSDB providers must use the same modeling technique rendering equal responses, our actual results are not supposed to be different even if we would use another WSDB [Cha14, Wsd13].

Our platform choice is limited to Android as one of the most widely spread mobile platforms. We will use various mobile devices running 4.1.2 version of Android.

1.3 Structure of the Thesis

The remainder of this thesis consists of three major parts: background and review of the related work (Section 2), analysis of TVWS spatiotemporal variability (Section 3) and discussion along with suggestions for technology improvement (Section 4).

In the review of related work we examine: regulations (Section 2.1), TVWS practical applications (Section 2.2), spectrum sharing models (Section 2.4.2), TVWS networks (Section 2.5), Medium Access Control (MAC) (Section 2.4.3), possible improvements of WSDB technology (Section 2.6.3), sensing (Section 2.4.1), Protocol to Access White Space Database (PAWS) (Section 2.6.1) and WSDB mobile usage optimization (Section 2.6.2).

In the analysis of TVWS spatiotemporal variability major section, we present our system (Section 3.1) used for data gathering and the data itself (Section 3.2).

In the last part of the thesis, we discuss our data and basing on the presented facts, we look for possibilities of the technology improvement and sketch the future research perspectives (Section 4). The conclusion (Section 5) provides a summary of the thesis.

2 Background and Related Work

This chapter will provide a review of recent research in TVWS and relevant fundamental CR concepts, standardization issues and practical applications. We aim at providing taxonomic perspective discussing various spectrum sharing approaches, development of WSDB technology and most recent efforts taken to optimize WSDBs mobile usage. We start with reviewing the regulations concerning TVWS, user classes and characteristics of the TVWS devices.

2.1 Regulations

In this section, we examine regulations related to TVWS. We are concentrating mostly on the USA and the European Union (EU) policies, but we shall overview the situation in other countries briefly too. To be consistent, we start by looking at the regulatory framework and its main entities. The topmost regulative authority of the world is the International Telecommunications Union (ITU). The worldwide harmonization of spectrum management is a mission of the Radiocommunication Sector (ITU-R) of the ITU. The allocations of the available frequencies from 9kHz to 275GHz are reviewed and revised during the World Radiocommunication Conferences (WRCs) held by ITU-R. The National Regulatory Authorities (NRAs) take actual decisions on spectrum regulations in particular countries. In heterogeneous conglomerates of countries, like the EU, there are additionally regional regulators, issuing common recommendatory policies to NRAs.

2.1.1 TVWS Users

As it is assumed under Licensed Shared Access (LSA) operation, TVWS users have unequal rights, and they form two groups: PUs and SUs, or incumbents and opportunistic DSA users. The protected PUs are all those who have bought the license or made some other kind of agreement regulating their spectrum usage. Commercial TV broadcasters are the main category of PUs. The Wireless Internet Service Providers (WISPs) operating in TVWS band may fall into this category too in case they obtain the license, however, currently they are relatively rare. SU can be virtually any opportunistic DSA device accessing TVWS band. Additionally, there are wireless microphones that have always operated on TVWS frequencies. They comprise the majority of a more common protected TVWS user group known as Program Making and Special Events (PMSE) equipment or Broadcast Auxiliary Services (BAS) [Web13]. Regulators suggest that WSDBs should encompass PMSE related information. The rules are that SUs must never cause interference to PUs and wireless microphones, and this is the central problem for efficient and safe utilization of TVWS.

2.1.2 The USA Regulations

In the USA, the responsibilities between regulators are divided as follows: National Telecommunications and Information Administration (NTIA) is responsible for federal government spectrum usage; FCC is in charge for all non-federal government spectrum use. All commercial broadcasting including DTV spectrum falls into the latter category.

The sensing options were explored by the industry first and in the year 2007, the FCC had performed tests with sensing TV-Band Devices (TVBDs) with unacceptable results [FCC07]. However, as it came to knowledge later, the device that FCC used was broken, and testing engineers did not use the prototype backup device instead of broken one [And07]. In 2008 FCC approved usage of TVWS by unlicensed devices, requiring that TVBD would consult FCC-approved WSDB to find out what channels are available. An additional requirement was that TVBD should listen to a spectrum with an interval of 1 minute to detect wireless microphones or other legacy devices [FCC08]. On February 27, 2009, the National Association of Broadcasters (NAB) and the Association for Maximum Service Television demanded a Federal court to withdraw the FCCs authorization of DSA operation on TVWS bands. The complainants alleged having proof that TVBDs are causing interference to PUs. However, in May 2012, the court challenge was finally dropped [Mel12]. In 2010, FCC removed sensing requirements for TVBDs, making spectrum access easier [FCC10].

2.1.3 The EU Regulations

In the EU, there are regional and national level regulators. The Electronic Communications Committee (ECC) of the European Conference of Postal and Telecommunications Administrations (CEPT) is in the regional regulatory role, issuing documents of recommendatory nature. The ECC works in cooperation with European Telecommunications Standards Institute (ETSI), an organization responsible for the development of the EU telecommunications standards, and the European Commission (EC). The NRAs like Finnish Communications

Regulatory Authority (FICORA) or Office of Communications (Ofcom) of the United Kingdom (UK) consider ECC given recommendations and take concrete decisions on the spectrum usage and sets of technical requirements unique to the country.

ETSI has published following documents regarding WSDBs and White Space Devices (WSDs): in February of 2014 technical report TR 103 231 defining web listings of WSDBs (only the UK had provided the information) [ETSI14a]; in April of 2014 harmonized European standard EN 301 598 defining requirements for WSDs [ETSI14b]. ECC of the CEPT brought out two reports: Report 186, Technical and operational requirements for the operation of white space devices under geo-location approach, came out in January 2013 [ECC13]; Report 236, Guidance for national implementation of a regulatory framework for TV WSD using geo-location databases, was published in May 2015 [ECC15].

European TVWS regulations technically differ from those of the USA in several aspects: the amount of TVWS spectrum is going to be smaller, between 470-790 MHz; the width of the TV channel in Europe is 8 MHz, compared to 6 MHz in the USA. There are also some terminology differences: TVBD is called WSD or TVWSD; TVWSDB refers to WSDB.

In Europe, first TVWS pilot project using WSDB technology, was started in Finland in 2012 [Kok12]. The project covered 40 square kilometers area surrounding the city of Turku and used WSDB provided by Finnish company Fairspectrum Oy[5]. T.B. Alemu has developed an assessment tool to estimate TVWS availability in Finland: `http://quasar.netlab.hut.fi` [Ale12].

The United Kingdom was the first country in Europe to liberate the TVWS for public use by the Ofcom decision in 2015 [Ofc15]. There are a number of commercial WSDBs operators qualified by Ofcom, including aforementioned Fairspectrum Oy, Spectrum Bridge Incorporated and others[6].

2.1.4 Other Countries

ECC published a survey with information related to WSDBs regulations outside of Europe [ECC16]. Infocomm Development Authority (IDA) of Singapore is planning to adopt WSDB approach for TVWS access governance and in

[5] `http://www.fairspectrum.com`
[6] For the full list see `https://tvws-databases.ofcom.org.uk`

March 2015 published a draft with requirements for WSDs. Canada has taken a similar approach as the USA and permitted the use of TVWS by DSA devices in 2012. In Japan, TVWS access is allowed in the 470-710 MHz band, and ISB Corporation provides WSDB service. The Independent Communications Authority of South Africa (ICASA) is supervising numerous pilot projects that we shall discuss particularly in Section 2.2. On 23 of October 2015, ICASA has published the Discussion Document On Dynamic And Opportunistic Spectrum Management. The document promotes opening 470-694 MHz band for DSA to facilitate broadband services development [ICA15].

2.1.5 TVWS Devices

FCC divides TV-Band Devices (TVBDs) into two categories by their mobility: Fixed versus personal/portable; and three classes according to maximum transmission power: 4W, 100 mW and 40 mW. *Fixed device* can transmit at 4W maximum of Equivalent Isotropically Radiated Power (EIRP) with a gain antenna [FCC10]. Fixed devices are required to register with WSDB. Maximum allowed power for *Mode-II* (independent mode) device is 100 mW without a gain antenna. Both Fixed and Mode-II devices obtain TVWS availability information directly from WSDB and can serve as a *master* device, sharing TVWS accessibility data with *slave* devices over the air. *Mode-I* (client mode) device with 40 mW maximum allowed transmission power operates in slave mode, obtaining a list of available channels from either Fixed or Mode-II device. Additionally, there are sensing-only devices, with a detection threshold of -114 dBm. In 2010, FCC increased the threshold for wireless microphones and other Low-Power Announcement Services (LPASs) stations of sensing-only devices to -107 dBm [Han15, FCC10]. Table 1 contains the summary of TVBDs characteristics.

Device type	Spectrum availability	Max power (EIRP)	Geolocation
Fixed	WSDB query	4W	Manual/built-in
Mode I portable	Fixed or mode II device	40 mW	Not required
Mode II portable	WSDB query	100 mW	Built-in
Sensing-only	Sensing	50 mW	Not required

Table 1: Summary of TVBDs characteristics [Han15, FCC10].

The EU regulations are different; sensing threshold is even lower: -120 dBm. There are no discrete power level gradations; WSDs can transmit at any power up to 10W.

2.2 TVWS Practical Applications

It is almost impossible to foresee all kinds of possible TVWS applications, so we mention some trends most frequently discussed in the literature: IoT, inter-vehicular communications, drones and robotics, cellular offload. Additionally, TVWS is considered as a promising and cost-effective approach to providing Internet connectivity in rural or remote areas and public Wi-Fi-like networks defined by Institute of Electrical and Electronics Engineers (IEEE) standards 802.22 and 802.11af.

Webb et al. find TVWS well-suited for M2M communication and rapidly growing IoT for the following reasons [Web13]:

- Free access (no licensing) minimizes network costs
- Excellent propagation properties result in large cell sizes, decreasing the number of required Base Stations (BSs) and reducing costs.
- Another positive effect of the good propagation is low transmission power, which in turn extends the battery life.
- The harmonization of the TV band is happening globally, which implies that IoT devices will use same frequencies.
- *Weightless* protocol [Web13] for M2M communications was initially designed targeting TVWS.

The shortcoming of TVWS for M2M and IoT is low availability in major US cities, where quite often no channels are available at all.

Many authors see an opportunity in developing TVWS vehicular networks [Ali15, Jia14]. According to Jiang et al., vehicular communications can significantly improve public safety, reducing the number of traffic collisions and other types of accidents. There are numerous driver's assist functions and entertainment services where wireless communication is required. Authors note, that IEEE standard 802.11p, allowing the vehicular communication on the 5.9GHz band is not likely to satisfy increasing spectrum demand in the situation when people's mobility is growing exponentially.

Explosive mobility growth also affects cellular operators, and scenario to use TVWS for offloading congested networks was presented in RFC6953 [Man13]. Bayhan et al. call the procedure *white space offloading* and investigate options for content-centric offloading, finding that it improves the capacity of the network almost by 67% in favorable circumstances [Bay16]. Madhavan et al. explore optimal TVWS network design taking into account cellular offloading scenario [Mad14].

Wireless Local Area Network (WLAN) IEEE standard 802.11af is offering Wi-Fi like network with improved propagation characteristics (approximately 500-600 meters with 100 mW BS). Wireless Regional Area Network (WRAN) IEEE standard 802.22 is expected to solve remote regions Internet connectivity shortages and opens up a new possibility for WISPs business.

The Singapore White Space Pilot Group deserves special note [Sin16]. The National University of Singapore uses TVWS for a system that meters the use of air conditioners. Singapore Island Country Club is optimizing the connectivity and deploying smart sensors for monitoring the moisture of the golf course and tracking golf buggies. In Changi district, where vessels can anchor for months waiting for the next destination, the Internet was available only by costly and unreliable satellite connection; now it is going to be replaced by cheap and robust TVWS network.

TVWS technology has particular importance for Africa and developing countries [Pie13]. TVWS combines qualities that make it unique pretender for narrowing what is known as *Digital Divide*, meaning the drastic inequality between Africa, where only 7% of households have some kind of the Internet connection, and economically developed countries. These qualities are:

- low cost due to the license-free operation
- minimal requirements for telecommunication infrastructure
- possibility to increase coverage gradually without the demand to start nationwide projects requiring substantial investments

Active steps towards the improvement are already taken, e.g. Google and Carlson Wireless are testing trial TVWS wireless broadband in ten schools across the Cape Town area [Car13]. Microsoft in a joint effort with other companies has been very active in promoting TVWS technology in Africa, and pilot projects are going on in Botswana, Ghana, Kenya, Namibia, South Africa and Tanzania [Mic16a].

2.3 TVWS and Cognitive Radio

Joseph Mitola III proposed Cognitive Radio (CR) in a seminar at the Royal Institute of Technology in Stockholm in 1998 and later published in 1999 [Mit99a]. CR is a kind of umbrella term and currently there are many related definitions and interpretations, originally being seen by Joseph Mitola III as a device that is aware of its operational environment and is capable of optimization of own spectrum usage by mimicking human cycle of cognition [Paa11]. The imbalance between spectrum congestion on one hand and under-utilization[7] of spectrum by licensed users on the other is one of the main challenges that CR is pursuing. The problem is mitigated with advanced DSA coexistence techniques, which cognitive devices use to find available spectrum. Naturally, the main concepts behind TVWS technology are rooted in CR paradigm, since the primary challenge is the coexistence of incumbents and opportunistic users.

2.3.1 Radio Environment Sensing

If we think of how environmental awareness can be achieved for a radio device, first probably comes the idea of listening to the spectrum or sensing. In most simple form, it can be Listen Before Talk (LBT) approach, meaning that the device listens for some time interval to the radio channel before starting the transmission. Developing the idea further, we can think of scanning all frequencies that are feasible for the device and identifying those where no operation is going on at the time. In the opportunistic environment, identified frequencies might be licensed to somebody, but DSA device can consider them contextually available. There is a special CR term for such spectrum regions, and they are called *spectrum holes* or *spectrum opportunities*. The

[7] According to Webb et al., licensed spectrum utilization rate is approximately 20% [Web13]. Authors point out that such measurements always have problematic nature due to weak signals of various radars systems, satellite communications and others, but there is a definitely room for improvement of spectrum usage efficiency.

concept stems from *spectrum pooling* defined by J. Mitola as a set of frequencies assigned for PU but unused at the present moment of time and current location, thus temporally available for SU [Mit99b]. One can think of them as spatiotemporally available bands or multidimensional structures within frequency, time and space [Tan09]. Complex sensing strategies have been developed for identifying spectrum holes, evolving from relatively simple LBT to cooperative approaches where sensing devices exchange acquired contextual information and build spectrum maps based on many data sources. Sensing is inherently a distributed approach; it does not require any infrastructure or coordinating entities, although cooperative sensing may use the central entity to fuse all the observations into a spectrum map of some sort and distribute the result among the participants. We shall return to sensing in Section 2.4.1.

2.3.2 White Space Database (WSDB)

Principally different to the sensing is a centralized approach, where spectrum availability information is stored in some infrastructural entity to which all the participants have safe access without fear of creating harmful interference to each other. In the development of TVWS technology, this idea was realized in a form of geolocation database service that is called White Space Database (WSDB)[8]. The operation principle is quite straightforward:

- PUs devices register with WSDB providing their transmitter characteristics.
- SU device sends a query over the Internet containing location and transmitter characteristics to the database.
- WSDB calculates protection zone of the PUs by applying propagation model to PUs registration information and sends a response to SU containing a list[9] of channels that are locally available for communication. The list also contains maximum allowed transmission power for each open channel.

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[8] In IEEE standard 802.11af, WSDB is called Geolocation Database (GDB), sometimes WSDB is referred to as an incumbent manager.

[9] Such list is sometimes referred to as White Space Map (WSM).

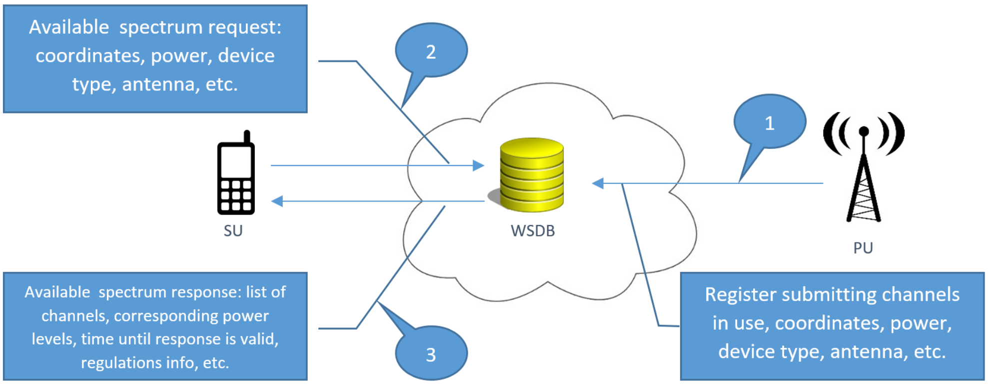


Figure 1: The operation of WSDB cloud service governing TVWS network.

Figure 1 displays the overview of the process. The obvious strength of this solution is ease of governance because of central management access point it provides, and regulators across the world, such as FCC or Ofcom, adopted this approach for TVWS. From the technical perspective, WSDB is usually implemented as a cloud service.

2.3.3 Beacons

Another notable option for spectrum management would be a network of radio beacons sending information of spectrum availability. Such a system would have some substantial benefits compared to WSDBs, meaning the absence of secondary communication channel requirement, known as a bootstrapping problem [Mur11]. In addition to that, devices would not need to have geolocation capability. However, the infrastructure and maintenance costs of such a network covering an entire country would be very prohibitive. Beacon's signal requires some spectrum allocation, and that would be another drawback.

2.3.4 TVWS Cognitive Radio Systems

In practice, there is no silver bullet or absolute winner, and the preferred way is to have the best of all three aforementioned spectrum sharing methods at once. Practical implementations of TVWS Cognitive Radio Systems (CRSs) usually combine all of them. Such are IEEE standards 802.22 and 801.11af defining WRANs and WLANs respectively. In these systems, there are central entities that have a connection to WSDBs and which serve as beacons for secondary devices. Standard 802.22 also implements a sophisticated sensing technique to ensure that there is no interference to neighboring networks and broadcasters. We will discuss these standards in Section 2.5 in more detail.

2.4 Cognitive Radio Overview

In the previous section, we had a short introduction to CR, and here we broaden the perspective by introducing more concepts vital for understanding complex CRSs, as well as the reasons behind technical solutions and regulations.

2.4.1 Sensing Techniques

Sensing is fundamental CR technique and along with WSDBs, it plays a major role in TVWS technology. There are sensing-only device class and numerous research papers displaying the benefits of WSDB augmentation with sensing [Ali15, Cha14, Zha13]. Additionally, sensing is used to minimize the risk of interference in CRSs like IEEE 802.22 WRAN. Here we overview techniques developed for sensing, discuss the considerations behind regulations related to sensing and reasons why sensing was superseded by centralized WSDB approach as coexistence enabler.

There is much research dedicated to sensing, and numerous non-trivial techniques are developed with varying level of complexity. We start by looking at the methods for local non-cooperative sensing [Ham13, Maj15]:

- *Energy detection*: the most common and algorithmically simple form of sensing, involves measuring the energy of radio waves of certain frequency and comparing the results with a predefined threshold. There is no way to distinguish noise from PU signal and method performs badly at low Signal-to-Noise Ratio (SNR) rates.
- *Matched Filter*: the technique assumes the presence of Gaussian noise and knowledge about some properties of the PU's signal such as preamble, pilot, synchronization words or spreading codes [Fit07]. In the case

of such conditions, this can be the optimal method for detection. It works by correlating the features of the observed signal with the known signal. Method's downside is implementation complexity and relatively high energy consumption.

- *Cyclostationary feature detection*: the cyclostationary process is characterized by statistical properties that vary cyclically over time. Signal is required to exhibit some periodic properties such as wave carriers, pulse trains, repeating spreading, hoping sequences or periodic prefixes [Che09]. Digitally modulated signals usually have features like those that we previously mentioned. The main problem with this method is the complexity like with the previous one.

- *Eigenvalues based detection*: the approach is based on analyzing the ratio between the eigenvalues of the covariance matrix of the received signal. The method is often called *blind detection* or *blind sensing* because no prior knowledge is needed about the noise level or PU signal characteristics. The drawback is computational complexity.

The matched filter and cyclostationary detection are applicable to TVWS since PU is known to be a digital TV station with a signal having a pilot and periodic properties that can be used. As we mention in Section 2.6.3, Zhang et al. and Chakraborty et al. used the method based on a pilot signal identification for the detection of PU presence [Zha13, Cha14]. Sensing techniques are not limited to those listed above, and M. Hamid proposes a method based on discriminant analysis [Ham13]. Tandra et al. mention Fast Fourier Transform (FTT) for digital TV pilot signal, run-time noise calibrated detection, dual Frequency and Phase Locked Loop (FPLL) pilot sensing and event-based detection [Tan09]. Detailed examination of those methods is outside of the scope of this work.

One of the fundamental problems with local non-cooperative sensing is a *hidden terminal* problem. Figure 2 shows such condition: the MWSD is outside of incumbent detection zone, but its own range intersects with PU's range and creates interference for the TV set, that cannot be detected. Same kind of a situation may arise due to mirroring, shadowing from obstacles or various fading effects.

One way to deal with the problem is to set sensing threshold to sufficiently low

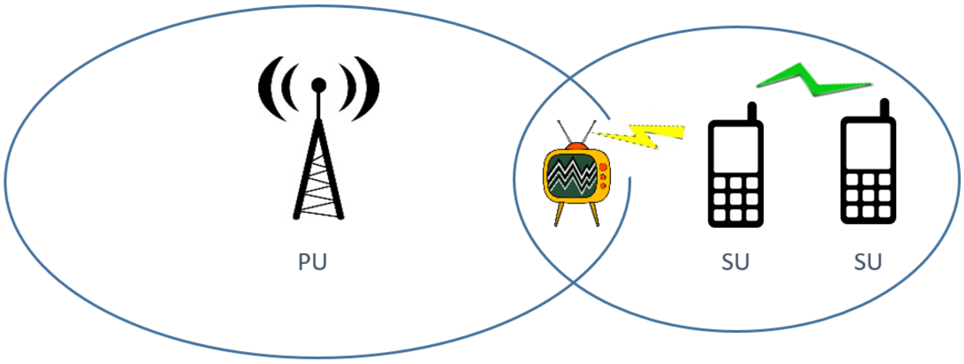


Figure 2: The hidden terminal problem: despite that mobile devices are outside of PU range, TV set on the border experiences interference.

level. This would imply that the device assumes itself to be in the worst case scenario all the time. This kind of implication will inevitably lead to overprotection of incumbents and substantial loss of available TVWS. The regulatory agencies had to take this choice and in Section 2.6.3 we present results of Saeed et al. showing the estimated fraction of TVWS lost due to extremely low sensing threshold level [Sae14].

Another solution to the hidden node problem is cooperative sensing. In cooperative sensing, multiple devices perform local sensing and then combine their findings in either distributed fashion, when each device builds a kind of spectrum map for itself or sending information to an entity called fusion center, which may be part of a BS functionality. The latter approach is used in IEEE 802.22 WRAN standard. However, cooperative sensing does not guarantee correct operation in case of the hidden terminal problem or alike, it has only a better chance of detecting the hidden terminal due to multiple measurements from different locations.

Sensing would seem to be the quite logical option for TVWS spectrum sharing, creating distributed solution without the need to maintain entities such as WSDBs and posing no requirement for the alternative communication channel, such as the Internet connection. Fundamental difficulties, like hidden terminal problem, are among of the reasons why sensing did not succeed as primary coexistence enabler. Setting sensing threshold level according to FCC or ECC requirements leads not only to overprotection of incumbents and TVWS loss but also to substantial technical difficulties with device implementation. Even sophisticated spectrum analyzers[10] have noise level above the -114 dBm and implementing sensing would make TVBDs unreasonably complicated and expensive.

2.4.2 Spectrum Sharing Models

There are two major approaches to spectrum sharing, which differ by the principle of operation: *spectrum underlay* and *spectrum overlay* [Ham13].

In spectrum underlay, the signal of SUs coexists with PUs on the same frequencies, which is achieved by using very low power level that hides the signal below allowed interference level. To compensate for the low power, underlay transmission utilizes very broad frequency range, and thus, systems that operate on such principle are called Ultra Wide Band (UWB) systems. The maximum Power Spectrum Density (PSD) that FCC allows for UWB systems is -41.3 dBm/MHz [Ema13]. For some frequencies the upper limit is below -80 dBm/MHz. UWB technology is subject to licensing and currently FCC allows operation of such systems between 3.1 GHz and 10.6 GHz for outdoor communication equipment[11]. The UWB technology might be appealing for use in TVWS range, and according to Saeed et. al, FCC had plans in 2002 to allow UWB communications also in TV bands, but the initiative was not supported by broadcasters [Sae12]. UWB systems are characterized by short operational range; nevertheless, they are capable of transmitting at relatively high data rates [Zha07].

On the contrary, the spectrum overlay uses normal transmission power. This implies that opportunistic users have to find the spectrum holes to avoid creating the interference to incumbents. Central management of spectrum resources provided by WSDBs makes the task of finding spectrum opportunities straightforward.

Jiang et al. analyze underlay and overlay sharing performance in Vehicular Network (VN) [Jia14]. Both techniques reach to quite high transfer data rates (65 - 80 Mb/s), as one may intuitively think, underlay sharing displays better results when the spectrum is scarce. Jiang et al. measure underlay versus

[10] E.g., WSA4000 that was used by Zhang et al. generates noise at -91dBm over a 6MHz TV channel [Zha13].

[11] There are other types of UWB systems with other operating frequency borders, e.g. through-wall imaging systems are operating below 960 MHz.

overlay performance for different densities of TV stations per square kilometer. When the density of TV stations per square kilometer exceeds 0,007, underlay clearly outperforms overlay, reaching throughput of approximately 24 Mb/s versus 11 Mb/s of the overlay. Another positive side of underlay is that it would not require WSDB querying.

2.4.3 TVWS Medium Access Control

In this section, we look at the Medium Access Control (MAC) techniques from the TVWS perspective. We constraint ourselves to issues related to opportunistic users coexistence, or so-called *horizontal sharing*. The reason is that PUs and SUs coexistence, or *vertical sharing*, is officially regulated and technically governed by WSDBs. There are two major cases when SUs competition for the medium may arise: either conflicting devices belong to the same or different networks. These situations are respectively referred to as *intra-network* or *inter-network* coexistence. According to Han et al. intra-network challenges in CR networks have been ubiquitously explored. Thus, we focus on inter-network coexistence issues paired with TVWS specific features [Han15]. This section is largely based on Han et al. comprehensive research on the topic.

Based on the previous work by Akyildiz et al. [Aky06], Han et al. provide the following taxonomy of coexistence approaches applicable to both intra-network and inter-network cases. At the top level, there are architecture assumptions, spectrum allocation behavior, and spectrum access techniques. *Architecture assumptions* spawn two kinds of approaches: centralized and distributed. The former implies the existence of some central entity that coordinates radio devices within the network, the latter assumes that network peers make their decisions independently, such are e.g. Cognitive Radio Ad Hoc Networks (CRAHNs), where self-organizing nodes are operating without infrastructure support in a dynamic network environment [Bay12, Cao08]. *Spectrum allocation* behavior can be cooperative, in case network nodes share their environment awareness and intentions, and non-cooperative, when nodes do not exchange any information, related to their behavior. Additionally, there are two *spectrum access* techniques or sharing models, overlay and underlay, that we discuss in more detail in Section 2.4.2. Finally, *network structure* can be homogeneous or heterogeneous, and some coexistence mechanisms may not support non-uniform networks, others fit better to heterogeneous environments or are capable of supporting both. Table 2 contains a summary of the methods for inter-network coexistence, which are classified in accordance with the taxonomy given above.

Method	Homo- vs. heterogeneous	Cooperative	Architecture	Description
TPC	Both	No	Any	Mutual interference is mitigated by adjusting transmit power
DCS	Both	No	Distributed	Based on observations of spectrum usage, each network selects the best available channels
LBT	Both	No	Distributed	Network peers perform CCA before starting the transmission
TDMA	Homogeneous	Yes	Distributed	Coordinated time sharing mechanism
Clustering-based solution	Both	Yes	Centralized	Cluster head coordinates inter-network communication and conflict avoidance
Game theoretical solutions	Both	Both	Distributed	Treat coexistence problem as a game where networks are players
IEEE 802.19.1	Heterogeneous	Yes	Centralized	Standard independent coexistence solution by using external coordination entities
CCC	Both	Yes	Distributed	Coordination information passed along dedicated channel

Table 2: Summary of TVWS inter-network coexistence methods [Han15].

Transmit Power Control (TPC) is a technique where interference is mitigated by adjusting transmit power of nodes. It is usually applied in combination with some other type of model, e.g. Wang et al. develop a game theoretic solution where CR devices negotiate their transmission power and spectrum usage [Wan08].

In Dynamic Channel Selection (DCS) network nodes observe spectrum and evaluate available channels, one with the lowest interference level is usually considered to be the best one. As in the case with Transmit Power Control (TPC), commonly there is some additional reasoning strategy to increase DCS efficiency. Yau et al. [Yau09] use Reinforcement Learning (RL) to model the cognition cycle with context awareness and intelligence among CR network peers. Shiang et al. [Shi08] propose Dynamic Strategy Learning (DSL) algorithm for DCS scheme with Quality of Service (QoS) support for general multi-radio wireless networks.

Already mentioned Listen Before Talk (LBT) mechanism has been used for inter-network coexistence in IEEE standard 802.11, commonly known as WLAN. The operation principle of LBT is based on performing a Clear Channel Assessment (CCA) check to decide if the channel is available before transmission. To guarantee fairness of access to the medium, the continuous transmission time is limited by a predefined temporal threshold. After limit expiration, transmission is interrupted, and CCA check is performed again.

An adaptation of Time-Division Multiple Access (TDMA) to solve inter-network coexistence issues is devised in IEEE standard 802.22. The proposed WRAN system supports normal (intra-network) and self-coexistence (inter-network) modes. Just one TVWS channel is required for operation in each mode. This is achieved by applying TDMA technique in the self-coexistence mode to share the medium across multiple WRAN networks. The approach is cooperative, and BSs negotiate what subset of 802.22 super-frame each client is going to use.

Villardi et al. introduce coexistence mechanism based on Cluster-Head Equipment (CHE) [Vil11]. CHE is a physical entity that collects relevant information for identifying coexistence opportunities and makes cognitive decisions autonomously. According to FCC classification, CHE is Mode II device with geolocation capability and connection to WSDB. CHEs act as beacons and exchange coexistence information mutually along the broadcast channel.

The game-theoretic reasoning seems to be quite attractive for dealing with

CRN related issues. It applies to either intra-network [Nie05, Wan08] or inter-network coexistence [Si10, Man13]. CRNs or individual network peers competing for spectrum are viewed as players with possible actions like selecting the channel or adjusting transmission power. Network performance metrics like throughput, delay, interference and others can serve as a utility function. The formal solution of non-cooperative game is supposed to converge to Nash Equilibrium (NE)[12], however, NE is not guaranteed to be Pareto-optimal[13] (and usually it is not), thus, optimality in term of spectrum utilization is not generally achieved. Despite that, the game theory continues to spur research, and a wide variety of cooperative and non-cooperative games including strategic form games, repeated games, asynchronous myopic repeated games and mixed strategy games has been applied to CRNs coexistence challenges [Aky09].

IEEE 802.19 is the Wireless Coexistence Technical Advisory Group (TAG) that is working on wireless networks coexistence issues. TAG is considering only networks that act opportunistically without a license or DSA users. With an increase in the technical variety of wireless networks, self-coexistence mechanisms designed for homogeneous systems were no longer sufficient and in May 2014 TAG 802.19 published standard 802.19.1 called TV White Space Coexistence Methods. The standard defines "... architecture, interfaces, messages, and procedures to provide coexistence services to different TVWS coexistence methods." [Fil15]. However, the standard does not deliberately define any coexistence algorithms leaving the choice open to the implementers. Filin et al. provide a description of an example system developed in conformance with this standard. The solution enables coexistence of three different net-

[12]NE is a solution concept of a non-cooperative game for two or more players. Each player knows the strategies of the other(s) players, and one cannot improve results by changing only their own strategy, i.e. everyone already has an optimal strategy given the strategies of the other(s) [Osb94]. John Nash (1928-2015) was an American mathematician who made fundamental contributions to game theory and other fields of mathematics. In 1994 he shared the Nobel Memorial Prize in Economic Sciences with Reinhard Selten and John Harsanyi [Kuh02].

[13]Pareto optimality, sometimes referred to as Pareto efficiency, is a state of resource allocation when improving wellbeing of one individual inevitably comes at the expense of other(s), i.e. there are no free resources left and everything is allocated to somebody. In terms of CR this means that all available spectrum is distributed among its users. Vilfredo Pareto (1848-1923) was an Italian engineer and economist who envisioned the concept in research of economic efficiency [And97].

works: WRAN based on IEEE 802.22 standard, Super Wi-Fi compliant to IEEE 802.11af standard, and local broadcasting service utilizing OneSeg TV transmitter. Figure 3 contains an architectural overview of the 802.19.1 standard system.

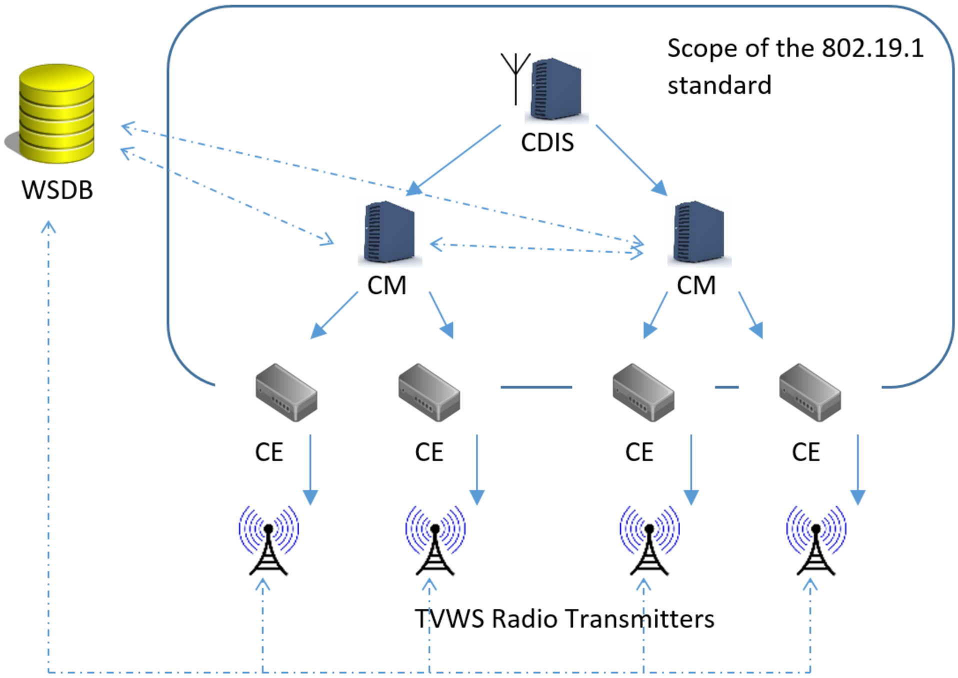


Figure 3: IEEE 802.19.1 defined coexistence architecture [Fil15].

The top-level entity is Coexistence Discovery and Information Server (CDIS), responsible for the discovery of neighboring TVWS networks. The second level entities are Coexistence Managers (CMs), which collect registration information from TVWS networks they serve, neighbor discovery data from a CDIS, and query WSDB for available spectrum. By the analysis of the gathered data CM makes coexistence decisions and either requests reconfiguration of the TVWS system which it supervises or negotiates transmission parameters with the neighboring CM. Coexistence Enabler (CE) is responsible for interface unification between a TVWS system and the CM. In a system designed by Filin et al. CDIS and CMs were ordinary PC machines connected with TPC/IP network. The operating results of the system were highly satisfactory; all SUs were automatically configured to use separate available TVWS channels.

Various coexistence methods use the Common Control Channel (CCC) technique, e.g. in already mentioned CHE as a broadcast channel of the beacons. Dedicated CCC is also used in regular wireless networks to broadcast control or emergency information. TVWS poses its challenges for CCC utilization: neighboring TVBDs may not have any common channel available, returning PU can block selected CCC, portable devices may move out of reach. Han et al. point out a possibility to use an out-of-band channel as CCC. Alternatively, if the out-of-band channel is not supported, it is possible to aggregate multiple guard bands between digital TV signals to form a CCC. The similar technique is Cognitive Pilot Channels (CPCs): the available band can be split into sub-bands handing over two first sub-bands to CPCs.

An interesting possibility is that WSDB would assume regulatory role also for SUs. RFC6953 [Man13] suggests a possibility for acknowledgment message by SU where it is possible to send information about the chosen channel for communication and other relevant details. If any other SU device asks for spectrum after the WSDB received an acknowledgment from the first device, WSDB could send a notification together with the spectrum message, stating that although the channel is free, it is going to be likely in use by another SU. The process is not yet formally defined, but there is an opportunity to reduce harmful interference among SUs.

2.5 TVWS Networks

In this section, we shall explore networking techniques being developed for TVWS. We also review fundamental concepts and architectures specific for CRNs. IEEE has published two major TVWS networking standards, and we shall examine them in detail.

Akyildiz et al. emphasize two traits specific for any CR device: cognitive capability and reconfigurability. The *cognitive capability* is the ability to capture or sense the information from the environment. It is not reducible just to observing some frequency ranges in search for available bands; it employs autonomous learning and action decisions to perceive the spatiotemporal variations in the spectrum. *Reconfigurability* denotes the ability of dynamic adaptation to the environment. In practice device can reconfigure itself by changing operating frequency or transmission power, switching to alternative MAC technique or taking another kind of action.

CRNs can belong to either of two classes: infrastructure-based CRN and the CRAHNs. Figure 4 by Bayhan et al. provides the overview of conventional, cognitive and ad hoc network architectures [Bay12].

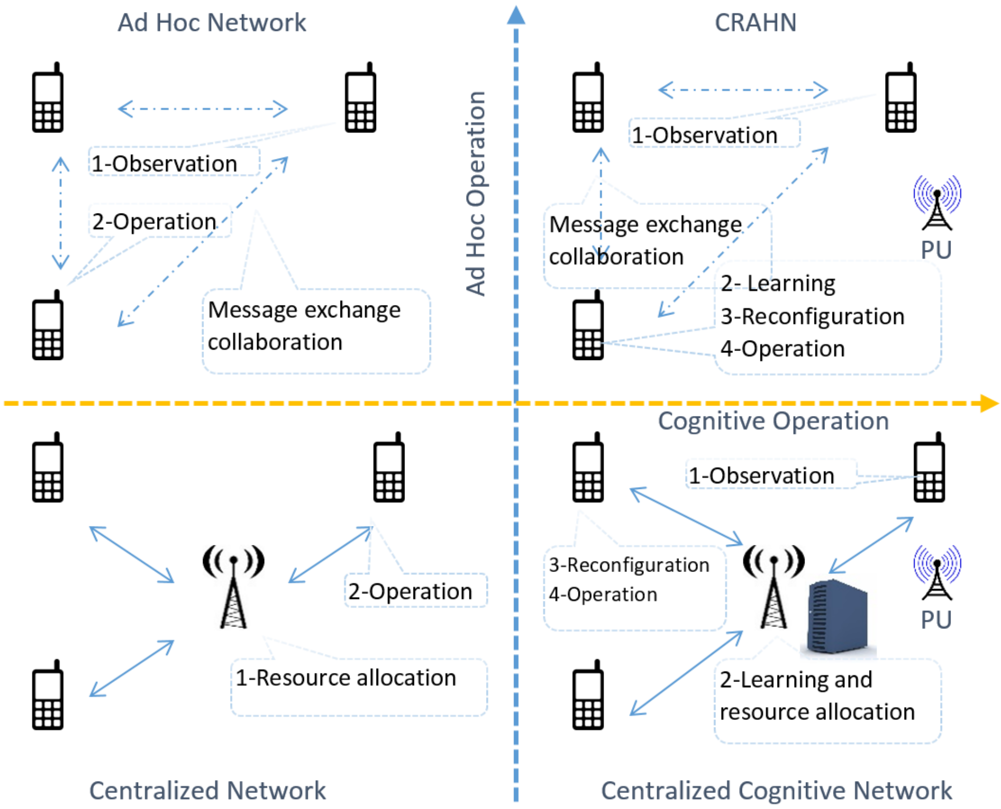


Figure 4: Comparison of different network architectural models [Bay12]. The vertical axis represents ad hoc shift, horizontal - transition towards cognitive paradigm.

The CRN with infrastructure has a central network entity such as a BS or an Access Point (AP). This entity aggregates the observations collected by the network peers and performs cognitive analysis based on the data. The central unit performs resource allocation and distributes reconfiguration decisions to network peers. Lacking centralized network infrastructure, CRAHN is fundamentally different. Akyildiz et al. characterize it as a mobile, continuously self-configuring network with the following key properties: the distributed multi-hop architecture, the dynamic network topology, and the spatiotemporal spectrum availability [Aky09]. Each CRAHN node must have full CR capabilities. Cooperation schemes play an essential role in CRAHNs because single participants with limited local perspective cannot predict the influence of their actions on the scale of the entire network. Nodes share individually observed information among each other.

Compared to traditional wireless medium, TVWS poses specific properties that must be taken into account when planning for a network. Madhavan et al. point to *power-spectrum tradeoff*, meaning that there is more spectrum available for devices that use less power. Authors query WSDB at the location of Empire State Building and find that there is no spectrum for *Fixed* and *Mode-I* devices while one channel is still available for *Mode-II* device[14]. Due to this fact, Madhavan et al. propose to use arrays of low power BSs, as opposed to traditional wireless networks where one high power BS serves a large area. This approach makes possible to establish TVWS network in spectrum-scarce locations and gives more fine-grained control over the spatial shape of the network, which is also important because of spatial availability variance of TVWS. These conditions create a novel challenge for BSs placement and authors formulate what they call *optimal BS composition problem*: "...minimum number of low-powered mode-I devices required to achieve a given set of long-term throughput targets". Madhavan et al. propose an algorithm for BSs placement based on mathematical modeling.

Murty et al. proposed Sense*Less*, which is a network relying solely on WSDB for spectrum access [Mur11]. The main goal was to investigate WSDB accuracy and determine how efficient spectrum sharing would be without sensing, and we shall examine these results in Section 2.6.3. However, the network design itself has some noteworthy aspects. It solves traditional shortcomings of the WSDB infrastructure such as the requirement of secondary communication channel or bootstrapping problem by extending BSs functionality with beacon roles. Beacons are advertising available TVWS channels; therefore, the client device can immediately use TVWS for communications. Geolocation requirement is also treated non-trivially. Authors explore the possibility that devices can use only safe channels, which are available in the entire region covered by the base station. However, empirical research conducted by authors leads to the conclusion that fraction of lost TVWS would be too significant. Thus, Murty et al. suggest preserving geolocation requirement for client devices. IEEE standard 802.11af for TVWS WLAN, which was approved in 2014, has many similarities with Sense*Less* network design.

[14]This is in congruence with our results obtained from Google WSDB.

There is an important direction in research devising *inter-vehicular* or Vehicle-to-Vehicle (V2V) and Vehicle-to-Infrastructure (V2I) networks intended for purposes such as improving public safety, collision avoidance, driver-assistance and entertainment [Jia14]. Currently, IEEE standard 802.11p allows vehicular communication to use 5.9GHz band (5.850-5.925 GHz), but the growing demand is pushing towards the exploration of new possibilities, such that TVWS offers [Jia14]. The specific challenges for infrastructure design arise from the fact that nodes of the vehicular network are fast moving objects. Al-Ali et al. propose a network model where base stations serve as beacons responsible for communication with WSDB [Ali15]. Relying on the fact that TV and 2G antennas are often mounted together, authors explore the correlation between 2G and TV Received Signal Strength Indicator (RSSI) to improve the quality of sensing. Enhancing sensing technique with the aforementioned method, Al-Ali et al. propose a decision algorithm that is achieving 25% reduction in the amount of required WSDB queries. To improve channel utilization and sensing further, authors explore novel Interference Alignment (IA)[15] technique.

As we mentioned before, there are two networking standards developed by IEEE for TVWS wireless networks, 802.22 and 801.11af. The first standard for TVWS was IEEE 802.22 published in July 2011, defining Wireless Regional Area Network (WRAN). In 2014, IEEE published an amendment 802.22a. The purpose of 802.22 standard is to provide wireless broadband access to rural and remote regions, but it may serve any purpose, including coverage of the major residential areas, resorts or campuses [Pie13]. The reach of the service is ranging from a minimum of 10 km to a maximum of 100 km. For single BS with EIRP of 4W the range can be approximately up to 30km given that propagation characteristics of the environment are excellent. The system topology is Point to Multipoint (P2MP), similar to cellular design. The central BS is connected over the air with a number of Consumer Premise Equipments (CPEs). One BS can support up to 512 CPEs. CPE is required to have two antennas, one directional for communication with BS and omnidirectional for sensing. The BS is gathering sensing information from CPEs and is capable of cognitive sensing, periodically evaluating the need to change communication channel. Sophisticated sensing technology is employed to meet QoS require-

[15] IA is a transmission strategy implying a coordination between transmitter and receiver pairs in order to align interfering signals in time, frequency, or space, thus simplifying interference cancellation techniques [Ela13, Cad08].

ments of media and other real-time applications, because simple solution such as LBT needs to interrupt the transmission for listening, having an adverse impact on network performance. Due to this reason, the standard uses Dynamic Frequency Hopping (DFH) sensing implementation that enables simultaneous transmission and sensing. The technique works by splitting available band in number of sub-channels and sensing one while transmitting on the other(s). After short period (two seconds in IEEE 802.22 standard) sub-channels are changed and thus entire bandwidth is sensed continuously [Xia08]. The performance of IEEE 802.22 network is comparable with Digital Subscriber Line (DSL), reaching 1.5 Mb/s in the downstream and 354 Kb/s in the upstream direction. The downstream (BS transmits, and the CPE receives) is Time-Division Multiple Access (TDMA). The upstream transmissions (CPEs transmit, and the BS receives) are shared by CPEs on a demand basis, according to a DAMA[16]/OFDMA[17] scheme.

IEEE standard 801.11af defines WLAN networks operating in TVWS frequency range. The standard was published in December 2013, and it is also known as Super Wi-Fi or White Fi, due to better propagation properties of TVWS than conventional WLAN operating frequencies in 2.4 GHz or 5 GHz bands. For example, Mode-II device operating at the maximum power of 100 mW will have the reach of approximately 500 meters. On the other hand, IEEE 801.11af offers less capacity than Wi-Fi due to less bandwidth. Figure 5 encompasses the main entities of the standard [Flo13].

There are two kinds of Geolocation-Database-Dependent (GDD) Stations (STAs): GDD-enabling (also referred to as APs) and GDD-dependent. The tasks of GDD-enabling STAs is to communicate securely with GDBs (WSDBs in our terminology), maintain the WSMs[18] and transmit a Contact Verification Signal (CVS) to inform GDD-dependent STAs that the WSM they received is valid. The Registered Location Secure Server (RLSS) acts as a local storage of spectrum information and has the capability to contact the GDBs directly. Under some regulative domains, RLSS can also provide information required for inter-network coexistence. GDD-dependent STAs operate under control of GDD-enabling STAs and receive spectrum availability information in the form

[16]Demand Assigned Multiple Access

[17]Orthogonal Frequency Diversity Multiple Access

[18]The WSM is a list of available TVWS channels and corresponding power limitations obtained from the GDB.

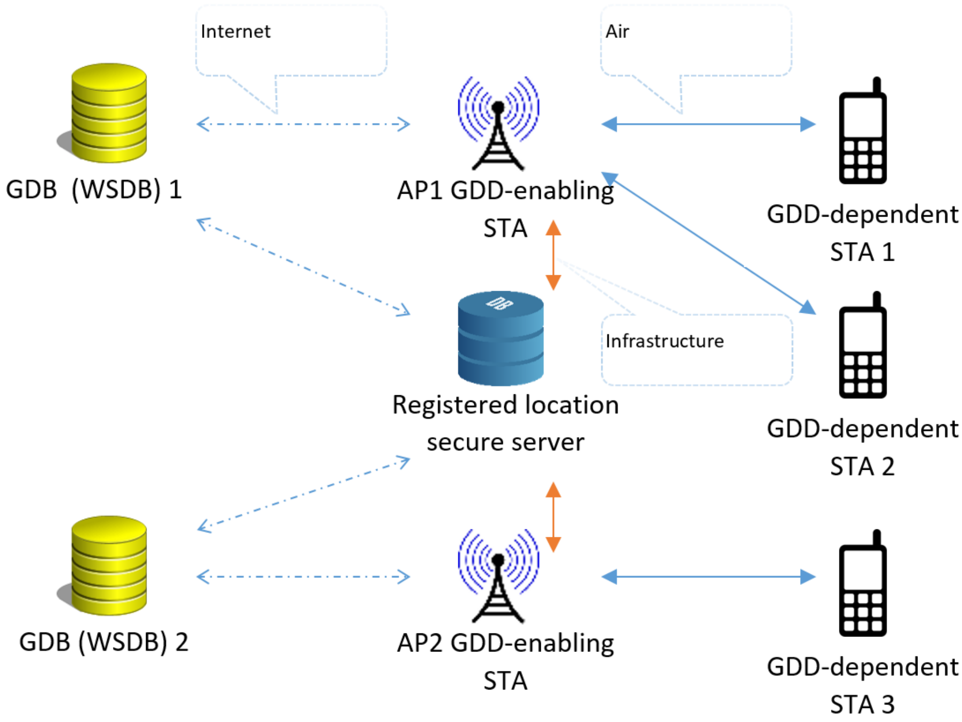


Figure 5: Architectural entities of 801.11af standard [Flo13].

of WSMs from either RLSS or GDD-enabling STAs [Flo13].

2.6 WSDB Technology Overview

In this section, we discuss research and standards related directly to WSDBs. First, we describe PAWS protocol that WSDs use to access WSDB. Second, we consider research on optimization of WSDB usage by mobile devices, and finally, we look at future directions of WSDB development aimed at improving accuracy.

2.6.1 Protocol to Access White Space Database (PAWS)

Internet Engineering Task Force (IETF) has developed the PAWS to define communication standards between White Space Devices (WSDs) and WSDBs. Informational RFC6953 [Man13] was published in May 2013, defining problem statement for protocol development and possible scenarios for WSDB and TVWS usage in general. RFC7545 [Che15], defining the PAWS protocol, got

Proposed Standard status in May 2015.

RFC6953 posed the following tasks that PAWS should be able to accomplish:

- Determine the WSDB relevant for querying, i.e. discovery protocol.
- The possibility of establishing a connection to WSDB using PAWS.
- Optional client registration with WSDB using PAWS.
- The format for querying the WSDB with parameters such as geolocation and device type.
- The format for query response containing a list of available TVWS frequencies and other relevant information.
- Sending an acknowledgment to the WSDB containing the information about selected channels and other device characteristics, such as transmission power.

PAWS is intended for global usage, having flexibility and extensibility to comply with regulations of many regulatory domains with possible differences in rules. Scenarios proposed for TVWS usage include:

- Master-Slave networks, where slave devices contact master by air and master device performs WSDB query on behalf of them over the Internet.
- Backhaul for any conventional Internet connection.
- Offloading of traffic from any conventional network to TVWS.
- Emergency ad hoc networks deployment.
- Opportunistic TV broadcasting.

RFC7545 [Che15] standardizes technical details of the protocol. Technically speaking PAWS is a lightweight protocol based on Hypertext Transfer Protocol (HTTP)[19], so it is assumed that both querying device and WSDBs have the

[19] HTTP is the protocol that browsers use to retrieve web pages from the Internet, for example.

Internet connection. PAWS uses JavaScript Object Notation (JSON)[20] data formatting and sends messages in plain text. The Listing 1 contains actual JSON message send by our TVWS data collection program to Google WSDB to get available spectrum.

Listing 1: Spectrum Request JSON Message


```
{
"jsonrpc":"2.0",
"method":"spectrum.paws.getSpectrum",
"apiVersion":"v1explorer",
"params":{
"type":"AVAIL_SPECTRUM_REQ","version":"1.0",
"deviceDesc":
{"serialNumber":"234892039420",
"fccId":"TEST",
"fccTvbdDeviceType":"MODE_2"},
"location":{
"point":{"center":{"latitude":42.9986,"longitude":-75.9983}}},
"owner":{"owner":{}},
"capabilities":
{"frequencyRanges":[
{"startHz":800000000,"stopHz":850000000},
{"startHz":900000000,"stopHz":950000000}]},
"key":"authentication key"},
"id":"any_string8492304032492394"
}
```


The Listing 2 contains actual JSON reply message from Google WSDB with available spectrum channels.

Listing 2: Spectrum Response JSON Message


```
{
"jsonrpc": "2.0",
"id": "any_string8492304032492394",
"result": {
"kind": "spectrum#pawsGetSpectrumResponse",
"type": "AVAIL_SPECTRUM_RESP",
"version": "1.0",
"timestamp": "2016-02-14T11:18:22Z",
"deviceDesc": {
"serialNumber": "234892039420",
"fccId": "TEST",
"fccTvbdDeviceType": "MODE_2"  },
"spectrumSchedules": [{
"eventTime": {
"startTime": "2016-02-14T11:18:22Z",
"stopTime": "2016-02-16T11:18:22Z"
},
"spectra": [{
"bandwidth": 6000000.0,
"frequencyRanges": [
{
"startHz": 5.4E7,
"stopHz": 5.12E8,
"maxPowerDBm": -52.799999947335436},
{
"startHz": 5.12E8,
"stopHz": 5.18E8,
"maxPowerDBm": 15.99999928972511
},
... ]
```


[20]JSON is a lightweight data-interchange format, that is completely human readable and efficient for computer processing.

```
}],
"needsSpectrumReport": false,
"rulesetInfo": {
"authority": "US",
"maxLocationChange":100.0,
"maxPollingSecs": 86400,
"rulesetIds": ["FccTvBandWhiteSpace-2010"]
}
}]
}
}
```


To address global operation challenges, protocol supports multiple rulesets: the device initiating the request can optionally provide identifiers of all the rulesets it supports and a set of parameters needed. The WSDB includes ruleset id in the response, and the device interprets response according to that ruleset. The ruleset id should generally include name of authority and version and it looks quite self-descriptive, e.g. *FccTvBandWhiteSpace-2010*.

The database discovery mechanism assumes that WSD has preconfigured list of WSDBs addresses (in the form of Uniform Resource Identifiers (URIs)). Some regulatory domains support listing servers, from which WSDs can download addresses of WSDBs. In such case, WSD can have preconfigured URI of the listing server. The standard also takes into account the situation where WSDB is changing its URI. Before moving to a new address, WSDB must notify clients by including *DbUpdateSpec* parameter with the new URI. The procedure must start two weeks before the old URI will stop functioning, and the WSD must update the entry in the list of WSDBs. In error situation when no WSDB is reachable, the WSD must consider that no spectrum is available.

The plans for the future development of PAWS include taking into account user priority, signal type, spectrum supply and demand; supporting payment or micro-auction bidding [Che15].

2.6.2 Mobile Optimization: The Nuna Algorithm

Since there is a growing interest for TVWS utilization by mobile devices, the energy efficiency comes into focus and thus it is important to minimize the number of required WSDB queries. Another important concern is FCC requirement for MWSDs to query for the spectrum availability every 100 meters as location changes. The latter is especially problematic for fast moving objects, such as cars or flying drones: there is always some delay in communications with WSDB, and it is possible that while waiting for the response the device moves another 100 meters [Mic16b]. In that case, instead of using the reply the device has to query the WSDB again. The situation can continue indefinitely long, and the utilization of TVWS becomes an infeasible task. The solution to the problem is simple, if path or trajectory of the movement is predefined: all required data can be fetched in advance. Additionally, PAWS offers the possibility to query for multiple locations in a single request. A. Majid calls such query technique a *multi-location WSDB query* [Maj15].

Situations, where the path is not known beforehand, are much more common in real life and represent a significant challenge. To deal with such cases, A. Majid proposes the Nuna Algorithm [Maj15]; that works by predicting the direction of movement based on the current direction, i.e. the algorithm assumes that the movement will continue in the same direction and sends multi-location queries in advance for locations that lay on the path. The best case for the algorithm is movement along a straight line; the worst is circular movement when all predictions are wrong. Because most of our roads and streets tend to be quite close to straight lines, the Nuna Algorithm shows superb efficiency results in an empirical research conducted by Majid. Compared to traditional approach Nuna shows around 30% energy savings on realistic routes, the only case when it is marginally worse is circular movement.

Given modern device such as a mobile phone, it is easy to see possibilities to improve Nuna by collecting information of user's regular routes and applying some statistical or machine learning techniques to get much better predictions. In the absence of such information, the Nuna Algorithm gives quite a good baseline.

2.6.3 WSDB Accuracy and Augmentation with Sensing

The accuracy of WSDBs is crucial to efficient utilization of TVWS and its commercial success. Much research is currently concentrating on the analysis of WSDBs precision and finding ways to improve it, mostly by taking into account local spectrum observations.

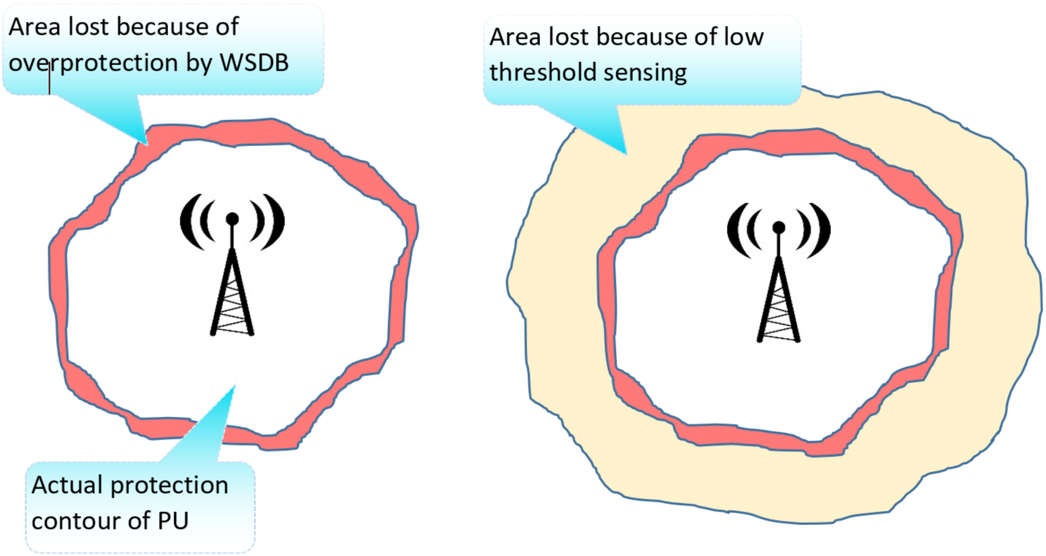
At the heart of WSDB operating principle is a radio wave propagation model. Areas, where spectrum is available for use, are calculated by application of propagation model to the list of known PUs, possibly taking into account terrain. The accuracy of model prediction determines the efficiency of spectrum utilization. Even in the case of using most advanced propagation model, inaccuracy is inevitable due to specific characteristics of local relief that causes among others shadowing, reflection and multipath fading. One of the most widely used is Longley-Rice Propagation Model (L-R) [Huf82], but there are many others and currently according to FCC recommendation commercial WSDB providers use F-Curves model [Wsd13].

Murty et al. [Mur11] analyze how good different propagation models are at the prediction of spectrum availability. The authors carried out the research by performing actual spectrum measurements in diverse locations with Ultra High Frequency (UHF) antenna and comparing the results with predictions obtained by applying different models. The results were in favor of WSDBs since L-R with terrain [Huf82] produced quite accurate predictions with a maximum fraction of TVWS lost around 20%. The simplistic models such as Egli or Free Space deviate more from the measured availability. Table 3 contains the approximate results.

Propagation model	Percentage lost (approximate)	
	Minimum	Maximum
L-R with terrain	0	25
L-R without terrain	10	45
Egli	30	60
Free Space	80	98

Table 3: Comparison of different propagation models performance applied to TVWS availability prediction [Mur11]. L-R with terrain exhibits the best results.

There is room for improvement in WSDB accuracy as shown in the article by Saeed et al. [Sae14]. The authors find that Irregular Terrain Model (IMT) (which is another name for L-R with terrain) is overestimating the signal power by up to 97% of the time. Using just sensing would lead to even greater underutilization of the TVWS. The sensing threshold levels are unrealistically low because the sensing device is assumed to be continuously in the worst case scenario involving the hidden terminal problem we described in Section 2.4.1. To clarify the situation, we compare the requirements for minimum field strength values at the border of the DTV station protected area with field strength values corresponding to the sensing thresholds. The required border values are 41dBμV/m by FCC and 56.21dBμV/m by ECC. The field strength values that match sensing thresholds are 26dBμV/m (-114 dBm) and 13dBμV/m (-120 dBm) [Sae14]. Figure 6 illustrates the approximate proportion of TVWS lost. This result does not contradict the subsequent research that uses sensing to improve utilization of TVWS because sensing levels that correspond to field strength values or some other techniques are used.



(a) Propagation model

(b) Low threshold sensing

Figure 6: The approximate fraction of lost TVWS in the case of using propagation model (a) and low threshold sensing (b) [Sae14].

To minimize the loss of TVWS, Saeed et al. propose to merge results of propagation model with actual spectrum observations. Authors call their prototype system Signal Prediction and Observation Combiner (SPOC) and suggest using crowdsourced resources of spectrum sensory readings. The major challenge of this approach is availability and reliability of up-to-date spectrum observation sources.

Zhang et al. propose to use public transportation system to gather spectrum observation information needed for propagation model enhancement [Zha13]. Authors attached the measurement device to the public transportation bus and gathered over one million spectrum observations across approximately 100 square-km area. In accordance with Saeed et al. [Sae14], it was found that commercial WSDBs overestimate the area of PU protection. Empirical research conducted by Zhang et al. estimates the size of a zone, inaccessible because of WSDB overprotection, to be about 33%. Authors find sensing of incumbent signals such as TV stations technically challenging due to low sensing threshold level (-114 dBm). High-end spectrum analyzer WSA4000 that was used in the research generates noise at -91dBm over a 6MHz TV channel. Therefore, authors developed a sophisticated technique for PU discovery, detecting first the pilot[21] of TV signal and then using this pilot to derive total power. Implementation of such sensing system in every TVBD would be quite prohibitive, so authors suggest an economically feasible solution of using a limited number of highly mobile devices dedicated for spectrum observations. Zhang et al. call their system *V-Scope*, having implemented and tested it successfully in the area of Wisconsin-Madison, USA.

Achtzehn et al. also investigate the accuracy of WSDBs and combining underlying propagation modeling with actual observations [Ach14]. The authors provide extensive mathematical apparatus for building large-scale simulation or measurement-based radio environment maps and show that relatively small measurement effort can reduce the mean absolute prediction error of 5.9 - 6.9 dB to 3.1 - 5.0 dB by applying appropriate spatial interpolation technique.

Chakraborty et al. [Cha14] emphasize that accurate estimation of urban DTV station protection contours is of particular importance because in the major metropolitan areas the demand for opportunistic TVWS use is the highest but at the same time presence of licensed PUs is the densest. Modern city relief is also very challenging for propagation models, making the augmentation of WSDB by spectrum observations almost a necessity. Authors measure actual incumbent signal levels in two districts of the New York City area and conclude that about 75% of TVWS is lost in New Jersey and 40% in Long Island. The opposite cases, meaning that WSDB erroneously allows the use of a channel where PU signal is present, are very rare. Authors used the same sensing technique as described by Zhang et al. [Zha13], using DTV pilot signal.

Compared with Murty et al. [Mur11] results, revealing 20% losses caused by inaccuracies of WSDBs, figures by Chakraborty et al. [Cha14], indicating up to 75% losses of TVWS, look much more dramatic. The latter findings make a bit gloomy outlook of the business case for TVWS unless WSDBs get augmented

[21] A group of preambles appended at the beginning of each TV packet to help decoding is called a pilot, it creates a predominant peak in the frequency domain of a TV signal.

with sensing data. A prominent finding of Chakraborty et al. is the fact that prediction errors are not randomly distributed, but tend to cluster, allowing to split the region into two parts: one where WSDB is reliable and other where actual observations are needed. Authors build a decision tree model based on factors, affecting WSDBs accuracy such as distance from the transmitter, obstruction and power to identify regions, where WSDB prediction is most likely to be erroneous.

Concerning different propagation models, Chakraborty et al. find that L-R with specific regional terrain does not display significantly better results than F-Curves, recommended by FCC. This result is incongruent with Murty et al. [Mur11] findings. The reason may be that Chakraborty et al. focus specifically on metropolitan area, while Murty et al. investigate diverse areas: "...across a driving path of 1,500 miles, at a set of 57 diverse locations including large cities, downtowns, suburbs, between large buildings, mountain ranges, forests, valleys, at the edge of water bodies, and also across areas of different population densities". According to Chakraborty et al. the L-R displays especially poor results for situations when the channel is actually available, and measured power level is below -114 dBm.

Compared with previously discussed research, Chakraborty et al. fill a significant gap answering the question about the locations where measurements should take place to maximize WSDB accuracy with a minimal amount of costly observations.

3 White Space Spatiotemporal Variability

While the purpose of the regulations is to ensure the protection of PUs operation from possible interference caused by opportunistic users, it is widely argued that some of the regulatory requirements make mobile usage of TVWS quite challenging [Maj15]. In particular, one such demand is that a new WSDB query is needed each time the device moves 100 meters. Another aspect is how often a renewal of the available spectrum information is required. Currently, WSDB itself defines the lease time of the spectrum, which is mostly two days according to our data (see Section 3.3). The main objective of the empirical research is to estimate the spatiotemporal variance of TVWS to assess necessity of regulatory constraints mentioned above. We investigate mobile

TVWS usage simulating real life like situations, e.g. a person going to work and back home, a tourist visiting major attractions in New York City, a cyclist going along coastal Santa Monica route and so on. Our data provides unique temporal perspective with more than six months of observations bound to specific locations.

3.1 The Data Analysis System

The system that we developed for the research consists of two entities: mobile application, communicating with WSDB, and back-end database, where the mobile application stores WSDB responses.

The Android mobile application issuing PAWS requests to WSDB and running on real mobile device gave as the possibility to measure the time required by a modern cellular gadget to obtain spectrum availability information from WSDB. Another point for developing the custom mobile application was to observe how frequent communication with WSDB would affect normal usage of the device. We did not perform power consumption or any other kind of exact measurements; the purpose was a subjective evaluation. Technically, the application was implemented as a background service with notifications. We used two mobile devices to run the application, one smartphone GT-I8160 (Samsung Galaxy Ace 2) and another tablet GT-P3100 (Samsung Galaxy Tab 2 7.0). Android version on both devices was 4.1.2 (Jelly Bean). The phone was used all the time as a normal smartphone.

We used RESTful back-end implemented on Microsoft Azure platform to store the details of the routes and the replies of Google WSDB. Figure 7 shows the overall architecture of the system and data flows.

The operation of the system proceeds as follows. When mobile applications is started, it contacts the service and downloads routes information. Each route has a starting time (possibly multiple times during a day) and associated set of locations or points, at which the available spectrum requests are send to WSDB. There is an individual delay between locations to emulate the realistic speed of movement and routes can represent walking pedestrian or moving by car or bicycle. After the Android device has retrieved the routes data, the mobile application schedules querying times for each location and sends requests to Google WSDB at appropriate times. The spectrum is re-

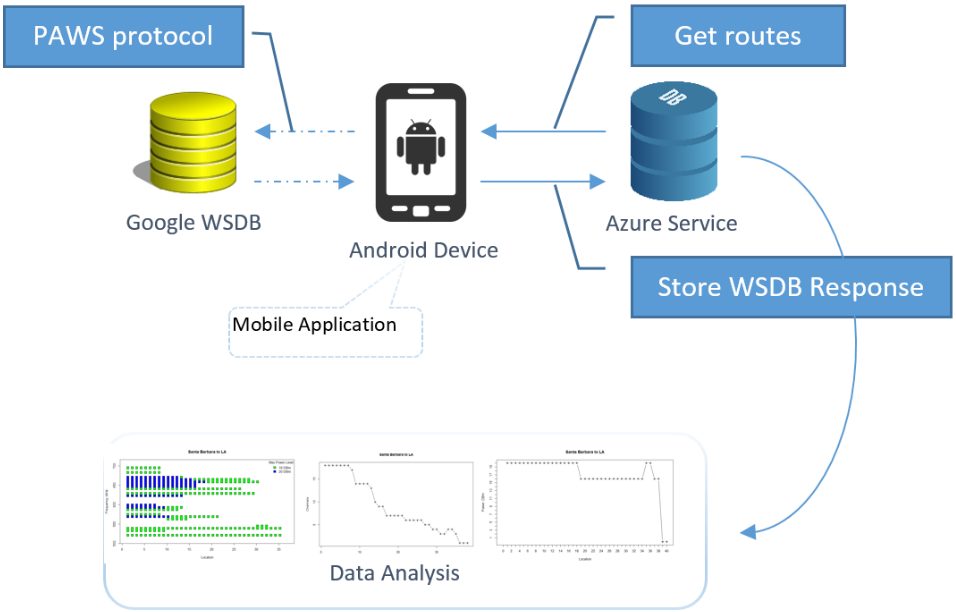


Figure 7: The architecture of our data collection and analysis system.

quested for Mode II device. After receiving the response from the WSDB, it is stored in Microsoft Azure platform database. The mobile application measures time from initiating the request to receiving the response, taking in account not only network delay and the time taken by the WSDB to process the request, but also the time required for the mobile device to issue the request and process the response. Spectrum availability information for each route is collected on a daily basis. The system is open for public at the address `http://whitespacespectrumweb.azurewebsites.net`, although the future availability cannot be guaranteed.

3.2 The Routes

We collect the spectrum availability information along ten routes located in different parts of the USA. Tables 4 and 5 contain the summary information on the routes and obtained data.

The metrics for analysis of gathered spectrum availability information include the number of available channels and maximum allowed transmission power (Available channels and Power columns). Different points (locations) of the

Route	Length, km	Average speed, km/h	Number of points	Population density, km^2		Available channels		Power, dBm	
				Min	Max	Min	Max	Min	Max
Montclair to Manhattan	24,6	58,2	52	2 305,5	27 672,6	1	1	16	16
Manhattan tourist 1	2,1	3	9	27 672,6	27 672,6	0	1	0	16
Manhattan tourist 2	2,9	3,7	11	27 672,6	27 672,6	0	1	0	16
Santa Monica bicycle	5,4	14,4	13	4,100	4,100	0	0	0	0
Sacramento 128	43,5	50	42	n/a	38	3	6	16	20
Berkeley	72	75	15	2 900	4 383	0	1	0	16
Santa Barbara to LA	117,2	92	40	810	3 198	0	17	16	20
LA to San Diego	126	83	14	1 545,4	3 198	0	17	16	20
Montana 90	218	68	56	n/a	926,5	13	28	16	20
Alaska	30,3	60	19	n/a	25,7	27	28	16	20

Table 4: Summary information about the routes and collected TVWS availability data, part 1. The population density is given according to the 2010 United States Census. The minimal population density is marked as n/a (not available) in case the route goes through unpopulated areas.

Route	Number of WSDB responses	Observations period			Temporal variability		Average lease time, minutes
		From	To	Days	Number of days with spectrum changes	Probability of daily change	
Montclair to Manhattan	20 777	18.08.2015	16.03.2016	211	0	0	2784
Manhattan tourist 1	1 791	19.08.2015	16.03.2016	210	2	0.0095	2809
Manhattan tourist 2	2 213	19.08.2015	16.03.2016	210	1	0.0048	1129
Santa Monica bicycle	2 582	20.08.2015	16.03.2016	209	0	0	2880
Sacramento 128	7 855	21.08.2015	16.03.2016	208	0	0	2880
Berkeley	2 894	21.08.2015	16.03.2016	208	0	0	2880
Santa Barbara to LA	6 198	04.10.2015	16.03.2016	164	2	0.0122	2880
LA to San Diego	2 169	05.10.2015	16.03.2016	163	9	0.0552	2880
Montana 90	7 965	16.10.2015	16.03.2016	154	2	0.013	2880
Alaska	2 776	16.10.2015	16.03.2016	154	0	0	2880

Table 5: Summary information about the routes and collected TVWS availability data, part 2

route had a different number of available channels and allowed transmission power levels. The maximum and minimum values are taken from the point having best or worst situation respectively. Temporal variability column of Table 5 contains two metrics. The first one, the number of days with spectrum changes, tells on how many days during observation period there were changes in channel availability or maximum allowed transmission power. We calculate the probability of daily change by dividing the number of days with spectrum changes by a total number of days in the observation period. It simply shows how likely there is a change in the spectrum accessibility on a daily basis. The average lease time column shows the average length of the period, on which the available spectrum at a certain location can be used, after that period the WSD should query WSDB again. In the succeeding sections, we discuss details of each route and data presented in Tables 4 and 5.

3.2.1 From Montclair to Manhattan

The real story about a couple living in Montclair and working in Manhattan is the inspiration for the route from Montclair to Manhattan [Ber10]. The route simulates moving by car, and it is approximately 25 km long. The average speed of the movement is 58 km/h. The observations took place from 18.08.2015 to 16.03.2016 and cover 211 days.

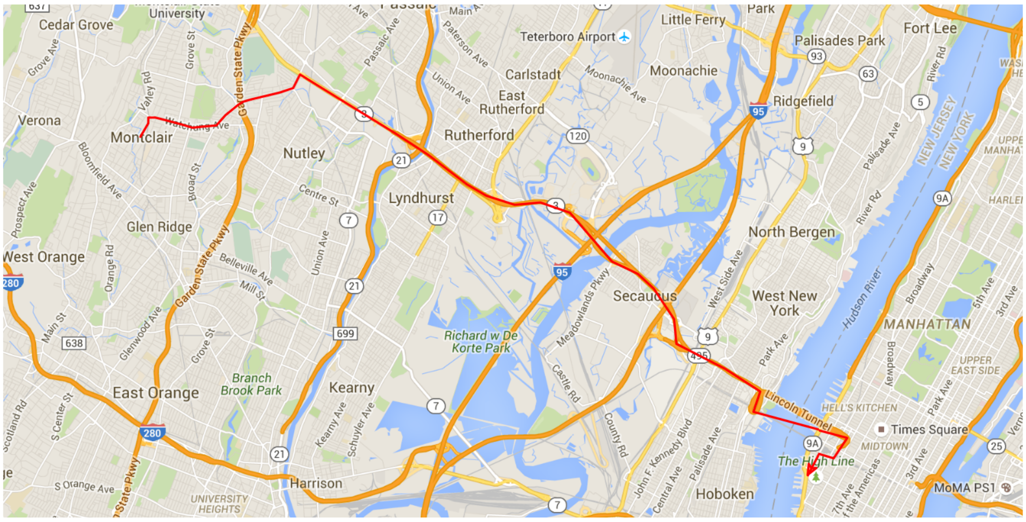
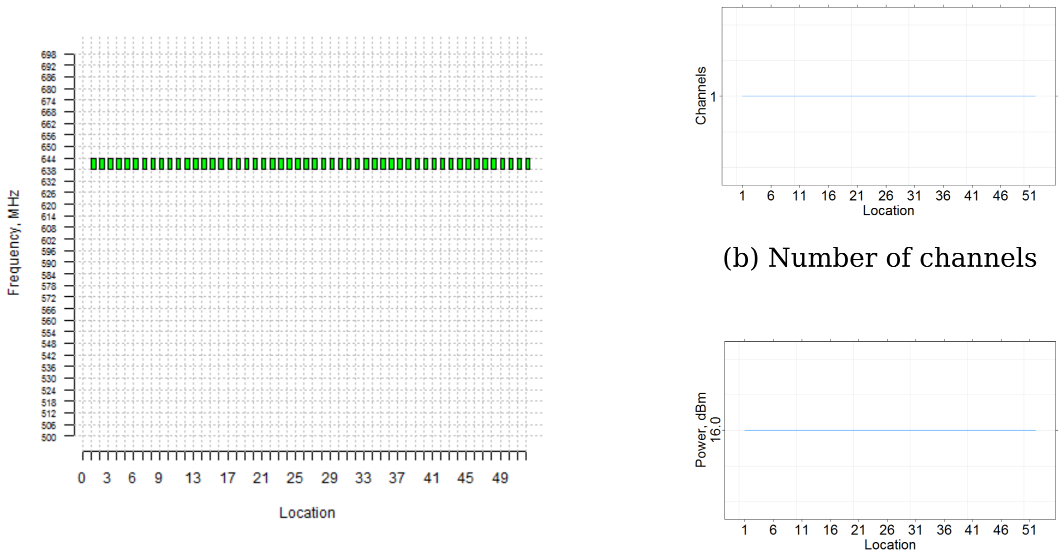


Figure 8: The route from Montclair to Manhattan.

Despite very high population density, one TVWS channel is accessible during



(a) Spectrum availability.
Green indicates 16 dBm power level.

(b) Number of channels

(c) Power levels

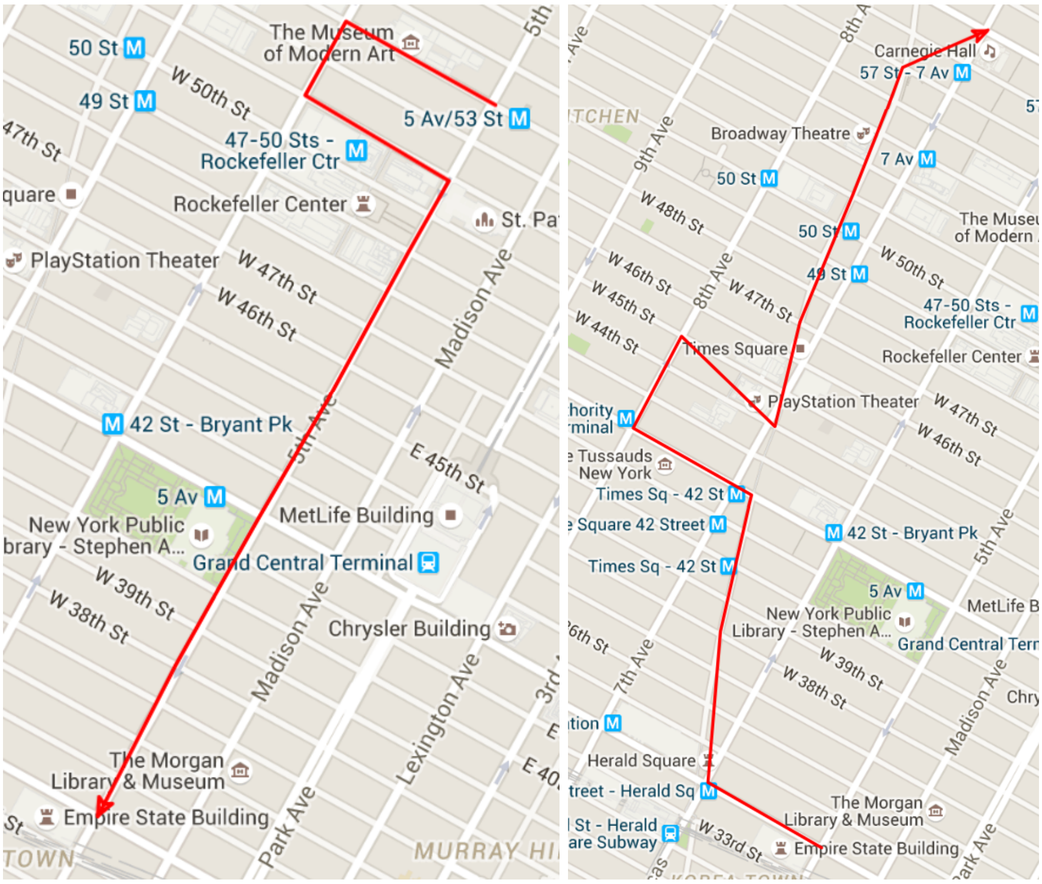
Figure 9: The route from Montclair to Manhattan spectrum availability.

the entire trip, as shown in Figure 9. The route is emulating going to work and back home, so it is repeated after 8 hours in the backward direction. No TVWS availability change was registered between morning and evening, and we detected no other temporal variations.

3.2.2 Manhattan Tourist Walk

The Manhattan tourist route goes along the major attractions of Manhattan and consists of two parts, as depicted in Figure 10. The length of part one is 2.2 km and part two is 3 km. The average speed of the movement is 3 km/h and 3.6 km/h respectively. The data was gathered from 19.08.2015 to 16.03.2016 and contains 210 days of observation.

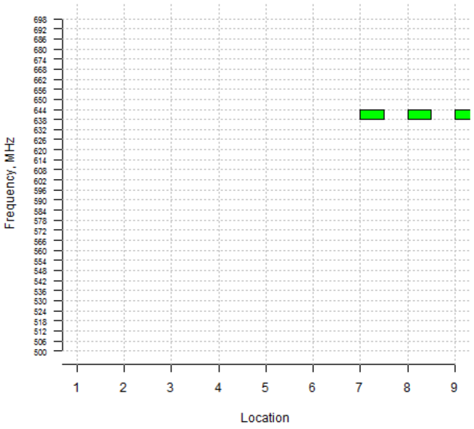
In the first part of the route, tourist goes from metro station to the Empire State Building. In the second part, after spending in the Empire State Building two hours, tourist proceeds to the Carnegie Hall. The Manhattan area is extremely dense populated, and spectrum resources are scares as expected, availability of the channels changes dramatically. As can be seen from Figures 11, 12 and 13, at the beginning of the route there are no channels available, except on period from 31.12.2015 to 01.01.2016. As the tourist proceeds



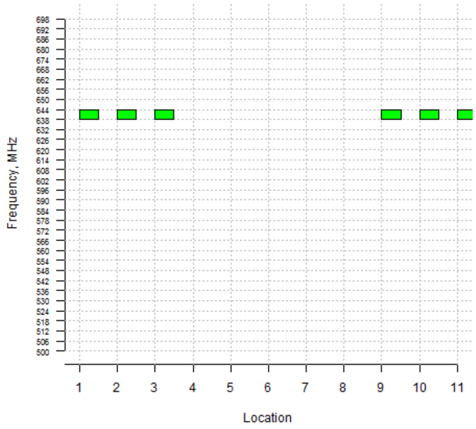
(a) Part 1 (b) Part 2

Figure 10: Manhattan tourist route

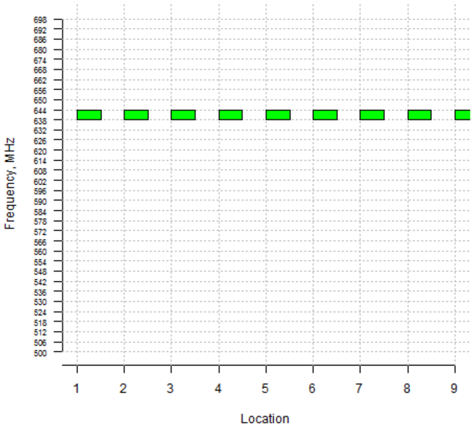
closer to the Empire State Building one channel becomes available. After two hours when the second part of the route is executed one channel is still available near Empire State Building, but in the middle of the second part of the route, there is no spectrum accessible on the period from 19.08.2015 to 01.01.2016. From 02.01.2016 to 16.03.2016, one channel is continuously available through the entire second part of the route. Figure 14 shows the probability heatmap of channel availability, meaning how likely each channel is available during the time span of data collection for the route. The heatmap values were calculated dividing the number of days the channel was available by the total number of days.



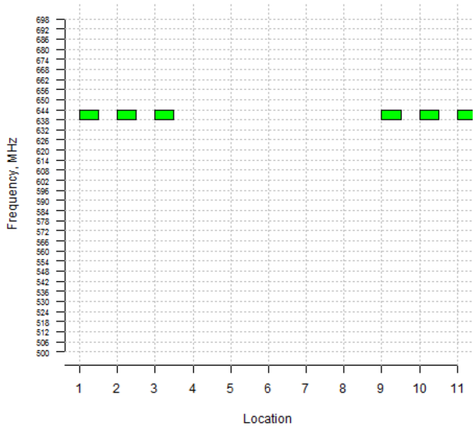
(a) Part 1,
from 19.08.2015 to 30.12.2015



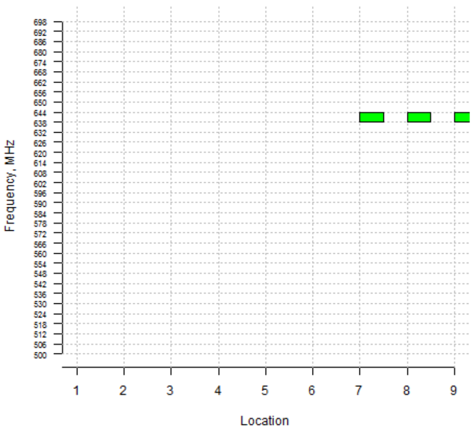
(b) Part 2,
from 19.08.2015 to 30.12.2015



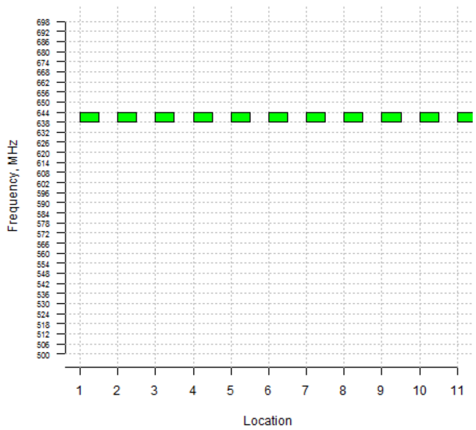
(c) Part 1,
from 31.12.2015 to 01.01.2016



(d) Part 2,
from 31.12.2015 to 01.01.2016

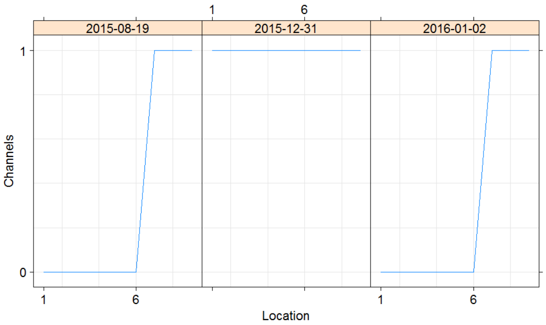


(e) Part 1,
from 02.01.2016 to 16.03.2016

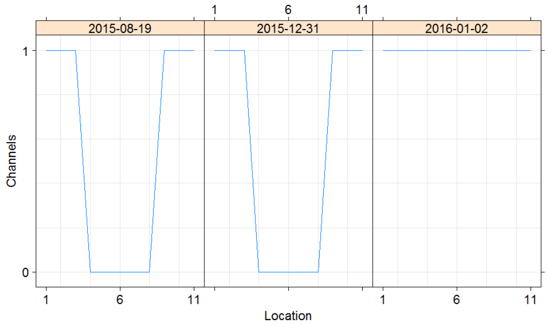


(f) Part 2,
from 02.01.2016 to 16.03.2016

Figure 11: Manhattan tourist route, spectrum availability.
Green indicates 16 dBm power level.

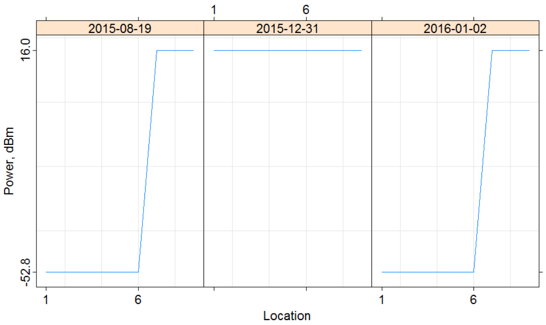


(a) Part 1

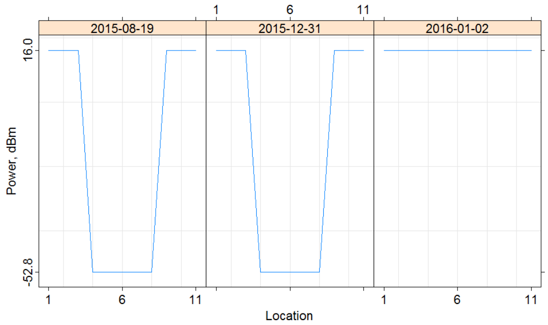


(b) Part 2

Figure 12: Manhattan tourist route, number of available channels.

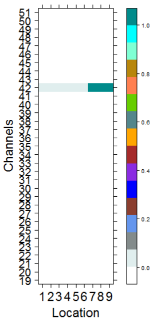


(a) Part 1

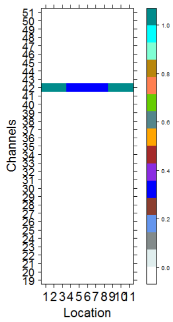


(b) Part 2

Figure 13: Manhattan tourist route, power levels.



(a) Part 1



(b) Part 2

Figure 14: Manhattan tourist route, probability heatmap of channels availability.

3.2.3 Santa Monica Coastal Bicycle Route

The famous Santa Monica bicycle route goes along the coastal line of Santa Monica. Figure 15 shows the geography of the route. The length of the route is 5.5 km, and the average speed is 14 km/h. The data was collected during the period from 20.08.2015 to 16.03.2016 and contains 209 days. These is no spectrum available along the route and no temporal changes, see Figure 16.

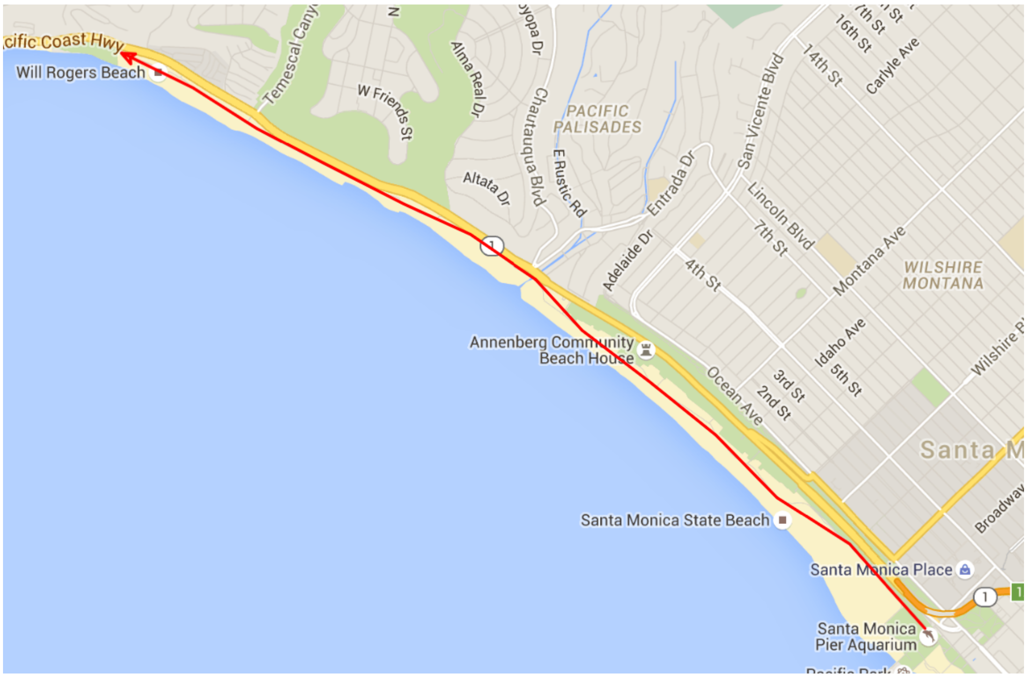
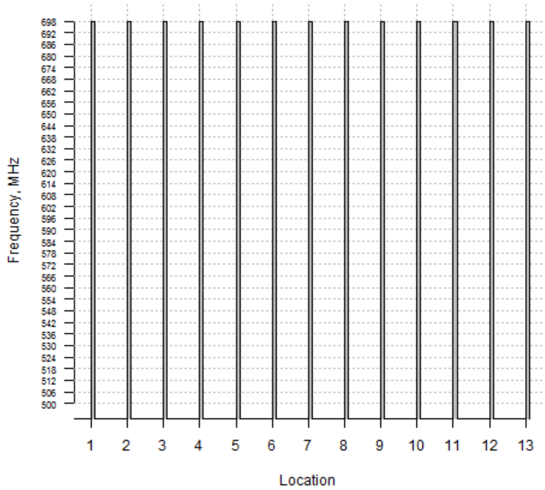
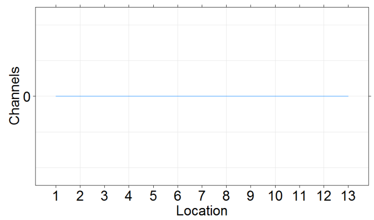


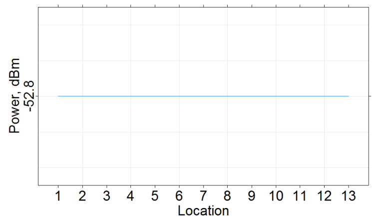
Figure 15: The Santa Monica coastal bicycle route.



(a) Spectrum availability.
Gray indicates -52.8 dBm power level.



(b) Number of channels



(c) Power levels

Figure 16: The Santa Monica coastal bicycle route spectrum data.

3.2.4 Driving Along Sacramento 128

The Sacramento route is going along road 128 across famous wine valley from Rutherford to Putah Creek State wildlife area, see Figure 17. The length of the route is 44 km, and the average speed is 50 km/h. The data contains 208 days, obtained during the period from 21.08.2015 to 16.03.2016.

The area is not of very high population density, and TVWS availability is plentiful, as represented in Figure 18. There are high transmission powers (20 dBm) available almost along the entire trip with sudden disruption near the final destination. There were no temporal changes during the measurement period.

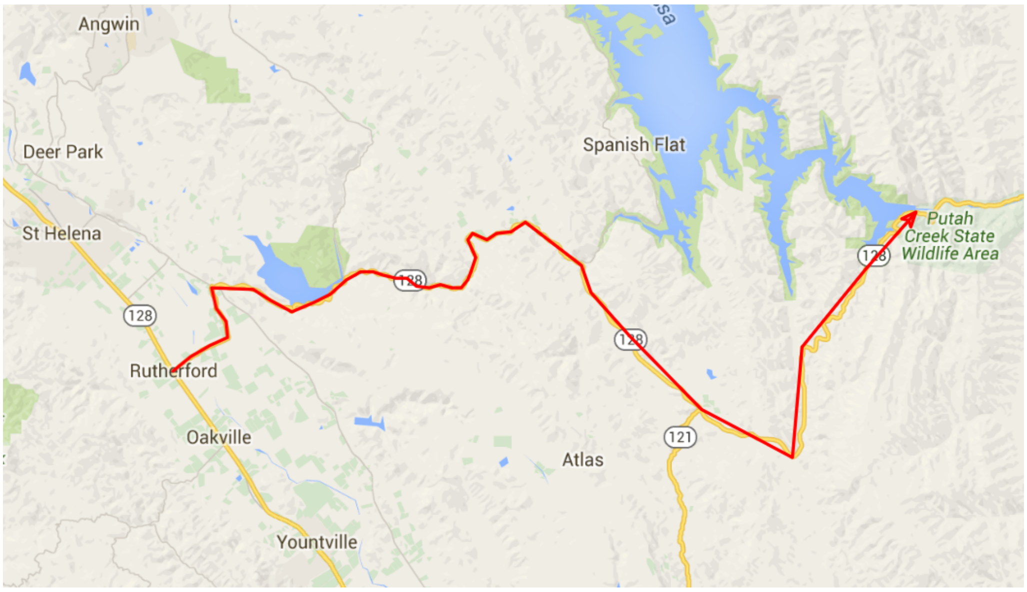
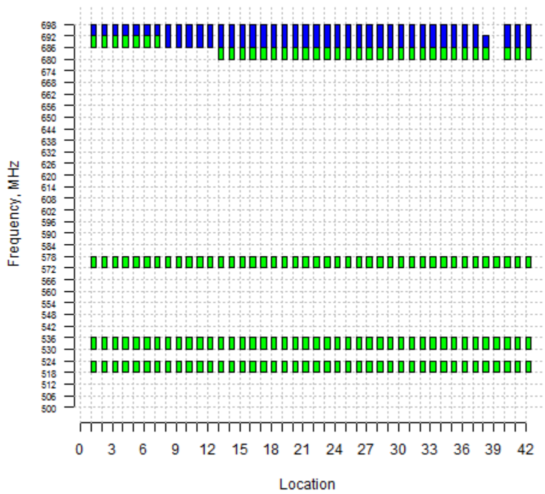
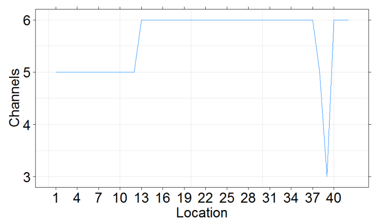


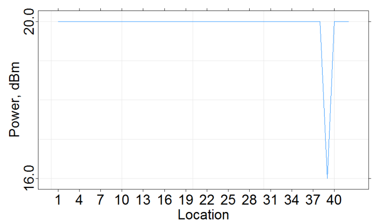
Figure 17: The Sacramento 128 route.



(a) Spectrum availability.
Green indicates 16 dBm power level,
blue 20 dBm.



(b) Number of channels



(c) Power levels

Figure 18: The Sacramento 128 route spectrum data.

3.2.5 Driving Around Berkeley

The Berkeley route is cyclical, and the purpose was to observe a spectrum variance across a large area. Figure 19 displays the geography of the route.

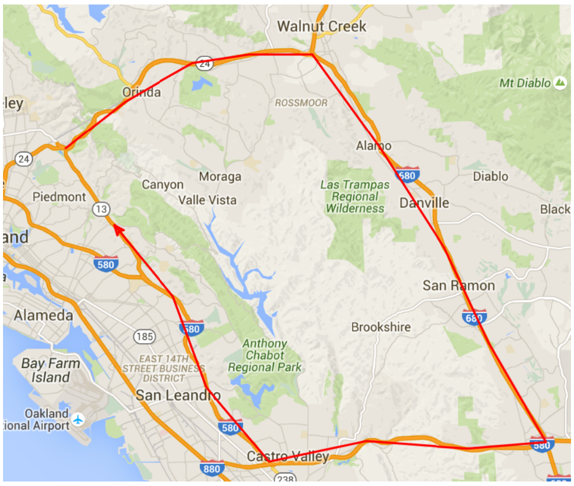
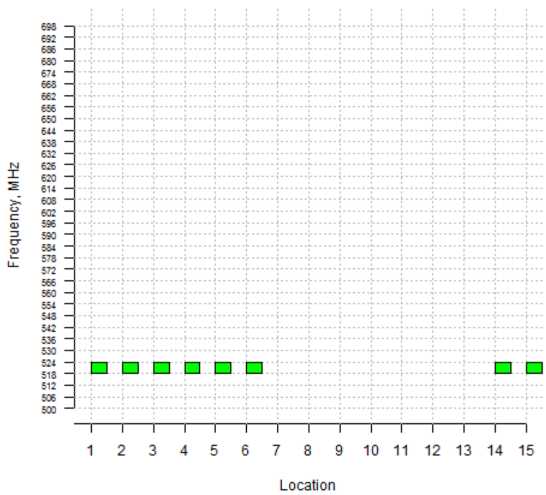
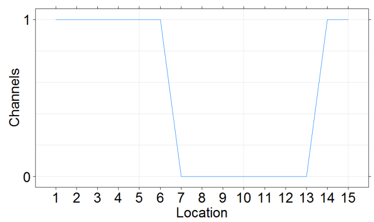


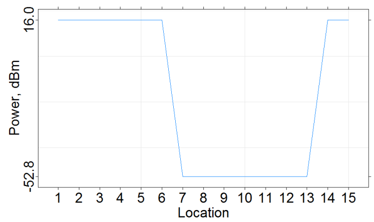
Figure 19: The Berkeley route.



(a) Spectrum availability.
Green indicates 16 dBm power level



(b) Number of channels



(c) Power levels

Figure 20: The Berkeley route spectrum data.

The total length of the route is 72 km, and the average speed is 75 km/h. The period of observations spans from 21.08.2015 to 16.03.2016 and comprises of 208 days. There were no temporal variations during the data collection period. The spectrum availability is poor with only one channel at the beginning of the trip and nothing in the middle part, as Figure 20 shows.

3.2.6 From Santa Barbara to LA

Figure 21 displays the route from Santa Barbara to LA by car. The length of the route is 117 km, and the average speed is 92 km/h. The data was gathered on 164 days from 4.10.2015 to 16.03.2016.

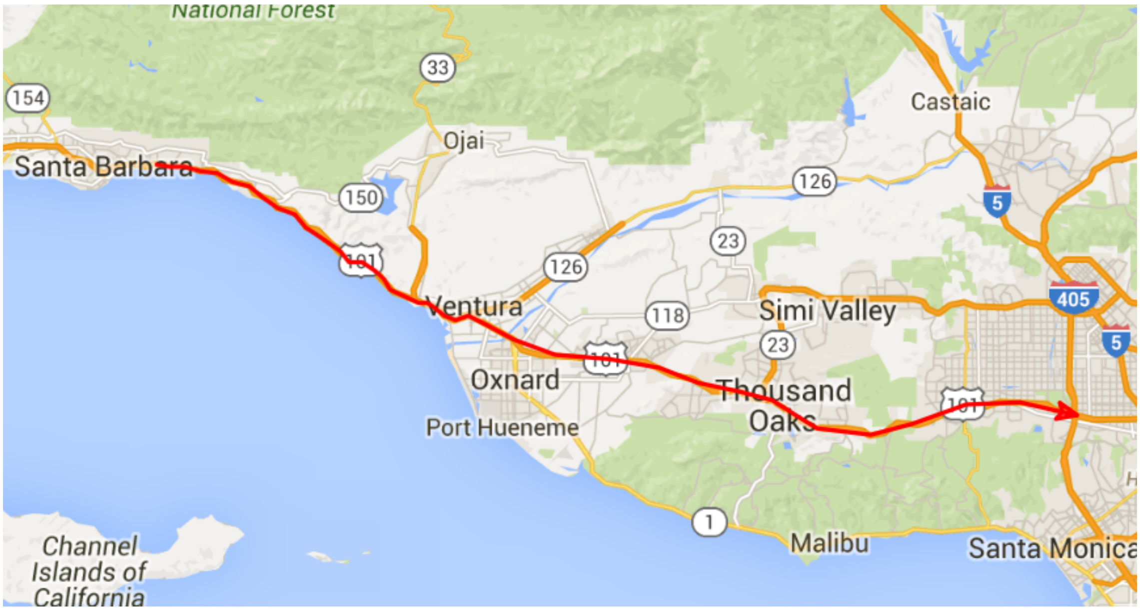
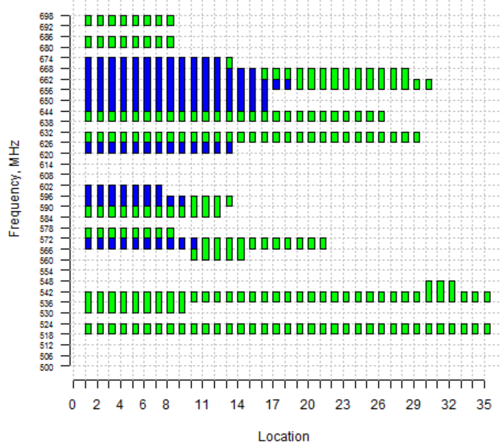
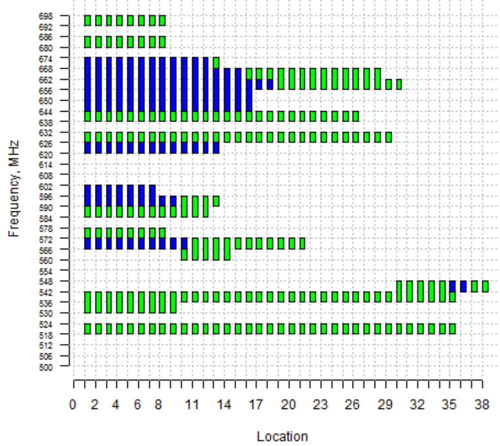


Figure 21: The route from Santa Barbara to LA.

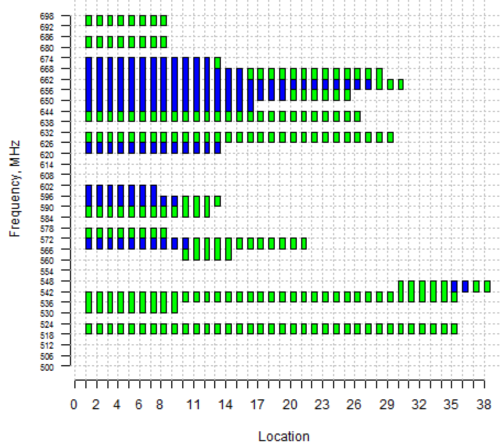
The offering of the free spectrum is generous at Santa Barbara and deteriorates towards LA, see Figures 22, 23 and 24. There are two major temporal changes in spectrum availability: on 08.10.2015 some spectrum at locations closer to LA became available and on 10.03.2016 more channels were freed up in the middle of the route. The Figure 22 (d) displays probability heatmap of channel availability during the research period. The probability heatmap was generated according to the same principles as for the Manhattan Tourist route (3.2.2).



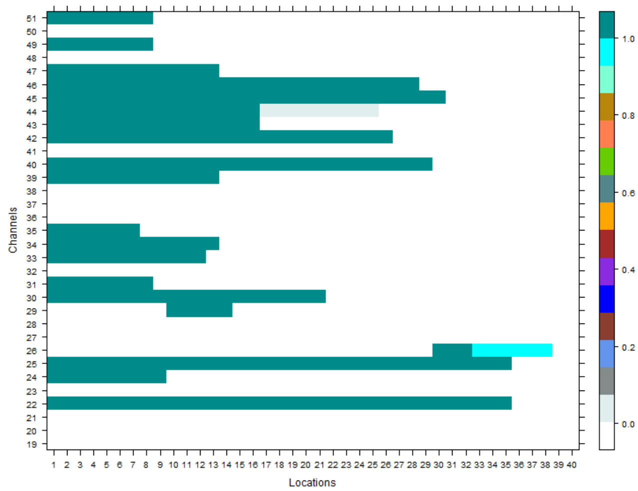
(a) From 04.10.2015 to 07.10.2015



(b) From 08.10.2015 to 09.03.2016



(c) From 10.03.2016 to 16.03.2016



(d) Probability heatmap.

Figure 22: Spectrum availability. Green indicates 16 dBm power level, blue 20 dBm.

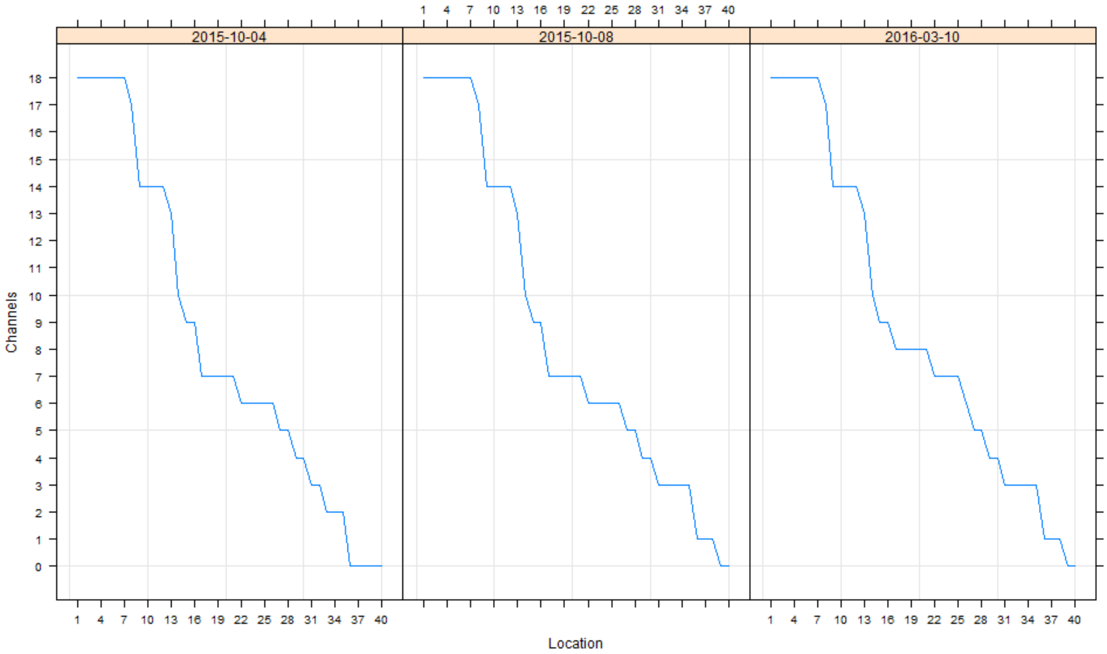


Figure 23: Number of channels

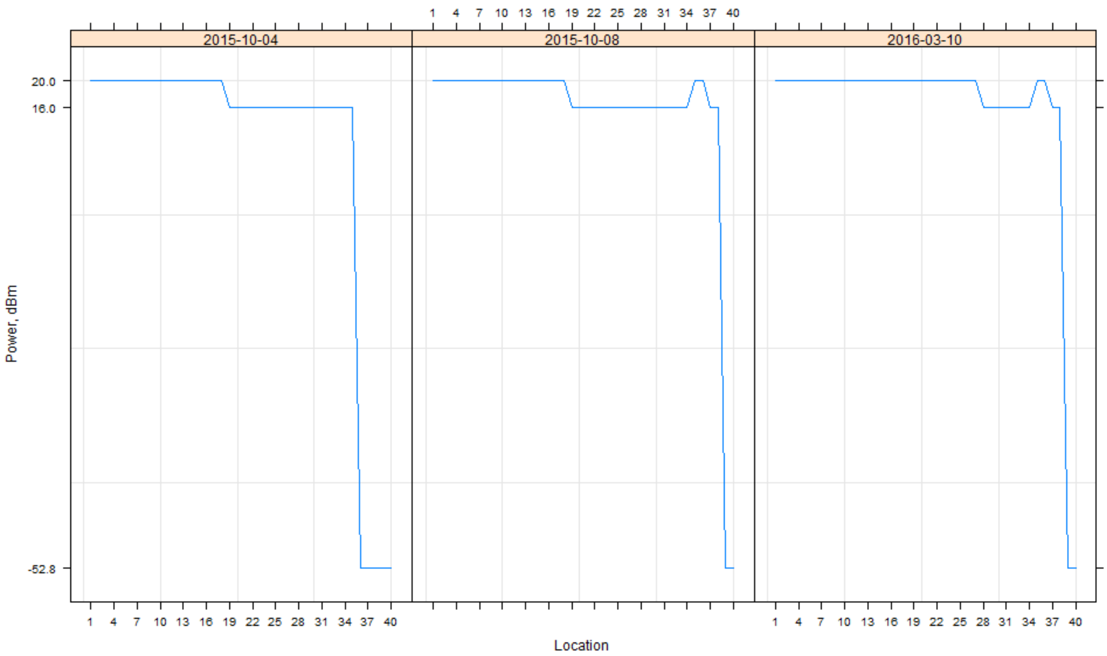


Figure 24: Power levels

3.2.7 From LA to San Diego

Figure 25 shows the route from LA to San Diego by car. The length of the route is 126 km and the average speed is 83 km/h. The data collection period spans from 05.20.2015 to 16.03.2016 and consists of totally 163 days. The availability of the TVWS is increasing as the route proceeds to San Diego, see Figure 26. Figures 27 and 29 show the number of channels accessible along the route and probability heatmap of channel availability. Figure 28 displays variability of the maximum allowed transmission power along the route. The route contains most of the temporal variations observed in the research: the spectrum availability changes nine times.

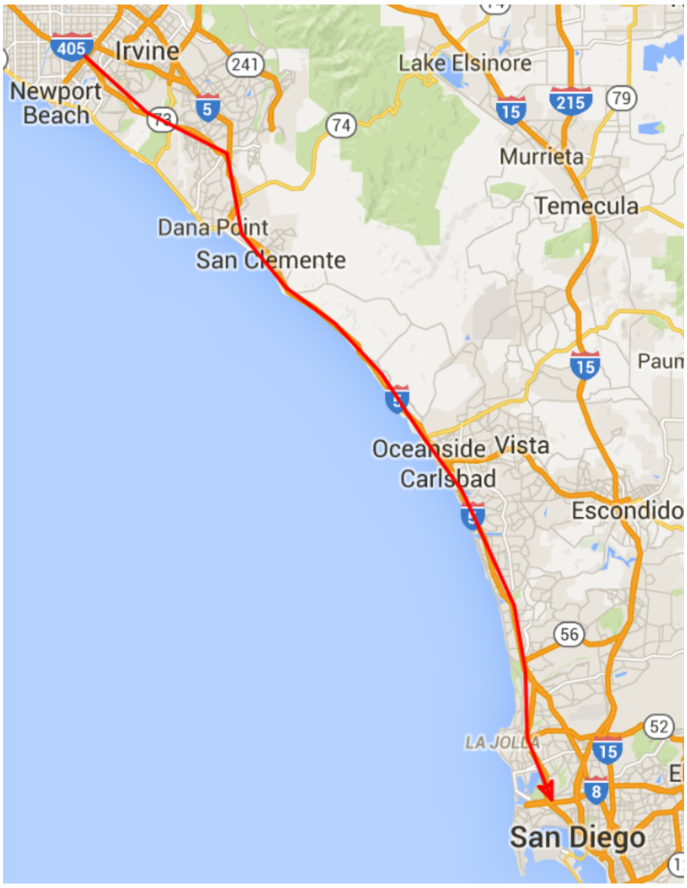
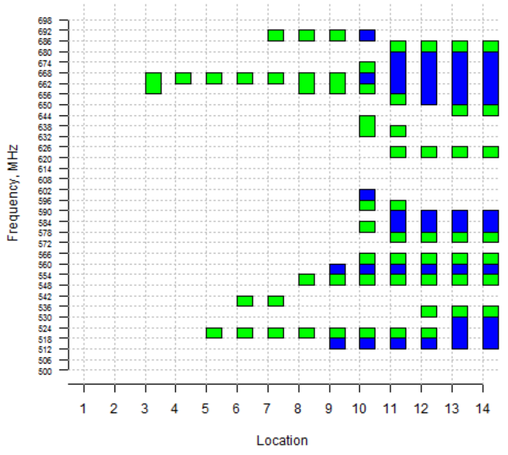
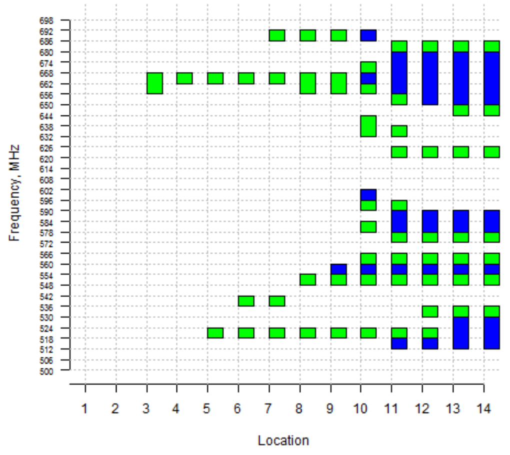


Figure 25: The route from LA to San Diego.

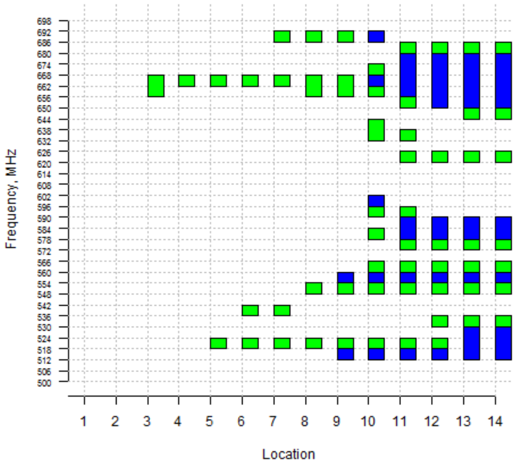
The Figure 29 displays probability heatmap of channel availability during the data collection period. The probability heatmap was generated according to the same principles as for the Manhattan Tourist route.



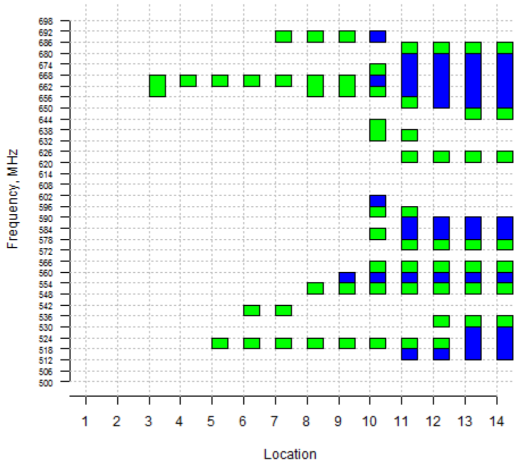
(a) On 05.10.2015



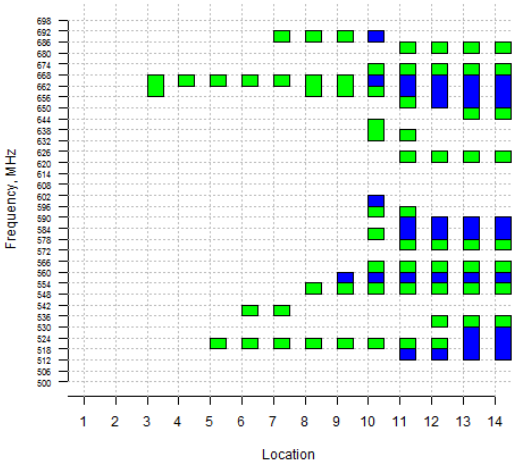
(b) From 06.10.2015 to 02.11.2015



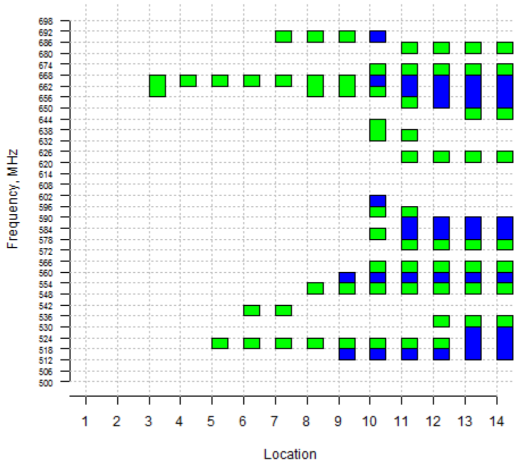
(c) From 03.11.2015 to 09.11.2015



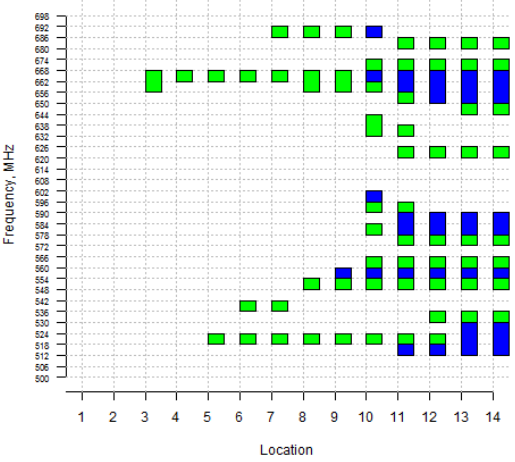
(d) From 10.11.2015 to 13.11.2015



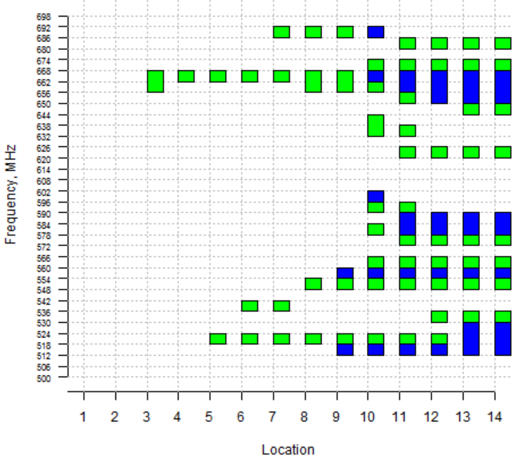
(e) From 14.11.2015 to 08.02.2016



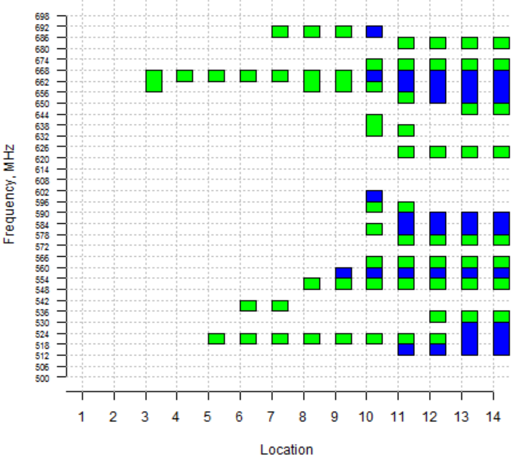
(f) From 09.02.2016 to 15.02.2016



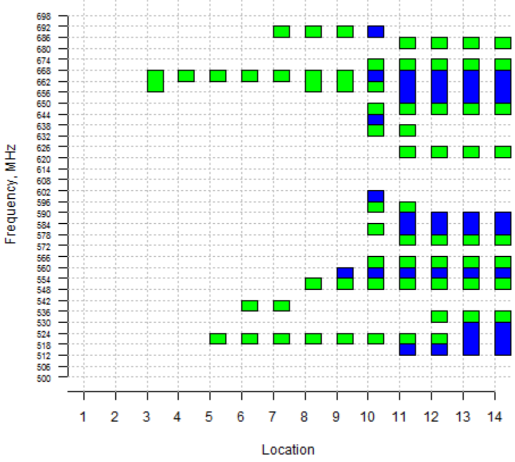
(g) From 16.02.2016 to 22.02.2016



(h) From 23.02.2016 to 03.03.2016



(i) From 04.03.2016 to 08.03.2016



(j) From 09.03.2016 to 16.03.2016

Figure 26: Spectrum availability. Green indicates to 16 dBm power level, blue to 20 dBm.

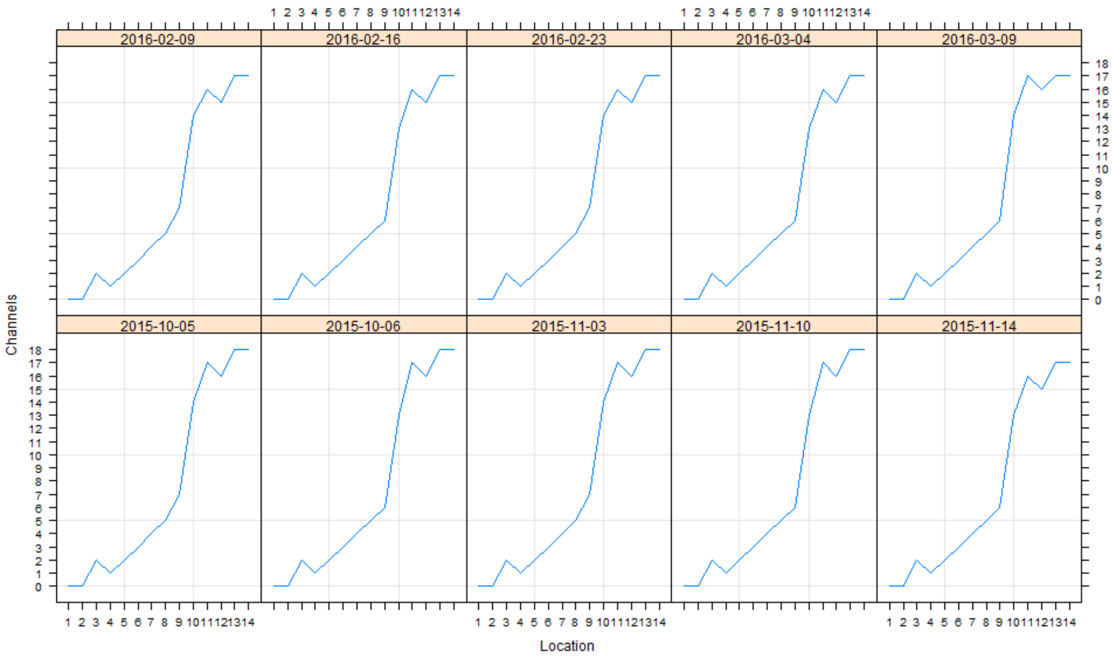


Figure 27: Number of channels

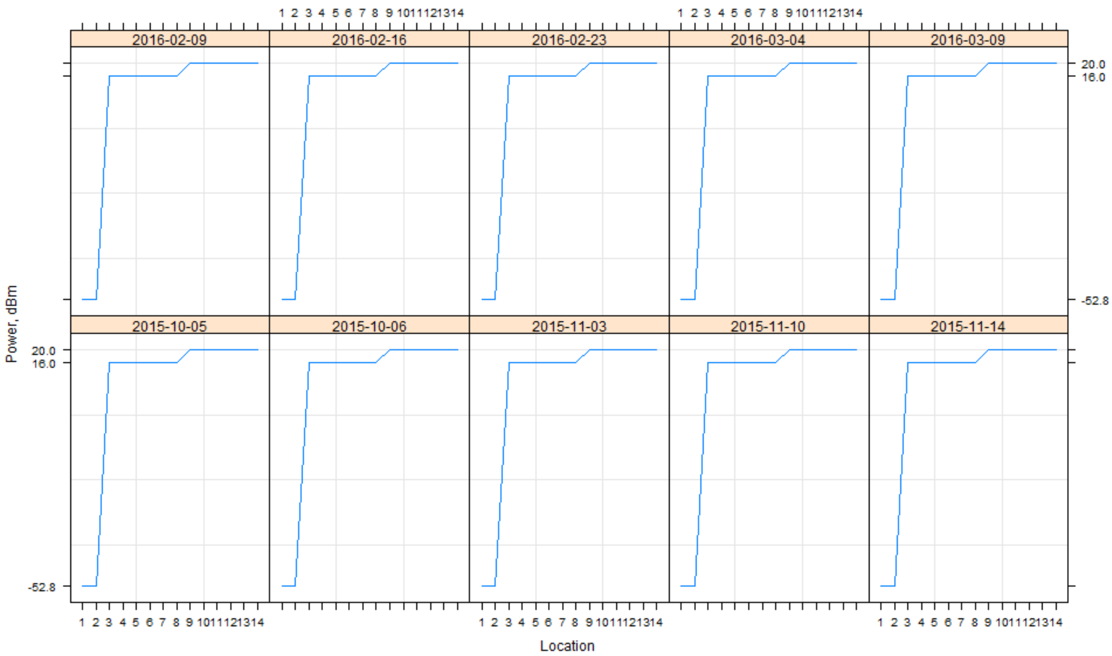


Figure 28: The route from LA to San Diego maximum allowed transmission power variability.

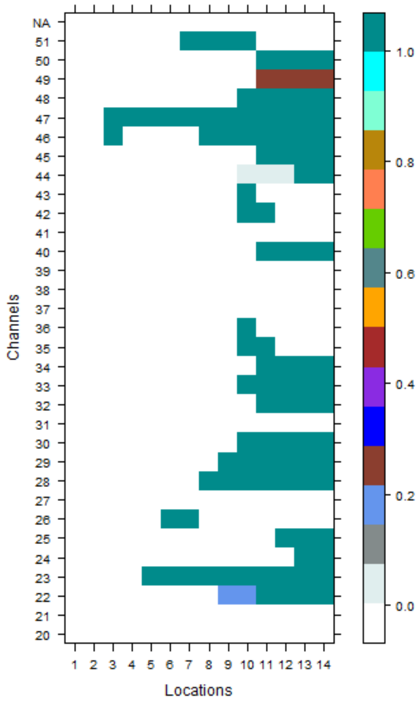


Figure 29: Probability heatmap

3.2.8 Driving Along Montana 90

The route from Bozeman to Billings goes along road 90. Figure 30 shows geographical details of the 218 km long route. The average moving speed is 68 km/h. The data was collected from 16.10.2015 to 16.03.2016, and it encompasses 154 days. As one would expect, the TVWS availability is diminishing near the towns but increases in rural area, see Figure 31. Taking into account that Bozeman is mid-sized town, and Billings is the largest city in Montana with population sizes of 41660 and 166855 respectively, TVWS availability is excellent. Figure 32 displays the variance of channel availability along the route. The maximum allowed transmission power along the route is always equal to 20 dBm, the maximal power for Mode II device.

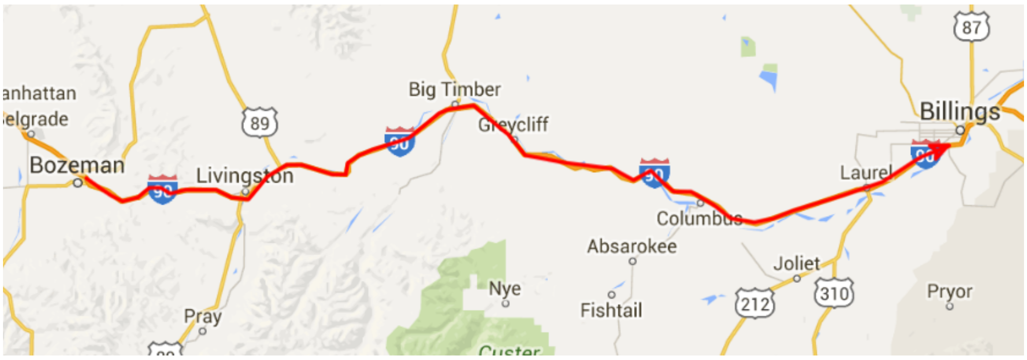
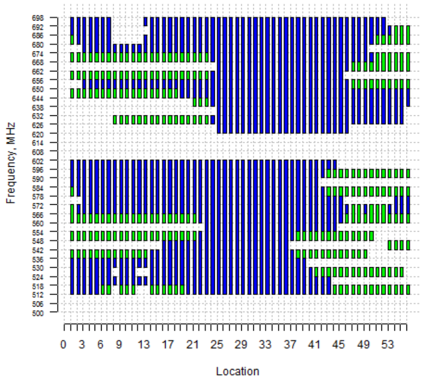
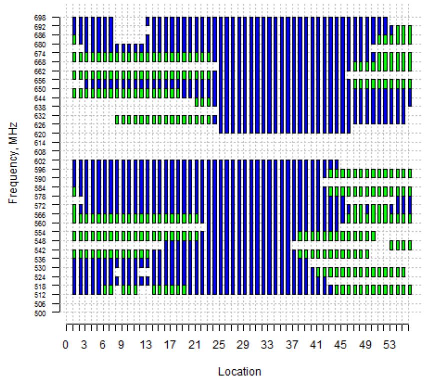


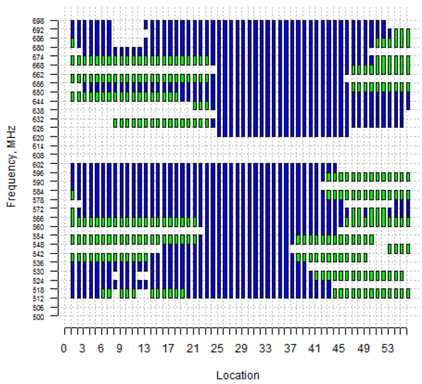
Figure 30: The Montana 90 route.



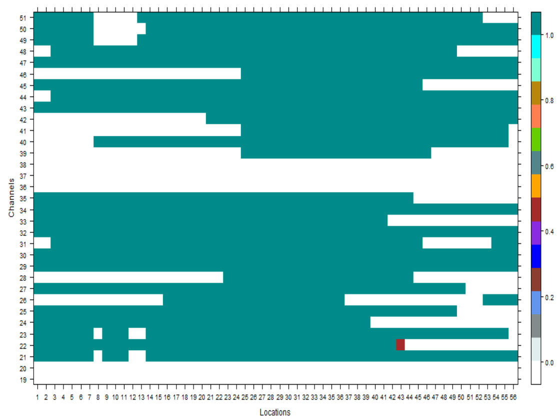
(a) From 16.10.2015 to 16.12.2015



(b) From 17.12.2015 to 08.03.2016



(c) From 09.03.2016 to 16.03.2016



(d) Probability heatmap.

Figure 31: The Montana 90 route spectrum data. Green indicates 16 dBm power level, blue 20 dBm.

There are temporal variations: the channel 22 (524-518 MHz) became unavailable on 17.12.2015 and available again after 08.03.2016 at point 43. This fact is easy to see from the probability heatmap presented in Figure 31 (d). The heatmap is generated as for the previous routes.

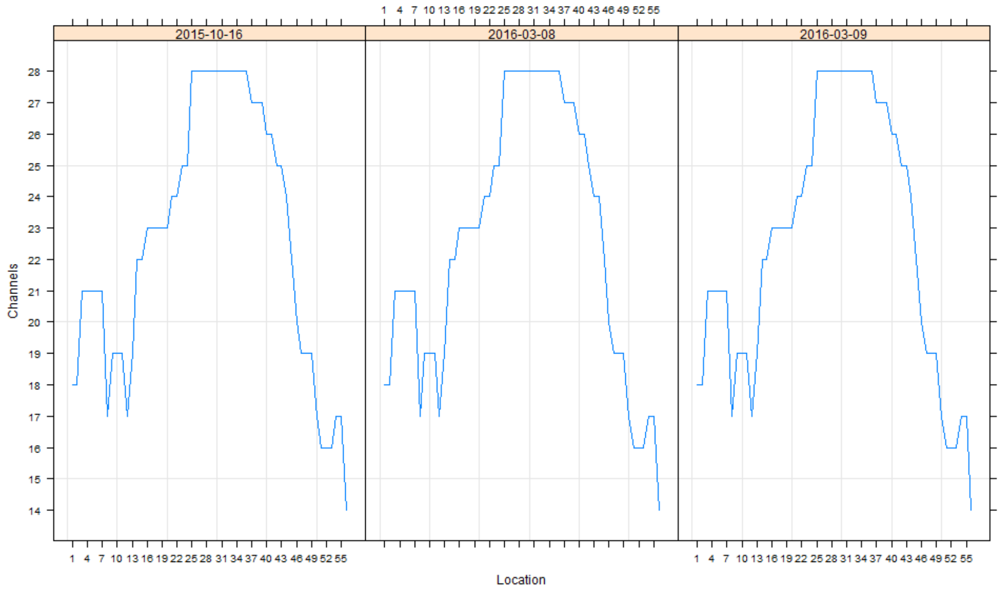


Figure 32: Number of channels

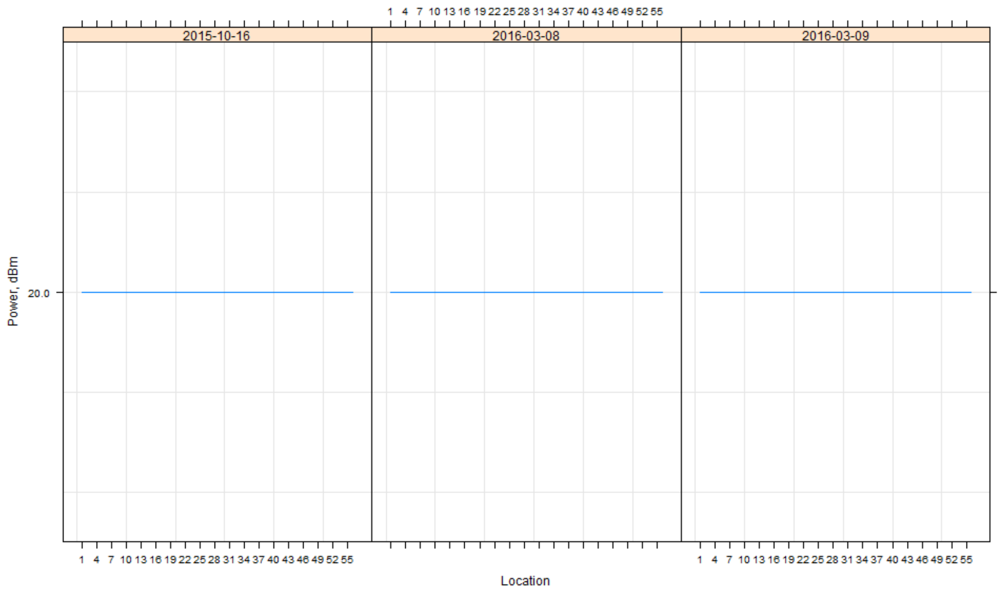
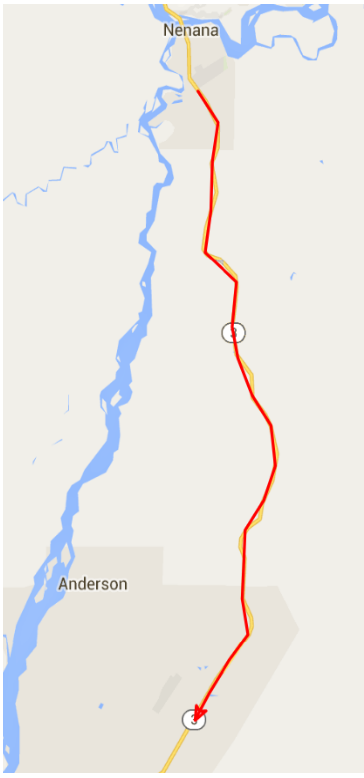


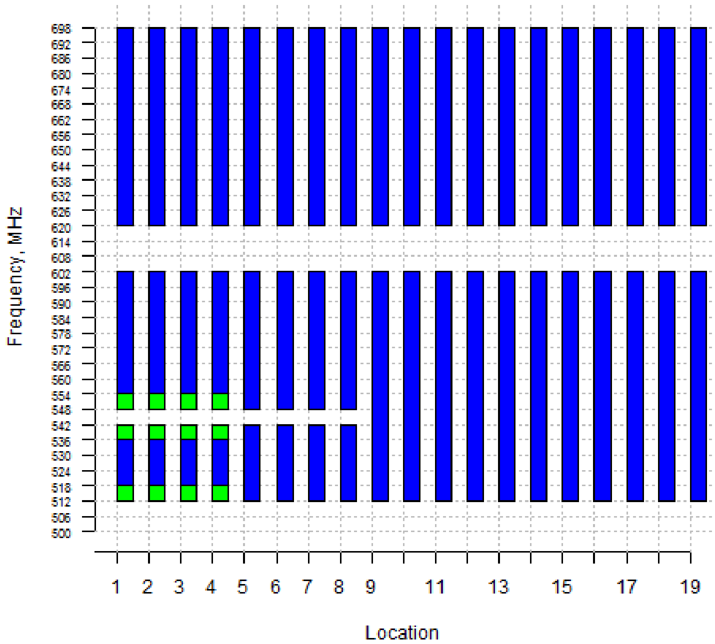
Figure 33: Power levels

3.2.9 Remote Alaska

The route from Nenana to Anderson goes along road 3, as shown in Figure 34 (a). The route is 30 km long, and the average speed is 60 km/h, the data was collected from 16.10.2015 to 16.03.2016 and contains 154 days. Almost all channels are free for 20 dBm transmission (see Figures 34), but despite remoteness and low population density, one channel is occupied near Nenana. As in the case of Montana route, the maximum allowed transmission power along the route displays no variance, and it is always equal to the maximal power for Mode II device, 20 dBm.

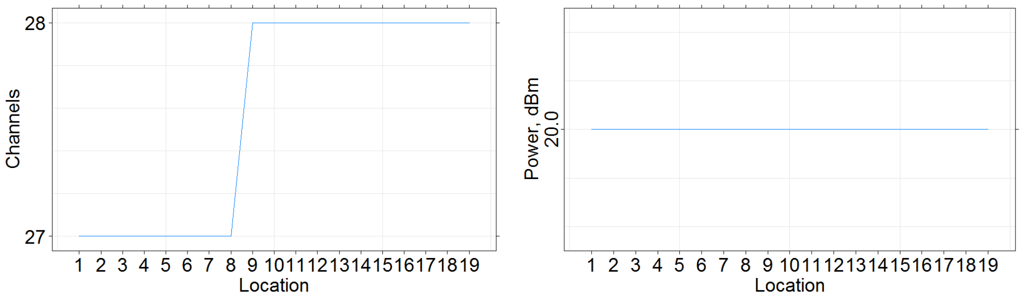


(a) The Alaska 3 route



(b) Spectrum availability

Figure 34: The Alaska 3 route and spectrum data. Green indicates 16 dBm power level, blue 20 dBm.

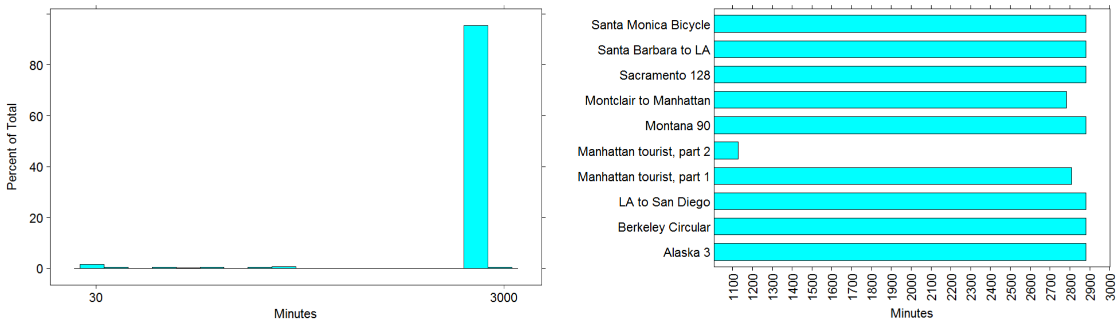


(a) The Alaska 3 route (b) Spectrum availability

Figure 35: The Alaska 3 route and spectrum data. Green indicates 16 dBm power level, blue 20 dBm.

3.3 Spectrum Lease Times

WSDB response along with available channels also specifies periods of time, on which given channel will be available. For the distribution of the values see Figure 36 (a), the shortest lease was only 30 minutes and the longest over two days. However, most of the channels were leased for a time of exactly 2880 minutes or two days. The routes located in the Manhattan area got all the small leases, as Figure 36 (b) shows. The reason is not quite clear; if Santa Monica route had some free channels, it would be possible to correlate high population density with the length of the lease period. However, without any additional information, we can also assume that Manhattan area can be an exceptional case for any other reason. Nevertheless, the majority of leases for Manhattan area equaling two days too.



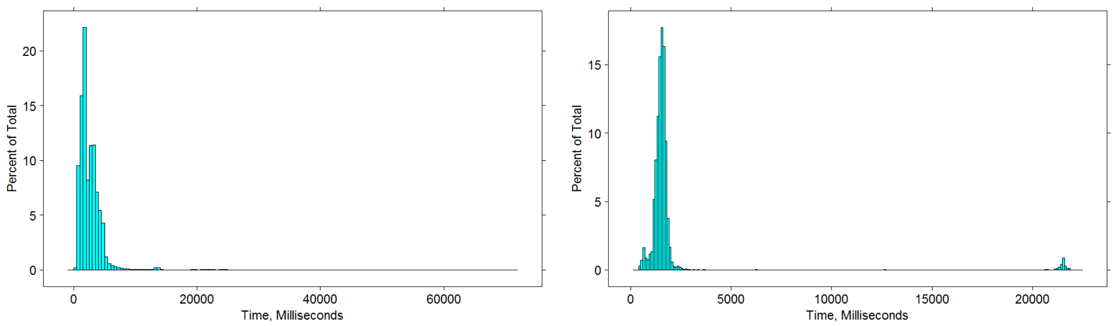
(a) Histogram, the largest peak is at 2880 minutes, or 2 days.

(b) Average lease time by routes.

Figure 36: Spectrum lease times.

3.4 Spectrum Request Execution Times

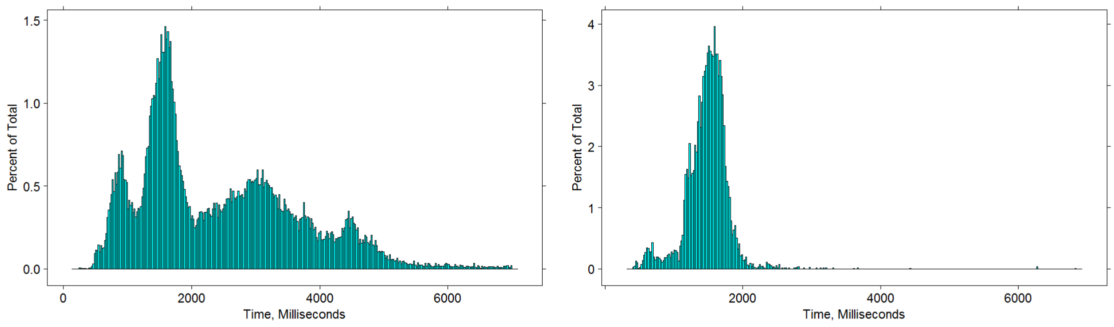
During the data collection, we also measured the time required to send the request to WSDB and process the response. In our research, the time is not only the pure response time of WSDB plus network delay but also the time required by the Android device to initiate network communication, time to serialize object model to JSON and time to deserialize the WSDB response. The measured times are also affected by the nondeterministic Java runtime garbage collection and possible automatic Android system updates. Figures 37 and 38 display the distributions of results. Both mobile devices handle the majority of the requests in less than two seconds.



(a) Phone

(b) Tablet

Figure 37: Available spectrum request execution time.

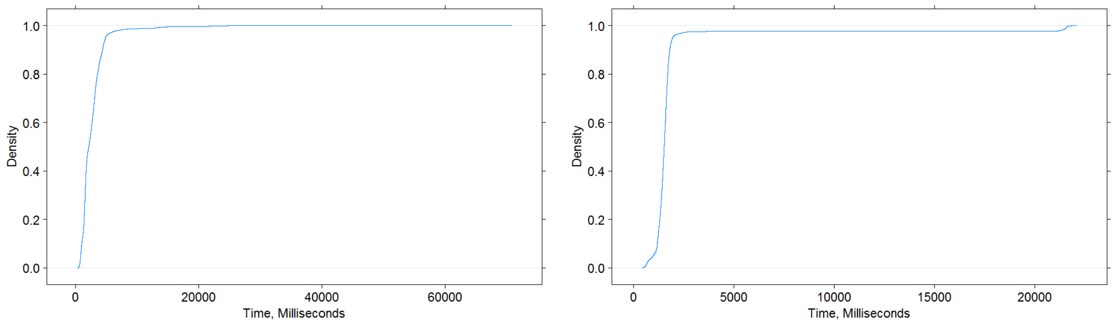


(a) Phone (b) Tablet

Figure 38: Available spectrum request execution time, closer look at the majority of results.

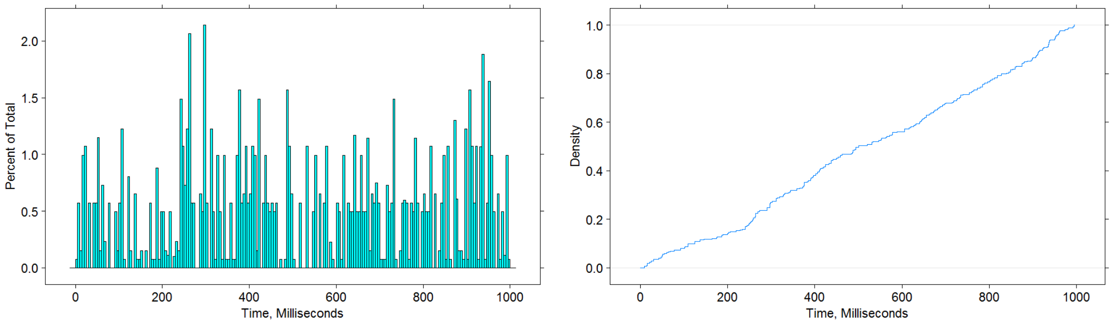
Figure 39 displays Empirical Cumulative Distribution Function (ECDF) of the execution times. Despite the low average duration, at worst a request can take almost 60 seconds to complete.

For other purposes than this research, we had a web server based application issuing spectrum requests to Google WSDB. We also measured execution times of the requests and presented them for comparison with mobile devices in Figure 39. Interestingly, some requests took less than a millisecond to complete, and none went above the second.



(a) Phone (b) Tablet

Figure 39: Available spectrum request execution time, ECDF.



(a) Histogram (b) ECDF

Figure 40: Available spectrum request execution time for server based application.

From the data presented above, we can conclude that the computational power of the device and network delay are quite relevant for efficient WSDB usage. Our phone, GT-I8160, having 800 MHz dual-core processor with 768 MB RAM performed slightly worse than the tablet, GT-P3100, which has 1.0 GHz dual-core processor with 1 GB RAM. The web server of the Azure cloud service with fast network connection displayed excellent performance, so we can assume that response times of Google WSDB itself are negligibly small.

3.5 Notes on the Data and Conclusions

Here are some observations and comments regarding the collected data. Maximum allowed power levels were either 16 dBm or 20 dBm, which correspond to 40 mW and 100 mW. All channels are allowed at the transmission power level of -52.8 dBm or 5.2 nanowatts. Such power would probably be sufficient for underlay transmissions, however, UWB communication systems are not allowed in TVWS frequency range (see Section 2.4.2). There is an obvious correlation between population density and the number of open channels, but even in remote areas of Alaska some channels were occupied, so it is not possible to assume that if population density is low enough, any channel can be used. The significant finding is very low temporal variance.

We can comment on the possibility of TVWS usage by a device moving at high velocity, as follows. If we think of a car, moving at 60 km per hour (which is about 16,7 meters per second), it is easy to calculate that in the case of two seconds delay time to use TVWS will be equal to $(100-(16,7*2))/16,7=3.99$ seconds. After that, the car needs to query WSDB again. So, the use of TVWS is possible assuming the average conditions but the QoS may be poor without optimization algorithms.

We did not notice any adverse effect of continues WSDB querying on the daily performance of our smartphone. There was no observable change neither in the lifetime of the battery nor the responsiveness of user interface. The mobile application running as a background service did not seem to affect the operation of the phone at all, despite issuing and processing hundreds of spectrum availability queries per day and sending the results to the back-end service. However, this opinion is subjective and probably more demanding user would have a different point of view.

One interesting point is also correctness of WSDB operation. On 14.03.2016, all channels were allowed on all points of all routes at maximum 20 dBm transmission power. We interpreted the results as erroneous and excluded them from the analysis. On the next day, Google WSDB operated normally producing expected results. We noticed no other anomalies like that during the data collection period.

4 Discussion and Future Research

To improve the mobile usage of WSDBs, one can exploit the fact that collected data indicates very low temporal variability in the TVWS spectrum. The route from Los Angeles to San Diego has the highest rate of temporal variability, there are spectrum availability changes on 9 of total 163 days, but even at this rate, the probability of daily spectrum change is very low: $9/163=0.0552$. Half of the observed routes have no temporal TVWS spectrum variations at all. Those facts suggest an idea of *spectrum caching* that would be most useful for mobile devices.

The operation principle of spectrum caching would not be much different from any other caching technique. The algorithm for communications with WSDB will change as follows: when MWSD is planning to use TVWS, the first task will be to check if the cache contains any point within 100 meters of the current location, if so, then check that the content of the cache for the location is valid (i.e. still can be used). In case the content is valid, use the cached data and transmit on the available channel(s), in case it is not, send available spectrum request to WSDB and update the cache with the new information. In case the cache was used, the next location to query for available spectrum (or to use the cached data) will be 100 meters minus the distance from current location to the point in the cache that was used (see Figure 41), not to break the rule of querying for spectrum every 100 meters as location changes.

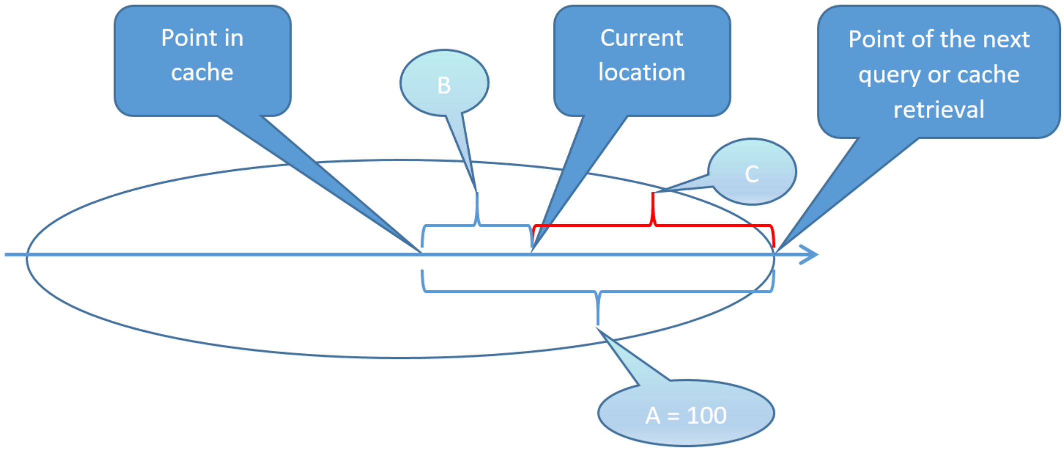


Figure 41: The distance to the next location of spectrum availability query, $C = A - B$.

The key to the viable solution is the cache validation method. The basic solution can use spectrum lease times as expiration dates, but with only two days being the maximum length of the lease period that our empirical data suggests this may seem like an inefficient solution, given that probability of daily changes is very low. Other option would be to make lease times longer or to loosen the regulations and allow WSDs to use cached spectrum with expired lease period. The latter is a risky option because it increases the chances of creating harmful interference.

An alternative solution would employ some method for online validation of the cache content. Such validation method should be more computationally efficient and utilize less network bandwidth than calculating and returning the complete list of available channels each time. The possible implementation of the solution can be a kind of versioning system where the mobile device and WSDB would keep track of the versions of their spectrum data. It is likely that online cache content validation by versioning will be more efficient than the traditional handling of available spectrum request. The method would require changes to PAWS and implementation of additional functionality to WSDBs.

The technical implementation of online spectrum cache validation implies defining a new PAWS method for comparing the versions of spectrum data. The simplest variant of such implementation would version the entire database without partitioning it into specific regions. Any modification of incumbents data will increment WSDB version and invalidate all the mobile spectrum caches. The communication for cache validation will be quite trivial: the MWSD would request the version of WSDB and invalidate the entire cache in case it is incremented. Despite obvious drawbacks, the method may be viable due to its simplicity and rare changes in PU data.

The shortcoming of the previous method, let us call it *simple caching*, is invalidation of entire cache data of all devices when WSDB update is likely to affect just a small area. The improved technique may split area covered by WSDB into regions, and when PU data is updated, WSDB should calculate which region is affected by the change and increment the version number of the region. The cache validation request would be more complex; the MWSD would need to provide own version field and the coordinates, so WSDB can determine the region and compare the versions. In case data is updated, WSDB would reply with the new spectrum availability information. We shall refer to this method as *partition caching*.

Additionally, in both approaches existing available spectrum request, PAWS method should return version field. In simple caching, receiving WSDB response with incremented version would invalidate the entire cache. In partition caching, it would invalidate the cache for the specific region. The MWSDs will have a task of maintaining the spectrum cache. It is also appealing to explore possibilities of IPv6 multicast technology in conjunction with spectrum caching. MWSDs can form multicast groups, and WSDBs can target those groups when notifying for updates. However, further discussion falls out of the scope of the current work.

The more complex scenario would be to use a subscribing model when mobile devices would receive push notifications from WSDB, but this design will have to deal with a large variety of MWSDs, and it is hard to estimate how feasible it would be from technical and economical points of view.

5 Conclusion

In this thesis, we explored research, regulations and standards related to emerging TVWS technology and underlying concepts of CR. We analyzed specific issues that may arise in the utilization of WSDBs by mobile devices and found that research related to the problem is quite scarce. Currently, the difficulties of fast moving devices are addressed only by the Nuna algorithm developed by A. Majid [Maj15] that uses the predictive method to query at locations lying ahead on the path of the movement for available spectrum. We hope that our thesis helped to fill the gap in the research field related to TVWS mobile usage.

We collected a vast corpus of TVWS availability data with unique temporal perspective over six months. We also gathered data concerning the time required by a modern mobile device like an Android smartphone or tablet to issue available spectrum request to WSDB and process the response. It took less than two seconds to process the most of the requests.

The data contains information on lease times of the available spectrum, and the analysis has shown differences between the area of Manhattan and other regions: in the former WSDB may lease a channel only for half an hour while in the latter time lease is usually two days.

Based on the empirical data, we suggested a new technique of *spectrum caching* exploiting the fact of the very low temporal variability of TVWS. The idea is that the MWSD can store TVWS availability data in the cache and instead of issuing new spectrum availability request each time it can compare the version of the cached data with the version of WSDB. We devised two flavors of the technique, simple caching and partition caching, differing by the implementation complexity and efficiency. Both variants of the spectrum caching would require minor enhancements to the PAWS protocol and changes in the WSDB operation. Comparison and detailed performance evaluation of simple caching and partition caching have fallen out of the scope of the current work. We sketched only basic requirements and implementation principles of the spectrum caching, requiring future research and evaluation of the techniques. The options of utilizing push notifications and IPv6 multicast protocol for MWSDs were barely touched and also require additional exploration.

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Glossary of Acronyms

AP Access Point. 9, 12

API Application Programming Interface. 5

BS Base Station. 6, 7, 9–12, 16

CCA Clear Channel Assessment. 14, 15

CCC Common Control Channel. 15, 17

CDIS Coexistence Discovery and Information Server. 17

CE Coexistence Enabler. 17

CHE Cluster-Head Equipment. 16, 17

CM Coexistence Manager. 17

CPC Cognitive Pilot Channel. 17

CPE Consumer Premise Equipment. 12

CR Cognitive Radio. ii, 1, 6, 8, 9, 14, 16

CRAHN Cognitive Radio Ad Hoc Network. 9, 14

CRN Cognitive Radio Network. 8, 9, 16

CVS Contact Verification Signal. 12

DAMA Demand Assigned Multiple Access. 12

DCS Dynamic Channel Selection. 14, 15

DFH Dynamic Frequency Hopping. 12

DSA Dynamic Spectrum Access. 1, 2, 4

DSL Digital Subscriber Line. 12

DSL Dynamic Strategy Learning. 14

EIRP Equivalent Isotropically Radiated Power. 3, 4, 12

FCC Federal Communications Commission. 2–5, 13, 16, 18, 20, 22, 23, 25

GDB Geolocation Database. 2, 12, 13

GDD Geolocation-Database-Dependent. 12, 13

GPD Gross Domestic Product. 1

HTTP Hypertext Transfer Protocol. 24

IA Interference Alignment. 11

IEEE Institute of Electrical and Electronics Engineers. 2, 6–8, 11, 12, 14–16, 18

IETF Internet Engineering Task Force. 24

IMT Irregular Terrain Model. 19

IoT Internet of Things. 6

IP Internet Protocol. 17

ISP Internet Service Provider. 3

JSON JavaScript Object Notation. 24

L-R Longley-Rice Propagation Model. i, 18, 19, 22

LBT Listen Before Talk. 1, 12, 14, 15

LPAS Low-Power Announcement Service. 3

M2M Machine-to-Machine. 6

MAC Medium Access Control. ii, 9, 12, 13

MWSD Mobile White Space Device. 4, 5, 8, 25

NE Nash Equilibrium. 16

Ofcom Office of Communications. 2, 4, 13

OFDMA Orthogonal Frequency Diversity Multiple Access. 12

P2MP Point to Multipoint. 12

PAWS Protocol to Access White Space Database. 24, 25

PU Primary User. 3, 4, 8, 13, 17, 18, 20, 21, 23, 24

QoS Quality of Service. 12, 14

RL Reinforcement Learning. 14

RLSS Registered Location Secure Server. 13

RSSI Received Signal Strength Indicator. 11

SNR Signal-to-Noise Ratio. 23

SPOC Signal Prediction and Observation Combiner. 19

STA Station. 12, 13

SU Secondary User. 3, 8, 13, 16, 17

TAG Technical Advisory Group. 16, 17

TDMA Time-Division Multiple Access. 12, 15, 16

TPC Transmission Control Protocol. 17

TPC Transmit Power Control. 14, 15

TVBD TV-Band Device. 3, 4, 17, 20, 23

TVWS Television White Space. i, ii, 1–15, 17–25

UHF Ultra High Frequency. 18

UWB Ultra Wide Band. 8

V2I Vehicle-to-Infrastructure. 11

V2V Vehicle-to-Vehicle. 11

VN Vehicular Network. 8

WISP Wireless Internet Service Provider. 7