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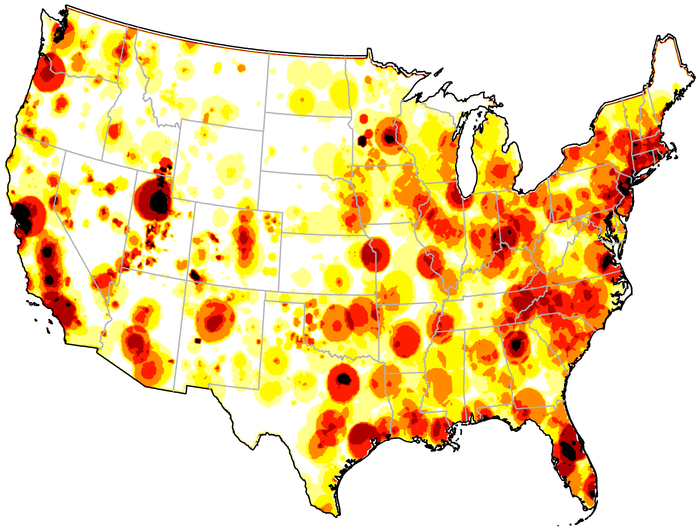

The performance of macro cellular networks operating in American TV white space

Master's Thesis in Complex Adaptive Systems

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Abstract

Secondary access to white space in the US TV spectrum is a mechanism/practice to provide spectrum for mobile broadband communication. The FCC's rules governing white space in the US are evaluated for a mobile broadband system using LTE system-level simulations. Promising link capacity estimates exist for US white space, although there is a need for more detailed simulations to compare with studies of European white space. This thesis determines the TV transmitter's total interference power, spread over the US and considering each available channel, where after mobile broadband performance can be evaluated in different use-cases with different channel selection criteria. TV transmitter data provided from a proprietary Ericsson database, SPLAT's implementation of the irregular terrain model and Monte-Carlo simulations are used to determine the TV interference power. Mobile broadband performance is then evaluated using an internal Ericsson LTE simulator with the FCC's rules accounted for. Available white space is found to be quite high, but the usability is limited by the use-case and the channel selection criteria. A mobile broadband system, based on LTE, deployed in TV white space would not provide sufficient coverage if typical site densities were used. Opportunistic traffic offloading from an existing network looks more promising and could in some regions provide significant capacity boosts. The US population is concentrated in certain regions, and the usefulness of the available channels at a certain location must be assessed with the population distribution in mind.

May contain nuts.

Acknowledgements

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Tom Baylis, Kista
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Introduction

The global mobile data traffic is growing at a terrific rate. Ericsson's 2012 traffic mobility report predicts that monthly global traffic will increase from $1.1\,\mathrm{EB}$ to $13\,\mathrm{EB}$[1] in the period from 2012 to 2018 [1, p. 10-11]. Cisco's traffic forecast predicts that mobile data will exceed $10\,\mathrm{EB}$ in 2016, increasing roughly 18 times from 2011 to 2016 [2]. This growth is sometimes seen as an explosion of traffic demand [3, p. 1] or a tsunami of wireless data use [4].

This increased demand for wireless data requires a larger portion of the frequency spectrum or more efficient use of it. The Federal Communications Commission (FCC), responsible for licensing and regulating the US spectrum, have filled frequency allocation charts [5], with few holes for further use. Redistribution of allocated frequencies and schemes for spectrum sharing are appropriate and needed. Even after the digital dividend was finalised [6] and the FCC's white space rules introduced, president Obama instructed the FCC to continue improving spectrum usage and open up more underutilised spectrum [7].

Spectrum is traditionally allocated to *primary users*, service providers who license a frequency block for exclusive use. A *secondary user* can utilise a frequency block at certain times and locations, under the condition that the *primary user* retains their level of service. A secondary use of spectrum can be realised in many

[1] 1 EB (exabyte) is 1000 million (10^9) gigabytes.

different ways, either by being geographically or temporally separated from the primary user, or by transmitting with a low power at short range, thus limiting harmful interference to the primary user's system.

White space Spectrum which can be used by secondary users is labelled *white space*. Primary users' exclusive rights to their spectrum are being changed to allow for white space usage while protecting the primary service. The Electronic Communications Committee, part of the European Conference of Postal and Telecommunications Administrations, published a report defining rules for white space use in the TV spectrum [8]. This framework has been assessed for Germany, and the results presented at IEEE DySPAN [9, 10]. The FCC published TV white space rules in 2008 [11] which will be the main topic of this thesis.

Previous work Mishra and Sahai take the FCC's rules and estimate the amount of available white space in the US [12]. Harrison, Mishra, and Sahai made bandwidth estimates in the available white space [13] thus indicating the total capacity of a system operating in white space.

The QUASAR[2] project [14] suggests some different uses of white space. These included among others *cellular use of white space*, *WiFi-like use of white space* and *secondary wireless backhaul* which are of interest for this thesis.

Gamarra [3] has considered secondary usage scenarios in the aeronautical band $960 - 1215$ MHz. Her licentiate thesis studied both the requirements for secondary access, and designed a method to assess the availability, modelling adjacent channel interference. She also proposed an indoor model for short range white space utilisation within a broadcast system which was experimentally tested [3].

The Federal Communication Commission's rules The 2008 rules, enabling the use of TV white space [11] allow secondary users to reuse the frequencies from TV broadcasters when outside a certain distance from the broadcast locations. The TV broadcast system uses frequencies between 54 MHz to 698 MHz, and is covered in more detail in section 2.3. Different services operating within the

[2] Project website: `http://www.quasarspectrum.eu`

frequency range, not part of the TV broadcast system still need protection from secondary users' signals. These services include radio astronomy observatories and the TV transmitters across the borders to Canada and Mexico. This thesis considers the latest version of the FCC's rules, including the updates and amendments from 2010 and 2012 [15, 16].

The FCC's rules rely on databases, accessible to secondary users which list protected services and their locations. A device can then poll the database with its location and receive a list of channels available for use. In 2011 Spectrum Bridge Inc. [17], and in 2012 Telcordia [18] were granted the permission to operate "TV bands database systems". These are often referred to as geo-location TVWS databases.

1.1 Purpose

The purpose of this thesis is to evaluate the realisable capacity of TV white space for use in a macro cellular system in the US. The FCC's rules will be evaluated to find the number of available channels. The interference from the TV transmitters will then be calculated to estimate the channel quality. Finally system level LTE simulations will be performed, where the capacity of a LTE network, deployed in the usable white space will be measured and compared to a reference system.

Two deployment use-cases for the macro LTE system will be considered, a *standalone cellular network* operating in white space, and an *offloading* WiFi-like use-case where the white space deployed network is used for capacity boosting.

1.2 Delimitations

The analysis is limited to the 48 contiguous American states between Canada and Mexico, thus excluding Alaska and Hawaii. TV transmitters within the US and along the Canadian and Mexican borders are considered.

The number of protected services is limited to the TV transmitters themselves, radio astronomy observatories and the Canadian and Mexican border regions.

TV translator sites and cable head ends receive the TV signal on one channel, and can be located outside the service contour of the signal source. Extra protection is thus needed to ensure that secondary users do not interfere with TV reception. There are no publicly available protection contours, so this protection has been excluded in this analysis.

The coarseness of the chosen pixels, roughly 10 by 10 km will be reflected in the detail of the final analysis. Available white space will reflect the general country wide availability and not so much specific locations with any certainty.

1.3 Outline

The thesis is split into three main threads; the TV coverage, the aggregate interference levels with the channel availability, and the performance of the LTE system.

The second chapter, *Background*, introduces different propagation models used in the TV coverage assessment and the simulator SPLAT's implementation of them. White space is then defined, and put into the TV context by the FCC's rules. Finally the chapter introduces basic theory of cellular networks and investigates approaches for evaluating the performance of the system.

The *White space assessment* chapter goes into more implementation-technical details of the simulations, thus describing the method. TV coverage calculations are defined on a grid, and the propagation model's parameters are noted. The FCC's rules are then applied to the TV coverage grid and a Monte Carlo method for determining the aggregate interference level is discussed. A side step is made, to make link capacity estimates, these are then compared and validated with external results. Finally the implementation of the LTE simulator is discussed together with the cellular network use-cases.

Results are presented in chapter 4, following the threaded style. First the TV coverage from an example transmitter is shown and the field strength calculated by SPLAT is compared to other models. TV interference power distributions are presented indicating the amount of available white space and its quality. The performance of the LTE network is presented, with its performance indicators and possible channel selection criteria.

The fifth chapter, *Discussion* will deliberate and compare the results from chapter 4 with previous work. Possible alternative scenarios will be introduced and presented for possible future work.

Conclusively, the bibliography and appendices end the thesis. The appendix contains some tables and important motivations which have been omitted from the main text to improve clarity and readability.

1.4 Data sources

This thesis uses a number of different databases and data sets. Their connections and use are depicted in figure 1.2 together with the major computational and simulation steps. The data used has been made available at different dates, which sometimes leads to smaller inconsistencies. These problems are noted in the text when they occur.

The TV transmitter database is provided by Ericsson, and is a proprietary set of transmitters valid for the 20th of April 2012. Transmitters in neighbouring Mexico and Canada are included along the border regions, and out of the 9392 listed transmitters 8239 are in the US. Each transmitter has a designated service type; digital TV, class A digital TV, low power digital TV and translator sites, there are also 320 analogue class A transmitters in the database, and the distribution is shown in figure 1.1. Translator sites receive a different transmitter's signal and relay or repeat it over a new area, possibly also on a different channel. The majority of the transmitters use a digital signal, and this thesis assumes that all transmitters are digital.

The TV transmitter's service contours are retrieved from the FCC's website [19]. Each contour is identified by a label, available in Ericsson's transmitter database, enabling the merging of the two datasets. These service contours are defined by 360 latitude and longitude pairs for each transmitter and their use will be discussed further in section 2.3 where the TV broadcast system is detailed.

The Shuttle Radar Topography Mission (SRTM), was an international project

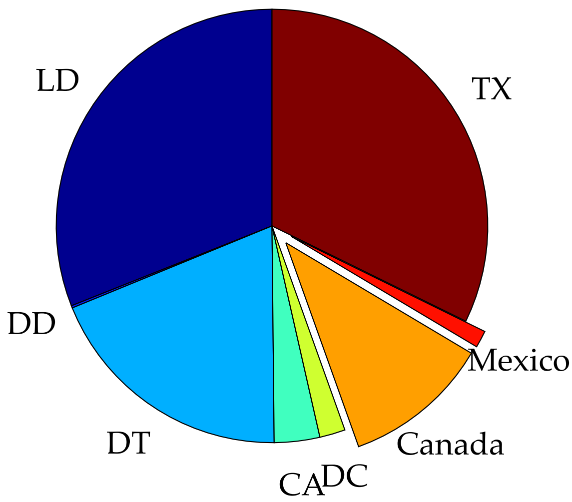

Figure 1.1: Ericsson's TV transmitter database contains transmitter data from Mexico, Canada and the United States. The US transmitters are divided into 5 major service types. Low power digital (LD), digital TV (DT) and translator (TX) transmitters encompass the majority of the entries. Class A digital transmitters (DC), the small number of distributed digital transmitters (DD) and the remaining analogue class A (CA) transmitters are assumed to provide coverage and interference in similar ways to the other digital transmitters.

lead by the National Aeronautics and Space Administration (NASA) and the National Geospatial-Intelligence Agency (NGA) which resulted in a high resolution topographic database. It is the source for the terrain elevation data needed in the TV coverage predictions. The eleven day mission created a high resolution topographic database of the Earth [20]. It covers nearly all the landmass between $60°$ North and $60°$ South with a resolution of 3-arc seconds, corresponding to roughly 90 m [21].

The US population density is used to plan the LTE deployment. It is retrieved from the 2010 Census Gazetteer, where the population density [22] and the cartographic shape [23] of the counties are provided.

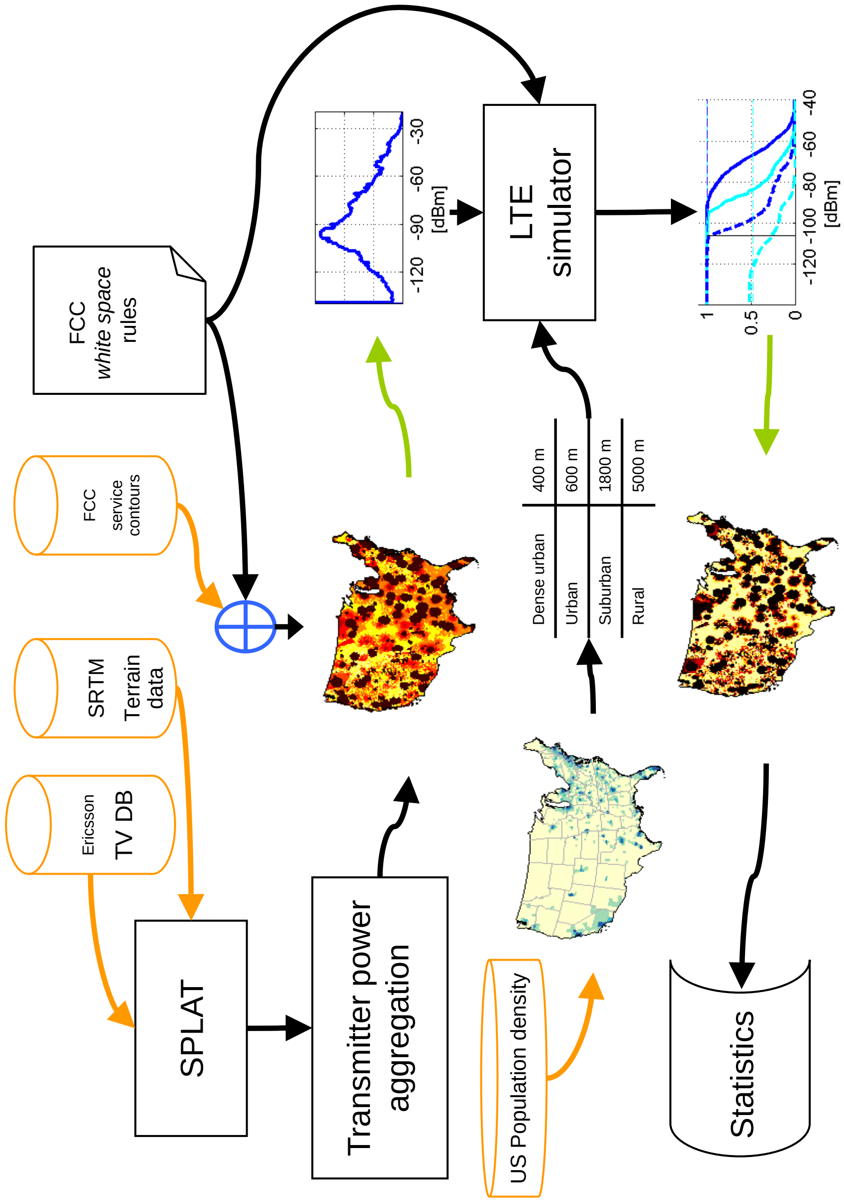

Figure 1.2: Connections between different data sources are shown with intermediate results. Ericsson's transmitter database, terrain data from the shuttle radar topography mission, the FCC's service contours and the US population density are shown in orange. SPLAT simulations, the TV power aggregation to determine the total interference and the LTE simulations are shown as black, rectangular boxes. Intermediate maps and graphs show caricatures of typical output in the various stages. The final statistics box is where the results from the two use-cases are sorted, selected and characterised.

2

Background

This chapter introduces the theory of radio propagation and the simulation software used in the TV coverage assessment. The US TV broadcast system is discussed with some of its basic deployment ideas. White space will be more formally defined and the FCC's rules for secondary access of the TV broadcast spectrum discussed. Finally some cellular network theory will be introduced together with ideas on how to evaluate the network performance.

2.1 Radio propagation

Radio signals are electromagnetic waves with frequencies ranging from 3 kHz to 300 GHz. Very high frequencies (VHF) $30 - 300$ MHz and ultra high frequencies (UHF) $300 - 3000$ MHz are of interest for this thesis [24]. The range contains the FM radio band $88 - 108$ MHz [25], the GSM-850 and GSM-900 bands [26, p. 9-10] and the TV frequency channels.

In describing the propagation of radio signals one could, in theory use Maxwell's equations and solve the partial differential equations in the regions of interest [27]. This approach poses a number of problems, the position of the transmitter and receiver must be known with an accuracy comparable the wavelength of the signal as must the positions of reflecting surfaces and obstructions. Since analytical solutions to the equations are limited to highly special cases; numerical methods could be appropriate.

The propagation of radio signals is instead determined by simplified statistical models. These simplifications take different effects into account such as reflection, diffraction and scattering [28, p. 25]. When considering one transmitter and one receiver, or two antennas in general the electromagnetic wave can be decomposed into a direct wave, following the straight path and indirect waves which are reflected or diffracted but end up at the receiver.

Fresnel zones are also important, these are ellipsoidal volumes surrounding the path between transmitter and receiver [29, p. 485]. Reflective obstacles inside the Fresnel zones will produce out of phase reflections which interfere at the receiver antenna. The first Fresnel zone contains the highest power signals, and to maximise received power the number of obstructions inside it should be minimised [29, p. 488]. A rule-of-thumb for good propagation conditions, says that $60\,\%$ of the first Fresnel zone must be clear of obstacles.

2.1.1 Basic models

Free space propagation is the simplest propagation model. The power of the electromagnetic wave is proportional to the inverse square of the distance from a point source [28, p. 32]. The power loss in dB, L_{FS} is given by

$$L_{\mathrm{FS}} = 20\,\log_{10} 4\,\pi + 20\,\log_{10} \frac{r\,f}{c} \tag{2.1}$$

where f is the frequency in Hz, r the distance from the source in meters and c the speed of light in meters per second.

The *plane earth propagation model* takes two path propagation into account, thus considering one direct wave and one ground-reflected wave [28, p. 36]. It is appropriate to use when the difference in path length between the direct wave and the ground reflected wave is much smaller than the distance between the two antennas [28, p. 36]. The source height h_t and receiver height h_r, both in meters are considered and the ground seen as perfectly reflecting mirror. Path loss in dB is then predicted by

$$L_{PE} = 20\,\log_{10} \frac{r^2}{h_t\,h_r}, \tag{2.2}$$

where again r is the distance in meters between transmitter and receiver.

2.1.2 Phenomenological models

Theoretical models indicate that the path loss increases with some power of the distance and different corrective terms are added depending on frequency, antenna heights and the intermediate terrain. Even though more advanced theoretical models exist it is common to make parameter fits to (2.3). A phenomenological model for path loss L, can be expressed in the form

$$L = A + B\,\log_{10} r + C\,\log_{10} f + D \tag{2.3}$$

where r is the distance between transmitter and receiver, f the frequency of the signal and A, B, C and D parameters determined by the model. A, B and C are recognisable from the free space model, and the D-term is used for small corrections.

The Okumura-Hata model [30], the Wireless World Initiative New Radio (WINNER II) model [31] and the International Telecommunication Union's (ITU) recommendation in P.1546-4 [32] are examples of models which follow the form of equation (2.3). Parameters and their applicable ranges for the different models are described in the references[30–32], which also describe how different side cases should be handled.

2.1.3 The irregular terrain model

The irregular terrain model, often called the Longley-Rice model, was developed to predict long term median transmission loss over irregular terrain [33]. Rice et al. note that the attenuation of a signal measured over the same distance, but different paths and times can vary up to 100 dB [34]. This motivates a statistical approach which takes the terrain and atmospheric effects into account.

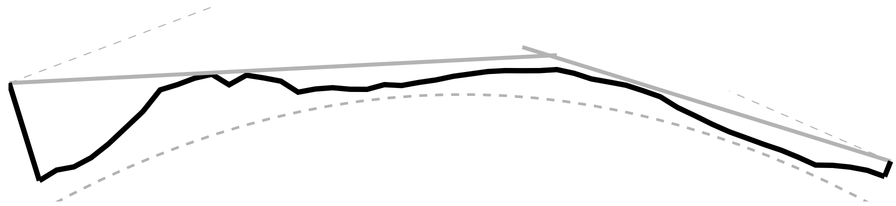

Figure 2.1: Irregular terrain geometry, where the transmitter and receiver lie behind mountains. The sea level, grey and dashed is shown below the thicker black terrain. Radio paths are shown as thick grey lines from the transmitter and receiver, which have their horizons marked with grey dashed lines. The angles between the radio path and horizon, the height and distance of the most significant mountain peaks and the angle between the two radio paths are all used by the irregular terrain model. Adapted from [34].

A terrain profile is used to determine obstructions, such as mountains or hills along the path and indicates which propagation effects to take into account. When the transmitter and receiver are within "radio" line-of-sight, two-ray optics determines the attenuation. But when the path is broken by one or more horizons different diffraction or forward scattering theories are applied [34]. In cases when it is unclear which propagation type is dominant, the effects from both methods are combined.

Attenuation also varies in time, and this is attributed to changes in the atmosphere. Different temperatures, levels of humidity and clouds must be included in the statistical interpretation of the propagation loss [34]. The computer model proposed by Longley and Rice [33] uses a radio climate parameter to signify the general characteristics. Parameters needed for the computer model are shown in table 2.1, together with some typical values.

The National Telecommunications & Information Administration's (NTIA) Institute for Telecommunication Sciences (ITS) developed and published an implementation of the irregular terrain model [35] based on the technical report by Longley and Rice from 1968. Hufford detailed updates of the implementation in a memorandum from 1985, and some smaller changes have thereafter been done in June 2007.

TV transmitter coverage in this thesis is calculated with the irregular terrain model from the National Telecommunications & Information Administration's

Table 2.1: Longley-Rice parameters used when running SPLAT.

Parameter	Value	Comment
Relative Permittivity	15.0	Average ground [39]
Earth Conductivity	0.005	S/m[a] for average ground [39]
Radio Climate	5	Continental Temperate [b]
Polarization	Vertical	
Time Variability	0.5	
Location Variability	0.5	

[a]Siemens/meter
[b]See SPLAT manual [39] for further information

(NTIA) Institute for Telecommunication Sciences (ITS). It is part of the SPLAT software package, together with an alternative model Shumate [37] developed. The two implementations are compared in appendix B, showing significant differences over flat terrain. Model choice and the consequences will be discussed in the results and the final discussion.

2.2 SPLAT and its modification

SPLAT (Signal Propagation, Loss And Terrain) is an open source signal propagation calculator [38]. It works as a wraparound program for either the irregular terrain model from the Institute for Telecommunication Sciences (ITS) or Shumate's irregular terrain with obstructions model to determine the field strength or path loss from a certain transmitter at a certain location. The software is written by Magliacane and released under the terms of the GNU General Public License Version 2.

SPLAT's main functionality is loading the terrain profile between the transmitter and receiver, and then calculating the path loss according to the propagation model. The loss depends on the terrain, earth conductivity, atmospheric effects and different diffraction effects in the propagation, as described by the Longley-Rice model. The transmit power and antenna directivity is then added producing the received field strength.

A modified version of SPLAT is used in this thesis. It enables multiple transmitters and receiver-locations to be supplied in batches and the point to point analysis is run between each transmitter and receiver-location. Dudda added this extra functionality during work on his master's thesis [9]. The memory management is also modified, so that more terrain data can be loaded at the same time.

2.3 Broadcast TV

The TV broadcast system in the US is governed by regulations set up by the FCC [40]. This thesis focuses on the radio frequencies and coverage areas of the transmitters. The frequency range used in broadcast TV is split into $6\,\mathrm{MHz}$ channel-blocks and numbered from 2 to 69 [40, §73.601 – §73.603], the exact frequency of each channel is shown in table A.1 of appendix A.

Channels 3 and 4 are often used by Video Cassette Recording (VCR) devices and Digital Versatile Disc (DVD) devices to modulate their output signals before passing them to the TV [11, C §149]. The FCC's own engineers noted that TV receivers seem extra susceptible to interference on these channels [11, C §149]. Channel 37 is reserved for radio astronomy and remote patient monitoring using Wireless Medical Telemetry Services [41]. Consequently there are no TV transmitters operating on this channel.

Each broadcast tower has a designated channel registered with the FCC, and the antennas are generally placed on high masts and transmit with high power. The antenna heights in Ericsson's database are measured from the average sea level, ranging from $5\,\mathrm{m}$ to $5137\,\mathrm{m}$[1]. The effective radiated power, which takes antenna gain and other pre-amplifications into account ranges from $1\,\mathrm{kW}$ to $3.9\,\mathrm{MW}$ with a median of $2\,\mathrm{kW}$.

Coverage is optimised and interference is reduced by assigning different trans-

[1]Antenna height must be considered together with the site elevation and the surrounding terrain. A low antenna on a high mountain is more efficient than an antenna located at the bottom of a valley.

Antenna *height above average terrain* (HAAT) is determined by calculating the average altitude of 50 points from the surrounding terrain, located on eight evenly spaced radials at $3-16\,\mathrm{km}$ from the transmitter site. The difference between the site elevation and the average terrain elevation is added to the antenna height resulting in an antenna height above the average terrain.

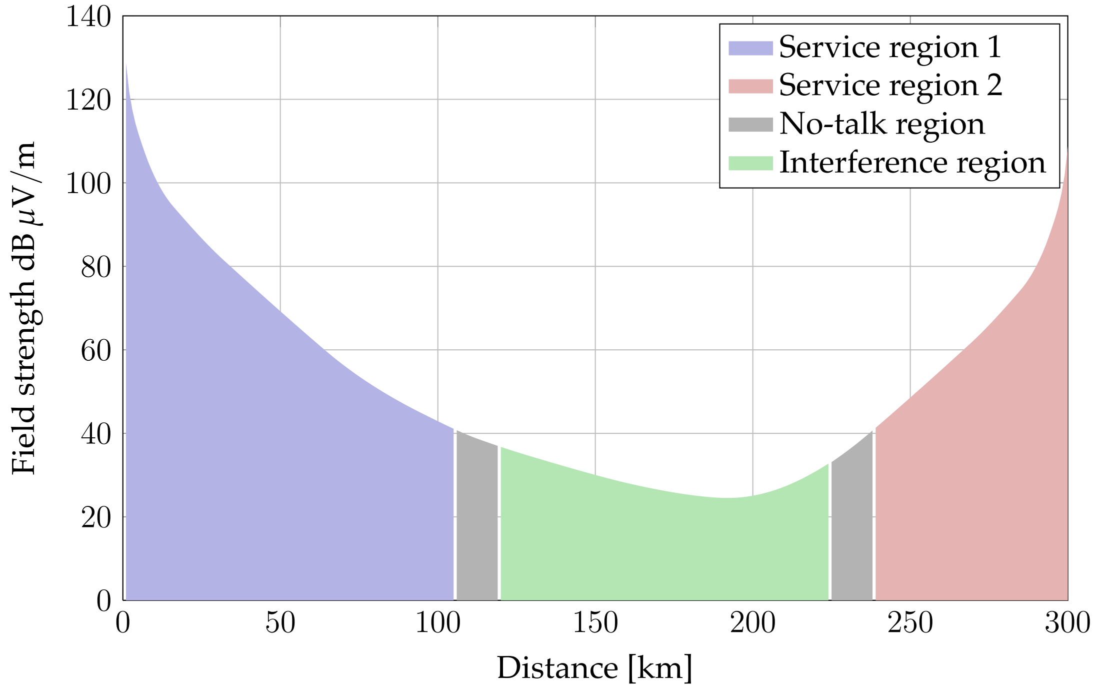

Figure 2.2: The service ranges in blue and red are shown for two co-channel transmitters and the curves are defined by the FCC's rules in [40, § 73.684]. Between the two transmitters, outside their service regions and no-talk zones, the field strength is combined from the two transmitters forming the interference region. These different regions are discussed and defined in section 2.4.1 on page 17.

mitters to different channels. Two transmitters geographically close to each other operating on the same channel (co-channel) or on adjacent channels must comply with stricter regulations on transmit power and directivity.

The FCC published a technical report in 1966 [42] with measured field strength curves and various interpolations from radio and TV broadcast antennas. The report formed the basis for the rules [40, § 73.684] which describe how the coverage area of a transmitter is defined. Field strength curves, denoted $F(L,T)$, are characterised with a time confidence $T\%$ and location confidence $L\%$. $F(L,T)$ is the lower limit, so that the field strength is equal to or above the curve $T\%$ of the time and at $L\%$ of the locations, providing a service guarantee. The curves are normalised to 1 kW transmitters and the chart shows different curves for transmitter heights. The field strength from a weaker or stronger transmitter are determined through different correction terms.

The *service range* of a transmitter is defined as the region where the field strength is above a certain threshold value. For analogue TV the $F(50, 50)$ curves are used, thus giving a region which receives a field strength higher than or equal to the cut off 50% of the time and 50% of the locations. Digital TV uses the $F(50, 90)$ curve meaning that the received field strength is higher than or equal to the threshold 90% of the time and in 50% of the locations. The threshold value for Channels 14 to 51 have a threshold of $41\,\mathrm{dB}\,\mu\mathrm{V/m}$, and thresholds for lower channel numbers are shown in table A.2.

Outside the service range, the field strength can still be high enough for a receiver to pick up the signal. The FCC will however not guarantee reception, since the TV transmitter system is not designed to provide service here. This region is referred to as the *interference range* as there is no exclusive TV transmitter operating there, and multiple transmitters can have interfering signals.

Digital TV in the US is transmitted using a modulation standard developed by the Advanced Television Systems Committee (ATSC) known as 8 level Vestigial Side Band (8-VSB) [43]. The transmitted bit-stream must appear noise-like and random so that the frequency response of the transmitted signal is flat [43, 44]. A flat power distribution in the spectrum gives the modulated signal a high spectral efficiency [43], but also makes the TV signal appear noise-like to other services on the same frequency [45].

WBGU-TV The WBGU-TV transmitter is described here as an example from Ericsson's TV transmitter database. Terrain and field strength calculations are shown for the transmitter in the results section to illustrate coverage. The transmitter is located between Detroit, Michigan and Indianapolis, Indiana as shown in figure 2.3. The tower is roughly $323\,\mathrm{m}$ above ground level[2] and transmits with an effective radiated power of $153\,\mathrm{kW}$ on channel 27.

The map in figure 2.3 shows the location of the transmitter and the service contour defined by the FCC. The contour is defined at the cut off value $41\,\mathrm{dB}\,\mu\mathrm{V/m}$ for channel 27. The contour in the figure looks circular, with a radius close to $85\,\mathrm{km}$, but this is due to the omni-directionality of the antenna and the map projection and is a general characteristic of all contours.

[2]The height above average terrain is $320\,\mathrm{m}$ and the height above sea level is $545\,\mathrm{m}$.

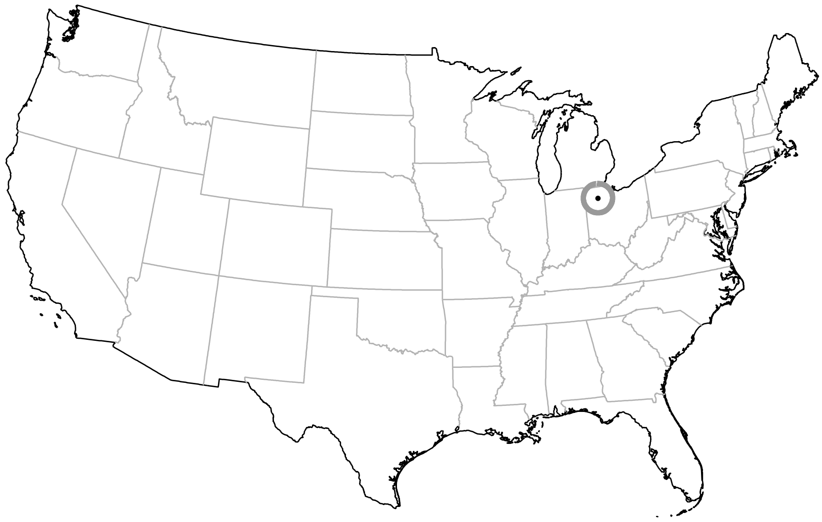

Figure 2.3: The location of the WBGU-TV transmitter and the FCC's service contour.

2.4 White space

White space is a term used to describe frequencies which are available for alternative uses at some time and location. As noted in the introduction, frequency blocks or channels were previously allocated through exclusive licenses where the licensee or primary user used the channel in the whole country or region. Examples include the aeronautical radio navigation band from $960 - 125$ MHz, $3500 - 3600$ MHz is reserved for radio location services, $88 - 108$ MHz FM radio broadcasting and $28 - 29.7$ MHz for radio amateurs [46].

The Electronic Communications Committee within the European Conference of Postal and Telecommunications Administrations describe white space in their introduction to CEPT report 24 [8, p. 4].

> So "White space" is a label indicating a part of the spectrum, which is available for a radio communication application (service, system) at a given time in a given geographical area on a non-interfering / non-protected basis with regard to other services with a higher priority on a national basis.

White space is thus frequency bands available for opportunistic use which are location and time dependent. Mishra and Sahai [12] note that locations where a *cognitive radio* can operate under a set of rules will constitute part of the white space. In [47], Haykin discusses cognitive radios as intelligent wireless communication systems which can learn and adapt to their environment and input. The two main objectives are to utilise the radio spectrum more effectively and provide a reliable means of communication. A cognitive transceiver[3] can reconfigure itself and use multiple radio channels, enabling the use of "free" channels at certain location [47].

The idea of white space and the adaptable radio transceivers leave questions concerning regulation. Which primary users need protection to retain their usage rights and how can the spectrum be reused without causing too much interference to the primary users?

The FCC published rules in 2008 governing the use of white space in the TV spectrum [11]. These rules and their application to a proposed system are the primary focus of this thesis.

2.4.1 The Federal Communications Commission's rules

This overview summarises the FCC's rules from 2008 [11] and revisions from 2010 [15] and 2012 [16] which are relevant for the thesis. Two device types are defined; *fixed devices* and *personal/portable devices*. Fixed devices use high power at permanent, fixed locations. Personal or portable devices are lower powered WiFi-like cards in laptops or smart-phones. A fixed device could be run by a local commercial wireless internet provider which use fixed transmission towers, and a portable device could be either a wireless connection point to a in-home local area network or a smart-phone [11].

Fixed devices must be aware of their location, either pre-set by a professional installer or have geo-location capability [11]. The antenna height can be up to 30 m, and the antenna's height above average terrain must be less than 250 m [16]. The transmission power is limited to 1 W delivered to the antenna, which may have a directional gain of 6 dBi [15]. Fixed devices can use channels 2, 5–20 to communicate with other fixed devices and channels 21–36 and 38–51 to communicate with both fixed and portable devices [11].

[3] Transmitter and receiver

Portable devices are allowed on channels 21–36 and 38–51 [11] and to transmit with a power of $100\,\mathrm{mW}$ with an isotropic antenna [15]. If the device is located inside the service contour of a transmitter, it may operate on an adjacent channel to the transmitter, but with a power limited to $40\,\mathrm{mW}$ [15]. The portable devices operate in two modes; Mode I or client mode is when the device is controlled by a fixed device which has determined the available channels in the area, Mode II is an independent mode when the portable device uses its own geo-location and database access to determine the available channels.

The fixed devices in these rules resemble LTE network base stations. A LTE system relies on communication between the base stations and the mobile user devices, and for this to work with the FCC's rules they must be allowed to use the same TV channels. The proposed cellular network in this thesis will then be restricted to channels 21–36 and 38–51, providing a maximum bandwidth of $180\,\mathrm{MHz}$.

TV transmitter protection

The FCC's aim is to protect existing TV receivers from the fixed and portable device's interference. In section 2.3 (p. 13) the service range was defined, the area inside will now be protected from secondary users. The objective of the rules is to ensure that the TV receivers keep receiving good TV signals inside the service region, without noticing interference from the secondary devices.

Inside the service contour no secondary device may operate on the same channel (co-channel) as the TV transmitter, and fixed devices may not operate on the first adjacent channels. As noted, the portable devices may use the first adjacent channels with reduced power. Outside the service contour a no-talk region, named by Mishra and Sahai [12], restricts secondary devices a little further. The size of the no-talk region depends on the unlicensed device's antenna height, and differs for the co-channel or the first adjacent channels. These sizes are shown in table A.3.

Other protected services

The radio astronomy and telemetry services on channel 37 receive extra protection even when there are no TV transmitters on the channel. No unlicensed devices may operate on the channel, or on the first adjacent channels [11]. The second adjacent channels, 35 and 39 are also protected unless there is a TV transmitter operating on channels 36 or 38 [15].

The previously discussed TV translator services and cable head-ends are sometimes located outside the service region of their source transmitter. These locations get keyhole shaped protection areas, directed towards the source transmitter to ensure continued reception.

TV transmitters in Mexico and Canada are protected inside the US borders, but in a smaller region. Any foreign transmitter with a service region which stretches into the US will have a no-talk region, as for the US transmitters, but the no-talk region will run along the country border instead of the transmitter's service contour.

Radio astronomy sites are protected through prohibiting the use of unlicensed devices on all channels within 2.4 km of their locations. The list of protected observatories is shown in table A.4 of the appendix. The very large array is a large radio astronomy observatory which can be up to 36 km across depending on the configuration of the antennas [48]. The facility is protected by a rectangular region on all channels.

2.5 Cellular Networks and LTE

LTE is an abbreviation of *Long Term Evolution* a radio access technology standard developed by the Third Generation Partnership Project (3GPP) [49, p. xxv]. This section introduces concepts in cellular network theory and their application within the LTE standard which are needed for this thesis.

A wireless network is sometimes modelled on a plane surface with multiple transmitting base stations, each one of them covering the circular region around

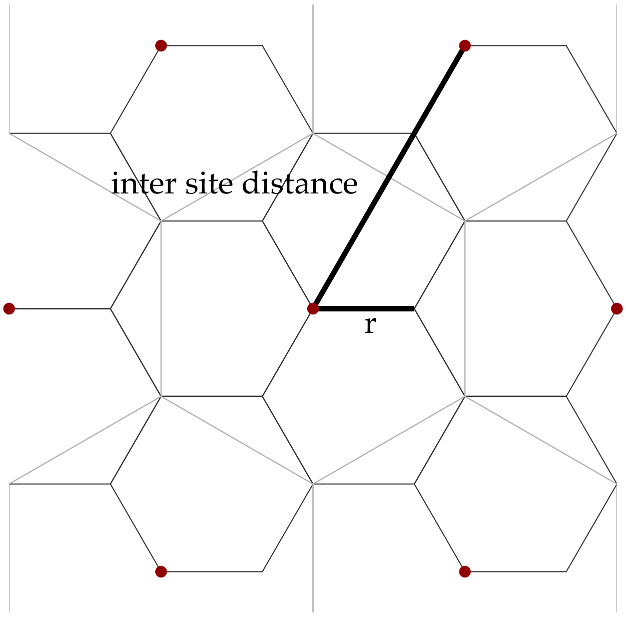

Figure 2.4: The hexagonal tessellation of the plane, each red point marks a base station serving three cells. The cell radius and the inter site distance are marked for the regular hexagons.

it. Since the plane cannot be tessellated by circles, the hexagon, a close approximation of the circle, is used to divide the plane into cells. Each cell can then be split into three sectors and these are considered as separate cells. This results in additional cells, but without the need for more base station sites. Figure 2.4 shows two hexagonal layouts, together with the base station locations. The cell radius, r and inter site distance d are shown in the figure. In the case of regular hexagons, the inter site distance is simply three times the cell radius.

Transmissions in communication systems are split into the uplink and downlink. The uplink is the transmission from mobile device or cell phone to the base station at the cell site, and the opposite transmission from base station to mobile device is called the downlink.

A cellular network is allocated a range of frequencies for its operation. Uplink and downlink must be separated in either time or frequency, referred to as time division duplex and frequency division duplex. Time division is done by scheduling the whole cell to do uplink and downlink transmissions in separate time slots typically a few milliseconds [49, p. 296]. Frequency division splits the frequency range in two, using one block for uplink and the other for

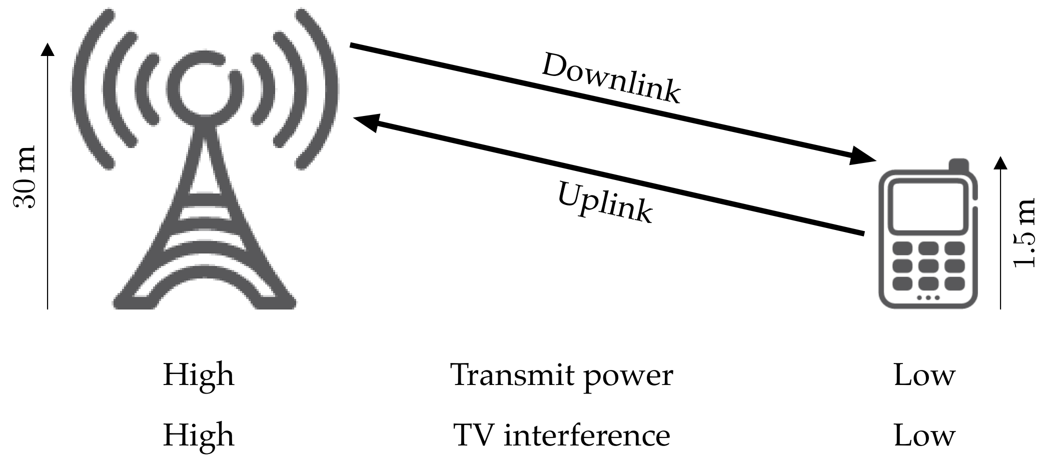

Figure 2.5: The relative transmission powers of a base station and mobile device are shown with their assumed height and TV interference level. Downlink transmissions gain from high power and low TV interference, while uplink suffers with low transmission power and high TV interference

downlink [49, p. 282]. LTE uses discrete frequency blocks 180 kHz wide, known as resource blocks, and a 6 MHz channel would contain 33 resource blocks. Frequency division could allocate half the blocks for uplink and half for downlink, while time division would use all blocks in each direction, and divide the time between them.

When spectrum is licensed to cellular network operators, the frequencies are in a contiguous block or split into multiple smaller blocks. With two frequency blocks frequency division duplex is natural, reserving the lower frequency block for uplink transmission and the upper block for downlink [49, p. 296]. Contiguous frequency blocks can be divided either way [49, p. 296].

A single user in the network is quite simple to understand. Data throughput is limited by the desired signal D to undesired signal U ratio together with Shannon's theorem [50, p. 182]. The desired signal depends on the transmitter power P_{tx} and the path loss L between the transmitter and receiver. The undesired signal consists of the thermal noise N_{th} and any interference I. Thermal noise N_{th} from the receiver electronics is set to 288 K or 15° C [51, p. 107]. For a single transmitter the interference can be neglected, but it becomes important when considering multiple users in the cell. The desired to undesired ratio is often denoted as the signal to interference and noise ratio

$$\gamma = \frac{D}{U} = \frac{P_{tx}\, L}{N_{th} + I}. \tag{2.4}$$

The link capacity is an estimate of the maximum bit rate which can be transmitted over the link and can be calculated using Shannon's theorem [50, p. 182]. The limits in coding and modulation in the transmitter, together with the demodulation and decoding in the receiver is taken into account by a scaling factor $\nu < 1$,

$$C = \nu B\ \log_2(1+\gamma). \tag{2.5}$$

C, the link capacity is the theoretical maximum bit rate for a link with a bandwidth B and signal to noise and interference ratio γ [50, p. 182].

Multiple users in a cell Each active user in the cell is scheduled time and frequency resources by its base station. The resource blocks available to the cell are divided between the active users according to some scheduling algorithm, which often take the signal quality into account. Orthogonal frequency division multiplexing (OFDM) ensures that the transmissions inside the cell are mutually non-interfering.

Neighbouring cells often share the same spectrum, and this frequency reuse causes problems. Users in neighbouring cells transmit using the same orthogonal basis functions, causing inter-cell interference which will disrupt the signal to noise and interference ratio significantly.

When a base station is transmitting to multiple users, total transmission power must be shared between each user and it can be useful to transmit in series to each user [49, p. 110]. There are many different scheduling algorithms, some consider link quality, others which aim to maximise throughput to some of the users [49, p. 112]. The simplest scheduler, known as a *round robin* scheduler shares the radio resources equally among the active users [49, p. 112].

2.5.1 Evaluating network performance

A cellular network's performance must be evaluated and compared to different references, especially when looking at the restricted conditions for operating in

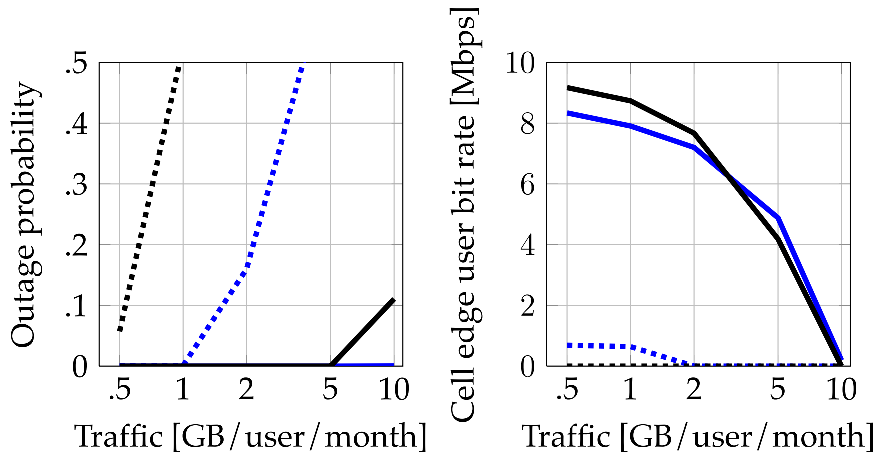

Figure 2.6: The outage probability and cell edge user bit rates depend on the requested traffic in the cell. These curves show the outage probability and cell edge user bit rate in uplink (dotted) and downlink (solid) for a reference LTE system with inter site distances of 400 m (blue) and 5000 m (black).

TV white space. This section will define some important performance indicators which will be used.

In a cell where the path loss depends on distance and the users are spread out quite uniformly, the users farthest away from the base station will have the lowest signal quality. With more simultaneous users, the cell load increases and the user location becomes more important. Note that users with the worst signal to interference and noise ratio are not necessarily near the physical cell edge. To catch both these effects, the *cell edge user bit rate* is defined as the experienced throughput of lowest performing 5 % of users. The throughput is measured in both the uplink and downlink and tells us what the worst off users are experiencing.

A related indicator, the *outage probability*, measures the proportion of dropped users. When the signal to interference and noise ratio, γ is too low, the data rate drops below a threshold and the connection is dropped. The radio resources can be rescheduled to users with better γ. The outage probability is the fraction of users with 0 throughput. Typically the outage probability increases with more simultaneous users, larger cells, or when more data is requested by the users.

With a round robin scheduler, users requesting a finite amount of traffic, and the users are distributed uniformly; the cell edge user bit rate can be seen as the worst user's experience, and the outage probability the proportion of time that the network fails.

The total served traffic throughput is used to estimate the overall network performance, without considering an individual user's experience. A network serving less than the requested traffic is either coverage or interference limited. High inter-cell interference, too low transmission power or large path losses are possible explanations. This ratio however tells us nothing of how users experience the functionality.

Network users' experience is more directly measured by looking at the *median user throughput*. It indicates how well traffic is shared between users and how functional the network is from a user perspective.

Spectral efficiency is a measure of how much information is transmitted over the allocated bandwidth. It is measured in bps/Hz which translates to throughput divided by bandwidth. The spectral efficiency of a cell and of an individual user are considered in this thesis. The cell spectral efficiency is the total served traffic of the cell divided by the channel bandwidth $6\,\mathrm{MHz}$, while the median user spectral efficiency uses the median user's throughput instead.

LTE reference system The LTE reference system is designed to be similar to the system operating in white space, but without the FCC's restrictions from section 2.4.1. It is assumed that 33 resource blocks with a centre frequency of $750\,\mathrm{MHz}$ are allocated to the network. The base station is allowed a transmit power of $60\,\mathrm{dBm}$ (i.e $1\,\mathrm{kW}$) and the transmit power of a mobile devices must be below $23\,\mathrm{dBm}$ (i.e $.2\,\mathrm{W}$) [52, p. 29].

Two different uses of the LTE system are discussed in this thesis, a standalone network and a network for offloading. If these were deployed using dedicated spectrum, the performance is expected or required to be comparable to the following:

A standalone network needs to provide coverage and capacity. It must provide good coverage or low outage probability throughout the area, and there must be enough capacity to ensure that even the users with the worst connections get some throughput. Standalone networks require both uplink and downlink to function satisfactorily well.

In an offloading scenario, coverage is provided by a different macro cellular network deployed in different spectrum. The additional offloading then adds extra capacity in either uplink or downlink or both, which can be used opportunistically. Traffic load is shared between the cellular system and the offloading system, meaning that the total extra throughput and the throughput distribution among users are, in this case more interesting than coverage and the worst user throughput.

3

White space assessment

This method chapter presents how SPLAT and the LTE simulator are used. Figure 1.2 shows how the different data sources and simulators are inter-connected, but the different sections describe in more detail how each step is implemented. The TV coverage assessment describes the pixel grid, the parameters for SPLAT and how the simulations are separated into 12 regions. The overlap between regions, referred to as the *maximum interference distance* is introduced, but discussed in more detail in appendix C.

The section on the TV transmitter interference powers and protection regions section illustrates how the FCC's rules are translated to the grid. This results in a mask for each channel, exemplified for channel 21 in figure 3.3. The aggregation of TV power is then described, so that the power received from each transmitter within the maximum interference distance contributes to the interference power in each pixel and channel. There is now enough information to estimate the link capacity of a cellular system. The method for this is discussed, together with the relevant assumptions regarding path loss, transmission power and parameters for Shannon's link capacity in equation (2.5).

Finally the cellular network simulations are described. In network deployment, the inter site distance is important in terms of initial cost and overall capacity. The choice of radio propagation model used in the simulator is determined together with the inter site distances according to the population density of the pixel. The standalone network and offloading network use-cases are defined, together with different criteria for choosing “good” channels based on the performance of the LTE network. Ericsson’s proprietary LTE simulator is described in basic detail with the parameters used for the white space and reference system simulations. Finally, a trick for reducing the number of simulations is used: Pixels with similar interference powers on a channel are grouped together in bins. The LTE performance with the interference power of the bin is then mapped back to all pixels in the bin.

3.1 TV coverage assessment

The TV coverage is assessed for the contiguous states, excluding Alaska, Hawaii and other island territories. The terrain data from the Shuttle Radar Topography Mission does not cover all of Alaska, but it would be possible to extend the analysis to Hawaii and the remaining US territories.

The main tool in the TV coverage assessment is the modified version of SPLAT, described in section 2.2. SPLAT’s grid mode is used for the receiver sites, so that the TV coverage can be estimated on a per-pixel basis. The grid is rectangular in the geographic longitude and latitude coordinates, stretching from $24.4°$ to $49.40°$ North, split into 400 longitudinal lines and from $124.7°$ to $66.9°$ West, split into 300 latitudinal lines. Only grid points on land and inside the contiguous state borders are used, which results in a total of 67608 grid points. In southern Florida a grid point represents an area of roughly $9.3\,\text{km}$ by $14.5\,\text{km}$, and near Lake of the Woods in northern Minnesota $9.3\,\text{km}$ by $10.5\,\text{km}$.

SPLAT uses parameters for the irregular terrain model. These include values for the terrain’s dielectric constant, conductivity, atmospheric bending and a general radio climate. The values are typically terrain and location dependent but this assessment uses the standard values shown in table 2.1. Finer location dependent details are overlooked so that a somewhat simplified but qualitatively correct coverage can be considered.

Ericsson’s database contains the necessary transmitter data to run SPLAT, and the example transmitter WBGU-TV’s data is shown in table 3.1. Some transmit-

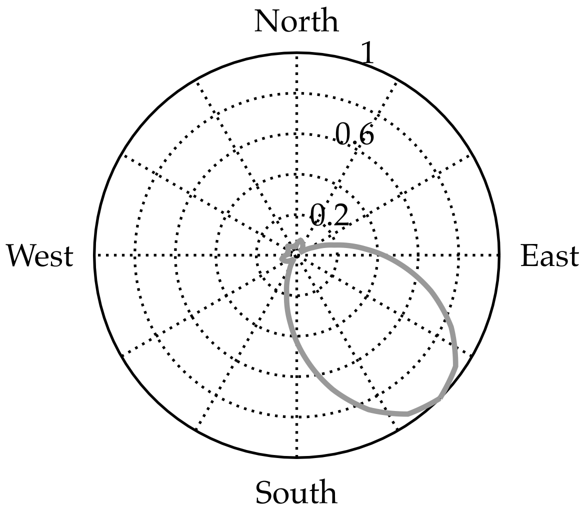

Figure 3.1: The relative, linear radiation power for WPXO-LD a low power transmitter located on the Empire State Building in New York. The main lobe is directed along an azimuth of 135° measured clockwise from true north.

Table 3.1: An example transmitter entry from the Ericsson database.

Field name	Example data
Name/Callsign	WBGU-TV
Channel	27
Effective radiated power (max)	153 kW
Antenna height (AMSL)	545 m
Location	41.136667° North
	83.906667° West
Antenna rotation	N/A
Antenna radiation pattern	N/A

ters have directional antenna, and their radiation patterns are also taken into account. The radiation pattern for transmitter WPXO-LD is shown in figure 3.1.

In the simplest case, the grid points and list of transmitters would be used as direct input to SPLAT. The result would be a field strength value from each transmitter at each grid point. Memory constraints make this approach impossible, and smaller portions of the US terrain must be calculated independently. If transmitter and receiver sites are separated by more than the maximum in-

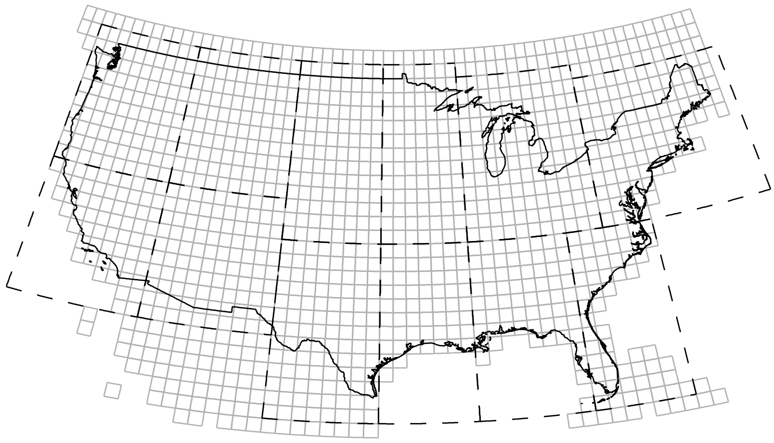

Figure 3.2: The 12 regions on which SPLAT is run and the terrain data files. The dashed lines show the regions and the solid grey grid shows the terrain data files.

terference distance, receivable field strength is assumed negligible and set to $-\infty$ dB μV/m. The distance is set to 400 km and the motivation is detailed in appendix C.

The amount of loaded terrain data is reduced by splitting the land mass into 12 regions, calculated separately. The regions are shown in figure 3.2. To avoid border effects the regions are extended with the maximum influence distance in all directions so that transmitters outside the region's border are taken into account.

The 9392 transmitters in Ericsson's database are sorted by channel and region. SPLAT is invoked on each channel and region so that the irregular terrain model can calculate the path loss between each transmitter and receiver site in the region. Transmitter directivity and transmission power then provide the field strength $E_{k,j}(x_i)$ for transmitter j operating on channel k at receiver site x_i. The received power $P_{k,j}(x_i)$ for an ideal, zero-gain, omni-directional antenna is then determined by

$$P_{k,j}(x_i)[\text{dBm}] = E_{k,j}(x_i)[\text{dB}\,\mu\text{V/m}] - 20\,\log_{10} f_j + 42.7809 \tag{3.1}$$

where f_j is the frequency in Hz of transmitter j.

3.2 Assessing TV interference levels and protection regions

The TV interference levels and protection regions are assessed using a set of Matlab scripts. Each channel has different protected areas requiring channel specific masks. The service contour and no-talk regions, depicted in figure 2.2 must now be translated to the pixel grid from the SPLAT simulations. Figure 3.3 shows the protected pixels on channel 21 as an example. Each transmitter's service contour, retrieved from the FCC [19] defines a polygon, and the pixels inside are marked as protected for co-channel operation and on the first adjacent channels.

The no-talk region outside a transmitter's service contour depends on the height above average terrain of the unlicensed device [16, p. 7]. In the LTE simulations, base stations are deployed on 30 m towers on flat ground, which would require a no-talk region of 14.3 km on co-channel operation and 1.8 km on adjacent channel operation. The adjacent channel no-talk region is neglected since the pixel grid is too coarse to resolve the difference. The co-channel no-talk region corresponds to roughly an extra pixel outside the service contour, but has also been neglected.

In the presentation of the FCC's rules in section 2.4.1, a low power option for mobile devices allowed their operation inside the protected contour on a TV transmitter's adjacent channels. These transmissions would allow for device-to-device communication or indoor WiFi-like routers to operate at short ranges in TV white space. High power TV transmitters on adjacent channels could cause problems to devices, since the allowed power leakage from the TV transmitters is quite high. Channel selectivity of these other devices would have to be good. These deployment ideas are not examined further in this thesis, but offer possible alternative reuses of available frequencies.

The radio astronomy observatories are protected on all channels, but since their protection region is small compared to the pixel size, the closest pixel is marked as protected. This grants a larger protection area, but will not contribute significantly to the overall protection. All pixels inside the longitude-latitude box protecting the very large array are marked as protected. The transmitters across the borders to Canada and Mexico are given a protection distance of 14.4 km from the border since the service contours of these transmitters are not available.

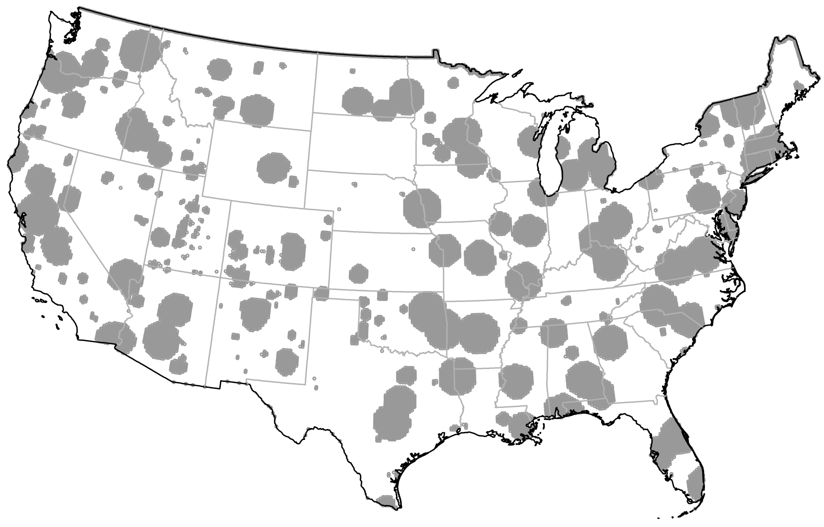

Figure 3.3: Protected pixels on channel 21.

Table 3.2: The adjacent channel leakage ratio (ACLR) for the n-th adjacent channel in dB for the TV transmitters is regulated by the FCC [53].

n	TV transmitter [dB]
0	∞
1	75.9
2	110

3.2.1 Aggregation of received TV signals

The total interference power in each pixel on each channel is determined by taking all the TV transmitters within the maximum interference distance into account. Neither the transmitters nor the device experiencing the interference has perfect amplification or filtering, so some energy leaking from adjacent channels must be taken into account. The n-th adjacent channels ($N \pm n$) to channel N will have adjacent channel interference ratios (ACIR) which take both the transmitter's and receiver's filters and amplifiers into account.

The TV transmitter's adjacent channel leakage ratio (ACLR) is regulated by the FCC [53]. Table 3.2 tells us that a transmitter must dampen any power leaking into the first adjacent channels by 75.9 dB, and the second adjacent channels by 110 dB. Base stations and mobile devices have different requirements for their adjacent channel selectivity (ACS), and these are defined for 5 MHz and 10 MHz

Table 3.3: The adjacent channel selectivity (ACS) for the n-th adjacent channels in dB for mobile devices [52, p. 82] and base stations [54, p. 43, p. 46].

n	Base station [dB]	Mobile device [dB]
0	∞	∞
1	46	33
2	54	37

channels [52, 54] and are assumed to work similarly for 6 MHz channels.

The combined adjacent channel selectivity and adjacent channel leakage ratio gives us the adjacent channel interference ratio in the linear domain

$$r_{\mathrm{ACIR}} = \frac{1}{\frac{1}{r_{\mathrm{ACS}}} + \frac{1}{r_{\mathrm{ACLR}}}}. \tag{3.2}$$

The values from tables 3.2 and 3.3 assert that the adjacent channel selectivity will dominate. To keep the aggregation of received power simple, the two effects are separated. This can be understood as first calculating the power received using a perfect filter, as if the adjacent channel selectivity was infinite and after this intermediate step, calculating the power received by an imperfect filter, from a perfect transmitter.

The first step will add the contributions from all transmitters influencing a pixel on a certain channel. A simple idea would be to sum the powers in the linear domain, scaling adjacent channel powers with the correct adjacent channel leakage ratio:

$$I_k(x_i) = \sum_{m \in \kappa(k)} P_m(x_i) + \sum_{c=-n}^{n} \frac{1}{r_{\mathrm{ACLR}}(c)} \sum_{l \in \kappa(k+c)} P_l(x_i) \tag{3.3}$$

$$\kappa(j) = \{\text{Transmitters on channel } j\}$$

The received power levels $P_m(x_i)$ are random variables, and the distribution of the interference power $I_k(x_i)$ is of interest. The value in dBm calculated by SPLAT is seen as the mean of a normal distribution with a standard deviation of 5.5 dB [32, p. 47]. The distribution of $I_k(x_i)$ is the sum of powers, each following a log-normal distribution.

The aggregation of received powers is now reduced to finding the distribution of a sum of log-normal random variables. Different approximation methods for this have been proposed [55–57], but for this application a Monte-Carlo method is used. Each of the received powers $P_j(x_i)$ is combined with its corresponding dampening from the adjacent channel leakage ratio to form a normal distribution in the logarithmic domain. The set of distributions at pixel x_i is sampled, converted to the linear domain, summed and then converted back to the logarithmic domain. The process is repeated N times. The N samples of $I_k(x_i)$ are then used to approximate the mean and standard deviation in the logarithmic domain of the interference power, which is assumed to be log-normally distributed. $N = 10000$ samples result in an approximation of the TV interference distribution. The stability with regard to the number of samples N is discussed in appendix D.

The interference level depends on the height of the receiving antenna, just as depicted in figure 2.5. In the Okumura-Hata model [30, Appendix 7.A] and Winner II model [31] the received power decreases linearly with receiver height in the logarithmic domain. To verify that this is applicable for the SPLAT results after the aggregation, two sets of interference powers were calculated, one for a receiver at $1.5\,\mathrm{m}$ and one at $10\,\mathrm{m}$. Their correlation and linear fitting is discussed further in appendix E.

Finally in the last step, the non-ideal receiver's adjacent channel selectivity is taken into account. The interference power from the adjacent channels is dampened according to the values from table 3.3 and then summed in the linear domain:

$$I_k(x_i)' = I_k(x_i) + \sum_{c=-n}^{n} \frac{1}{r_{\mathrm{ACS}}(c)}\, I_{k+c}(x_i) \tag{3.4}$$

An error source introduced by this separation of adjacent channel leakage and selectivity calculations will be comparable in size to the product of the adjacent channel selectivity and the adjacent channel interference ratio. This product ensures that the largest contribution from a transmitter on the third adjacent channel will be $33\,\mathrm{dB}$ lower than the contribution from the second adjacent channel. Modelling the leakage and selectivity, only the first two adjacent channels are accounted for, which is an approximation in itself. When adding this small contribution in power from channels further away, the model comes closer to the physical reality.

When comparing $I_k(x_i)'$ to the environment, it can be useful to note that the thermal noise present in a 6 MHz wide TV channel is $N_{th} = -106.22$ dBm[1]. The received power at the edge of the service contour is 41 dB μV/m $\simeq -90$ dBm.

The observed interference powers range from below -180 dBm to nearly 0 dBm, and are shown in figure 3.7 for channel 21 and then discussed in detail in the results chapter. For low interference power, typically when the interference power is below -126.22 dBm (1 % of the thermal noise), there should be little or no influence on secondary users.

The interference power is determined by assuming an omnidirectional receiver antenna. For a mobile device this will typically be the case, and is assumed in the later LTE simulations. Base stations however often use directional antenna with a single site serving three or more sectors. The interference power will be directional, coming from the contributing TV transmitter so different base stations at the same site will see varying levels of interference. These aspects are not considered, but could raise or lower the interference power received from different directions.

3.2.2 Link capacity estimates

Interference power and background noise are combined as the undesired signal in equation (2.4). The desired signal is constructed using the transmitted power and the path loss to a receiver at distance d. Each pixel x_i will then have a signal to interference and noise ratio $\gamma_k(x_i, d)$ on channel k will thus depend on the interference power $I_k(x_i)'$ and also the path loss $L(x_i, d)$. Location x_i dependence of the path loss reflects different pixel's deployment scenarios, which in turn depend on the population density. The distance between the receiver and transmitter d, is used to place a user somewhere in a fictive cell, either on the cell edge or closer inside the cell.

The Third Generation Partnership Project (3GPP) set some default parameters for determining the baseline link capacity [51]. A theoretical Shannon capacity in equation (2.5) is limited by the attenuation factor ν, which is set to 0.4 in the uplink and 0.6 in the downlink [51]. Modem throughput and decoding limitations are considered by setting a minimum γ of -10 dB, and a maximum throughput of 2.0 bps/Hz in uplink and 4.4 bps/Hz in downlink [51]. The link's

[1] $N_{th} = B\, k_B\, T$, where $B = 6$ MHz, $k_B = 1.3806488 \cdot 10^{-23}$ W/Hz/K [58] and $T = 15°$ C.

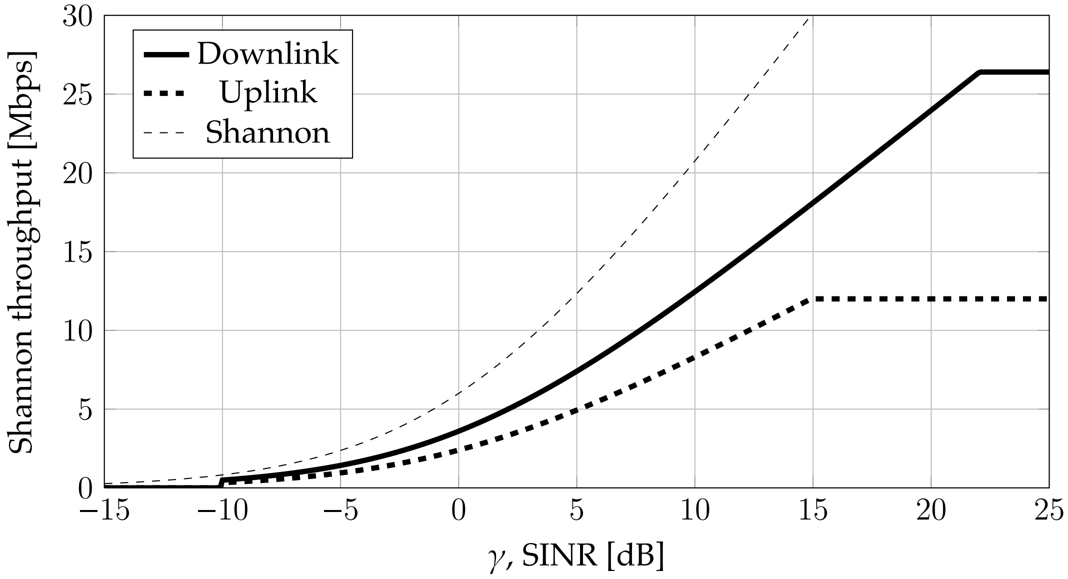

Figure 3.4: The link capacity of a 6 MHz channel in uplink and downlink as a function of signal to interference and noise ratio γ. Both the uplink and downlink have no throughput for $\gamma < -10$ dB and reach their maximum throughput at roughly $\gamma = 15$ dB for the uplink and $\gamma \simeq 22$ dB in downlink. Shannon's theoretical upper limit ($\nu = 1$) for a noisy channel is shown as a dashed line.

total bandwidth is set to 6 MHz.

The FCC's rules and the parameters from 3GPP allow us to estimate the throughput of a LTE system operating in the available white space. In the downlink, the base station can transmit with 1 W [15] and in uplink the power is limited to 100 mW [15]. Figure 3.4 shows the link capacity under these assumptions in uplink and downlink, compared to the theoretical Shannon limit ($\nu = 1$) for different interference powers.

3.3 Cellular network capacity estimation

The cellular network operating in the white space will be simulated using Ericsson's proprietary state of the art LTE simulator. In this thesis, the focus is the general characteristics of the network, and evaluating this over the entire US. Two use-cases, previously mentioned, will be considered; the deployment of a

Table 3.4: Each grid pixel is grouped into one of the four scenarios, based on the population density of the pixel. The inter site distance of each scenario is listed together with the proportion of pixels in each scenario.

	Population density [km^{-2}]	Inter site distance [m]	%-age of pixels
Dense urban	> 1000	400	1.9
Urban	$500 < 1000$	600	1.9
Suburban	$100 < 500$	1800	14.6
Rural	< 100	5000	81.6

standalone cellular network operating in the TV white space, and an offloading network which provides opportunistic capacity to an existing network without the need to guarantee coverage.

3.3.1 Population density based deployment

Base station deployment is constrained by cost, so the density of base stations is often chosen to reflect on the population density of the area. With more users present, there is more potential profit, so it is logical to add capacity. The US population density is available from the 2010 census and provides a density for each county, together with the county's shape. All pixels in a county are assigned the same population density of the county. Four deployment scenarios; "dense urban", "urban", "suburban" and "rural" are assigned to pixels based on the population densities shown in table 3.4, and their geographic locations are shown in figure 3.5. Inter site distances of the cells and the propagation models are set from the assigned scenario. There are few references to the choice of the inter site distances and the ranges of population densities, so the values in table 3.4 are chosen for easy comparability with previous results [9].

A scenario reflects the terrain type and the density of buildings, two options which the LTE simulator takes into account by using different propagation parameters. The dense urban and urban scenarios use Okumura-Hata's metropolitan options [30, Appendix 7.A]. Suburban and rural scenarios use the corresponding propagation parameters from the Okumura-Hata model. The deployment can be seen as macro cellular, as the propagation models for the scenarios all assume that the base station antennas are placed above roof height.

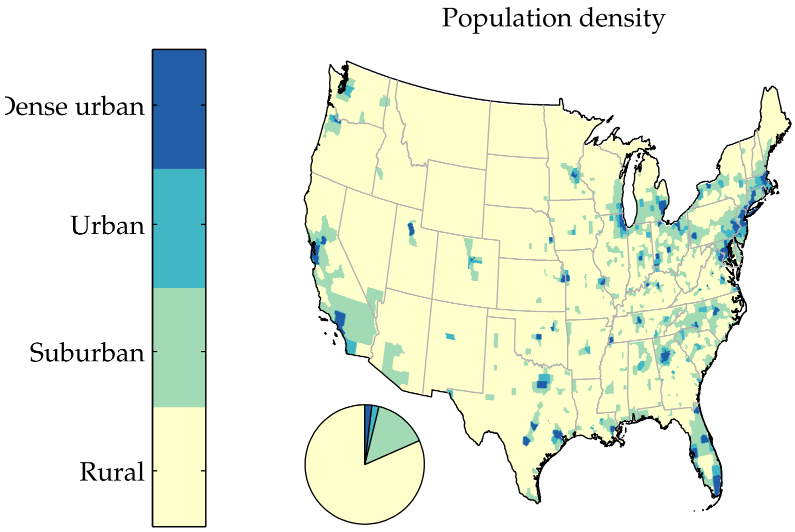

Figure 3.5: The US population density for different pixels, based on the population of each county.

3.3.2 A standalone macro cellular network

The standalone cellular network is deployed with cells which are intended to serve the users uplink and downlink needs. Base station site locations are freely chosen, but the density of sites depends, as discussed in the previous section, on the population density.

One of the main requirements of a standalone system is that it provides good coverage, and for this we must define coverage measures. The aim of these selection criteria is to choose channels with a certain quality. It is neither cost efficient nor end-user friendly to deploy a LTE system with poor coverage or low capacity. A single channel with large capacity might motivate higher costs in base station and user equipment hardware, meanwhile if many channels are selected which together provide large capacity, the technical limitations might render the deployment infeasible. Two criteria were previously defined [9]. These criteria measure the coverage and the capacity available to the worst off users, setting a minimum level of throughput and availability.

1. The white space system provides sufficient coverage if the outage probability is below $5\,\%$ ($1\,\%$).

2. If the cell edge user bit rate of the white space system is higher than $10\,\%$ ($50\,\%$) of the cell edge user bit rate of the reference system the system provides sufficient coverage.

Both frequency and time division duplexes are evaluated on the $6\,$MHz channel. Frequency division would require two $6\,$MHz channels to be available, one used for uplink and the other for downlink. The requested traffic on each channel corresponds to 1000 simultaneous users, with 1 or 10 GB/month each. Traffic could be split over more of the available channels, and this would assume an ideal carrier aggregation, where each device supports all the selected channels. Each pixel is considered independently, but the size and relative number of deployed systems is not considered. The parameters used by the LTE simulator are discussed in more detail in section 3.3.4.

3.3.3 An offloading enabled network

The offloading scenario assumes that there is a functioning LTE network, deployed in dedicated spectrum which provides coverage. TV white space is used for opportunistic spectrum expansion when extra capacity is needed, thus not requiring coverage or availability but instead focusing on a significant throughput boost. The deployment could be WiFi-like, similar to a scenario proposed by the QUASAR project [14], but here the suggested macro cell deployment based on the population density is used. These criteria select channels with significant amounts of extra throughput, both overall for the whole cell, and the median user and are formulated with comparability to previous work [9] in mind.

1. The white space cell's total throughput spectral efficiency is at least $25\,\%$ ($50\,\%$) of the total throughput spectral efficiency achievable by a reference offloading system in dedicated spectrum.
2. The median users must have a spectral efficiency (of the achievable bit rate) of at least $25\,\%$ ($50\,\%$) of the median user's bit rate spectral efficiency of a reference offloading system in dedicated spectrum.

The first criteria is a general cell-performance comparison, and requires the spectral efficiency of the white space cell to be at least $25\,\%$ ($50\,\%$) of the reference system's cell spectral efficiency. A downside to this criterion is that it ignores the distribution of bit rates among the active users. The second criteria instead compares the bit rate spectral efficiency of the median users of the white space system and reference system, thus selecting channels where the network has managed to serve many or most of its users. Selection criteria for the offloading use-case are evaluated independently for uplink and downlink transmissions. Channels which are good for downlink transmissions may not be useful for uplink, which will be shown by these comparisons.

3.3.4 The LTE simulator

The LTE simulator is static in time. A simulation is setup with users distributed in the cellular system, requesting data in uplink or downlink. Upon completion, the instantaneous throughput of each user is presented for further analysis. The cellular network consists of multiple (21) cells, with wrap-around boundary conditions, so that each cell has the correct number of neighbours and the area is effectively infinite in size.

Active users in the network start by determining the transmission power and path loss to the base stations. The main functionality is shown in figure 3.6, which shows how uplink and downlink transmissions are calculated. Inter cell interference from neighbouring cells is calculated and the signal to interference and noise ratio, γ is updated in each iteration loop. Users with high γ can lower their transmission power, possibly reducing the inter cell interference in neighbouring cells. Resource elements can be rescheduled based on the channel quality of the users, thus resulting in a bandwidth and signal to interference and noise ratio for each user which determines the throughput. Each iteration loop changes and optimises the users' throughputs, but also changes how each cell resources are used. This utilization or load measure reflects how the cell interferes with its neighbours, and thus the signal to interference and noise ratio of its users. A stable utilisation value is iteratively determined, so that the inter cell interference is taken into account correctly for all users in the network. The algorithm is discussed in detail in [59].

Once a stable utilisation is found, bit rates are assigned each user. The Shannon theory mapping in equation (2.5) could be used, but more realistic link layer performance data is provided in the simulator. These reflect the performance of

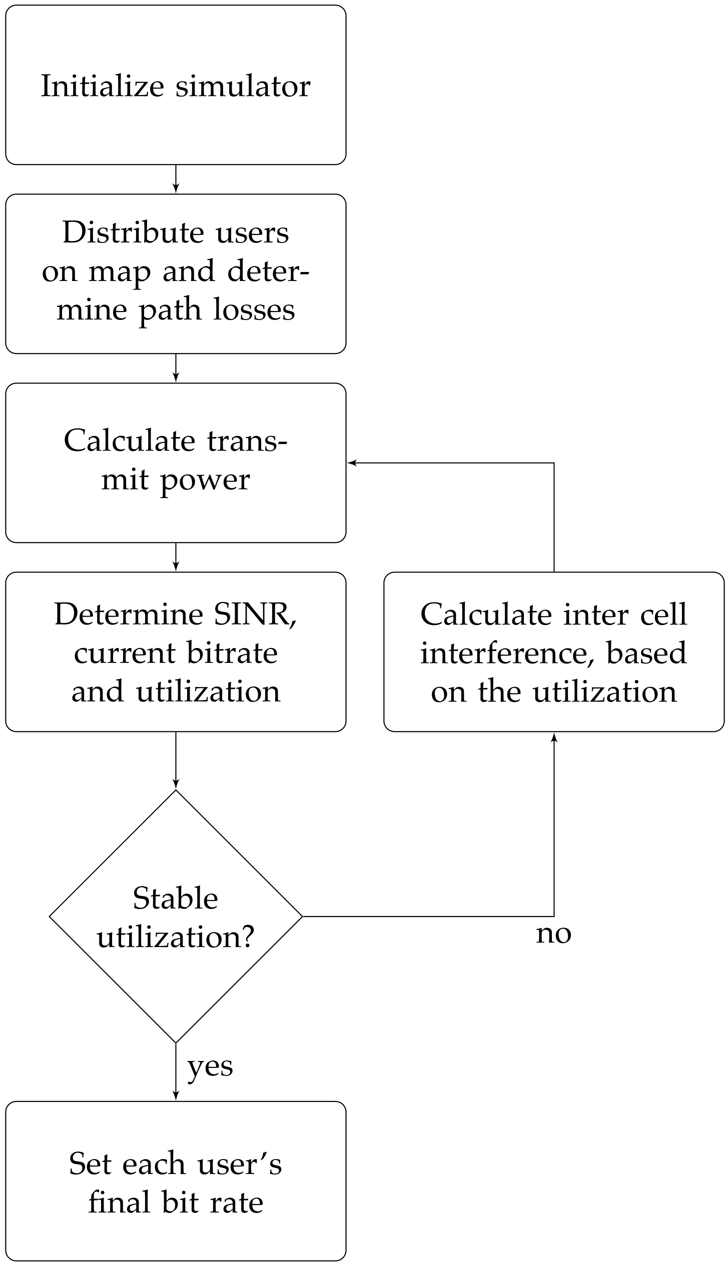

Figure 3.6: LTE system simulator operating in equal buffer mode.

Table 3.5: Simulation options for reference network and network deployed in white space.

	White space	Reference
Number of base stations	21	
Sectors per site	3	
Total resource blocks	$33 \simeq 6$ MHz	
Thermal noise floor (6 MHz channel)	-106.22 dBm	
Path loss model	Okumura-Hara	
Maximum transmit power, Uplink	20 dBm	23 dBm
Antenna height, Mobile device	1.5 m	
Noise figure, Mobile device	2.2 dB	
Antenna gain, Mobile device	Isotropic	
Maximum transmit power, Downlink	30 dBm	60 dBm
Antenna height, Base station	30 m	
Noise figure, Base station	9 dB	
Maximum antenna gain, Base station	14 dBi, (-20 dB at 70°)	
Minimum allowed bitrate	56 kbps	
Carrier frequency	$512 - 698$ MHz	750 MHz

transmitter and receiver algorithms found in typical products used today.

The instantaneous bit rate of each user depends on where the users are located in the system, and the average of many realisations is used to find the general behaviour. TV interference acts as white noise to the LTE network, and is then easily modelled by raising the noise floor of the system.

Requested traffic and performance indicators

Data traffic in the time-static simulator is defined by the number of bits per time period and area unit. If we assume that the users spread their data requests evenly over 16.7 hours per day, the number of bits per second (bps) can be rescaled to GB/month. A system with 1000 users requesting 1 GB/month would require the network to provide an overall average bit rate of 4.4 Mbps[2].

[2] 1 GB/user/month · 8000 Mbit/GB · 1000 users/(365.242/12 days/month · 16.7 hours/day · 3600 seconds/hour) = 4.4 Mbps

$1\,\mathrm{GB}$/user/month and $10\,\mathrm{GB}$/user/month traffic loads are tested in the simulations. A network's total served throughput is an overall performance measure, but does not indicate how well individual users are served. Detailed network performance, as noted in the background chapter section 2.5, is evaluated using the cell edge user bit rate, the outage probability and median user throughput.

In some locations multiple channels will be available for deployment of the LTE system. The total traffic requested by the users could then be split over the available channels, resulting in a larger capacity. If all 30 TV channels were available for LTE use, the traffic could be shared between them.

The LTE simulator is run for each of the four scenarios with different numbers of active users. Two traffic levels are simulated for both duplex modes. Each run of the LTE simulation gives the performance indicators at each of the interference powers.

3.3.5 Interference power binning

Interference powers on each channel at each pixel are within the same range, and consist of the aggregation of approximate signal powers. The exact interference power is not of great interest, since the validity of SPLAT and the aggregation must be ensured with measurements. To reduce the number of LTE simulations the interference powers are sorted into bins. Instead of running an individual LTE simulation at each pixel on each channel, all pixels with similar interference levels on one channel share the results from one LTE simulation.

The pixels are sorted into static bins $1\,\mathrm{dBm}$ wide, from $-150\,\mathrm{dBm}$ to $-20\,\mathrm{dBm}$ in the uplink case and from $-140\,\mathrm{dBm}$ to $-20\,\mathrm{dBm}$ in downlink. Pixels with interference powers below the lower limit are sorted into the lowest bin, and pixels with higher interference powers are removed. Interference powers at and above $-20\,\mathrm{dBm}$ will result in non-functioning LTE networks and we can consider these pixels equivalent. The lower limits $-140\,\mathrm{dBm}$ and $-150\,\mathrm{dBm}$ group together pixels where the interference power is too small to influence the LTE system. Figure 3.7 depicts the histogram of pixels sorted into different interference power bins for channel 21. The two peaks at $-140\,\mathrm{dBm}$ and $-150\,\mathrm{dBm}$ show the number of pixels with interference powers below the limit. Uplink and downlink interference distributions are shown, and their peaks are roughly $30\,\mathrm{dBm}$ apart,

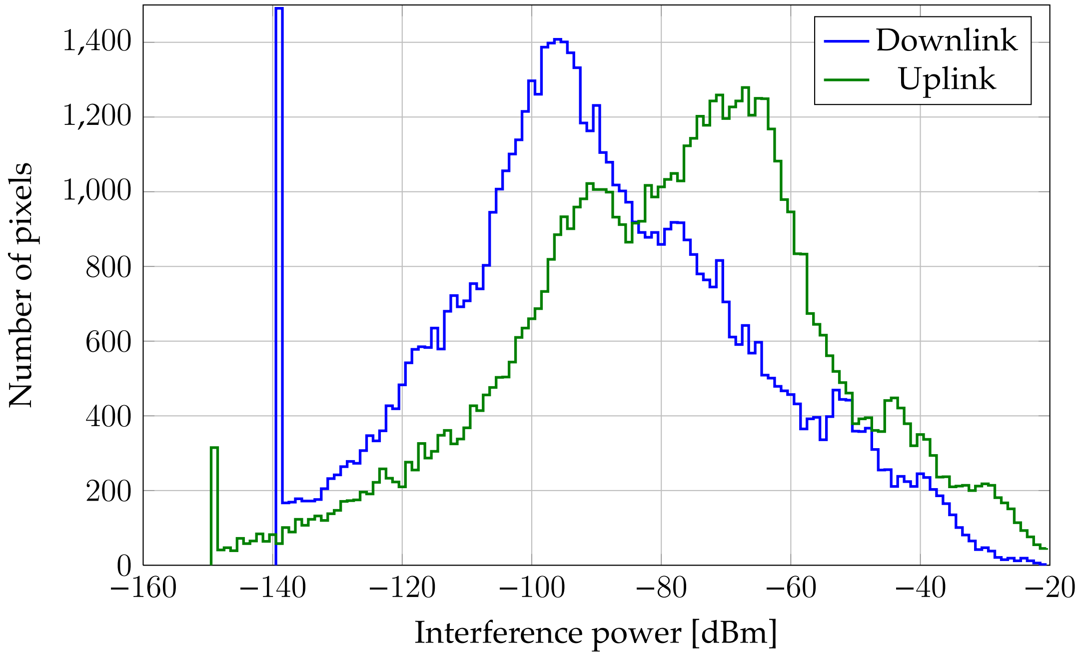

Figure 3.7: The interference power on channel 21 is shown for downlink and uplink. The large peaks at −140 dBm and −150 dBm, contain all pixels with lower interference power.

meaning that an average pixel will have very poor uplink functionality. The large difference in interference powers between uplink and downlink is mainly due to receiver height and channel selectivity of the receiver.

Figure 4.7 on page 51, displays the total served traffic for different interference powers, and the overall results indicate that interference powers above −40 dBm result in non-functioning LTE systems. When the interference power is below −130 dBm, the LTE system in white space typically performs close to the reference system, allowing exceptionally low interference powers can be grouped into the minimum bin.

4

Results

The results follow the ordering of the white space assessment chapter. First the TV coverage and signal propagation results are shown for WBGU-TV, the example transmitter. This ensures that the output from SPLAT is reasonable, and comparable to the FCC's $F(50, 50)$ curves.

The distribution of available channels and their interference powers are then shown, illustrating the amount of white space available. A map shows the number of available channels, which together with the population density map in figure 3.5 provides an initial feeling for how many people will be able to use the available channels. The distribution of link capacity estimates, using all available channels is then shown as an introduction to the LTE simulation results.

LTE system performance is presented for each of the two use-cases. Overall traffic for different interference powers is discussed, and the channel selection criteria for the standalone network applied. Requiring both uplink and downlink functionality severely limits the number of usable channels. The offloading network selection criteria seem more promising. Total provided throughput based on the criteria is then shown and compared to two different reference systems.

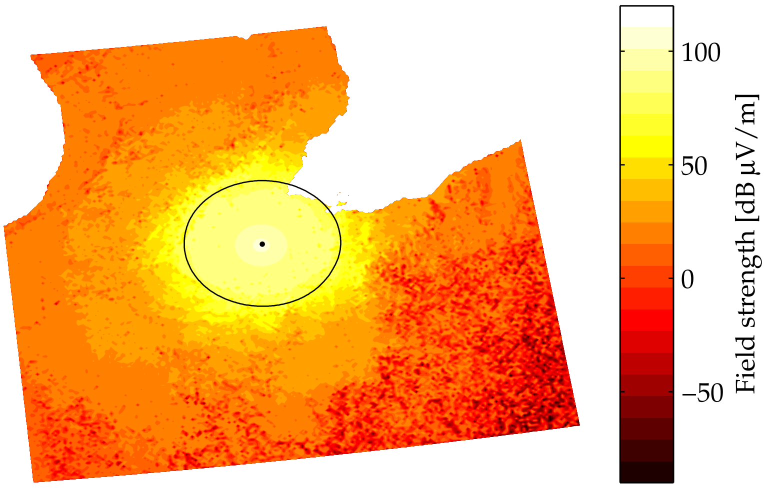

Figure 4.1: Field strength of the WBGU-TV transmitter plotted over terrain. The black ring shows the FCC's service contour.

4.1 TV coverage assessment

The SPLAT calculations provide the receivable power from each transmitter at each of the grid points. Figure 4.1 shows how the field strength varies round the example WBGU-TV transmitter. When comparing this to the terrain elevation shown in figure 4.2, it is clear that the hillier areas block the signal and leave the areas beyond in radio shadow.

Figure 4.3 shows a comparison of different propagation models for the WBGU-TV transmitter. Terrain and SPLAT field strength are sampled due north from the transmitter's location. The service area cut off is at 41 dB μV/m on the FCC's $F(50, 50)$ curve, so all receivers with roughly 100 km of the transmitters should be within range. Note how the field strength calculated by SPLAT starts to drop outside the service area. At larger distances, SPLAT estimates a value about 10 dB above the $F(50, 50)$. For this transmitter, the interference determined in these simulations will presumably be slightly higher than if the $F(50, 50)$ curves had been used.

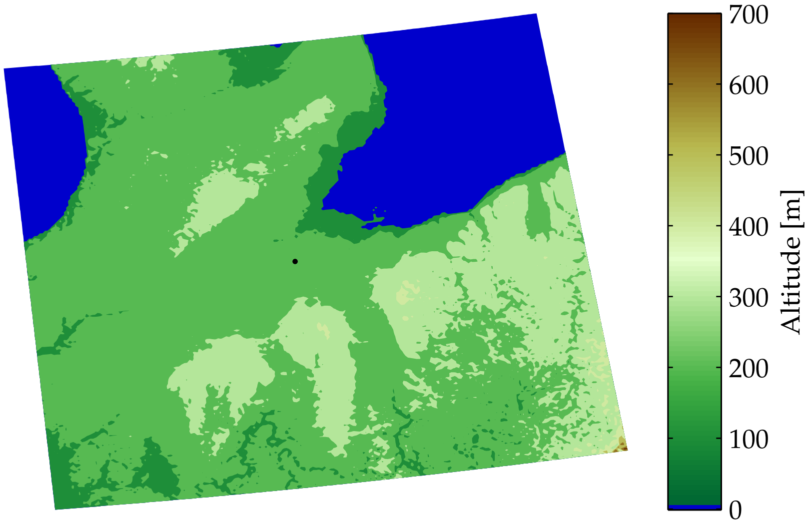

Figure 4.2: The terrain elevation surrounding the WBGU-TV transmitter. The black point shows the location of the transmitter.

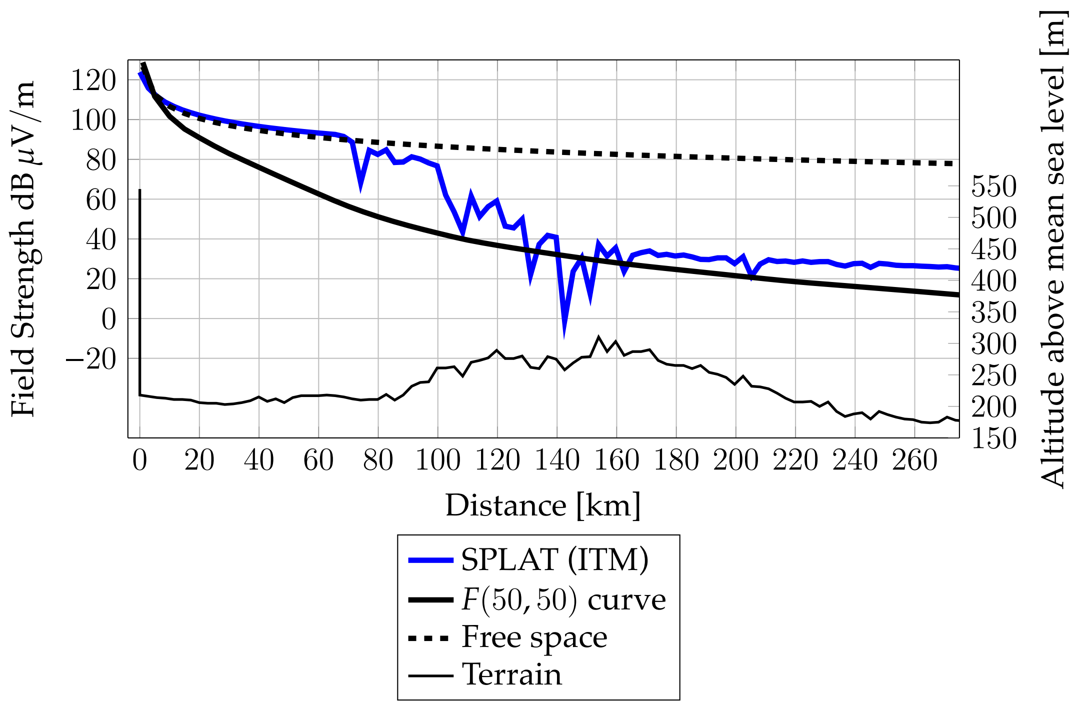

Figure 4.3: Field strength model comparison for WBGU-TV transmitter. The terrain elevation is shown with the height scale on the right, and the height of the transmitter at shown at 0 km. The figure ignores the earth's curvature.

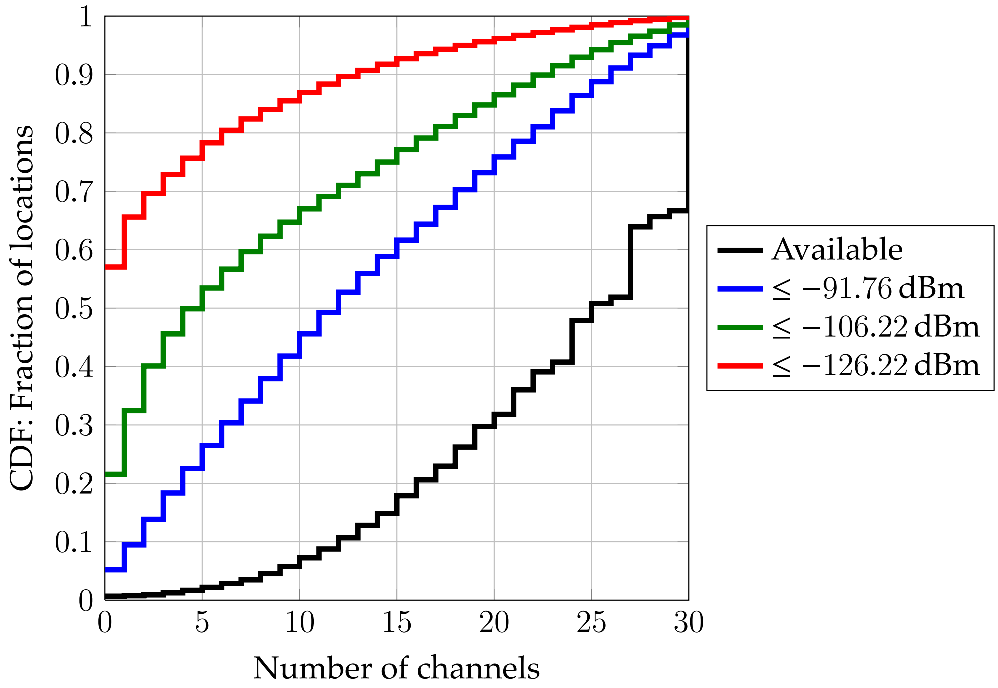

Figure 4.4: The proportion of locations with the number of available channels for base stations, also filtered by TV interference level.

4.2 TV interference levels and the available white space

Evaluating the FCC's rules for secondary use, and applying it to the grid of pixels the proposed amount of white space becomes apparent. Figure 4.4 shows the proportion of pixels with a certain number of available channels. With the restricted channels available for base stations, 10% of locations have 12 channels or less are available for use, 50% of the locations have at least 25 channels. From just analysing the protected regions there seems to be a great potential for secondary users.

The number of channels with TV interference power for a base station below given limits are also shown in the figure. These power levels are useful when looking at the performance of the cellular systems, for example in figure 4.7. TV interference is considered negligible when comparable to 1 % of the thermal noise, i.e. −126.22 dBm, and lower of higher interference powers indicate channel quality. Figure 4.4 indicates that channels with interference power below −106.22 dBm are quite common, only 20 % of locations have no such channels.

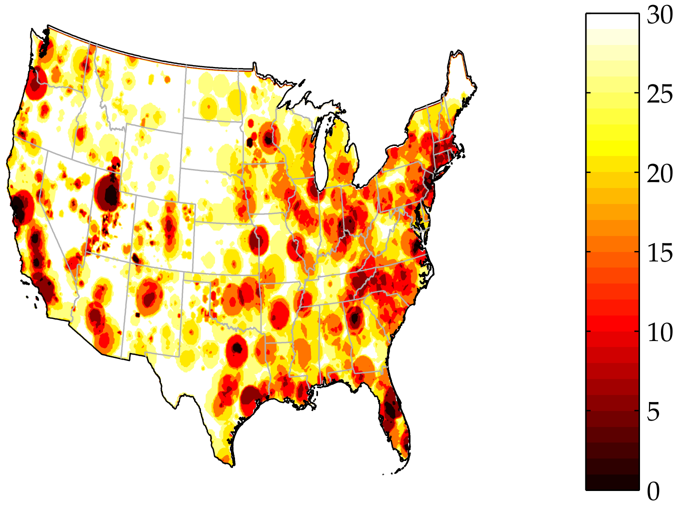

Figure 4.5: The number of available channels, according to the FCC's rules.

The geographical distribution of available channels tells a somewhat different story. Figure 4.5 shows the number of available channels on the US map, and the more populated regions, such as the east coast, Florida and California have less available channels than the central and northern states. There seem to be more channels available in locations where there are fewer people.

4.2.1 The estimated link capacity

Link capacity estimates are derived using equations (2.4) and (2.5). Aggregate TV interference power and the different link configuration options for the uplink and downlink transmissions result in bit rate estimates for the available channels in each pixel. The estimates correspond to the throughput available to a LTE system which provided the maximum throughput on all available channels.

The link is estimated with the transmit powers allowed by the FCC in white space. Path loss between the receiver and transmitter is determined using the pixel scenario, so that an appropriate model is used. The separation distance is set to half the inter site distance.

Figure 4.6 shows the distribution of link capacity estimates for uplink and downlink. A median location has an estimated spectral efficiency of $0.33\,$bit/s/Hz in

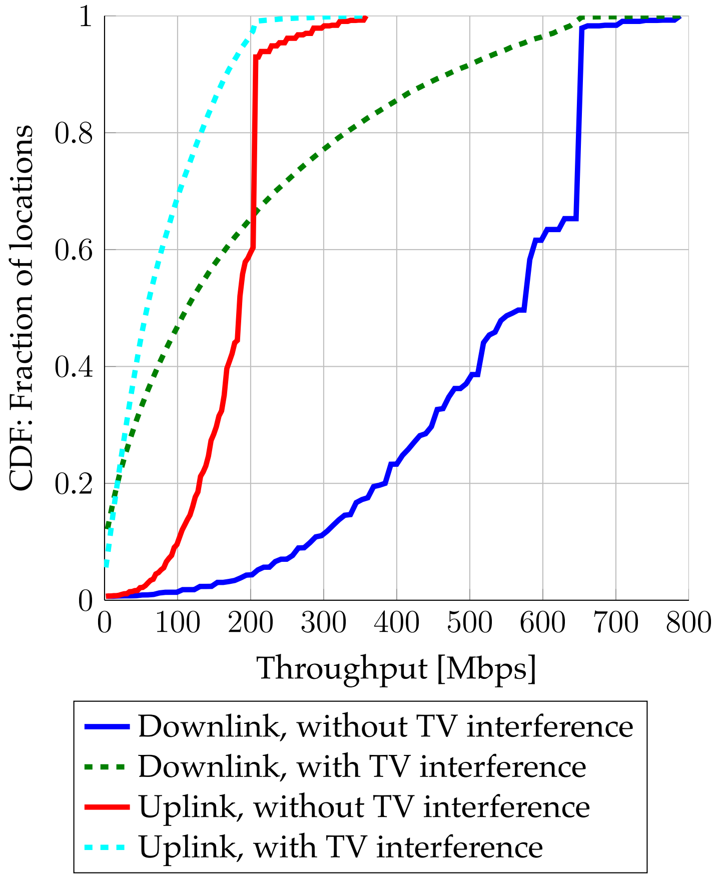

Figure 4.6: The aggregate link capacity for a single secondary device over the distribution of pixels in the US. The device is using all available channels at each location.

uplink and 0.65 bit/s/Hz in downlink. The figure shows the link capacity with the TV interference as a smooth curve, since the capacity is limited by both the FCC's availability and the interference power. The solid lines in the figure are less smooth since they ignore TV interference power but are restricted to use the channels allowed by the FCC. The difference between the curves thus illustrates how much to link capacity decreases due to TV interference. A median location would have an achievable capacity of roughly 120 Mbps when TV interference is taken into account, but could, if no TV interference was present have a throughput of 580 Mbps in downlink.

Link capacity estimates by Harrison, Mishra, and Sahai [13] look slightly different to figure 4.6. They consider all available channels, including channels 2 to 20 which have been left out of this report since the FCC's rules make them incompatible with LTE. Looking at figure 4 of [13] the regional variations in the raw capacity seem to correspond to the channel availability from figure 4.5, the more populated regions have lower capacity. Their figure 4 in [13] is determined with the users at $1\,\mathrm{km}$ from the base station. Comparing Harrison, Mishra, and Sahai's results to figure 4.6, the range of capacity seems reasonable; some parts of the US have link capacities near $1000\,\mathrm{Mbps}$, but the lower bandwidth available for the estimates in figure 4.6 decreases the maximum accordingly.

4.3 Performance of the cellular network

The reference network, operating without interference from the TV transmitters is mainly limited by the cell size and the different propagation models used. Figure 2.6 shows how the outage probability and the cell edge user bit rate depend on the number of users in the cell, when looking at dense urban and rural deployment. A real world cellular network deployment would use more of the spectrum, possibly two $10\,\mathrm{MHz}$ blocks or more. It would lend more bandwidth to the users and thus a higher capacity, but would not necessarily lower the outage probability.

The question is now if the standalone network operating in white space can provide coverage or not, and how much offloading capacity we could expect from the opportunistic deployment.

Figure 4.7 illustrates the results from the LTE simulator, where the thick lines show the behaviour of the network operating in white space and the reference system in dedicated spectrum is shown with thin lines. The white space system loses all the served traffic for high interference powers, an expected result since the signal to interference and noise ratio in (2.4) approaches 0. When the interference power is below $-126.22\,\mathrm{dBm}$, about $1\,\%$ of the thermal noise power, the white space system and the reference system have similar behaviour, at least when lightly loaded with $1\,\mathrm{GB/user/month}$.

Downlink transmissions are more robust than the uplink and manage to some extent to transmit the requested traffic for higher interference powers. This comes from two factors, the base station's transmission power ($30\,\mathrm{dBm}$) is much

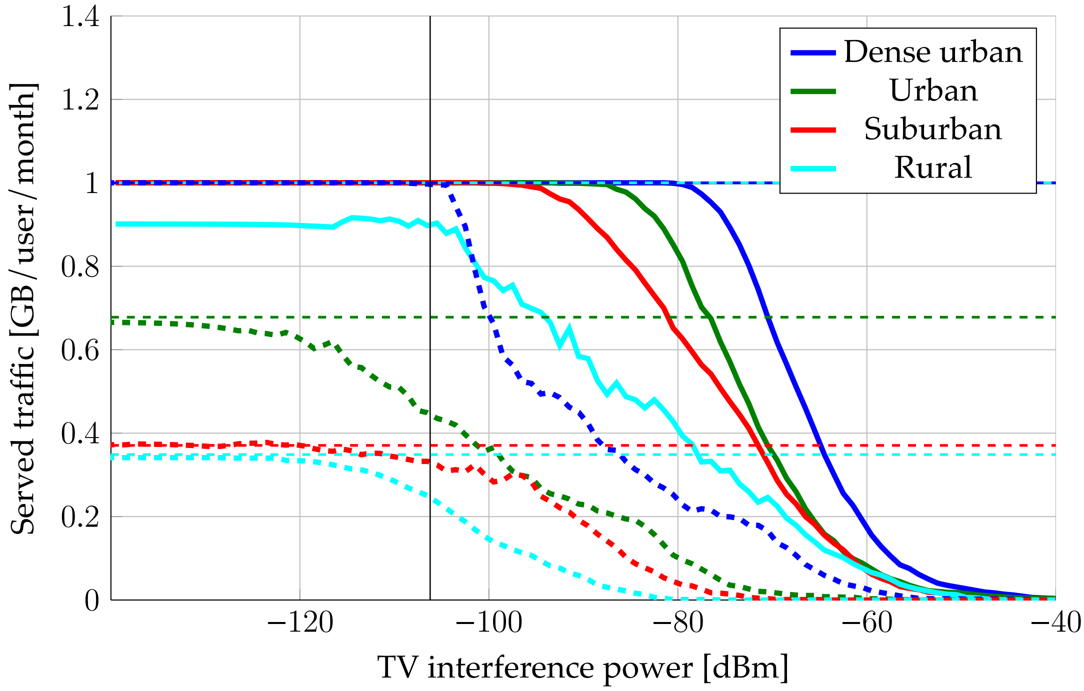

Figure 4.7: The traffic served in the LTE network for different interference power. Solid lines show the downlink and dotted lines the uplink. The thin lines show the reference system, operating in dedicated spectrum. The system is operating in frequency division duplex mode on channel 21 but the behaviour is similar on all channels. Each of the 1000 users request 1 GB/month. The vertical black line marks the thermal noise floor at −106.22 dBm.

higher than the mobile device's (20 dBm) and the TV interference power is lower since the user is only 1.5 m above ground. The uplink transmissions fail to supply the full requested traffic and in all but the smallest cell, an effect also seen in the reference system. This indicates a problem in coverage, where the mobile device's power is too low to function.

The influence of the cell size and propagation model change the performance as expected. Urban cells (green) are more susceptible to the TV interference than the dense urban (blue), an effect only influenced by the cell size since both use the same propagation model. Increasing cell size means that the performance decreases, when a fixed amount of traffic is served in the network.

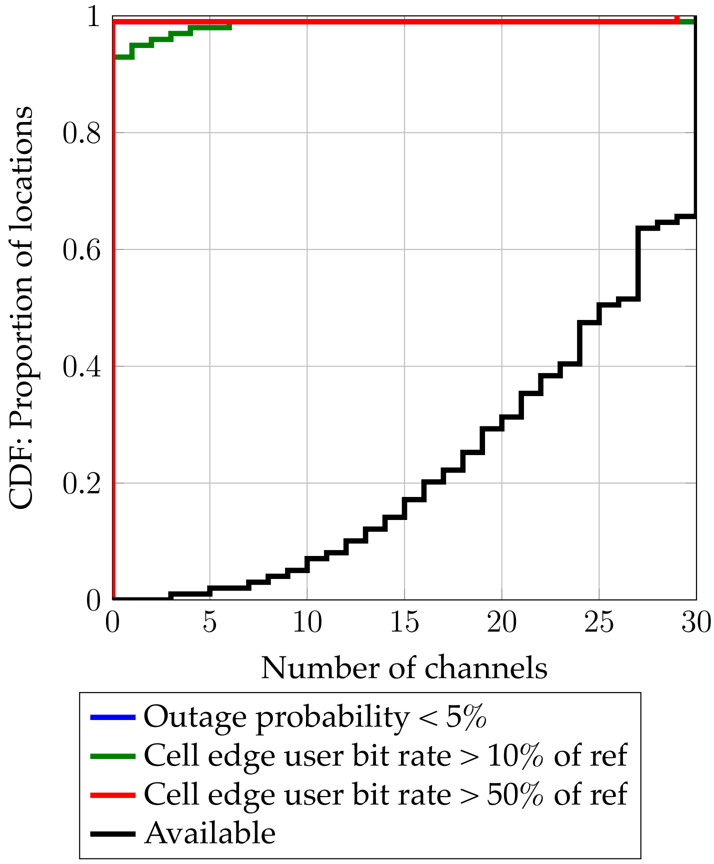

Figure 4.8: The distribution of the number of channels which fulfil the standalone network criteria.

4.3.1 Standalone network deployment

The standalone network results are presented for a frequency divided network. 33 resource blocks of each channel are tested for both uplink and downlink and the performance of each cell size is evaluated. The cell deployments are then mapped back to the US map so that the population density controlling different deployments is taken into account.

Figure 4.8 shows the number of channels which fulfil the selection criteria for a standalone network. The criteria must hold in both uplink and downlink, and in comparing the cell edge user bit rate with the reference system's the inequality is strict. From figure 4.7 we learn that only the dense urban cells manage to provide the requested data in both up link and downlink conjointly with TV

Table 4.1: The reference LTE system, operating in dedicated spectrum without the FCC's power limits. 1000 users request 1 GB/month each.

Scenario	Cell edge user bit rate		Outage probability	
	Downlink [Mbps]	Uplink [Mbps]	Downlink	Uplink
Dense urban	7.05	1.08	0.1 %	0.1%
Urban	7.80	0	0.1 %	32%
Suburban	9.15	0	0.1 %	62%
Rural	9.56	0	0.1 %	65%

interference below -104 dBm, all other cell sizes loose traffic, indicating higher outage probabilities. The performance of the reference system, as shown in figure 4.7 is hardly better for the uplink in larger cells. This translates to the cell edge user bit rate criteria, where the white space system is required to outperform the reference system, which in turn is dysfunctional with cell edge user bit rates of 0 bps. It is unreasonable to expect an improved or equal performance with the added TV interference and the lower transmission powers present in the white space system.

The channel selection criteria are nearly always limited by the uplink, which follows from the uplink performance of the reference system. Table 4.1 shows the reference system's performance indicators for the different deployments with their inter site distances. 1000 users with 1 GB/month is a too high load for the largest cells and the low uplink power. Figure 2.6 indicates that less traffic would lower the outage probability for the largest inter site distance. Lowering traffic improves the downlink cell edge user bit rate, but this is of little use when the uplink still performs poorly.

A "proper" standalone network operating on a single 6 MHz channel should contain both uplink and downlink in the same spectrum. This would be done by either time division or frequency division duplex with 16 resource blocks each. Tests with this limited spectrum gave worse performance than the above results.

If single channels are dedicated for uplink and downlink at least two channels are needed. Less than .8 % of pixels have two channels or less available, according to the FCC's rules implemented in this thesis. Figure 5.1 on page 59 tells us that about 3 % of the population will have 2 channels or more available, so the skewed population distribution is significant when considering the realisability.

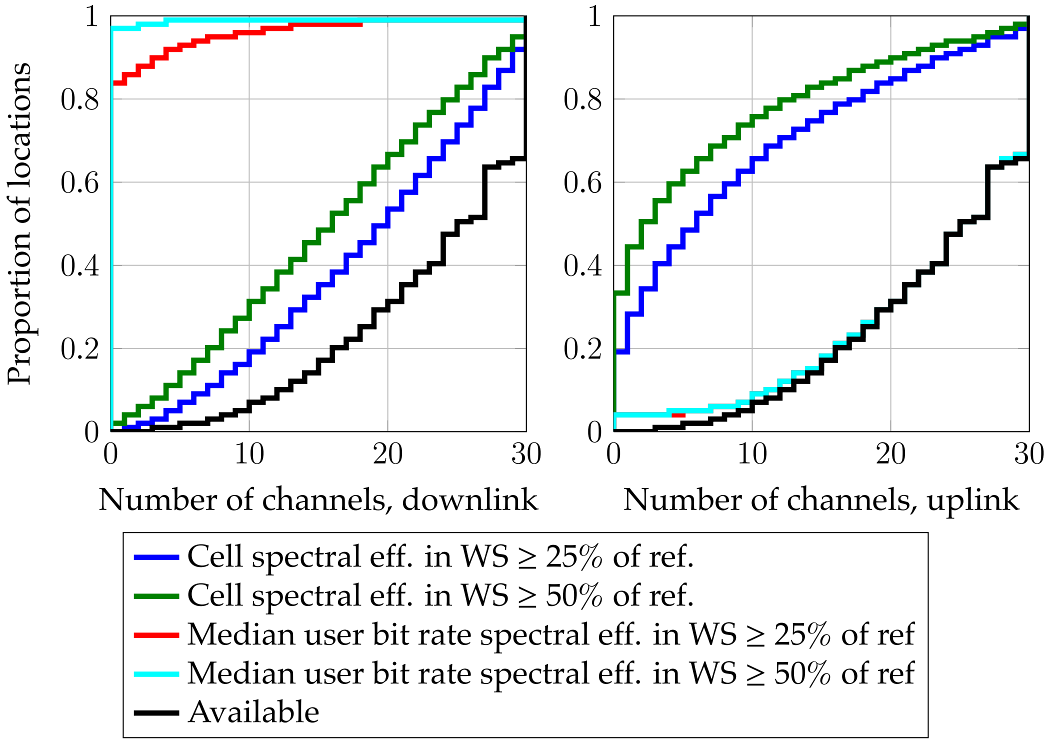

Figure 4.9: The number of channels fulfilling the offloading criteria when users request 1 GB/month. The number of channels available is shown as a black line for reference.

4.3.2 Offloading network

In the offloading scenario an increase in requested traffic is also assessed. The channel selection criteria presented in section 3.3.3 are evaluated and the cumulative distributions are shown in figure 4.9 for 1 GB of requested traffic. Figure 4.10 shows different selection criteria when requesting 1 GB/user/month.

In uplink the cell spectral efficiency criteria are selecting good channels, where the total cell throughput is high. Channels fulfilling the criteria, shown in figure 4.9 are fewer than the available channels, but there is little difference between the throughput achieved on these selected channels compared to the throughput on all channels, as shown in figure 4.10. The median user bit rate spectral efficiency criteria is not as useful in the uplink, since the outage probability is higher. In the rural pixels, the median user throughput will be zero for both the white space system and the reference system and the selection criteria simply

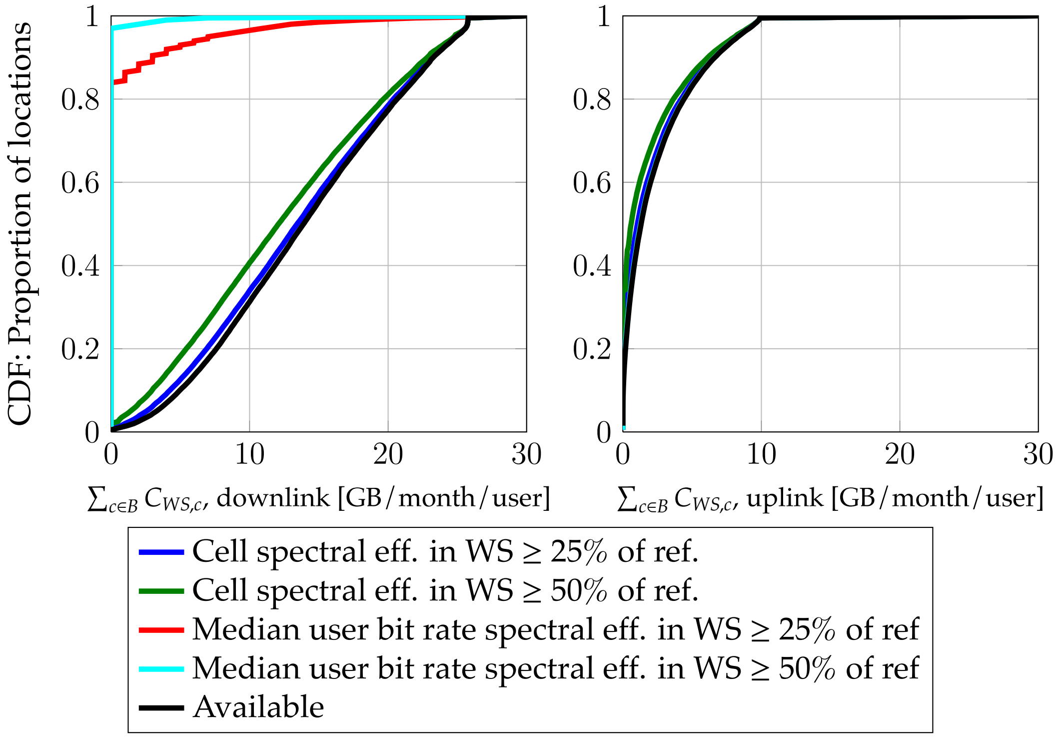

Figure 4.10: The total throughput on the channels selected by the offloading criteria. The users request 1 GB/month.

chooses all channels.

In downlink, the cell spectral efficiency criteria is equally efficient, fewer channels are selected, but there is little decrease in throughput, compared to the available channels. The median location would have close to 25 channels available, and the cell spectral criteria would select 19 (15) of them, but the throughput would only decrease from 14 to 13, (12) GB/user/month. The median user throughput criteria is more efficient in the downlink, selecting a small number of channels which fulfil it, and the corresponding throughput is thus much smaller.

The total throughput is calculated when each channel has the same amount of requested traffic, regardless of how many channels are used. Traffic sharing between available or used channels is not considered in this report.

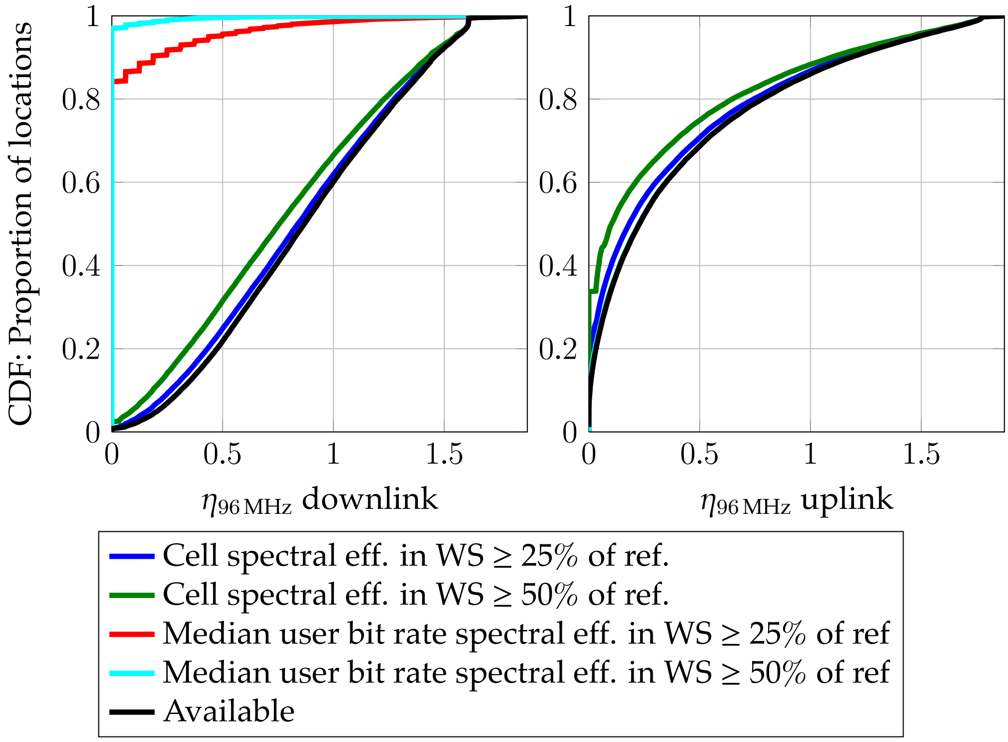

Figure 4.11: Relative spectral efficiency of the selected channels to a reference system deployed in 96 MHz. The users request 1 GB/month.

Spectral efficiency comparison The spectral efficiency of the LTE systems operating on the selected channels will now be compared to two different systems. First, a LTE system deployed in 96 MHz of dedicated spectrum and corresponds to 16 copies of the simulated reference system. The total throughput on the selected channels in white space will be compared to the total throughput of the reference system with 96 MHz of spectrum. Figure 4.11 shows the distribution of the quotient

$$\eta_{96\,\mathrm{MHz}} = \frac{\sum_{k \in M} C_{WS,k}/B}{16\, C_{DS,6\,\mathrm{MHz}}/B} \tag{4.1}$$

where $C_{WS,k}$ is the throughput on channel k in white space and the set M corresponds to the respective selection criteria. $C_{DS,6\,\mathrm{MHz}}$ is the reference system's throughput and B the bandwidth of 6 MHz. In theory there is 180 MHz of spectrum which could be used by the white space system, nearly twice the spectrum of the reference system.

The spectral efficiency is not great when comparing to fixed spectrum. Using

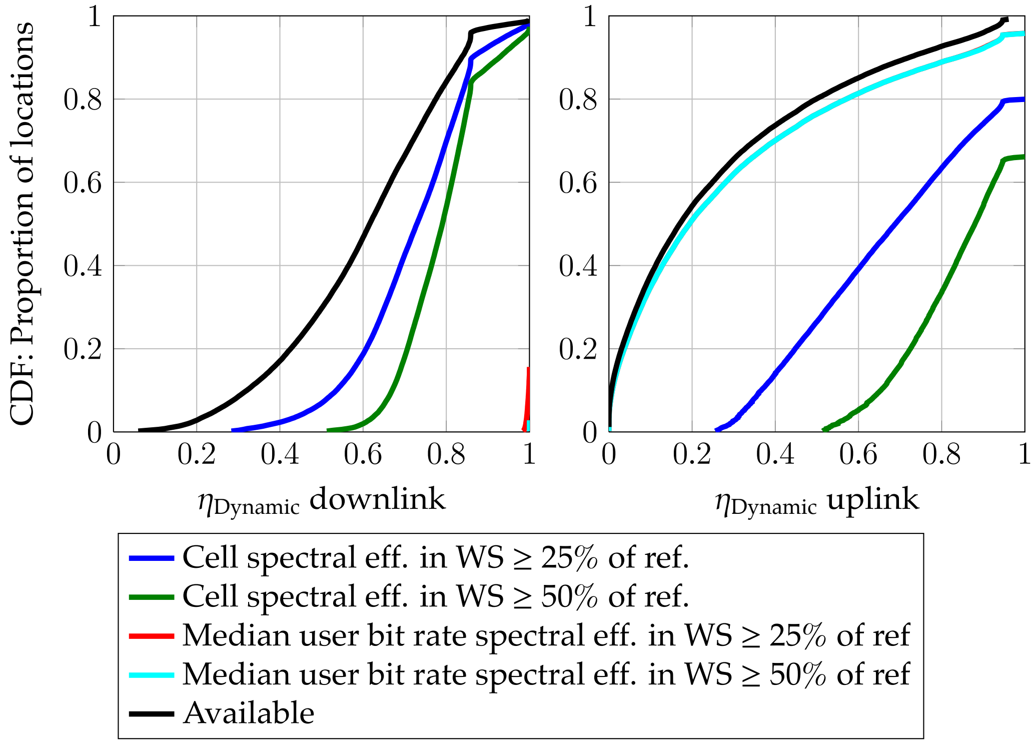

Figure 4.12: Relative spectral efficiency of the selected channels to a reference system operating in the same number of channels. The users request 1 GB/month.

the cell spectral efficiency criteria in downlink, we learn that roughly 60 % of locations have a worse cell spectral efficiency than the system in 96 MHz of dedicated spectrum. In the second comparison, the spectrum efficiency of the white space system will be tested against the actual available spectrum at that location. A similar quotient

$$\eta_{\text{Dynamic}} = \frac{\sum_{k \in M} C_{WS,k}/B}{C_{DS,6\,\text{MHz}}/B \sum_{k \in M} 1} \tag{4.2}$$

is defined, containing the same terms as before. In this way, the location dependent channel availability, as determined by the different criteria, is taken into account and locations with few selected channels will score relatively better than the fixed spectrum comparison in figure 4.11. Figure 4.12 shows the distribution of η_{Dynamic}, this practically compares two systems operating on the location-channels selected by the different criteria, where one system has the TV interference and the other does not. Even if this is a poor distribution of throughput, it tells us which selection criteria are best a selecting high quality channels.

5

Discussion & Conclusions

The main objective of this thesis was to evaluate the capacity and performance of mobile broadband system operating in the US TV white space. The FCC's rules were interpreted for a LTE application and the TV bands database system was emulated using pixel masks. This resulted in finding the distribution of available channels where mobile devices and fixed base stations could interoperate, and the device's transmission powers.

The interference power from the TV transmitters was then estimated. SPLAT and the irregular terrain model were used to determine the field strength received from each transmitter in each location. The received power was then aggregated, taking adjacent channel leakage and adjacent channel selectivity into account resulting in the interference power at each location on each channel. Combining the interference power with the protected areas, defined by the emulated TV bands database, resulted in the distribution of available locations and channels in white space, with their corresponding interference.

Finally system level simulations were performed for a LTE system operating in the determined white space. The results from two use-case scenarios indicate how the LTE system performs under the FCC's conditions and the estimated interference power.

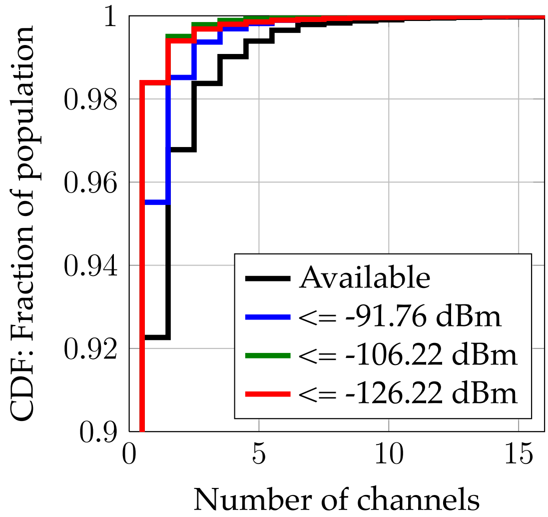

Figure 5.1: The number of available channels in each pixel is now weighted with the relative population density of the pixel. Note the axis limits. The decreasing number of channels fulfilling the criteria is no longer guaranteed, since the population density weights change the relative number of channels for each person per area.

5.1 What have we learnt?

The channels available The FCC's rules allow secondary use in many locations, and on many channels. Figure 4.4 shows that there are close to 33 % of locations have all 30 channels available, and only 2 % of locations have less than 5 channels available. There is a huge location potential here, but looking at the population density in figure 3.5, the population is highly concentrated in some smaller regions. The number of channels available to the population then becomes more interesting, and figure 5.1 shows that only 8 % of the population has one channel or more available.

Considering the usability of the white space channels in terms of people, there is less to gain on channels 21-51. There are more and larger protected TV transmitters near the densely populated areas, so there are fewer channels with locations outside protection in these areas. Figure 5.2 shows how the number of available channels and different population densities are correlated. The visible "banding" effect is caused by the protecting the two first adjacent channels of a transmitter, so that a pixel protected by a transmitter service contour is protected on

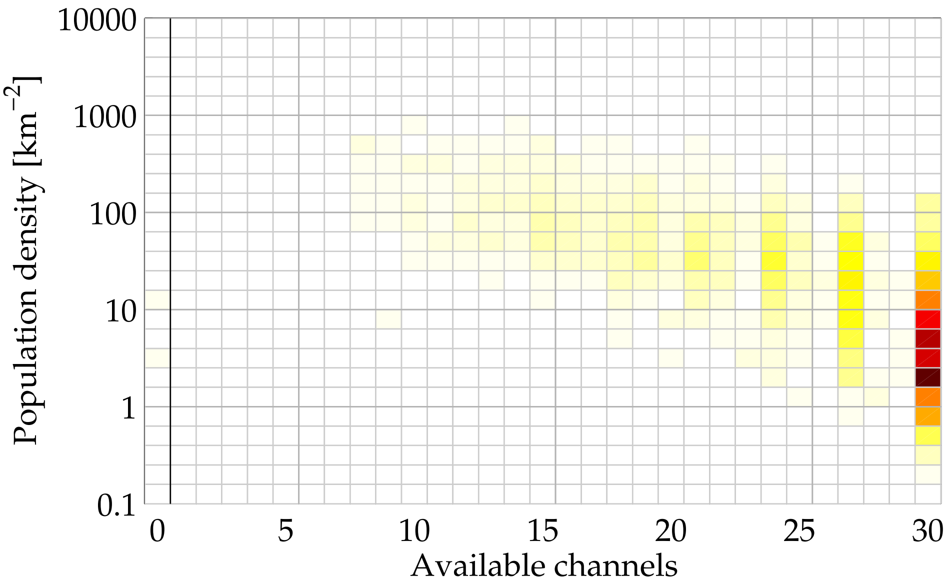

Figure 5.2: The correlation between available channels and the population is strong. Regions with low population densities have worse TV coverage, and thus more available white space, while regions with more people have better TV coverage and thus less available channels. Note that the colour scale is linear, so that bins containing few pixels appear empty (white).

three channels.

Spectrum is needed where people will use it, and if it is already used for broadcasting digital TV, should it be reused for something better?

Propagation models The choice of propagation model is vital in calculating the coverage of a TV transmitter. Differences between the FCC's curves, SPLAT's irregular terrain model and the new irregular terrain with obstructions model, compared in detail in appendix B are significant, especially in the interference region between the coverage areas of two transmitters. These differences cause significant shifts in the total interference power which a device operating in the white space must cope with.

The interference power The aggregate interference power from the TV transmitters is high. Looking at the edge of a single transmitter's service contour[1] and comparing to the case when the TV interference is negligible compared to the thermal noise[2] the interference power can vary significantly. The results show us that the LTE uplink transmissions in the smallest cell are operating with a very tight link budget, so that when the interference power is close to the thermal noise in magnitude the outage probability passes 5 %, thus failing the selection criteria for standalone operation.

Standalone LTE deployment The standalone selection criteria fail for nearly all locations, mainly due to requiring both uplink and downlink to function simultaneously. Figure 4.7 and table 4.1 show that even the reference system cannot fulfil the criteria when it is restricted to a 6 MHz channel, with 1000 users. Both the reference system and the white space deployed system are limited by coverage in uplink, especially in the largest cells. The path loss from users farthest from the base station becomes too large for an uplink to function.

Even if the dense urban deployment was used, with the 400 m inter site distance, over the whole US, there are less than 10 % of pixels which have an outage probability below 5 %. Despite the coverage limited rural and suburban cells, the standalone use-case would not provide required coverage since the TV interference is too large.

The sensitivity of network's performance in relation to inter site distance is evaluated by comparing the performance of an identical network, deployed with half the inter site distances. Intuitively, the cell edge bit rates should improve and the outage probability decrease since the previous network is coverage limited. Selection criteria find more channels available, but there are few locations which fulfil the strictest criteria, requiring the cell edge user bit rate in the white space system to be at least 50 % of the reference system's. Standalone operation remains difficult even with smaller cells.

The offloading network The less strict offloading selection criteria provide a more promising usage of TV white space. When offloading downlink traffic, the lightly loaded system in figure 4.9 shows many available channels, 50 % of

[1]Defined at 41 dB μV/m which ranges from −90 dBm to −93 dBm depending on frequency.
[2]Roughly −126.22 dBm

locations would have at least 15 channels available if looking at the cell spectral efficiency criteria. If we compare the white space spectral efficiency against a reference system operating on $96\,\mathrm{MHz}$ of dedicated spectrum $55\,\%$ of locations achieve the same or better spectral efficiency. The cell spectral efficiency criterion is thus selecting 15 channels or more which can be used.

The median user bit rate spectral efficiency criteria selects channels which are more adept at sharing the traffic among users. Fewer channels understandably provide less total throughput, but the strictest criteria for downlink, when the spectral efficiency must be better than $50\,\%$ of the reference system's, removes roughly $96\,\%$ of locations. The remaining $4\,\%$ of locations could correspond to roughly $4\,\%$ of dense urban and urban pixels.

Figure 4.12 shows how well the selection criteria filter the high quality channels compared to the total available channels. The stricter criteria reduce the spectrum, but provide a better spectral efficiency. In the uplink case, the spectral efficiency increases from 0 to roughly $28\,\%$ by just applying the nicest selection criteria. Stricter criteria increase the spectral efficiency up to about $52\,\%$ for all locations, so that $35\,\%$ of locations have $\eta_{Dynamic} = 1$. $\eta_{Dynamic}$ is generally higher for the downlink case but the stricter criteria still improve the relative spectral efficiency. It is however, still important to consider that the spectral efficiency often is zero both for the white space system and the reference system.

5.1.1 New York & New Jersey

A small case study was done of New York, parts of New Jersey and Long Island. The region is roughly $100\,\mathrm{km}$ by $100\,\mathrm{km}$ and the TV interference power has been calculated for $1\,\mathrm{km}$ by $1\,\mathrm{km}$ pixels. Figure 5.3 shows the smallest possible interference power over all available channels. The central parts of the map, such as Manhattan, Queens, Bronx and along Hudson River have high TV interference, mainly due to the large number of high power TV transmitters on some channels and lower power transmitters protected on others. Further away the best channel's TV interference is lower and potentially usable.

Picture an operator who was to select a single channel to use for downlink offloading. The coverage, where channel use is allowed, and the distribution of TV interference would both have to be considered. For this case study, a com-

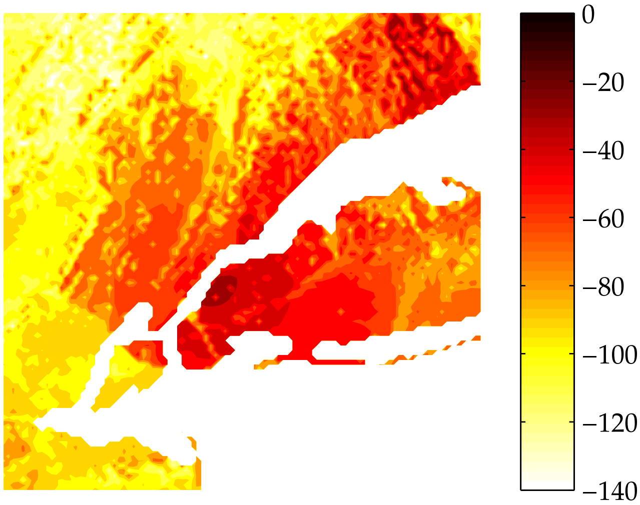

Figure 5.3: The lowest TV interference power in dBm on the available channels is shown for a 100 km by 100 km region centred on New York.

promise would have to be made since channels with good coverage have higher TV interference than channels with poorer coverage.

Channel 35 is selected, and using the 6 MHz channel would not require any significant modifications to existing hardware, and it might then be economically viable to deploy it with small inter site distances. Figure 5.4 shows the downlink throughput distribution for two dense urban deployments, one with an inter site distance of 200 m and one with 400 m. The smaller inter site distance system has worse throughput, presumably from an increased inter cell interference and could be improved with a more optimal transmission power. A median user in the 400 m system would get about 7 Mbps when about 15 % of users would not gain anything from offloading. The 90th percentile could however get close to 17 Mbps.

Just looking at the distribution is not enough, the map in figure 5.3 indicates that even when using the "best" channel many of the central parts have an interference level which effectively drowns the macro cellular LTE network. Offloading traffic with macro cells will not work well, regardless of the chosen channel. It would be possible to use more channels, spreading traffic between them, but the available channels are not contiguous in this area and would require hardware to support a wide range of frequencies. Central Manhattan is still an area where a macro cellular deployment in white space is not viable. When looking

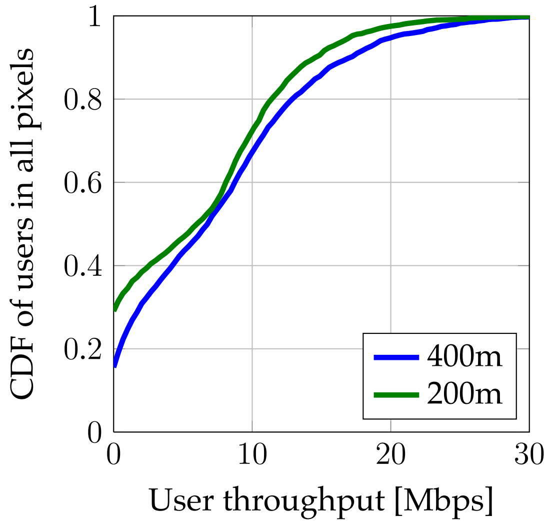

Figure 5.4: The downlink throughput distribution for a macro cellular network operating on channel 35 in the vicinity of New York, shown in figure 5.3.

at smaller scales, building locations, and shadowing become important. There could easily be small places where the TV interference is much lower than these coarse estimates predict.

5.2 Conclusions

Standalone networks operating in white space have difficulties providing coverage and guaranteeing service to the worst-off users. The channels available for a standalone network often have significant interference from nearby TV transmitters reducing the cellular capacity. Many rural parts of the US have more channels available, with lower TV interference power, but the large cell sizes assumed in this thesis together with the FCC's limited transmission power leave the cellular network limited in functionality. The uplink is more susceptible to TV interference and is thus the limiting factor for a standalone network, and the few locations which have a functioning uplink will most likely be sparsely populated.

Opportunistically offloading traffic from an existing network to a white space system is more realistic. Median locations, with the assumed inter site distances in this report could provide enough throughput for $12\,\text{GB/user/month} \simeq 50\,\text{Mbps}$ in downlink, depending on which channels are used. Downlink spectral efficiency would be close to $.5\,\text{bps/Hz}$, with 19 channels are selected for the median location. The skewed population distribution of the US means that most of the population will not enjoy this extra capacity. Smaller cells, possibly dense indoor deployments would improve offloading capacity, since wall dampening and the shorter distances improve signal to interference and noise ratios.

The FCC's rules allow for non-fixed devices to use channels 2, and 5-20, and small mobile router equipment could be installed in places where extra capacity is anticipated. More permanent offloading could be done with higher fixed base stations as tested in this report.

The limited geographic spread of each channel's usage area means that the devices would have to use the full spectrum. Antenna, amplifiers and so on for these frequencies together with existing technologies could increase costs, which might be difficult to justify to operators and end users.

If a small number of TV channels were re-assigned for mobile broadband use and TV transmitters moved to other channels, the resulting dedicated spectrum would be viable for either standalone operation or offloading. Removing TV interference, and the protected geographic regions near TV transmitters would improve coverage and with dedicated spectrum the transmission power limits could be removed. This would give more freedom to the operator to deploy and tune the cellular system for improved uplink transmissions. Fine tuning would be possible for a white space deployment, but with the added complexity of different channels and protected regions.

5.3 Outlook and future work

The accuracy of the TV interference power could be improved by increasing the pixel resolution. More local variations could then be considered, and it would be reasonable to study a smaller area or region. The number of channels available could be more realistically studied using one of the approved TV band databases. Services such as the cable head ends, private land mobile radio would then receive correct protection, and the number of available channels would correspond better to reality.

Inter site distances, both the assumed ones in this work and the actual use in a real world deployment need to be considered. The choice of inter site distances determines much of the final result and should be done with consideration to existing deployments. Large cells have difficulty in providing uplink coverage, even without extra TV interference.

If the power of a mobile white space device is restricted to $40\,\mathrm{mW} \simeq 16\,\mathrm{dBm}$ the FCC's rules allow it to operate inside the service contour of a TV transmitter, albeit on one of the adjacent channels. These devices would have to cope with the adjacent channel leakage from the TV transmitter, which inside the contour would be above $-14\,\mathrm{dBm}$[3], and have good channel selectivity. It might be possible to design very short range offloading systems with these parameters. Indoor systems are desirable, since the TV signal, and thus their interference will be dampened when passing through walls. Machine-to-machine networks, or interconnected sensors could also use white space where low data-rates are expected.

When allowing the secondary usage of TV spectrum the FCC knew that there would be a lot of available channels. Part of this spectrum, is after review not as useful as one might first have thought. The existing TV transmitters cause unnecessary interference outside their service regions, but lowering the transmission power would only unfriend TV viewers. One solution is to use indoor systems, exploiting the wall dampening to reduce the interference and short distances which accommodate the low transmit powers determined by the FCC.

[3]The power at the edge of the service contour is roughly $-90\,\mathrm{dBm}$ and emissions to the first adjacent channel must be dampened $75.9\,\mathrm{dB}$, shown in table 3.2.

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A

FCC tables

This appendix contains tabular data from the FCC used for evaluating the white space rules. Table A.1 shows the frequency range of each of the TV channels [60], and table A.2 the cut-off values for TV service contours [11, Table 1, p. 57]. Table A.3 shows the required separation distance from a TV transmitter service contour for different heights above average terrain (HAAT), defining the no-talk region for white space devices [16, Table in §15, p. 7]. Protected radio astronomy observatories are shown in table A.4, listed in [16, § 15.712 (h)].

Table A.1: Channels and their frequency range.

Channel	Frequency (MHz)	Channel	Frequency (MHz)
2	54–60	27	548–554
3	60–66	28	554–560
4	66–72	29	560–566
5	76–82	30	566–572
6	82–88	31	572–578
7	174–180	32	578–584
8	180–186	33	584–590
9	186–192	34	590–596
10	192–198	35	596–602
11	198–204	36	602–608
12	204–210	37	608–614
13	210–216	38	614–620
14	470–476	39	620–626
15	476–482	40	626–632
16	482–488	41	632–638
17	488–494	42	638–644
18	494–500	43	644–650
19	500–506	44	650–656
20	506–512	45	656–662
21	512–518	46	662–668
22	518–524	47	668–674
23	524–530	48	674–680
24	530–536	49	680–686
25	536–542	50	686–692
26	542–548	51	692–698

Table A.2: Criterion for Definition of TV Station Protected Contours, Analogue TV use F(50,50) and digital TV F(50,90).

Type of station	Channel	Contour cut off [dB μV/m]
Analogue TV	2–6	47
	7–13	56
	14–69	64
Analogue Class A	2–6	62
	7–13	68
	14–69	74
Digital TV	2–6	28
	7–13	36
	14–51	41
Digital Class A	2–6	43
	7–13	48
	14–51	51

Table A.3: Minimum required separation distance (no-talk region) between unlicensed devices and TV service/protection contours.

Antenna HAAT[a] (m)	Required separation	
	Co-channel (km)	Adjacent channel (km)
< 3	4.0	0.4
3 – 10	7.3	0.7
10 – 30	11.1	1.2
30 – 50	14.3	1.8
50 – 75	18.0	2.0
75 – 100	21.1	2.1
100 – 150	25.3	2.2
150 – 200	28.5	2.3
200 – 250	31.2	2.4

[a]Height above average terrain

Table A.4: The locations of radio astronomy observatories

Radio astronomy observatory	Latitude	Longitude
Allen Telescope Array	40.8178°	−121.4733°
Arecibo Observatory	18.3461°	−66.7531°
Green Bank Telescope (GBT)	38.4331°	−79.84°
Very Large Array (VLA)	34.0789°	−107.6178°
Pie Town	34.3011°	−108.1186°
Kitt Peak	31.9561°	−111.6117°
Los Alamos	35.7750°	−106.245°
Ft. Davis	30.6350°	−103.9442°
N. Liberty	41.7714°	−91.5739°
Brewster	48.1314°	−119.6819°
Owens Valley	37.2317°	−118.2761°
St. Croix	17.7586°	−64.5842°
Hancock	42.9336°	−71.9867°
Mauna Kea	19.8044°	−155.4581°
Table Mountain Radio Receiving Zone	40.1339°	−105.2444°
Sugar Groove Naval Radio Research Observatory	38.5161°	−79.28°

B

Propagation model comparison

The SPLAT simulator, version 1.4.0 [38], can use two different propagation models; the traditional Longley-Rice based irregular terrain model supplied from the National Telecommunications & Information Administration [35] and a new irregular terrain with obstructions model proposed by Shumate [37]. Shumate argues with multiple short articles in the IEEE Broadcast Technology Society Newsletter from 2007 to 2011 [62–73] that there are problems with the software implementation of the irregular terrain model. The irregular terrain with obstructions model is an attempt to update and correct the faults.

Shumate submits the modifications as a petition to the FCC's proposed rule making in the matter of "Establishment of a Model for Predicting Digital Broadcast Television Field Strength Received at Individual Locations", which is part of their work on the Satellite Television Extension and Localism Act of 2010 (STELA). The act requires among other things, the FCC to [74]:

> develop and prescribe by rule a point-to-point predictive model for reliably and presumptively determining the ability of individual locations, through the use of an antenna, to receive signals in accordance with the signal intensity standard in § 73.622(e)(1) of [the Commission's rules], or a successor regulation, including to account for the continuing operation of translator stations and low power televi-

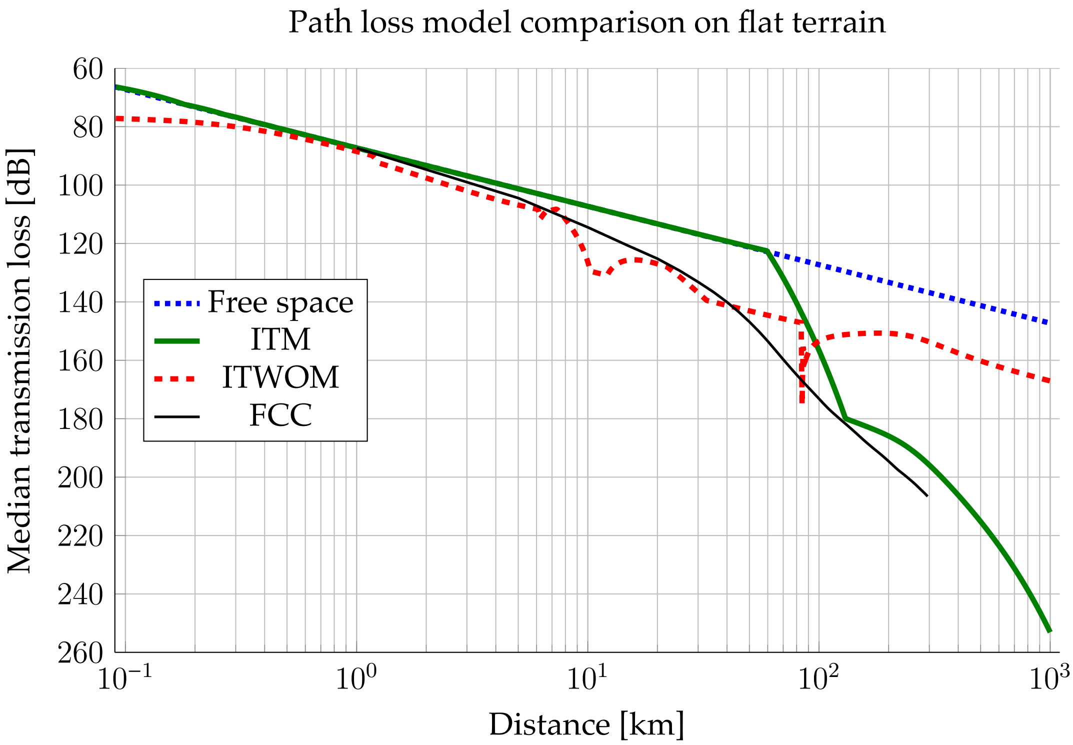

Figure B.1: SPLAT's two propagation models predict path loss over flat terrain. The transmitter height is 320 m, receiver height 10 m and frequency 551 MHz. All path losses are calculated for 50 % time and 50 % location confidence.

sion stations.

Shumate's new irregular terrain with obstructions model was not accepted as a new standard, but remains under the consideration of the FCC [75].

Figure B.1 shows the path loss predicted by the irregular terrain model (ITM) and the irregular terrain with obstruction model (ITWOM). The calculations are performed with flat terrain, with a transmitter height of 320 m, receiver height at 10 m and frequency of 551 MHz. For comparison the free space path loss is shown together with the FCC's 1966 propagation curves [42] often denoted $F(50, 50)$ for time and location confidences of 50 %. The Longley-Rice parameters were set as shown in table 2.1. The behaviour of Shumate's new model beyond 70 km seems unphysical. The irregular terrain model corresponds better to the FCC's $F(50, 50)$ curve at large distances.

C

The maximum interference distance

There is no simple way of determining the maximum range of a TV transmitter. The maximum interference distance was used to ensure that all transmitters which reach a certain pixel are taken into account. Any edge effects which might occur from the regional divisions shown in figure 3.2 should be removed as long as each region is extended to include all transmitters within the maximum interference distance of the regions pixels. Figure C.1 shows how the received power from transmitters with increasing distance falls. The median and mean power approach the thermal noise of -106.22 dBm at 400 km.

Transmitters further away will deliver less power, and are expected to drown out by the interference of closer transmitters. In pixels where the power from these distant transmitters would be significant will have an overestimated channel quality. Thus the available white space will be slightly overestimated.

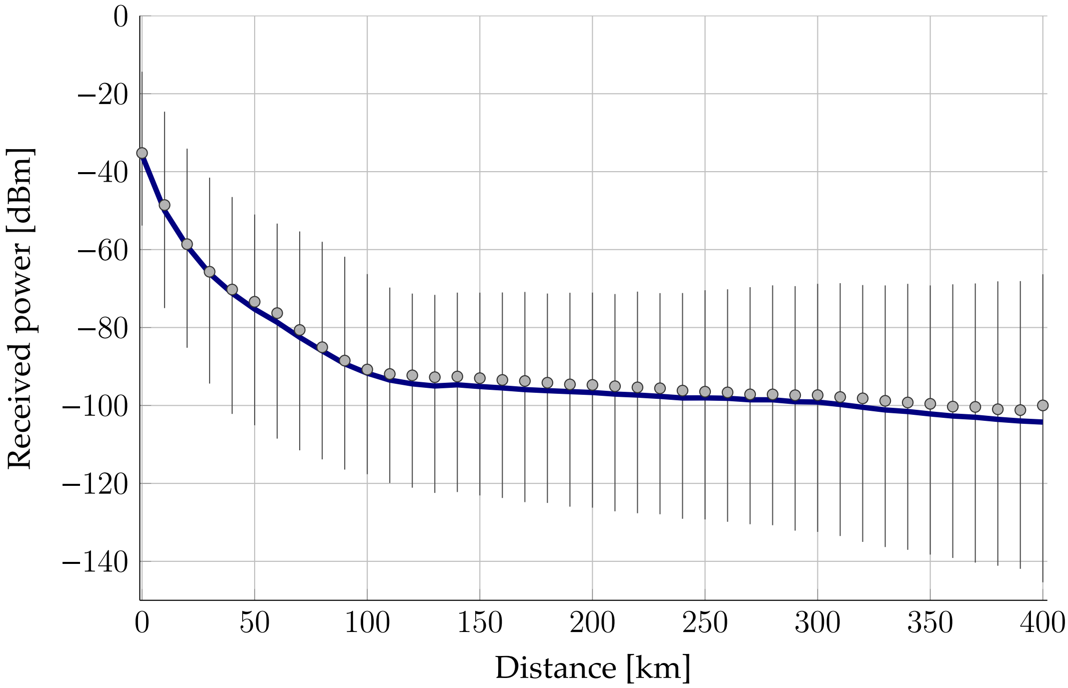

Figure C.1: The distribution received powers for pixels at a certain distance from the transmitter is shown. The circles with their bars show median, 10th quantile and 90th quantile, while the solid blue line the mean received power. Background noise for this bandwidth is roughly −106.22 dBm.

D

Determining the sum of log-normal random variables

In this thesis, Monte Carlo simulations have been used to find an approximation of the distribution of the sum of log-normal random variables. This sum is the aggregate interference power from multiple transmitters, whose received power is normally distributed in the logarithmic domain. The mean power measured in dB is denoted $< P_{dB} >_j$ for transmitter j, and it has a standard deviation of $\sigma = 5.5\,\mathrm{dB}$.

In the aggregation, not only co-channel transmitters are considered. The adjacent channel leakage ratio, defined and discussed in the main text, section 3.2.1, requires us to consider transmitters on adjacent channels.

The linearity of the expectation operator ensures that the adjacent channel interference ratio can be taken into account before or after the sampling. If X is a log-normal stochastic variable,

$$X \sim \log \mathcal{N}\left(\mu,\ \sigma^2\right) \tag{D.1}$$

with parameters μ and σ^2, the expected value of the rescaled variable $e^\alpha X$ is thus

$$\mathbb{E}\left[e^\alpha X\right] = \int_0^\infty e^\alpha x \frac{1}{x\,\sigma\,\sqrt{2\,\pi}}\, e^{-\frac{(\log x - \mu)^2}{2\sigma^2}}\,\mathrm{d}x = e^\alpha\, e^{\mu + \sigma^2/2} = \mathbb{E}\left[Y\right] \tag{D.2}$$

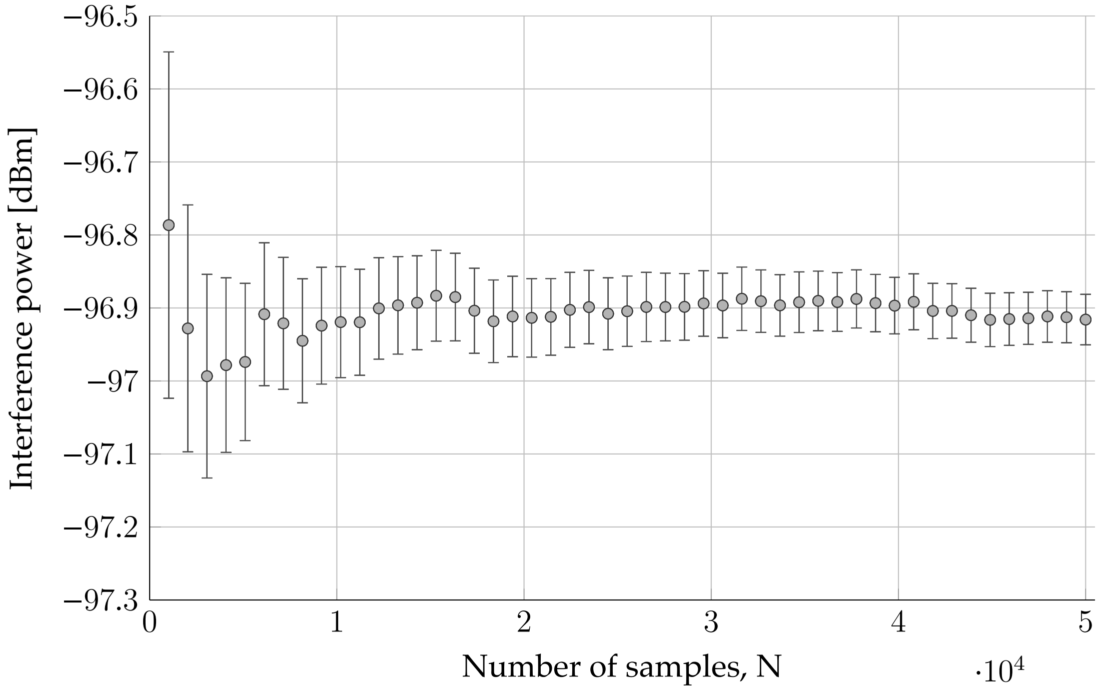

Figure D.1: Example Monte Carlo summation of the powers from 4 co-channel and 26 adjacent channel transmitters. The mean power and its standard deviation are shown. This summation used a maximum of $N = 50000$ samples from the 30 transmitters. Other evaluations in this study used $N = 10000$ samples. In this pixel, there is one co-channel transmitter with a power of -96.9 dBm which dominates the others at powers below -130 dBm (both co-channel and adjacent channels). The difference between the mean interference after $N = 10000$ samples and $N = 50000$ samples is roughly 0.1 dB $\simeq 2\,\%$ in the logarithmic domain.

where Y is a log-normal stochastic variable with parameters $\mu + \alpha$ and σ^2. In practical terms, adjacent channel transmitters are included with a reduced mean power $< P_{dB} >_l - r_{ACIR,dB}$ as if it where a low power co-channel transmitter, as this yields the same expected value.

When all interfering transmitters are included each with their adjusted power, they are used by a Monte-Carlo sampler. The sampler takes N samples from each normal distribution, converts them to the linear domain, and adds each of the samples, resulting in N aggregate samples which are converted back to the logarithmic domain. Figure D.1 shows how the interference power stabilizes with increasing N.

When aggregating the interference power for all grid points on all channels, N was set to 10000. Figure D.1 shows a sample point which is sampled 50000 times, indicating that there is only a small difference 0.1 dB in taking 10000 or 50000 samples. These interference powers are sorted into 1 dBm wide bins, and the error of order 0.1 dB will have little further effect. The dominant transmitter in this pixel on the co-channel has a power of -96.9 dBm, while the others are below -130 dBm.

E

Interference power-height correlation

TV interference power at different receiver heights should be correlated. The received signal in the plane earth and more advanced propagation models show a dependence on receiver height. This section verifies that the correlation still holds after the signals from multiple transmitters have been aggregated into a total interference. To minimise the number of simulations the interference power in dBm at the base station and the mobile device are assumed to be linearly related. To verify this, the correlation coefficient of the received interference power at the two heights was calculated on a per channel basis. The coefficient worked out to be 1, with p-value of 0 indicating that the correlation is significant.

A linear fit was calculated for each channel and used in the later simulations, figure E.1 shows channel 21 as an example. Contours in the figures represent the two dimensional histogram of interference powers. The interference power relation is shown for all channels in figure E.2. The correlation is the same as for the single channels, and independent of the different channel's frequencies.

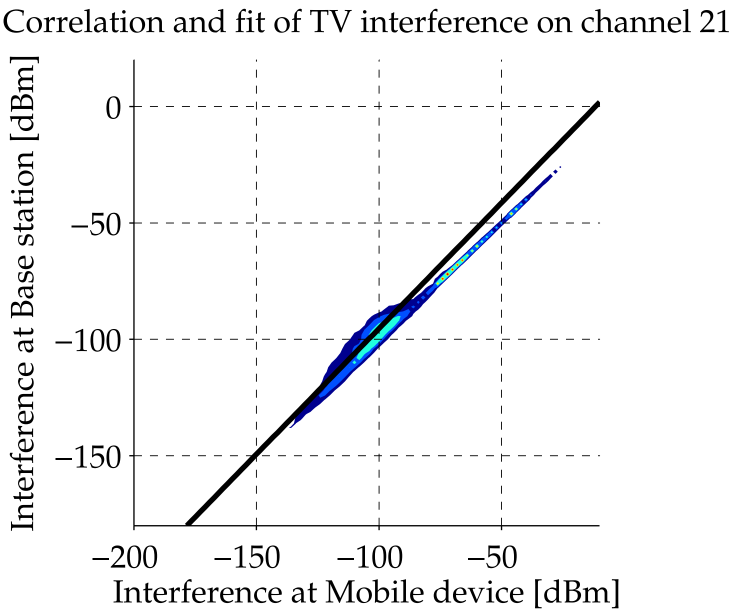

Figure E.1: The correlation between TV interference on channel 21 for a receiver at 10 m and 1.5 m is strong. The linear fit shown corresponds to $I_{BS} = .91 \cdot I_{MS} - 3.2$.

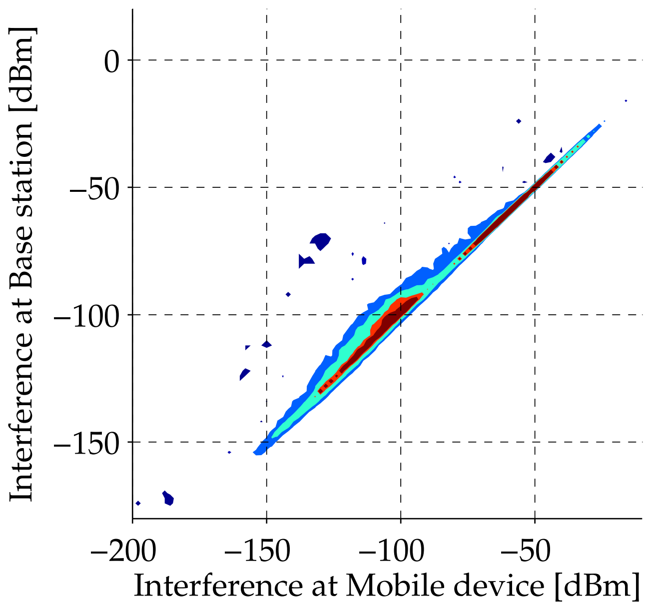

Figure E.2: The correlation of the aggregated TV interference for a receiver at 10 m and 1.5 m is shown, here for all channels together. The interference levels on each channel at the two received heights were sorted into bins and then added together.