The Impact of the TV White Space Unlicensed Spectrum on the Wireless Industry Competition

by

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Abstract

In November 2008, the United States FCC voted to allow unlicensed use of the spectrum designated for TV broadcasting. After the analog-to-digital transition was completed in June 2009, space between channels was no longer needed for the successful transmission of TV signals. These unused portions of the UHF spectrum, popularly referred to as white spaces, represent a new opportunity for wireless networks, offering the potential for more unlicensed bandwidth and long transmission ranges.

This thesis aims to throw light on the real potential of the newly released spectrum TV white space (TVWS) to enhance unlicensed networks features and to enable new services, by studying existing standards and previous deregulations, using historical data as a reference. This work arrives at the conclusion that due to strict laws and spectrum-sharing challenges, rural wireless service providers are the ones most likely to be using this spectrum as a Wi-Fi enhancement in their access points.

This research assesses the real impact of the TVWS in wireless industry competition. Using a System Dynamics model, it analyzes the influence of TVWS new propagation conditions on the relationship between network user adoption, coverage, and service price, to model the evolution of the industry. The model has been calibrated with real data from telecom equipment market prices. Subscriber and coverage information from the main US mobile markets are used as inputs to adjust the network user adoption parameters.

The results show that the new frequency will enhance the adoption of unlicensed networks but will not significantly affect subscribers of traditional licensed networks. This research also analyzes TVWS adoption scenarios and arrives at the conclusion that the scenario that would maximize TVWS social benefits would be the one in which both licensed and unlicensed operators accommodate and deploy networks in those regions that are profitable for them.

This accommodation requires cooperation between unlicensed and licensed operators and could be done in several ways. For example, it could be done by means of direct negotiation, as is actually the case in the 5GHz band, where the Wireless Internet Service Providers operators directly discuss issues with interfering links. However, incumbents in the TVWS band are larger and more numerous, and therefore the author's recommendation is to have a regulatory framework in place that could help define the appropriate areas for licensed and unlicensed use. Thus regulatory bodies could preserve fairness while ensuring proper market competition.

Before companies and authorities take any action, it is important for them to be aware of the factors that can modify the role/influence of the TV white space on whether subscribers choose licensed or unlicensed services. Thus, the thesis assesses how external factors, such as application/service availability or white space spectrum efficiency improvement, can substantially enhance TVWS network features, inducing subscribers to switch from licensed to unlicensed networks, and thereby affecting the licensed operators' subscribers.

Finally, this thesis recommends that the authorities advocate for an accommodation of licensed and unlicensed operators based on an analysis of technology and economic modeling. However, the thesis does not discuss the legal aspects, such as the interactions of FCC authority and US antitrust laws.

Thesis Supervisor: Charles H. Fine
Title: Chrysler LFM Professor of Management and Engineering Systems

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1 Introduction and Thesis Motivation

In November 2008, the United States Federal Communications Commission (FCC) voted to allow unlicensed use of the spectrum designated for TV broadcast use. After the analog-to-digital transition was completed in June of 2009, guard space between channels was no longer needed for the successful transmission of TV signals. The unused portions of the UHF spectrum, popularly referred to as "white space," or TVWS, unleash a whole new set of opportunities for wireless networks, offering the potential for more unlicensed bandwidth with long transmission ranges.

While this policy change represents new avenues for growth, it becomes important to study the real impact of this new unlicensed band. Specifically, one needs to identify under what circumstances the new available frequencies can change the dynamics of the wireless access industry as we know it now. For example, what dimensions should Telecom Equipment manufacturers and independent service providers consider important to assess the effect of the Whitespace spectrum on unlicensed spectrum business opportunities? Are the business opportunities limited to rural areas? Is the technology to fully leverage the potential of these white-spaces already there or in the making? Which technology options to use the white-spaces will actually turn out to be more viable? What steps need to be taken in terms of technology and deployment to make the use of white-spaces most effective?

One other key aspect to this assessment lies in the ever-growing ubiquity of wireless in our lives. With the explosion of data processing capabilities in mobile devices and the enhancement of wireless technologies, there has been a surge in wireless data consumption and the emergence of completely new wireless services. New applications such as smart metering, remote healthcare, cloud computing and remote machine control will generally require large investments in order to provide the required connectivity not only to people but also to machines. This connectivity is expected to fulfill people's needs in very diverse aspects and become the platform for new eco-systems, much beyond standard voice service where it all started. With this growing wireless world, comes the promise of new and substantial revenues - which naturally creates a huge expectation around the TVWS opportunities. Because TVWS may create significant changes in the uses of the unlicensed spectrum, it is specially relevant now, when devices typically attached to licensed spectrum networks, mobile phones, and devices usually connected to unlicensed routers, laptops, are converging, Carter (2006), see Figure 1-1.

This thesis will assess the possibilities of the newly released spectrum TVWS to change the role of the unlicensed industry by enhancing unlicensed networks features and by enabling new services. The assessment will be supported with mathematical models where the influence of TVWS propagation conditions in network user adoption, coverage and services price will be studied to define the evolution of the industry.

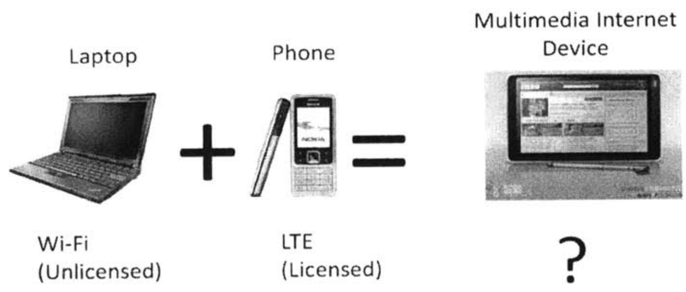

Figure 1-1: The synergy for wireless mobile devices can change the unlicensed network adoption trends

1.1 Questions that this Thesis addresses

The new TVWS regulation has made available an incredibly versatile resource (frequencies from portions of the radio spectrum: 54-72 MHz, 76-88 MHz, 174-216 MHz, and 470-806 MHz.). Therefore, the first question that this thesis will address is, who will likely use the TVWS and for what purpose? Chapter 3 analyzes the main players in the unlicensed spectrum and suggests who is likely to be interested in the TVWS. What purpose the TVWS will be dedicated to, - is a complex question that will be answered in Chapter 2, which analyzes *three TVWS aspects*. First, *the regulatory framework*: the spectrum offers good propagation characteristics, but the regulations involve many restrictions for incumbent protection that constrain usage to certain geographical locations. Second, *the physical challenges*: the fact that the spectrum will be a shared resource also implies physical challenges that will reduce the possible usages of the spectrum. And third, *the standardization process*: this will determine which standards are going to be in place and, therefore, which devices will most likely implement TVWS first. By narrowing down the scope of the TVWS to certain operators, equipment, and services, future investors in the wireless unlicensed spectrum can more clearly see the real opportunities of this new addition to the spectrum available for unlicensed devices.

In Chapter 4, a business dynamics simulation model, representing competition between two wireless industries, will be used to assess the evolution of the role of the unlicensed spectrum in the wireless industry. In Chapter 5, the model will be used to provide an answer to the question, what will be the impact of white space on unlicensed spectrum adoption? Later, in chapter 6, different sensitivity analyses will be performed using different external factors, to answer the question: what variables such as the availability of external services or the improvement in wireless technology can be combined with the new TVWS features to enable unlicensed spectrum adoptions to perform substantially better than licensed networks?

Also, in Chapter 7, the model is used to analyze the critical importance of wireless operators' strategies to leverage the advantages of the TVWS spectrum. Factors such as service price or coverage availability are enhanced by TVWS, but cannot be successfully leveraged without an appropriate proper attitude on the part of the operator. To address this issue, the model will be programmed with the appropriate strategies for both wireless industries, and some conclusions will be outlined about strategies that will enhance the social benefits possible with various uses of the TVWS . TV White space: Why is the TV spectrum different?

This section aims to clarify the particularities that make the TV spectrum so special. As will be further studied in Chapter 2, more than 455 MHz in the 5GHz band are dedicated to unlicensed purposes. Why, then, are TVWSs so special? – 5GHz band frequencies are relatively high, and their propagation conditions are not optimal; however, the TV spectrum resides in the low band (less that 1 GHz), and because of this, it has several characteristics that make it especially suitable for personal communications in rural areas. First of all, it is better suited for mobility because its waves are longer and can thus better propagate through walls and foliage (Snider, 2006) and (Lennett. 2008). Second, the low-frequency spectrum requires less energy to travel the same distance as higher frequencies, and this means that mobile devices require less powerful, lighter, and smaller batteries. Third, for the same power, the frequencies that propagate longer will also make it possible for an operator to have less infrastructure in less populated regions—, i.e., fewer towers and more limited access. According to a study carried out by Intel, (Kibria & Knudsen, 2005), rural wireless networks transmitting on the 700 MHz TV band can provide a better quality of service with coverage of four times the area than a network transmitting at 2.5 GHz. This can reduce unlicensed rural deployment costs by 75% (Snider, 2006). In light of all of these factors, TVWS looks like a promising improvement for unlicensed spectrum networks.

This research will focus on how improved coverage and network cost reductions made possible by the TVWS will influence unlicensed user adoption. The effects on the unlicensed networks of the TVWS will be assessed with a competition model that recreates the concept of two industries, licensed and unlicensed, competing for the same resources.

1.2 Licensed vs. Unlicensed, a Real Competition

In this thesis, the evolution of the unlicensed networks is measured as the result of a competition. The idea of a competition between licensed and unlicensed wireless industries is not new; indeed it has already been used in other literature. See (Nguyen et al., 2011), (Lehr, 2005) and (Lehr and McKnight, 2003).

According to a historical definition of the economic term of "Competition" in Stigler (1957), "competition is used in the sense of rivalry in a race — a race to get limited supplies or a race to be rid of excess of supplies." Stigler continues with a description of competition as "a process of responding to a new force and a method of reaching new equilibrium." In the same historical review, Stigler refers to Sidgwick and Edgeworth as differentiating between "commercial-competition" which happens within an industry, and "industrial-competition" as that requiring the ability of resources to flow between industries.

This thesis applies the concept used in (Sidgwick, 1883) of industrial-competition, between two industries, licensed and unlicensed wireless industries— in which, in addition to resources, customers can flow between industries. The competition between the two is simulated with a model that implements the dynamics of licensed and unlicensed industries competing for the same set of customers. The model is used to assess how the competition process responds to the new force introduced by the white space. By comparing the different equilibriums reached between the licensed and unlicensed wireless industries when TVWS is in place and when not, the real impact of the TVWS on the entire wireless industry can be understood.

1.3 Thesis Scope

This work focuses on the de-regulation of the TV bands only in the USA. Investigation of similar de-regularization in other countries such as UK has not been covered here. Further, the main focus of the analysis in this work is on the impact of this policy change in rural and suburban areas in the USA, where the TVWS will most likely be available. A summary of the main areas of investigation can be found in Appendix B.

This research will describe various aspects of the TVWS de-regulation, including the database and geo-location incumbent protection requirements for the use of the TVWS. However, no additional information about these two requirements will be provided in this document. Furthermore, for the purposes of the simulation, it will be assumed that database and geo-location are already in place and that their potential technological and economical inconveniences will already be obvious factors in the competition process.

2 TV White Space Regulation and Standards

2.1 Introduction

In 2008 the FCC proposed several rules that would allow the operation of unlicensed devices in TV white space (TVWS), while protecting the incumbents.[1] The rules set forth requirements, outlined in the second section of this chapter, which are especially important for the industry, as they represent a challenge to develop equipment and networks capable of legally operating in the TVWS.

TVWS availability is time- and position-dependent. It can include the following spectrum bands: 54-72 MHz, 76-88 MHz, 174-216 MHz, y 470-806 MHz. This new spectrum availability — subject, of course, to FCC regulations — has ignited the development of new wireless standards. Standardization activities around the TVWS will be described in the third section of this chapter and include the IEEE 802.22 for WAN and ECMA 392 for personal and portable devices. Recently, too, the 802.11 has begun to adapt the protocol 802.11y to TVWS.

The heterogeneity of devices, together with the dynamic nature and incumbent protection requirements of TVWS, are the challenges that must be addressed by regulators and any groups that would set new standards. These challenges, which will be thoroughly described in the third section of this chapter, can be classified in three categories: spectrum availability detection, interference mitigation and spectrum sharing.

2.2 Regulatory and Technical Background

This section will walk the reader quickly through the main regulatory and technological events that have made possible the deregulation of the TV frequencies. It is important to understand that the TV band is not an isolated deregulation and that this set of spectrum liberalization policies has been going on for decades accompanied always with significant improvements in wireless technologies.

The FCC "Part 15" which regulates "unlicensed devices" has existed since 1938. In its five first decades few proceedings were issued. Part 15 regulations did not start with a restricted part of the spectrum; the rules referred to "Unlicensed Devices" able to operate in any band. It was not until 1989 that the FCC expanded its Part 15 rules to encompass the operation of low power, unlicensed spread spectrum systems in the 900-928 MHz, 2,400-2,483.5 MHz, and 5,725-5,850MHz bands (Carter 2009). In 1993, with the advent of digital modulation techniques, the FCC allowed the use of U-PCS (Unlicensed Personal Communication Devices) to operate in the bands 1,910-1,920, 1,920-1,930, and 2,390-2,400MHz. Later, in 1997, the FCC recognized the need to transfer large amounts of data by medical, educational, business, and industrial users and amended Part 15 to allow operation of Unlicensed National Information Infrastructure

[1] In the second report and order from the 4th of November, FCC (2008).

(U-NII)[2]. A few years later, in 2002, the Wireless Ethernet Compatibility Alliance filed a petition for rule making. In response, the FCC made an additional 255 megahertz of spectrum in the 5.47-5.725 GHz band spectrum available for Unlicensed National Information Infrastructure (U-NII) devices. This addition also harmonized the USA U-NII bands with those of other countries (Carter, 2009). Finally, in 2008, with the Second Report and Order in the Matters of "Unlicensed Operation in the TV Broadcast Bands" and "Additional Spectrum for Unlicensed Devices below 900 MHz and in the 3 GHz Band", the FCC provided rules for use of the TV frequencies under unlicensed operation (FCC 2008). These rules establish special mechanisms to protect incumbents and will be described in the next section.

2.3 US A TV White Space Regulation

In this section the FCC final rules, FCC (2008), of the secondary unlicensed operation in the TVWS will be briefly described to explain the constraints implicit in the use of the TVWSs. The FCC divides the devices in two categories: fixed and personal or portable. The fixed devices can transmit up to 4 EIRP W with a spectral density of 16.7mW/kHz, and they must have the geo-location capabilities and means to recover a list of available channels from an authorized database. The fixed devices cannot operate in adjacent channels of active TV broadcasting channels. Personal and portable devices can be classified in two types: Mode I and Mode II. Likewise, Fixed, Mode II devices, must have access to an authorized database and geo-location capabilities; however, they are allowed to operate in adjacent channels. Mode I devices must obtain a list of available channels from a Fixed or a Mode II device. They do not require database or geo-location capabilities, but they must discontinue transmission after 60 seconds if no signal is received from Fixed or Mode II devices. (Ghosh et al., 2010)

As can be seen in the Table 2, there are many restrictions in the channels that can be used by both Fixed and Portable devices.

Device types/ Capability		**Allowed TV Channels**	**Max EIRP**	**Incumbent protection requirements**	**Allowed on Adjacent channels**
Fixed		Ch 2 – 51 (except Ch 3, 4 and 37)	**4W**	Geo-location/Database	No
Personal/ Portable	Mode I	Ch 21 – 51 (except Ch 37)	100 mW	Enabling signal from Mode II or Fixed device.	Yes (< 40mW EIRP)
	Mode II		100 mW	Geo-location/Database	Yes (<40 mW EIRP)

Table 2-1: Overview of the FCC rules for TVWS. Source Ghosh et al. (2010)

[2] Unlicensed National Information Infrastructure (U-NII): Define bands dedicated to license-exempt operations. Within the UNII, there are three types of licensing regimes: UNII-1: Regulations require use of an integrated antenna. Power limited to 50mW. Only indoor. UNII-2 is also available for outdoors. Subject to extra rules about detecting radars and getting off a radar band when a radar is active. UNII-3/ISM: Overlaps with the ISM Band. Both indoor and outdoor Power limited to 1W.

Any TVWS device must wait 30 seconds before occupying a channel detected as available. If a channel is occupied meaning: already occupied by an incumbent? or after the TVWS device occupies], the TVWS device must perform sensing to check availability every 60 seconds. When an incumbent is detected, TVWS devices must cease transmission within 2 seconds. (Ghosh et al., 2010)

The rules also dictate that in adjacent channels, transmission shall be at least 72.8 dB below the highest average power in the operating channel. The spectrum mask necessary to meet this rule cannot be easily implemented in a portable device; therefore, this rule represents a handicap to the manufacture of TVWS mobile devices. Finally, the strong FCC incumbent protection rules will confine TVWS devices to rural areas where incumbents have less presence. (For further details of the regulation, see FCC, 2008.)

2.4 Standards Related with TV White Space

Standards have played an important role in the implementation of communications and network systems in the last four decades. The IEEE and ETSI standard organizations in the United States and Europe, respectively, have been very active in the development of standards for wireless networks, and have recently dedicated resources for the development of standards for the TVWS, targeting fixed and personal/portable devices. A summary of the most relevant TVWS Standards is listed below.

802.22

The IEEE 802.22 Working Group (WG) has developed a standard that defines a physical (PHY) and MAC layer specification for wide regional area network (WRAN), in which Cognitive Radio is used in the physical and Medium Access OSI layers of the air interface. The Cognitive Radio devices will be able to sense the immediate spectrum, and the standard will describe the way cognition in communications is to be used in networks and devices. The standard is connection oriented and the Base Station controls the resource allocations within its cell. User data rates will be 1.5 Mbps in the downlink and 385 kps in the downlink. Up to 255 Customer Premises Equipments per cell per 6 Mhz TV channel will be supported and the standard will implement incumbent detection by using spectrum sensing geo-location and database, frequency agility and self-coexistence mechanisms[3]. The 802.22 standard scope has recently been extended to include portable devices although vehicular mobility is not fully covered by the standard.

The IEEE 802.22 group has also been working on an 802.22 additional extension standard (IEEE 802.22.1). The protocol defines a beacon signal that will be transmitted when a licensed wireless microphone is in operation. The beacon signal will be generated by the wireless microphone **base station** with 250mW (as compared to 10mW for microphones). This will enable the white space users to determine that a channel is busy. The main objective of this protocol is to avoid interferences with licensed wireless microphones. The standard also implements the needed security features for the microphone beacon authentication

[3] See in the Appendix B, the 802.22 architecture description together with PHY and MAC Layer protocol specification summary

IEEE 802.19.1

The IEEE 802.19 WG is designed to provide standard coexistence methods among dissimilar networks and devices in the unlicensed spectrum. Within 802.19, a new group, IEEE 802.19.1, has been recently designated to ensure the coexistence of 802.22 devices. The standard will create different interfaces that will allow the different entities to become aware of new networks or devices operating in the TV frequencies. The 802.19.1 operating network will have the information necessary to handle reconfiguration requests by the devices and antennas and to implement the coexistence decision.

The standard is being developed at the moment of the writing of this thesis and is expected to be ready in late 2012 at the earliest[4]. Although the standard is still under development, the group has already decided some interfaces that should be defined, such as: the interface to communicate with different coexistence managers and discovery servers, the interface that enables the communication between coexistence managers and devices, and the interface that will enable communication between the coexistence and discovery managers and the TV WS Database.

IEEE 802.11 af

The IEEE 802.11 family includes wireless modulation techniques that use the same basic protocol; in particular, the IEEE 802.11y, standard that describes the Wi-Fi Devices Operations in the USA in the 3650-3700 MHz band. This standard was created in response to the FCC 2007 rules for a novel "light licensing" scheme in the 3650-3700 MHz band. Under this provision, licensees pay a small fee for a nationwide, non- exclusive license. If buyers want to deploy a high-powered base station, then they have to pay a higher fee. It is remarkable that while the scope of 802.11y was limited to operations in the 3650-3700 MHz band in the US, care was taken so that, if the light licensing concept was well received, only small changes would be necessary to adapt the standard to other bands. After November 2008, when the FCC approved the usage of unlicensed devices in the unused TV Band, the group 802.11 "TGaf" was established to adapt the 802.11y to the TV frequencies.

The 802.11af is expected to have its first draft D1.0 to be voted among the IEEE members in late 2011[5]. The 802.11y standard already defines intelligent devices that can consult the FCC-required Databases and that can manage other low cost devices. In addition to this, the 802.11 standard already supports carrier sensing, energy detection, and channel switching. For more information about 802.11 af PHY and MAC protocol features see Appendix A.

ECMA 392

CogNeA is an open industry alliance that has developed an industry-wide standard (ECMA 392) for the operation of low power personal and portable devices over TV white spaces in the Ultra High Frequency (UHF) television bands. The alliance's main contributors are: BT, Cambridge Consultants, ETRI, Philips, Samsung Electro-Mechanics, MaxLinear. The Georgia Electronic Design Center (GEDC) at Georgia Institute of Technology and Motorola are part of CogNeA; their focus is primarily on maintaining the Quality of Service (Qos) in streaming for TV.

The standard was approved in December 2009 by ECMA TC48 TG1, a Swiss entity in charge of developing standards and technical reports for high data rate wireless

[4] Information provided by Mika Kasslin, Nokia.
[5] Information provided by Mika Kasslin, Nokia.

communications using TV white spaces. The standard is meant for indoor and outdoor operations; it is meant to overcome the coverage and wall penetration problems inherent to ISM[6] bands solutions by using the effective propagation qualities of TV frequencies. The standard proposed by CogNeA will be able to work as stand-alone (just those devices with CogNeA services) or in a more flexible way that would connect and adapt existing DLNA[7] devices.

ECMA 392 does not implement the sensing and geo-location features required by the FCC regulation; the standard leaves them as a black box solution — which is preventing the standard's adoption by the industry. (Appendix A provides a brief technical description of this standard.)

2.5 TV White Space Challenges

In the future, different networks and different devices will have to coexist in the TVWS, see Figure 2-1 for illustration of the TVW coexistence possibilities, and clearly some mechanisms will have to be in place to avoid interference and allow interoperability.

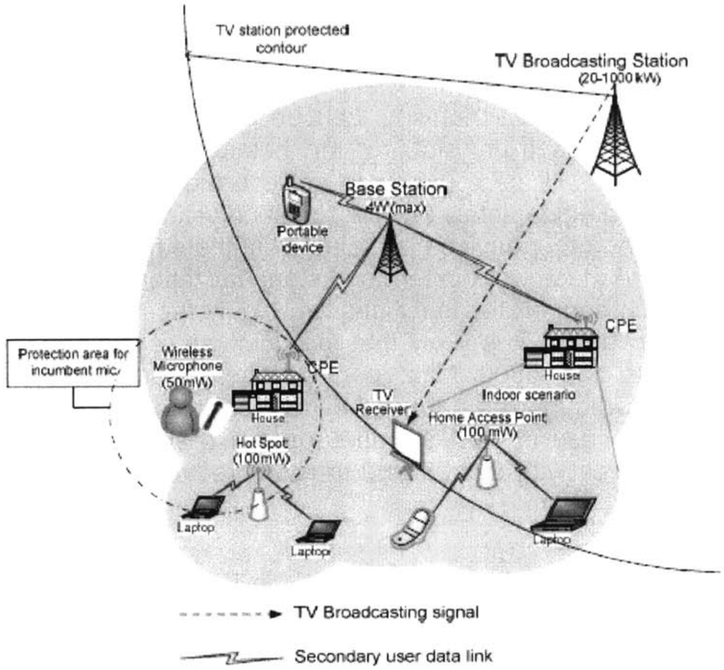

Figure 2-1 TVWS possible modes of operation. Source Ghosh et al. (2010):

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[6] IMS bands: The ISM bands are defined by the ITU-R in 5.138, 5.150, and 5.280. Communication devices using the ISM bands must tolerate any interference from ISM equipment, these bands are typically given over to uses intended for unlicensed operation, United States of America, and uses of the ISM bands are governed by Part 18 of the FCC rules, while Part 15 contains the rules for unlicensed communication devices, even those that use the ISM frequencies.

[7] Digital Living Network Alliance (DLNA) is a cross-industry organization of leading consumer electronics, computing industry and mobile device companies.

Two important challenges related to coexistence are the identification of TV channels available and not used by incumbents and the detection of coexisting secondary networks. For these purposes, FCC rules propose two possible solutions: a white space Data Base (WSD), a repository that can be queried by TVWS devices in order to retrieve the channels available; and Spectrum Sensing, which is the process of scanning the RF Spectrum in order to detect the presence of incumbent signals. Spectrum availability will also include the detection of coexisting secondary networks, which may share the same protocol or which may have different technologies within the TVWS. In order for coexistence with secondary networks to be successful, protocols will have to implement robustness mechanisms such as intelligent management of out-of-band sensing or a secondary network database (which will inevitably cause a loss of efficiency in the protocol.) (Ghosh et al., 2010)

A second issue for the TVWS unlicensed usage comes from interference which will come from Incumbents and other networks operating within the TVWS. The strong propagation characteristics of the spectrum will increase the interference problem. Use of the WSD is supposed to solve the problem of interference to and from incumbents; however, there will be still unresolved issues. For example, if the incumbent interference is high enough, it can prevent the device from signaling incumbent detection. The interference can also come from other TVWS networks, when the channel selection process is not coordinated. The solutions for interference problems will need a synchronized access approach. This will not be easy for competing networks to implement.

Finally, the last issue related with the TVWS coexistence will come from the dynamism of TVWS. One channel can be detected as available by two devices and both can start transmission in the same channel, each expecting it to be available. To solve this issue, cooperative and non-cooperative mechanisms can be implemented for networks sharing the same protocols. However, spectrum sharing for heterogeneous scenarios can be very challenging: strenuous efforts will be required to solve issues such as coordination between different medium-access strategies, inter-network communication and synchronization, and the selection of a channel that no other device has selected at the same time (Ghosh et al.,2010). All of these challenges will require much work in terms of standardization, especially in the case of co-channel operation, in which cooperative solutions are highly recommended. If such efforts are not in place or are not successful, it is likely that the outcome of this frequency release will be similar to the 2450 MHz and 5800 MHz bands, where backhauling standards, due to interference, are moving to frequencies not used by non-cooperative local access protocols like 802.11(Wi-Fi). If this is the case in TVWS, non-cooperative standards such as 802.11af and ECMA will cause interferences with 802.22 and thus will reduce the adoption of this standard (802.22).

2.6 Conclusions

Regulations to protect incumbents will likely restrict the TVWS to the rural areas where fewer channels are used by broadcasters. In terms of power restrictions, the regulations seem generally to accommodate fixed and mobile communications in the TVWSs. However, the spectrum mask required by the FCC represents a challenge for TVWS mobile device manufacturers.

Standards for Wide Area and Local Area Networks are being developed and in combination encompass a wide range of network approaches and create a unique situation, since the same medium (unused TV frequencies) can be used for residential, back-hauling, and point-to-multipoint purposes.

This coexistence of different types of devices using different protocols using a dynamic resource in the time and space will be one of the biggest challenges that operators in the TVWS will face. Important regulatory efforts have been made in order to protect incumbents. However, great efforts are yet to be made by standard developers and regulators in order to enable the successful coexistence of the different TVWS networks.

In the next chapter, the questions of who will use TVWS, as well as why and how, will be tackled. By answering these questions and by looking again at the coexistence issue described in this chapter it will be possible to make real assumptions about the real possibilities of this spectrum in the future.

3 TV White Space Ecosystem Analysis

3.1 Introduction

The objective of this section is to describe the ecosystem in which the operation in the TV white space will develop. It will address the surrounding technologies, describe different players' interests, and reach some conclusions as to the most likely usage of these frequencies. Finally, it will speculate about which entities will be most likely to use this part of the spectrum.

The chapter will begin with a brief review of the players in the rural ecosystem and then will continue with a section discussing the most likely usage of the white space frequencies. The focus of Section 3.4 will be the framework in which the technologies will compete and collaborate using the newly released frequencies; and Section 3.5 will offer a very rough idea of why various entities might be opposed to this usage of the white spaces.

3.2 Who will benefit from the TVWS?

Due to the incumbent protection rules[8] the TVWS will likely be available mainly in rural areas, where wireless traditional operators, coexist with Wireless Internet Services Providers, or WISPs, who provide wireless broadband access to customers who, either because of their remote location or their specific needs, prefer the local WISP to the fixed broadband operators.

By using a mixture of unlicensed 5GHz and lite-licensed 3.6[9] GHz spectrum, the WISPs now offer a unique backhauling infrastructure which has been gradually decoupled from their access networks where they use primarily the Wi-Fi standards.

A great many WISPs have moved to or are in the process of moving to 5 GHz, using Wi-Fi technology adapted for outdoor P2P[10] and P2MP. At this point, there are around 2000 WISPs in the U.S.A. Many of these are rural, with only a few hundred to a few thousand subscribers each; but they are proliferating because of low-cost radio gear from Ubiquiti and low-cost routers from MikroTik. There are also large national WISPs such as NextWeb[11] and TowerStream[12] that have more than a few hundred thousand customers. Altogether, large and small WISP operators provide services to more than four million customers[13]. Figure 3-1 and Figure 3-2 indicate the approximate sales volume from both groups of U.S. WISPs.

[8] See Chapter 2 for further details

[9] "Lite Licensing" is a novel and progressive frequency allocation model in which network operators (ECNS licensees) would pay a relatively small fee for a nationwide, non-exclusive license. They then pay an additional nominal fee for each base station they deploy. All their stations must be clearly identifiable, and in the event these stations cause interference that cannot be mediated by technical means, licensees are required to resolve the dispute between themselves

[10] Point to Point and Point to Multi Point

[11] http://www.telepacific.com/pdfs/Financial%20Quick%20Facts.pdf

[12] http://ir.towerstream.com/releasedetail.cfm?ReleaseID=623673 NextWeb serves of connectivity to 3200 companies, assumed an average of 100 employees per company

[13] Number of customers calculated by dividing Revenue data and ARPU available information from ABI research

Given the number of customers and operators dealing with the unlicensed spectrum in the rural U.S. scenario, one can see the potential value that lies in developing new equipment for the TV frequencies.

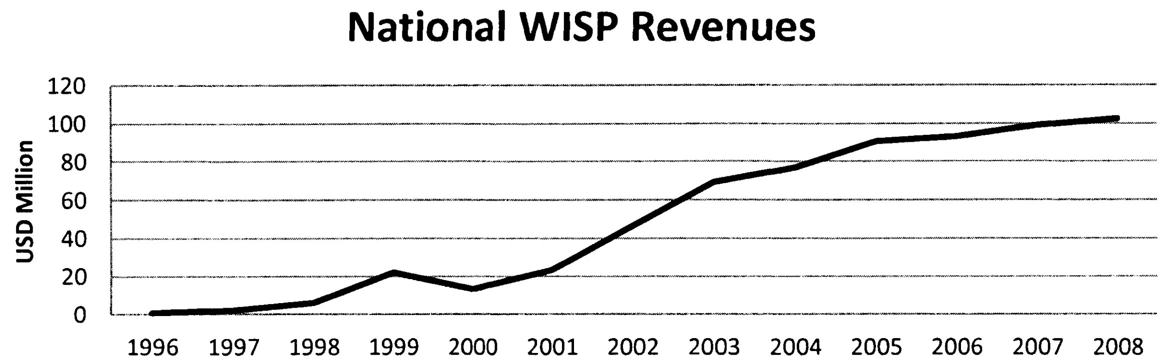

Figure 3-1: Aggregated Revenue from NextWeb, Tower Stream, Keyon, Trillion Digital and US Wireless. Source: Orbis Financial Database

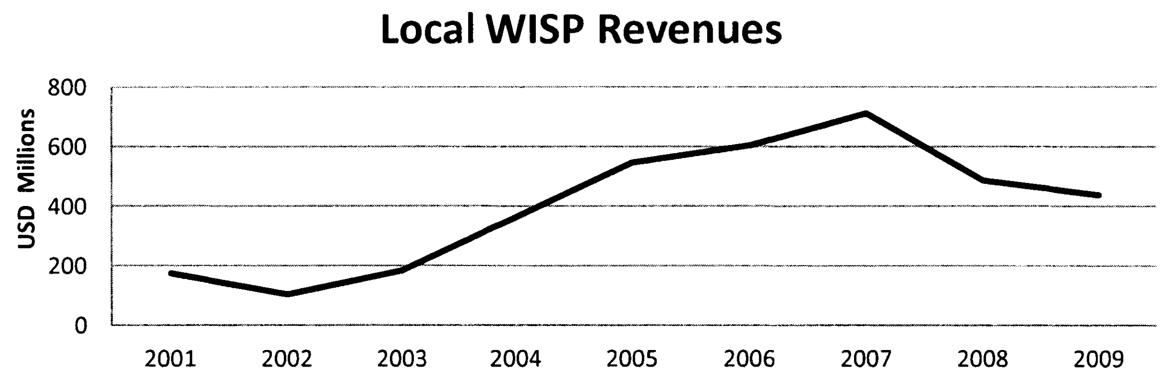

Figure 3-2: Aggregated Revenue for USA WISP operators: Source WISP Database and Orbis Financial Database

3.3 How will Rural WISPs benefit from the TVWS?

Why is the new white space so valuable for the WISPs, and how can they benefit from the policy change? The white space frequencies have much better propagation characteristics than the 5GHz band used by WISPs for backhauling purposes; but although *a priori* backhauling[14] looks like the most appropriate usage for these frequencies, it is still unclear what the real use of TVWS will be and how it will be influenced by the final regulatory framework.

As studied in chapter 2, two important standards are being developed for the TVWS: 802.11af, which assumes the use of TVWS as an enhancement of the existing Wi-Fi networks and 802.22, which implements a wide regional area network and implies the use the TVWS for longer range transmissions.

[14] Backhaul: concerned typically with transporting traffic between distributed sites or access points.

The protocol 802.11af assumes that TVWS will increase the range of the Wi-Fi routers. Chip manufacturers have shown their interest in taking advantage of the new TV white space in their Wi-Fi chips[15]. The fact of having an additional feature in the 802.11 could temporally allow a considerable increase in the price per chip. If White-fi networks are implemented in the end of their 5 Ghz links, WISPs could reduce considerably their infrastructure and thus their investment per customer. This improvement in network efficiency could make the business case for the rural communications more attractive.

The standard 802.22 assumes a wide area infrastructure operating within the unlicensed spectrum. The standard allows the use of TVWS for backhauling and access purposes. WISP operators will be able to develop their networks entirely with TVWS by replacing/combining their 5GHz with 802.22 Base Stations and will be able to provide mobility and additional services by implementing 802.22 access features.

As of this writing, there are no 802.22 or 802.11af networks; therefore, for the purposes of the study, it will be assumed that WISPs will incorporate TVWS standards as a way to reduce costs in their infrastructures. The assumed cost reduction ratio will be 5:1[16] (Snider, 2006), regardless of the TVWS standard adopted.

Many questions arise as to how this cost reduction will impact the WISPs' revenues and growth strategies. Moreover, it is intriguing to speculate about what role TVWS can play in enabling new services, in changing user habits, or in advancing high-performance outdoor Wi-Fi development. Such questions will be further addressed in the last chapters of this research.

3.4 Which Technologies will coexist with the TVWS Standards?

The last two sections described how TVWSs will likely be adopted by rural WISPs, since they are already operating within unlicensed spectrum. This section will first describe which are the unlicensed technologies used in the bands dedicated for unlicensed devices, and later it will discuss other standards that will coexist with future TVWS technologies.

As described in chapter 2, TVWS is one more slice of spectrum available for unlicensed devices. The dominant standard in the existing unlicensed bands in USA is 802.1, which has been adapted for different frequencies with distinct versions. To illustrate this, a list of the existing unlicensed bands and their associated customization of the protocol 802.11 can be seen in Table 3-1.

---

[15] http://groups.winnforum.org/p/cm/ld/fid=181

[16] Intel study, Snider(2006) In the study, the assumption is a ratio reduction of 4:1. For simplicity of calculation ,and according to the estimation of industry (NSN) experts consulted for this thesis, the assumption will be 5:1.

	ISM: Industrial, Scientific, and Medical			UNII Band	
FREQUENCY	902 to 928 MHz	2,400 to 2,483.5 MHz	5.15 - 5.25 GHz	5.25 - 5.35 GHz	5.725 - 5.825 GHz (ISM overlap)
TX POWER	36 dBm EIRP	36 dBm EIRP	23 dBm EIRP	30 dBm EIRP	36 dBm EIRP
	(4 Watts)	(4 Watts)	(200 mW)	(1 Watt)	(4 Watts)
APPLICATION	LONG RANGE	CAMPUS LINKS	INDOOR USE ONLY	CAMPUS LINKS	LONG RANGE
	(Several Miles)				(Several Miles)
Data Rates	3Mbps	11 Mbps/54Mbps	11Mbps/54Mps	11Mbps/54Mps	11Mbps/54Mps
PROTOCOL	Propietary	802.11g (FHSS DSSS)	802.11a (OFDM)	802.11a (OFDM)	802.11a (OFDM)

Table 3-1: Wireless Internet Service Providers Technologies

The technology that will probably be adapted for the new spectrum is 5GHz links using Wi-Fi technology, adapted for outdoor P2P and P2MP[17] . This assumption is supported by the fact that operators working in the unlicensed spectrum have a great incentive to reduce the number of 5GHz links in order to make their unlicensed operation more cost-effective. Therefore WISPs using unlicensed spectrum will be able to leverage the benefits of the additional spectrum.

The new TVWS spectrum will release the potential of Wi-Fi technology and will essentially put WI-Fi on the same "playing field" as other widely used wireless standards such as LTE or Wimax. The current advantage of Wi-Fi technology is the reduced cost of equipment compared with other wireless technologies, which also require big up-front investments in spectrum. Therefore, the success of new TVWS standards depends on the evolution of other wireless technologies. A huge reduction in cost in LTE, for example, could preclude the consolidation of the TVWS standards. (See Table 3-2, showing other standards commonly used by standard operators.) The success of TVWS technologies will depend on whether operators prefer to deploy TVWS or standard wireless technologies in the rural areas.

Standard	**Protocol**	**Primary Use**	**Downlink (Mbit/s)**	**Uplink (Mbit/s)**	**Band**
UMTS- HSPA+	3GPP	Licensed	21-84-672	5.8-22-168	850 MHz, 1.9, 1.9/2.1, and 1.7/2.1 GHz
	3G transitional				
UMTS-TDD	3GPP/3G	Licensed/Unlicensed	16	16	450, 850 MHz, 1.9, 2, 2.5, and 3.5 GHz[
UTRA-TDD					2 GHz
WiMax-Advanced	IEEE	Licensed/Lite-licensed/Unlicensed	128	56	2.3, 2.5, 3.5, 3.7,3,6 and 5.8 GHz
	3G Transitiona-4GI				
LTE -Advanced	3GPP		100-150-300	50-75	
	3G-4G				

Table 3-2: Incumbent Licensed Standards[18]

[17] Information provided by Brough Turner, founder of netBlazr Inc., a radically new form of wireless ISP. Previously he was co-founder and Chief Technology Officer at Natural MicroSystems and NMS Communications.

[18] Source: http://en.wikipedia.org/wiki/LTE_(Long_Term_Evolution)

In summary, White-Fi as a Wi-Fi enhancement can provide a strong business case for unlicensed WISPs and can serve as a competitor to licensed standards such as LTE or Wimax (Finneran, 2004) in rural areas. The success of the Wi-Fi technologies adapted for TVWS will depend on how well licensed standards are developed for low-density environments.

3.5 Which Operators will coexist with Rural WISPs?

Thus far, this thesis has described the reasons why operators would deploy TVWS. The next section will discuss which parties are likely to be opposed to TVWS deployments, and why.

Every operator deploying access technologies within the licensed spectrum can foresee their revenues decreasing if white space improves the business case for operators using unlicensed spectrum. The licensed operator's scenario is more fragmented in rural areas than in urban settings, In rural areas traditional incumbents such as Verizon and AT&T share their business with many small operators who own local licenses and operate regionally. These small operators can afford licensed networks largely because governmental incentives such as the broadband stimulus plans, have been put in place. These incentives are designed to bring broadband to sparsely populated and remote areas where extending high-speed Internet service is cost prohibitive without a public-private partnership (Morris, 2011)

With the advent of LTE, and the emergence of new funding sources, promoted by the American Recovery Act 2009[19], the incumbent operator's strategy in rural areas is changing, and two different trends are notable. On one hand, big players such as Verizon or NetAmerica Alliance are looking to form partnerships with smaller operators with whom to collaboratively build and operate 4G LTE networks (Lasar, 2010). NetAmerica, for example operates an IMS core and integrates rural independent licensed holders that are deploying converged 4G wireless/wireline networks. On the other hand, other big licensed players such as ATT&T prefer to cover rural areas by acquiring local telecom operators or by purchasing spectrum licenses in rural areas and small cities

To sum up, the operator scenario in rural areas is less consolidated than in urban areas. Moreover big incumbents have started to move toward integration arrangements, thanks to new wireless platforms and to large government incentives for coverage of rural areas. The success of these big licensed operators and alliances that would cover rural areas with licensed and powerful technologies such as LTE might restrict adoption of TVWS.

[19] These are the facts: The American Recovery and Reinvestment Act of 2009, the $787 billion economic stimulus package signed into law by President Obama in mid-February 2009, promises $7.2 billion for the expansion of broadband facilities and services. The Obama administration has earmarked $4.7 billion to be dispensed by the Commerce Department's National Telecommunications and Information Administration and for broadband construction grants, and the remaining $2.5 billion to be dispensed by the Department of Agriculture's Rural Utilities Service in grants, loans and loan guarantees. http://servicecenter.fiercemarkets.com/files/leadgen/motorola_ebook_8.12.09_web.pdf

3.6 Conclusions

The release of TVWS will affect only a $400, million subscriber market, which are the sum total of WISPs revenues and a small part of the $7.2 billion to be allocated for broadband developments under the American Recovery and Reinvestment Act of 2009. However, this policy change could well have an enormous impact on chip and device manufacturers, who can increase their sales and prices by adding a new connectivity features.

Interestingly, the new FCC regulation raises another important question: to what extent can the unlicensed spectrum networks be enhanced in order to directly compete with well established licensed operators? Further narrowing this issue, can the white space, through better propagation characteristics, enhance existing unlicensed protocols in order that the latter compete more robustly with licensed ones?

In the next section of this thesis, a model will compare both wireless industries — licensed and unlicensed. The model will be calibrated to White-Fi environment information, and it will be used to measure the impact of the new frequency release on the unlicensed industry, to see under what circumstances the adoption of the unlicensed spectrum could be a detriment to licensed operators.

Finally, to keep scenarios to a minimum, this thesis has assumed that traditional operators using licensed spectrum will not move into the white space, since they would lose the leverage of their main asset: "Spectrum". But this does not necessarily have to be the case. On one hand, it is possible that licensed operators may decide to leverage their backhaul network and start moving towards a wholesale market, selling hotspots with White-Fi included. On the other hand, the future may see traditional operators going to the white space with LTE[20] solutions in those areas where they do not own spectrum. Indeed, there is a working group inside the wireless innovation forum dedicated to fit TD-LTE to the white space frequency. TD-LTE[21] (Paolini, 2010) and (Rowles, 2010) is TD (Time Division) LTE and it is used if a "paired spectrum" is not available for separation of a UL/DL[22] connection path. TD-LTE will be better able to leverage uplink and downlink distribution —a very attractive feature for internet connectivity. It will be interesting to see if, in the TWS to TD-LTE fitting process, the interference problem is addressed (Churchill, 2011).

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[20] Long Term Evolution is a standard for wireless communication of high-speed data

[21] http://www.fiercebroadbandwireless.com/story/td-lte-most-powerful-weapon-lte-arsenal-against-wimax/2010-03-29 : There are two versions of LTE. FDD-LTE uses the FDD paired spectrum with two separated channels, one for the uplink and one for the downlink, which is the type of spectrum most mobile operators have. TD-LTE uses TDD unpaired spectrum channels that combine uplink and downlink, and split resources on the basis of real-time demand.

[22] Uplink/DownLink

4 Wireless Access Competition Model

4.1 Introduction

In Chapter 3, we discussed why TVWS, as an extension of Wi-Fi, was a direct competitor to other licensed access technologies, such as LTE or WiMax. This chapter will discuss the different dynamics of both industries; it will also examine how the different heuristics for each wireless platform have been implemented in the dynamic model. The chapter will end with the calibration of the model to real data. The model is described at greater length in Appendix C, which includes more formulas, tables, and implementation details.

4.2 Two Competing Industries

The different heuristics and rules regulating the two wireless industries, licensed and unlicensed, are discussed below.

Different Operator Strategies

For unlicensed wireless networks, the barriers to entry are very low, and one finds considerable competition and small players. By contrast, in the licensed industry, because of high barriers to entry, only large players are to be found. The licensed operators have to build extensive infrastructure and tend to provide end-to-end service to their customers. The result is an asymmetry in the industry. On the one hand, big players tend to spend more on getting more customers by investing in advertisements; but smaller, unlicensed players are able to slowly infiltrate those markets where the big players are not interested or do not offer a properly customized service.

The different nature of the players also conditions the way they extend and deploy their networks. Once big players decide to deploy a network, their entry costs are so high that they must install an extensive wireless infrastructure in order to reach a large number of customers and recover their initial expenditures. When unlicensed operators, on the other hand, deploy their networks, they are usually sure about the number of customers they are going to cover, and thus certain of the profitability of their newly deployed network extension.

Different Externalities

Both industries are influenced differently by the evolution of external players involved in the communication process. The success of external internet companies, which is what Google, Microsoft, and Skype will be called in this thesis, can affect both unlicensed and licensed operators in different ways. On one hand, if external services companies succeed, unlicensed operators will be able to offer new services and make their businesses more profitable. On the other hand, this same success can also harm licensed operators such as ATT or Verizon, as can already be seen in the reduction of roaming benefits for these companies because of Skype's success. Also, the mobile and fixed devices ongoing convergence has various implications for licensed and unlicensed operators. As suggested in Chapter 3, smarter devices will likely absorb part of the network intelligence and will complement the missing capacity of unlicensed networks.

Different Cellular Networks

In terms of network infrastructure, both industries offer different solutions. While licensed networks tend to have end-to-end connectivity, small unlicensed access wireless operators tend to offer last-mile solutions with small access infrastructures offering lower levels of scalability. Network planning and dimensioning is different, too, for while unlicensed operators are deployed to offer connectivity service to an "always on[23]" customer, wireless licensed networks are deployed according to the needs of a "by-call customer"[24].

In terms of protocols and standardization, there are notable efforts going on in both the licensed as well as the unlicensed arenas. Access equipment vendors seem to be relying on existing standards before manufacturing any new equipment. However, because of lower investment requirements, the number and diversification of vendors in the unlicensed spectrum is higher than in the licensed industry. As a result, equipment vendors for licensed operators are big and specialized, and they have become experts at big bidding; while unlicensed equipment vendors, being smaller and differentiated, tend to sell their products via resellers.

Different Infrastructure Costs

Equipment used by the licensed industry tends to be costly, with huge capacities to serve wider coverage areas. Moreover, these operators require major investments in hardware, as well as in installation, configuration and maintenance processes. In the unlicensed industry, on the other hand, the equipments are commoditized and operators make great efforts to reduce subscriber prices. The licensed industry, because of its centralized nature, requires many resources for managing complexity as opposed to small unlicensed networks, which are, in most cases, self-maintained, with operative personnel reduced to one technician per 500 customers[25]. It is important to note here that the unlicensed industry will face problems if and when they scale up their small infrastructures[26]. However, due to its open nature, the unlicensed industry can leverage its "crowd-sourcing" power.[27] Many WISP owners actively share experiences in technical forums, with the result that equipment vendors can save on engineers to provide guidance to operators, but also operators can obtain help to manage and operate their small infrastructure for free.

Different Financials

The barriers of entry are extremely high for licensed operators, due to high spectrum and infrastructure costs. However, because of the exclusivity of their ownership of spectrum, capital is more readably available to them. Big operators can guarantee a quality of service level, as well as a wider coverage; this reduces the risks and maximizes the possibility of gaining new customers — which in turn attracts capital. However, unlicensed operators, because of the many uncertainties they face in terms of quality of service and competition for the same spectrum, have more difficulty obtaining capital. Nevertheless, the unlicensed operators do not need large-scale investment, for the cost of their network is lower. In addition, unlicensed

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[23] Users are always connected
[24] Users connect only when they are going to actively use the network
[25] Interview with Matt Larsen, owner of WISP Vistabeam and WISPA association WebSite
[26] Interview with Matt Larsen
[27] This can be verified by visiting, ubiquity forum, a web site where small ISPs share their issues with equipment and network management systems.

network clients usually pay for the router, a basic part of the equipment, which relieves the operator of a significant source of cost.

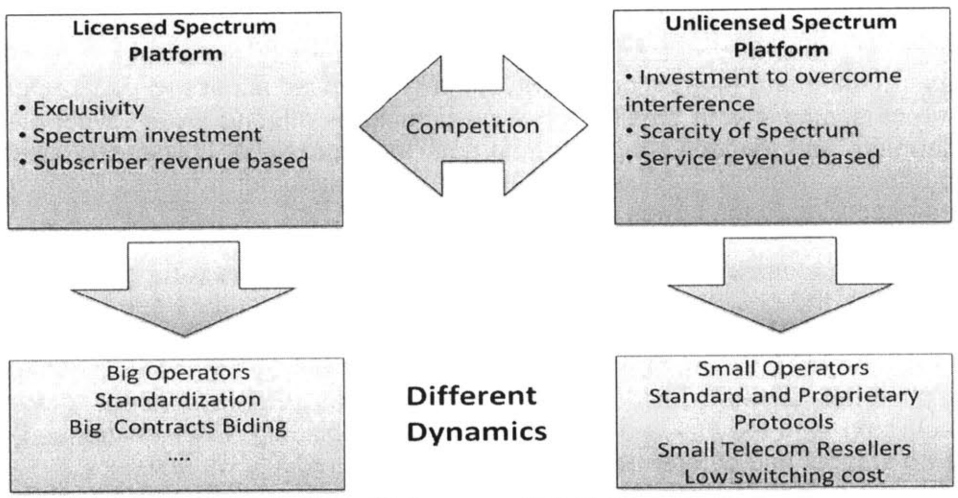

Figure 4-1: Two competing industries

4.3 Model

The model that follows simulates the evolution of two competing wireless industries: one represents the licensed spectrum industry; the other, the unlicensed spectrum industry. Both industries here offer similar services and compete for the same customers. A service generation mechanism will be activated according to various dynamics that will be described later. Users will adopt services in each platform depending on price, service availability and coverage. The two platforms and the modules implemented in the model are shown in Figure 4-2.

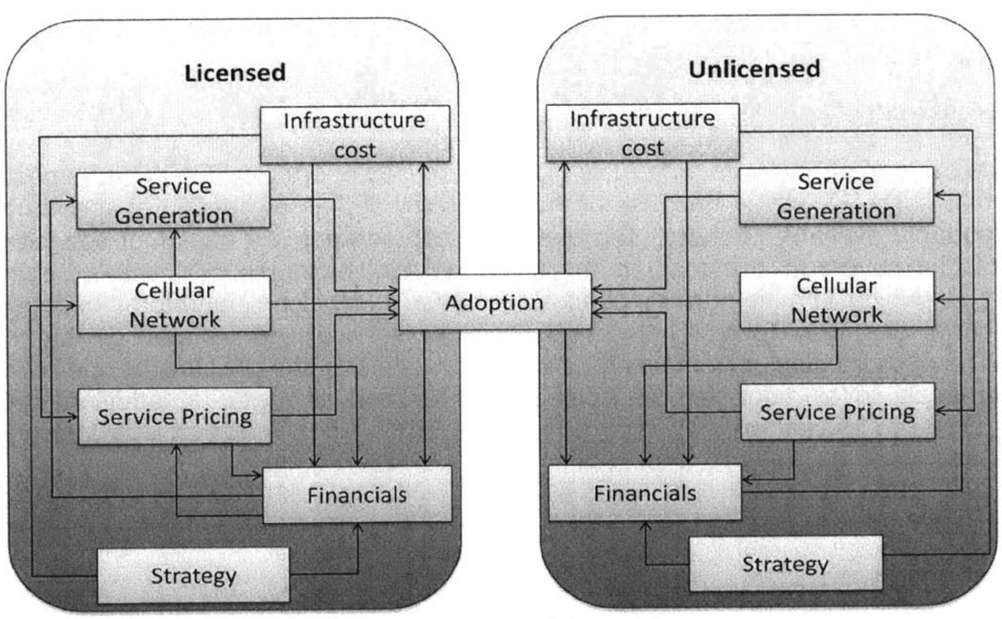

Figure 4-2: Top view of the model

Arrows in the diagram correspond to the functional connections between the sectors

The flows regulating the input and output from the different stocks will be modified by different dynamics explained in subsequent sections. The model has been developed and enhanced according to principles associated with the system dynamics approach to modeling complex feedback systems.[28] In general, the objective is to develop realistic models that reproduce observed patterns of behaviors and to suggest other possible behaviors with an endogenous structure (J.B. Homer, 1986).

4.3.1 Overall Structure of the Model

The model consists of six independent modules for both industries: Cellular Network, Infrastructure Costs, Financials, Adoption, Services Generation, Services Pricing and Strategy, and one module which is uniquely shared, User Adoption (See Figure 4-2) Each module will represent different dynamics inside a wireless network, and a mechanism of shared variables will be in place for information transfer between modules (Pardue, 1999) and (Pavlov, 2003).

4.3.2 Services Generation

By default, each operator will deliver a general service "Data + Voice Subscription" per subscriber. There will be a subjective variable called **service availability** which will provide a measure for customers to choose between platforms and switch from one to the other. The factor **service availability** value will depend on two kinds of services:

External Services: Services provided by external service providers, such as Google or Microsoft, through their platforms.

Internal Services: Services provided by operators inside the platform.

The level of external services will be represented by an exogenous variable. The level of internal services will be represented by an endogenous variable which will depend on the market share of the platform operator. Operators with a big spread between their capacity and their predicted demand will generate services and applications internally in order to gain market share; this dynamic has been inspired by other work from (Rubinfeld and Singer, 2001) and (Bernhardt, 1977) [29]. By creating internal services and applications, operators will not only

[28] A system dynamics simulation model involves stock-and-flow structures and a set of decision functions controlling the flows. These decision functions must have basis in a real world where rationality prevails and should respond realistically to all conditions, no matter how extreme. This may require the usage of nonlinear functions. B. Homer(1986)

[29] Rubinfeld and Singer(2001) : For vertical foreclosure to be an effective anticompetitive strategy for extending market power under Carlton's recent approach: (1) there must be scale economies in the production of the complementary good, and (2) there must be some customers who want only the output of the rival. The first condition applies in this case, since especially big operators from the licensed spectrum platform have internal resources skilled to create new internal applications or services.

increase their revenues by selling more services, but they will also attract more customers by offering exclusive applications/application bundles (i.e. not available from competitor's platforms) and thereby degrading the quality of offerings by external services/application providers.

In the model the internal service production level will be calculated based on the following formulas

$$S^*_{ServicesNeededLevel} = (1 + \varepsilon_{CapacitytdDemandRatio}(\frac{R_{CapacityvsDemand}}{Rf_{CapacityvsDemand}} - 1))$$

EQ 4-1

where

$S^*_{ServicesNeededLevel}$ Current Services Level required for earning the needed demand for the excess of capacity.

$R_{CapacityvsDemand}$ Current Ratio Capacity to Subscribers Demand

$Rf_{CapacityvsDemand}$ Actual Reference Ratio Capacity to Subscribers Demand

The Service Level required in every moment is not the real service level offered; there will need to be a delay due to the time needed to develop a new service in the platform. Therefore, the actual level of services offered by the operator will be calculated as a first order delay represented by the following formula:

$$S_{ServicesLevel} = \int_0^t \frac{S^*_{ServicesNeededLevel}}{\tau_s}$$

EQ 4-2

The external service level will have a fixed value which will represent the percentage of services offered by non operators companies through the existing access networks.

4.3.3 Service Price Setting

A simple, robust model of price-setting consistent with the behavioral decision processes of information available will be created, based on the model proposed by Sterman (2000) page 814. The price in equilibrium is assumed to be the price expected by traders, which can be adjusted gradually to the actual level of costs. In the model, mobile operators want to recoup

The second condition also applies, since subscribers do not see the applications or services accessible via a mobile data subscription as an added value to the subscription.

capital investment. Therefore, when subscriber revenue is too far off from the average monthly infrastructure cost per user, the level of costs will be translated as an increase in prices. The stronger the pressure, the bigger will be the adjustment. When operator costs per user, due to better leverage of their network, fall below user revenue, there will be pressure to reduce prices.

$$\frac{dP}{dt} = \frac{(P^{*} - P\ )}{\tau^{P}}$$

EQ 4-3

P^{*} is the Price in Equilibrium or anchor price followed by firms
P Price
τ^{P} Time to adjust the price

The anchor price P^{*} is the industry reference price and it is adjusted in response to pressures arising from unit costs and market share related to the firm's target share.

$$P^{*} = MIN(P^{Max}, P^{Expected} * (1 + \theta^{c} * (C^{Variable} / P^{Expected} - 1) * (1 + \theta^{Share} * (\frac{K^{f}}{K^{Total}} - 1))$$

EQ 4-4

where

P^{*} is the modified anchored price searched by firms.
P^{Max} Maximum price[30]
θ^{c} Sensitivity of Price to Network Variable Costs
$C^{Variable}$ Industry/Platform Variable Costs
$P^{Expected}$ Price Expected according to cost per service
θ^{Share} Price Sensitivity to expected firm market share. It is assumed that both industries (Licensed and Unlicensed) will aspire to have 100% of market share
K^{f} Capacity of Industry/Platform
K^{Total} Total Industry Demand

4.3.4 Adoption

Each network platform will offer services at a certain price in the covered area. The service user adoption in each platform will depend on the value of the following variables: price,

[30] In the telecom services industry the fixed and variable cost per service is difficult to calculate, since price depends mainly on network utilization. In the original formula taken from Sterman et al.(2007) the price is limited by a minimum price which is the unit cost. Here, the price is limited by a maximum price which will be set based on industry standards.

coverage and service availability. The User Adoption Rate will be defined by an extended Bass model represented by the following formula:

$$D_i = \alpha_i * P_{Modified} + \frac{\beta_i * P * A_i}{N} + (1-\gamma_j) * A_j * S_i^A$$

EQ 4-5

where the first term $\alpha_i * P_{Modified}$` represents the user adoption due to external sources of awareness and α_i is recognized as an advertisement effect. The second term $\frac{\beta_i * P * A_i}{N}$ represents a logistic model of growth for users who will adopt due to social exposure and imitation and β_i is recognized as Word of Mouth effect. The third term $\gamma * S_i * S_i^A$ represents the user adoption rate due to user switch between platforms.

Advertisement Effect

This effect depends exclusively on the Potential Population and an external advertisement factor:

$$\alpha_i * P_{Modified}`$$

α_i represents the advertisement factor and will be a parameter to be estimated statistically from previous experience data.

$P_{Modified}$ Represents the Population willing to adopt and it will depend on the Coverage, Service Availability and Price.

$$P_{Modified} = N^* * FractionWillingToAdopt - A_i$$

EQ 4-6

$$N^* = N * AdoptionFraction$$

EQ 4-7

where

N represents the Total Population

$AdoptionFraction$ represents the number of people who might ever adopt.

A_i Adopters of platform i.

The fraction of users willing to adopt will depend on the attractiveness of the platform and (its service benefits relative to costs) which will be defined by a function of the Coverage, Service Availability and Price:

$$FractionWillingToAdopt = F(Coverage) * F(ServiceAvilability) * F(\Pr ice))$$

EQ 4-8

By substitution of 4-8 in 4-6 we obtain the following formula for $P_{Modified}$

$$P_{Modified} = ((N^*) * F(Coverage) * F(ServiceAvilability) * F(\Pr ice)) - A_i$$

EQ 4-9

The functions $F(Coverage)$, $F(ServiceAvailability)$ and $F(\Pr ice)$ define the percentage of the population willing to adopt the platform and are defined by the following formulas:

$F(Coverage)$

This function defines the Platform attractiveness due to the coverage. Coverage will be the main factor in the platform attractiveness:

$$F(Coverage) = Coverage * MAX(0, 1 + -\varepsilon_c(\frac{Coverage}{Coverage^r} - 1)$$

EQ 4-10

Coverage is an endogenous variable that defines the level of surface covered by operators.

$F(ServiceAvilability)$

This function defines the Platform attractiveness due to the service availability.

$$F(ServiceAvailability) = MAX(0, 1 + -\varepsilon_s(\frac{ServiceAvailability}{ServiceAvailability^r} - 1)$$

EQ 4-11

$-\varepsilon_s$ Demand Curve Slope at a reference Price

Service Availability is an endogenous variable that defines the level of services in terms of quantity of services and quality. This variable depends on the coverage, installed base and number of services.

$F(\Pr ice)$

This function defines the Platform attractiveness due to the Service Price.

$$F(\Pr ice) = MAX(0,1 + -\varepsilon_d (\frac{\Pr ice}{\Pr ice^r})$$

EQ 4-12

$-\varepsilon_d$ Demand Curve Slope at a reference Price.

Price is an endogenous variable that defines the average revenue per service.

Word-of-Mouth Effect

This term represents the part of population who adopt because of having favorable reports from existing users and the formula for this is the following:

$$\frac{\beta_i * P * A_i}{N}$$

EQ 4-13

β_i Represents the Word-of-Mouth factor and will be a parameter to be estimated statistically from data on sales adopters.

A_i Adopters in each Platform

P Represents the potential users and is defined by the formula

$$P = N^* - A$$

EQ 4-14

User Switching Effect

Users in each platform will be able to switch, driven by two main factors: the attractiveness of the other platform and the platform switching costs. In order to represent the number of users changing platforms, a logit choice model will be used. The users switching from platform j to platform i will be given by the following formula:

$$Switchers_{ji} = (1 - \gamma_j) * A_j * S_i^A$$

EQ 4-15

Where:

A_j Represents the adopters of platform j

γ_j Indicates the platform j switching costs

S_i^A Indicates the platform j attractiveness and its value is determined by the formula:

$$S_i^A = Attractiveness_i / \sum_j Attractiveness_j$$

$$Attractiveness_i = \exp(\varepsilon_p * P_i / P^r) * \exp(\varepsilon_{CO} * C_i / C^r)$$

EQ 4-16

Where:

ε_p and ε_{CO} are the Sensitivities of Platform Service attractiveness to Price and Coverage

P^r and C^r Price and Coverage Reference at which demand equals the reference population

4.3.5 Cellular Network

In this research, the licensed industry is assumed to be a Wimax network, where the bandwidth is allocated in 5MHz channels. The network will have frequency reuse factor of 1[31]. Unlicensed networks are represented by a 5GHz link infrastructure with Wi-Fi Access Points for the Base Case[32]. For the White Space case33, the model will assume that the 5GHz sites will cover five times the area of the standard 5 GHz links, thanks to the White Space enhanced Access Points.

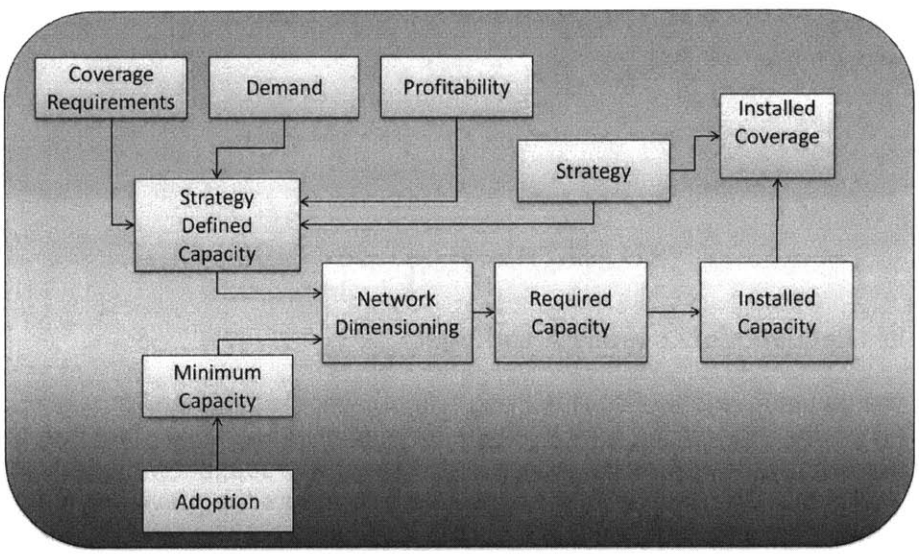

Figure 4-3: Network Capacity Wireless Networks

[31] Reuse factor, also known as frequency reuse factor, is the number of distinct frequency sets used per cluster of cells.

[32] As mentioned in the first part of this chapter. Base Case will represent the evolution of both industries assuming no release for unlicensed use of TVWSs.

[33] White Space Case will represent the evolution of both industries assuming the release of TVWS for unlicensed use

4.3.5.1 Network Dimensioning

In order to calculate the number of sites to be installed every year in the network, the model takes into account three factors: first, the minimum required capacity needed to provide service to existing adopters, and, second and third, the coverage and capacity stipulated by the operator growth strategy, which will be defined in section 4.3.5.2. The maximum of these three factors will be the desired capacity per year. Each year, operators will order additional capacity to increase their actual capacity to the desired capacity. Once the requested capacity is installed, the coverage will be readjusted to the new value of the installed capacity. Each of these steps will be explained with further detail in the next sections.

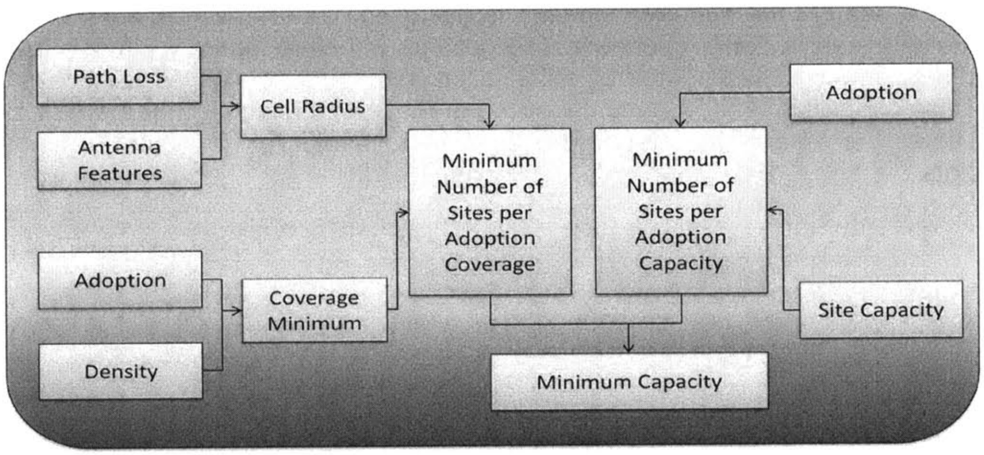

Figure 4-4 Minimum Capacity calculation process

Number of Sites Required for Covering Area Target

First, the minimum number of sites required to cover the adopters' occupied area will be calculated. This is done by getting the maximum amount of signal power that can be lost in the path from the antenna to the receiver, "path loss". Then, a propagation model will be used to calculate the cell radio. The propagation model takes as inputs the previously calculated "path loss" and antennas gain and sensitivity.

$$Path\ Loss = (EIRP - Rx\ Sensitivity - Building\ Loss) - Body\ Loss - Fade\ Margin$$

EQ 4-17

Where:

$EIRP$ Effective isotropic radiated power
$Rx\ Sensitivity$ Power indicates the level of signal needed in the receiver
$Building\ Loss$ Signal losses due to buildings
$Body\ Loss$ Signal losses due to body absorption

Fade Margin Allowance in the received signal level can be reduced without causing system performance to fall. For Mobile Wimax, this value is between 5-10dB.

$$Cell\ Radio = 10^{\frac{(Path\ Loss - 46.3 - 33.9*\log(F) + 13.82*\log(HAAT) + (1.1*\log(F) - 0.7)*Hcpe(1.56*\log(F) - 0.8) - Correction\ Suburban))}{(44.9 - 6.55*\log(HAAT))}}$$

EQ 4-18

Finally, the Cell Radio will be used to calculate the number of sites needed per area covered (dividing area covered by cell area).

$$Numberofsitesperadoption\ coverage = \frac{A_{Adopters}}{\pi * CellRadio^2}$$

EQ 4-19

Number of Sites Required for Covering Population Target

After calculating the minimum number of sites required for covering the operator targeted area, the next step will be to calculate the minimum number of sites required by operator targeted capacity. For that, the covered area and the table density function will be used in order to calculate the population to be covered by the operator coverage target. The total number of sites required by coverage population will be the result of dividing the number of population to be covered by the cell capacity.

$$NumberofSitespertargetcapacity = \frac{TargetedSubscribers}{Subscribers / Site}$$

EQ 4-20

Minimum Capacity to Provide Service to Every Adopter

A third restriction in order to calculate the minimum number of sites required from adoption is the minimum capacity required to provide service to every adopter taking in account capacity of the base stations. This minimum capacity will be calculated based on the number of subscribers and subscriber capacity per site.

$$NumberofSitesperadoptioncapacity = \frac{Subscribers}{Subscribers / Site}$$

EQ 4-21

Minimum Capacity to Provide Service and Coverage to Every Adopter

Finally, the minimum capacity will be defined by the highest restriction of the three, and will be calculated with the following formula.

$$NumberSites_{\min} = \max\left(\frac{TargetPopulationArea}{\pi * R_{\max}^2}, \frac{AdoptionSubscribers}{Subscribers / Site}, \frac{TargetPopulation}{Subscribers / Site}\right)$$

EQ 4-22

R_{max} Cell Radio calculated with Link budget and the Hata Model

$Subscribers$ Existing subscribers

$Subscribers / Site$ Base Station capacity

$AdoptionSubscribers$ Subscribers who have adopted

$TargetPopulation$ Population targeted by operator growth strategy

$TargetPopulationArea$ Area targeted by operator growth strategy

4.3.5.2 *Growth Strategies*

Operators inside each industry will share the same growth strategy. Each strategy will be defined by different investment motivations. The model will implement three strategies based on three main Growth Drivers that will define the market share pursued by operators in each industry. See in the Table 4-1 three investment drivers implemented in the model, followed by detailed explanation of each strategy.

Growth Driver	Growth Strategy Drivers Description[34]
Uncontested Demand	*Growth based capturing uncontested demand faster than competitors*
Coverage	*Growth based on a Coverage Target proposed for a technology and regulatory compromises*
Profitability	*Growth based on the reinvestment of previous years margins*

Table 4-1: Growth Strategy Drivers implemented in the model

Growth Driver: "Coverage"

This growth will be driven by Operators establishing a percentage of the area to be covered in a certain amount of years. This is regardless of the demand and competitors movements. The intended operator growth will be modeled by a simple logistic growth model where the input parameters will be:

- The target Coverage: $C_{TotalCoverageTarget}$, that represents the percentage of area to cover

- The time to achieve that coverage, $C(t)_{Target}$ will represent in every moment the capacity desired by operators.

[34] The model does not implement individual firm drivers but the aggregation of firms in two different industries; therefore, the expected market share of the whole industry would be 100%. Future model implementations with individual firms should consider this growth driver as well.

$$C(t)_{Target} = \frac{C_{TatalCoverageTarget}}{1 + e^{-\frac{2*\ln(\frac{C_{Target}}{C_{Initial}}-1)}{TimeToCover}*(t-\frac{TimeToCover}{2})}}$$

EQ 4-23

$$S^{*}_{Coverage} = \frac{C_{Target}}{D^{e}}$$

EQ 4-24

$C_{TotalCoverageTarget}$ is the Area targeted by operators

Time to Cover: is the time that operators fix to cover a region

$S^{*}_{Coverage}$: Platform Market Share desired

D^{e} Forecast Industry Demand

Finally, the capacity defined by this growth driver is defined by the formula:

$$K_{DesiredCapacity} = MAX(K_{min}, S_{Coverage} \bullet D^{e})) = MAX(K_{min}, C_{Target}))$$

EQ 4-25

where:

$K_{DesiredCapacity}$ Operators' desired capacity

K_{min} Operator' actual capacity

$S_{Coverage}$ Desired Market Share driven by the Coverage target

D^{e} Industry Demand forecast

C_{Target} Coverage indicated by plans

Growth Driver: "Uncontested Demand"

This growth will drive operators to seek to grow faster than their competitors; for this, they will estimate the total industry demand and their competitor capacity and will try to grow enough to fill the demand gap.

For estimations, operators have to be aware that there will be a delay to acquire the required capacity so they will need to forecast the demand λ years ahead. Firms demand forecasting is captured in this model with the heuristics proposed in (Sterman et al., 2007) which proposes that firms will extrapolate demand λ years in advance and continuous growth will be assumed. The expected growth rate in demand, g^r, is estimated from reported industry demand, D^r, over a historical horizon, *h (in years)* (Sterman et al, 2007)

$$D^e = D^r \exp(\lambda * g^e)$$

EQ 4-26

$$g^e = \ln(D^r / D^r_{t-h}) / h$$

EQ 4-27

The Reported demand D^r will be based on data reports and a simple exponential first-order delay will be assumed:

$$\frac{dD^r}{dt} = (RealDemand - D^r) / \tau^r$$

EQ 4-28

where

τ^r : Data Reporting Time

$RealDemand$ Capacity (network investment) needed to provide service to actual sum of both platforms' users.

Because this growth driver will push operators in each platform to achieve their own and competitors' forecasted demand, the firms should monitor their rivals actual and planned capacity (not publicly announced) and capacity under construction. In the model, it is assumed that there is a delay τ^c to acquire the competitor capacity information.

$$\frac{dD_{Competitor}^{e}}{dt} = (D_{Competitor} - D_{Competitor}^{e}) / \tau^c$$

EQ 4-29

Knowing the competitors' expected demand, the formula for the uncontested demand will be the total industry demand less the sum of competitors' demand. In the model, the firms are aggregated in two industries; therefore, the uncontested demand will be the forecast industry demand less that of competitor's platform capacity.

$$D^r{}_{Uncontested} = D^e - D^e{}_{Competitor}$$

EQ 4-30

$D^r{}_{Competitor}$: Forecast Competitor Capacity

D^r : Total Forecast Demand

$D^r{}_{Uncontested}$: Total Uncontested Demand

τ^r : Reporting Time

Under this driver growth, operators will aim to cover all the uncontested demand; therefore, the targeted market share will be $S^*_{DemandForecast}$.

$$S^*_{DemandForecast} = \frac{D_u^{\ r}}{D^e}$$

EQ 4-31

Growth Driver "Profitability"

This growth driver will lead operators to increase their investment in Capacity as their profitability grows. This is a determinant growth driver in the unregulated spectrum industry where operators are small relative to the industry[35].

$$E_{EffectofExpected\Pr ofitabilityonCapacity} = \frac{\sum P_{Service} * S_{ServiceperSubs} * S_{PlatformSubscribers} - \sum Sites * C_{OperatingCosts}}{\sum P_{Service} * S_{ServiceperSubs}s * S_{PlatformSubscribers}}$$

EQ 4-32

$E_{EffectofExpected\Pr ofitabilityonCapacity}$: Profitability effect on desired capability

This value is represented as the Total Revenues less the total costs divided by the total Revenues. When above zero, it will increase the willingness of operator to increase the capacity. When this value is below zero, it will decrease the operator motivation to invest in capacity

$P_{Service}$ Price per service

$S_{ServiceperSubs}$ Number of services per subscriber

$S_{PlatformSubscribers}$ Number of subscribers in the platform

$Sites$ Number of Network Radio Stations

$C_{OperatingCosts}$ Operating Cost per year per site

The Effect of the expected profitability in new investment $P_{Expected\Pr ofitabilityonCapacity}$, will be implemented with a function described in Sterman (2000) for commodity markets. Where the input parameter is $E_{EffectofExpected\Pr ofitabilityonCapacity}$ and the output will be a value between -1 and 1 that will represent the market share pursued by operators for next year. If $P_{Expected\Pr ofitabilityonCapacity}$ is above one,

[35] The Effect of profitability in capacity has been adapted from Sterman (2000) and has the following value: Revenues-Costs/Revenues . Originally in (Sterman 2000), this variable had the following formula: (ExpectedLongRunPrice-ExpectedProductionCost/Expected LongRunPrice).

the operators will increase their capacity, pursuing more market share; if it is below one, operators will pursue less market share and will reduce their capacity.

$$P_{Expected\,Profitability\,on\,Capacity} = f_{Table\,of\,effect\,of\,expected\,profitability\,on\,Capacity}(E_{Effect\,of\,Expected\,Profitability\,on\,Capacity})$$

EQ 4-33

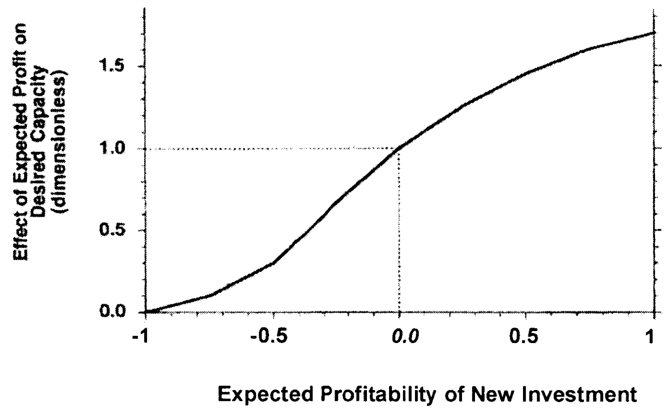

Figure 4-5: Table of effect of expected profitability in desired capacity. Sterman(2000)

The market share pursued by this growth driver will be defined by the following formula:

$$S^{*}_{Profitability} = \frac{K_{Platform} * P_{Expected\,Profitability\,on\,Capacity}}{D^{e}}$$

EQ 4-34

Where

$S^{*}_{Profitability}$ Modified operators' Target market share

$K_{Platform}$ Actual operators' capacity

$P_{Expected\,Profitability\,on\,Capacity}$ Effect of profitability in the desired operator market share

D^{e} Forecast Industry demand

Strategies defined in the model

Based on which of these drivers define the growth in operators, three different strategies have been implemented in the model. Each strategy will define the operators pursued market share S^{*}. A "Coverage Driven" strategy will define a growth based on coverage target established by operators. An "Aggressive Strategy" will be pursued by operators growing fast to capture the uncontested demand or investing all their revenues. A Conservative strategy will define operators which accommodate to competitors and base their growth to new customers and excess of revenues to invest. See in Table 2 the formulas that define the market share in each of the strategies.

Strategy	Growth Drivers Formula	Target Capacity
Coverage Driven	$S^*_{Coverage} = \frac{C_{Target}}{D^e}$	$K_{DesiredCapacity} =$ $MAX(K_{min}, S^*_{Coverage} \bullet D^e))$
Aggressive: Growth based on competitors' growth	$S^*_{DemandForecast} = \frac{D_u^r}{D^e}$ $S^*_{Profitability}$ $\frac{K_{Platform} * P_{Expected ProfitabilityonCapa}}{D^e}$	$K_{DesiredCapacity} =$ $MAX(K_{min}, MAX(S^*_{ForecastedDemand}, S^*_{Profitability}) \bullet D^e))$
Conservative: Growth tied to Profitability	$S^*_{Profitability}$ $\frac{K_{Platform} * P_{Expected ProfitabilityonCapa}}{D^e}$ $S^*_{DemandForecast} = \frac{D_u^r}{D^e}$	$K_{DesiredCapacity} =$ $MAX(K_{min}, MIN(S^*_{ForecastedDemand}, S^*_{Profitability}) \bullet D^e))$

Table 4-2: Strategies Defined for the Model

4.3.5.3 Installed Capacity

The model will represent the yearly growth of each network as the difference between the desired capacity and the capacity installed or being installed. The purchase of the desired additional base stations will take a one year delay, and so will take the installation and integration in the actual infrastructure, in total there will be a total delay of two years before the extra desired capacity will be installed

Once the base stations are integrated they will form part of the installed base. The model will assume that each year a 3% of the installed base becomes obsolete or has to be replaced by new equipment.

4.3.5.4 Coverage

The coverage will be understood as the area covered by each platform, which is the area where there is at least one **"channel"** available. The relationship between coverage and the installed capacity will be calculated with a density table. This table has been calculated based on the table used by (Hallahan and Peha, 2008) in page 25. The table relates the percentage of coverage needed to cover certain amount of subscribers in USA.

Density Table								
Population	77148	2.46E+07	4.43E+07	7.61E+07	1.06E+08	1.27E+08	1.50E+08	1.54E+10
Coverage%	0.01	0.109649	0.184211	0.263158	0.421053	0.592105	0.991228	1

Table 4-3: Population Density

4.3.6 Infrastructure Costs

From the overall cost structure of mobile networks, only the radio access network and the Network Operating Center (NOC) have been included in this model. The radio access network involves the antennae and equipment needed to transmit and receive the signal and it is the part of the model where the network specific technology for each network is implemented. The NOC includes the infrastructure to manage alarms, network measurements and configuration parameters.

Wireless Network Cost Structure Model

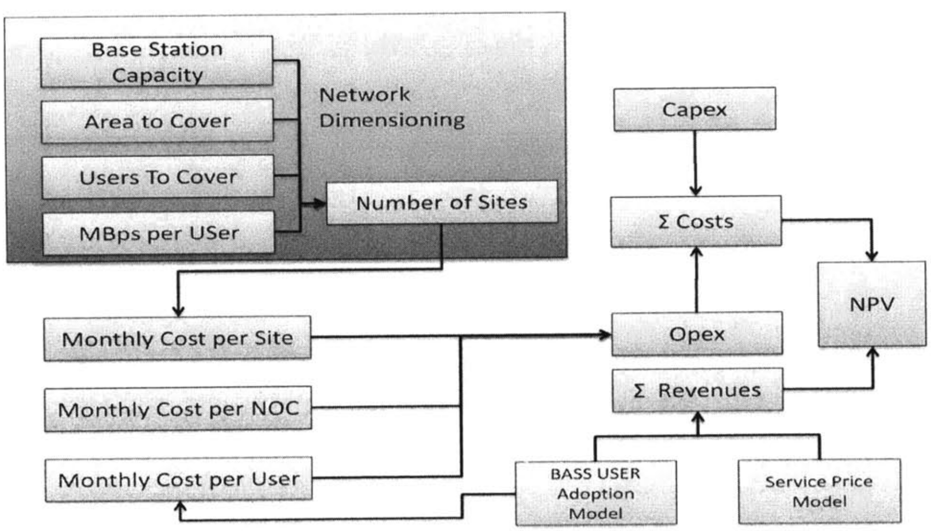

Figure 4-6: Wireless Network Infrastructure Costs Model

This part of the model is meant to provide a general overview of the difference in costs incurred in a traditional licensed network compared with an unlicensed counterpart. The costs are divided into two types, according to their nature: Capital Expenses and Operating Expenses. Capital expenses (CAPEX) include the costs incurred when a network is rolled out, and they relate to the cost of equipment and its installation and configuration. Operating expenses (OPEX) refer to the costs related to operating and managing the network and they are mainly related to the site leases, monthly electricity expenses, and operating personnel.

Spectrum costs will be assumed to be $3 per user (Mudhafar, 2007), A total amount of spectrum costs will be calculated based on the population living in the target coverage area. It will be assumed that the spectrum costs will decrease with an exponential decay, having paid most of the spectrum in the first two years. This will mean a heavy cost load for licensed spectrum operators in the first years.

4.3.7 Financials

The financials part of the model keeps track of both wireless industry' revenues and expenditure streams The initial number of access points will be simulated by assigning the stocks of users and capacity with initial values based on historical data. The yearly Operating Costs and Capex Costs will be subtracted from the yearly revenues. The resulting profits or losses from each year will be divided by a discount rate and accumulated in a stock representing the Net Present Value of each network. The model will assume an infinite source of capital, no capital costs, and no equipment amortization or depreciation costs.

In order to see the profitability of the network compared with its competitor a simple NPV formula will be implemented. The profits will be calculated as Revenues less Costs.

$$\pi = R - C^{Opex} + C^{Capex}$$

EQ 4-35

R Revenues are equal to ServicesperSubscriber*Subscribers*Cost

C^{Opex} Operating costs will be calculated as Site NumberofSites*AnnualCostsperSite

C^{Capex} Cost due to Investment in Network Growth

The Net Present Value will be calculated with a standard discount rate *d* for both industries.

$$\frac{dNPV}{dt} = e^{(-d*t)} * \pi)$$

EQ 4-36

Where ^{d} is the Discount Rate.

4.4 Model Calibration

For the sake of simplicity and for reasons explained below, in the model implemented in this thesis, Wimax Mobile technology and price parameters have been chosen to calibrate the licensed industry that will compete with 5GHz White Space enhanced networks.

The justification for comparing a fixed technology such as White-Fi with a mobile access technology is the following: roaming capabilities have been traditionally incorporated in network equipment rather than in small personal devices, this author believes, because the intelligence required for the latter was not yet developed. With the advent of Software Defined Radio and Cognitive Radio the handset intelligence capacity is much broader (Merino, 2002), making it possible for small roaming-capable devices to switch network, antenna, technology, or frequency at their convenience. Indeed, as this thesis is being written, Nokia has already announced a TV white space device (Churchill, 2011b).

A nationwide rural network will be assumed where a population of 154 M users will be distributed in an area of 919.728 km^2 corresponding to the suburban and rural areas of the main Wireless markets in the USA, listed in the Appendix B.

The model will have a time frame of 15years, based on the adoption curve of Mobile Wireless Telephone subscribers which can be found in FCC (2010) pg 11-4. Showing that 90,5%[36] of population in USA have adopted the Mobile Wireless services from 1993 to 2008.

Different techniques have been used for the calibration of the model: Available technology-specific data from access and network operation have been used to calibrate the infrastructure cost structure and cellular network capacity. Interviews with operators and equipment vendors have been used to calibrate the different growth strategies for the two networks infrastructures. Finally, times series have been created in order calibrate the Bass User Adoption and the Price Setting Model.

4.4.1 Infrastructure Cost and Capacity Calibration

Data available in equipment re-sellers websites as well as in vendor's catalogs have been used in order to calibrate the different costs of equipment for every industry. Different configuration and capacity information has been also used in order reflect the different expenditures behind the two wireless industries.

Total Costs	Wimax	5GHz	5GHz+White-Fi
CAPEX			
Cost per Site (Capex)	$140,305	$26,734	$41,040
Cost per Market(NOC)	$510,000	$0	$0
Cost per Subscriber	$629	$895	$895
OPEX			
Monthly Cost per POP+Site	$8,821(Approx 5 % Site Capex)[37]	$881 (Approx 10% Cost per Site Capex)	$881 Approx 6% Cost per Site Capex)
Yearly Cost per Noc[38]	$11,952,500 (80* Site Capex)[39]	3,120 (Approx 12% Cost per Site Capex)	$3,120(Approx 8% Cost per Site Capex)
Monthly Cost per Subscriber	$10	$1	$1

Table 4-4: Total Costs Summary. Sources (Motorola, 2011) and (Ruckus Wireless. Inc., 2007)

[36] Population USA 2010: 308,745,538. Source: United States Census. Mobile adoption started in 1990 and in 2008 there are 279,646,000 mobile subscribers. In 18 years the adoption of mobile phones is of 90,5% of USA total population.

[37] Yearly Cost per NOC is NOC Monthly Costs*12= 1.192.500 which has been assumed in the model as Site Capex*80.

[38] It will be assumed only one NOC.

4.4.2 Network Dimensioning Calibration

Capacity Parameters

First, the Area covered per site will be defined with the Link Budget and the propagation path loss calculated with Hata Model[40] and the data found in Table 4-4 Then, the capacity will be estimated by the number of users accepted per site. See also in Table 4-5 the parameters that define the site capacities. Finally, the number of sites will be defined by the maximum between Capacity Required by Strategy and the Capacity Required because of Adoption.

	Wimax	5GHz	5GHz+White-Fi	Units
Subscriber Capacity	324[41]	114	114	Subscriber/Site
Frequency	2,500	5000	5000 + 0.6	MHz
EIRP	23.98	23.98	23.98	dB
RX Sensitivity	-125	-125	-125	dB
RS Building Loss	7	7	7	dB
RS Body Loss	3	3	3	dB
Fade Margin	8	8	8	dB
HAAT	30	30	30	m
CPE H	1.5	1.5	1.5	m
Correction Suburban	-9	-9	-9	dB

Table 4-5: Capacity Parameters

4.4.3 Bass User Adoption Model Calibration

In the model, an extended Bass Adoption formula has been used to simulate the user adoption explained in section 4.3.4. Here, the calibration of the two configurable factors in the Bass equation EQ 4-5 described below will be described.

$$D_i = \alpha_i * P_{Modified} + \frac{\beta_i * P * A_i}{N} + (1-\gamma_j) * A_j * S_i^A$$

EQ 4-5

The configurable factors are α_i= Advertisement Effectiveness Factor and β_i = Word of Mouth effect, Sterman (2000). These factors will be calibrated with real data for both industries, licensed Wimax user adoption calibration will be performed with data corresponding to the

[40] Reference of extensions used for frequencies further than 2.5GHz

[41] Assuming 16QAM ½, then bps = (hz * FEC * Modulation_order) / 1.24 , therefore bps = (5 Mhz * 1/2 * 4) / 1.24, and then capacity for 5 Mhz with 16QAM 1/2 are 8.1 Mbps – Dividing this by Average Speed required per subscriber (assumed 3 Mbps) and overbooking factor of 40 the each user requires 75 kbps. 8100/75 = 108 users per sector. Assumed three sector per site = 324 users per site

evolution of a real Wimax operator in the USA, ClearWire. Wimax subscriber and coverage information in the USA from the last 7 years has been taken from ClearWire newsroom webpage. See in Table 4-6 subscriber information.

Because of the recent TV white space deregulation, no information about the user adoption the TVWS is available; therefore, the subscriber information to calibrate the Bass Model parameters in the unlicensed module, is taken from the available user adoption information about the UNII[42] bands in the 5GHz band licensed exempt spectrum. This licensed-exempt band has been selected in order to calibrate the user adoption in the model because these frequencies have been highly adopted in rural areas for backhauling and access. The subscriber information from small rural operators WISP is not publicly available; therefore, the number of customers has been calculated by dividing WISP operators' revenue and ARPU available information. In detail, the process to calculate 5GHz customers has been the following: first a list of USA WISP operators using the 5GHz has been taken from the WISP website[43]. Next, from the almost 2000 WISP list, a sample of 79 representative companies has been selected and information about their revenues has been obtained from Orbis Financial database. The average revenue per company has been multiplied by the number of companies obtained from Wisp directory, obtaining the revenues attained by the Wisp industry. Later, the revenues are divided by the ARPU to get the approximate number of subscribers. The ARPU information is obtained from publicly available information in ABI Inform\Dateline ProQuest service[44]. See below the two time series of user adoption obtained to calibrate the Bass model.

Subscriber information for Wimax and 5GHz		
Year	**5GHz**	**Wimax**
1997	15.567[45]	-
1998	44.756	-
1999	109.088	-
2000	263.906	-
2001	3.510.012	-
2002	1.648.222	-
2003	2.086.142	-
2004	2.880.032	10.000[46]
2005	4.334.391	60.495
2006	5.432.873	198.771
2007	6.563.715	378.097
2008	5.213.325	459.097
2009	5.303.919	724.273
2010	-	4.300.000
2011	-	8.800.000

Table 4-6: Number of subscribers per year in the USA from Clear Wire and estimated number of subscribers from aggregated USA WISP companies

[42] Unlicensed National Information Infrastructure which consists of different bands dedicated for unlicensed devices. See section 3.4

[43] http://www.wispdirectory.com/

[44] ABI http://www.abiresearch.com/home.jsp

[45] Orbis Database.

[46] Assumed Subscribers first year.

The calibration of the parameters for the Bass model has been performed with the help of Vensim DSS[47] Module. See in the Table 4-7 the calibrations results. On the left side, the initial values can be observed and on the right site, the parameters after the calibration are to be found.

Model Parameters Starting Point		Final Model Parameters After Calibration	
Licensed (Initial)		**Licensed (Calibrated)**	
α_i Advertisement	0.2	α_iAdvertisement	0.008
β_iWord of Mouth	0.2	β_i Word of Mouth	0.94
Unlicensed (Initial)		**Unlicensed (Calibrated)**	
α_i Advertisement	0.2	α_iAdvertisement	0.102958
β_i Word of Mouth	0.2	β_i Word of Mouth	0.00001

Table 4-7: User Adoption Calibration parameters

The Bass Adoption model calibration sets more favorable advertisement conditions for the licensed networks adoption, which can be explained by the greater advertisement campaigns big operators can afford. Also it sets a stronger Word of Mouth effect for licensed networks compared to unlicensed. This can be explained by the local and restricted area of impact of Wisp operators, which will reduce the possibility of adoption spread by imitation or influence. See comparison between real data and model output in the Figure 4-7 and Figure 4-8.

47 http://www.vensim.com/software.html

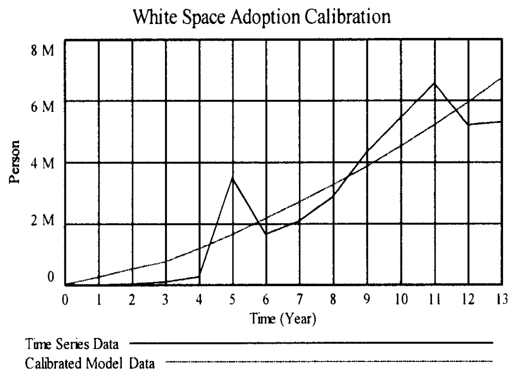

Figure 4-7: Rural Wisp Subscription Adoption. Real Data and Model output comparison

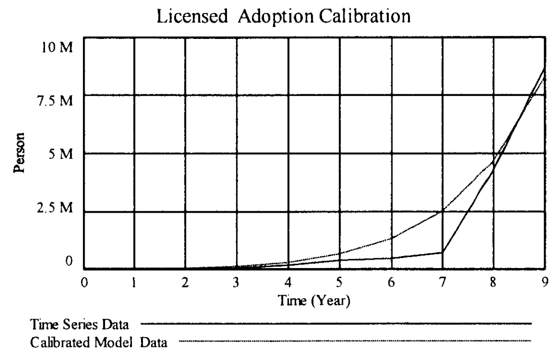

Figure 4-8: Wimax Subscription Adoption. Real Data and Model Output Comparison

4.4.4 Strategy and Service Generation Calibration

Strategy: Based on interviews with licensed and unlicensed operator's representatives, the model will reflect the different dynamics present in the two industries in terms of growth and service generation. From the three possible model strategies -- "Coverage", "Aggressive" and "Conservative" -- the best strategy for each industry has been chosen for the base case. Therefore, Operators in the licensed spectrum wireless business will roll out their networks based on target coverage; therefore, their growth strategy will be set to "Coverage". The model will represent the industry as an aggregation of licensed operators that will have as a coverage target 100% of the main suburban and rural areas in the USA[48]. The time to deploy sites and cover the area will be set to 15 years[49]. Based on real unlicensed operators' growth plans[50], the unlicensed industry will be modeled with a very conservative strategy, focusing on reinvestment of profits and coverage of uncontested demand. Service generation will be calibrated differently for the different industries.

Services: The different industry motivations to create internal services (explained in point 4.3.2) will be implemented asymmetrically in the model. Licensed operators will be more sensitive to the excess of demand in order to create internal services. They own bigger infrastructures than unlicensed operators, which are usually smaller, have more local structures, and prefer to leverage their networks by offering third- party external services

[48] See in Appendix B main USA mobile markets taken as reference.

[49] Time taken by existing operators to deploy their networks in USA Ref (FCC,2010, p 11-4)

[50] Assumption made base upon WISP owners interviews: **Question:** What is your main growth driver: Answer: "The main growth driver is that if we can get enough customers to cover the cost of deployment and maintenance, then it is a good business decision to extend a network. This leads to new customers. Covering before another WISP operator is not really a big consideration, although WISPs will often stay out of each other's way"

5 TV White Space impact in the Wireless Industry

5.1 Introduction

In previous chapters, a generalized TV white space framework regarding regulation and protocol development for the wireless industry has been provided for assessing the possible impacts of the TV spectrum policy change. In addition, a model that simulates the competition between licensed and unlicensed wireless access industries has been described for the purpose of measuring the impact of white space on both industries.

In this chapter the calibrated model will be used to measure the impact of the White Space in the unlicensed vs. licensed competition. The model will be run first with the existing unlicensed spectrum and later, with White Space in order to compare the two equilibriums reached in the competition. Also in this part, several analyses will be performed to shed some light about which circumstances can increase the potential of TVWS to enhance unlicensed networks.

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5.2 A nationwide White Space unlicensed wireless access network

In this section, the model calibrated with wireless network cost structures and appropriated Bass User Adoption parameters will be used to assess the impact of introducing white space in the rural wireless access industry.

The following is a summary of the parameters used by the model which have been thoroughly described in chapter 4:

- A nationwide rural network will be assumed where a population of 154 Million users will be distributed in an area of 919.728 km^2 corresponding to the suburban and rural areas of the main Wireless markets in the USA, listed in the Appendix B.
- Both wireless industries will compete for the same customers and will roll out their networks in the same areas.
- For the purpose of the Net Present Value (NPV) simulation, only the cost structure, price and user adoption dynamics modules will be active. The "services" dynamics have been deactivated in this first simulation and they will be activated later in other tests. It will be assumed that only one generic service, "Data + Voice", will be adopted per user at a maximum price of 70$/month.
- A conservative strategy will drive growth in the unlicensed wireless industry, where the coverage expansion plans will be designated either by the coverage of the

uncontested demand or by the investment of excess of profits, whatever implies less spending[51].

- The licensed industry growth will be simulated with a coverage-based strategy[i52]. The licensed operators will be assumed to cover the whole area in a fifteen-year plan.

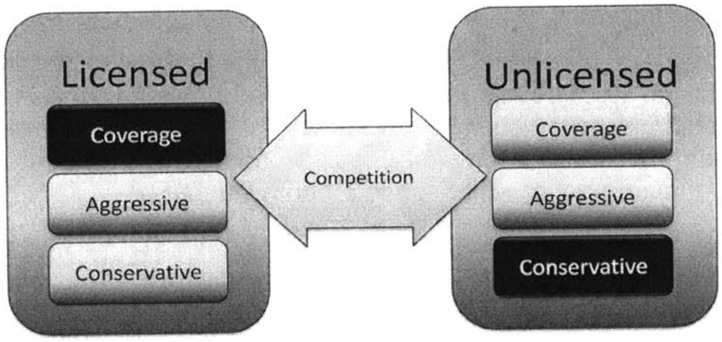

Figure 5-1: Licensed adopt a Coverage Growth Strategy vs. Unlicensed Conservative Growth Strategies for the Base Case

The model has been run twice. The first Base Case run, simulates a competition between Wimax and Standard 5GHz and Wi-Fi access points. The second run introduces White Space and simulates the competition between Wimax and White-Fi access points. The Business Case will not be a static calculation with fixed technology costs and user revenues. In fact, the NPV for each technology depends on the user adoption, the price evolution, the growth selected strategy, the implementation time and competitor movements. In the next sections, the Base Case and White Space variable values will contrasted and analyzed in order to study the White Space consequences in the wireless industry evolution. The variables chosen to be analyzed will represent the main parts of the model, Net Present Value to show the cost structure and financials evolution, Subscribers, to describe the adoption model progress, Coverage; to highlight the Network Dimensioning and Capacity deployment and the service price to represent the Service Generation trajectory.

5.2.1 Net Present Value

The Figure 5-2 shows the NPV evolution of the unlicensed network for the Base (dotted line) and the White-Fi case (continuous line), as can be seen, there is an improvement in the NPV of about twice the value when comparing both cases. However, the Figure 5-3 shows that the NPV for the licensed Network does not get affected by the introduction of the TVWS.

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[51] See definition of Conservative Strategy in Chapter Four

[52] See Chapter Four for more details.

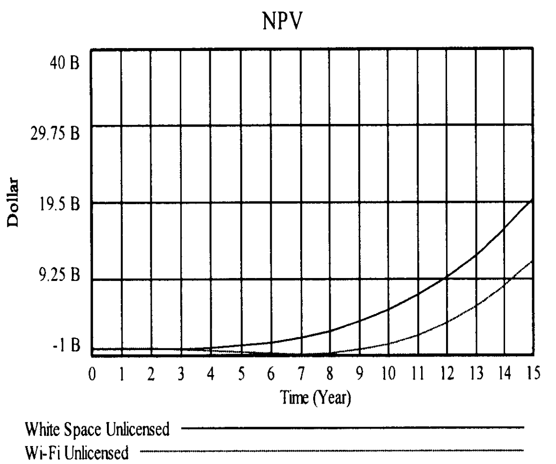

Figure 5-2 Bold line represents unlicensed networks Net Present Value when TVWS is available. Dotted line represents NPV for unlicensed networks when no TVWS is available

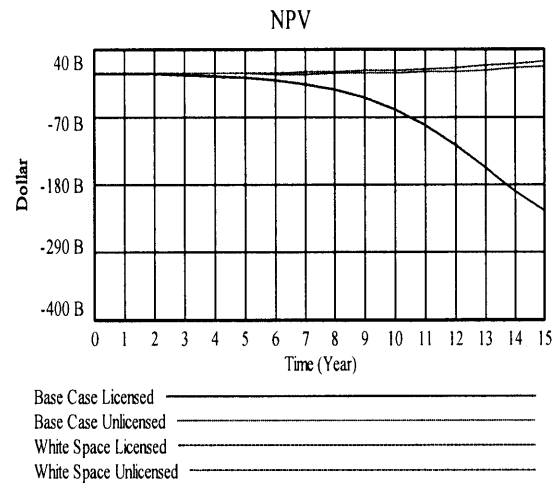

Figure 5-3 Bold line represents NPV for incumbent operators in both cases (with and without WS available) — when TVWS is available and when not., White Space Licensed and White Space Unlicensed (two different dotted lines) represent the different NPVs achieved by unlicensed networks in both situations; when TVWS is available (White Space Unlicensed) and when it is not (Base Case unlicensed)

5.2.2 Subscribers

White space introduces an improvement in the user adoption as can be seen in the Figure 5-5. Because of better coverage users adopt more unlicensed networks. However, the licensed user adoption remains at the same level, see Figure 5-4.

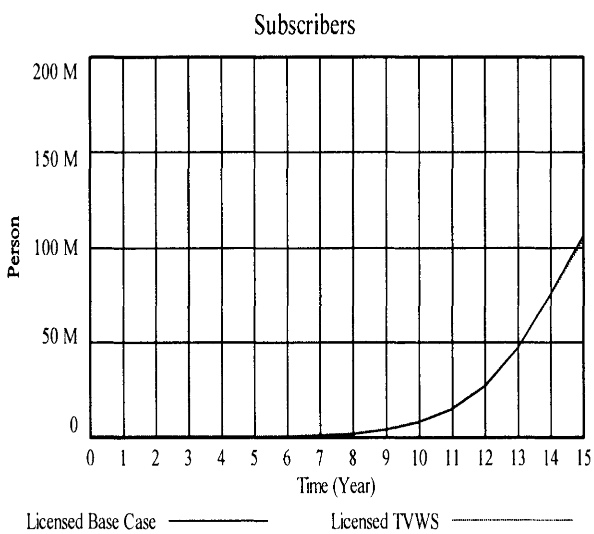

Figure 5-4: Both lines represent the Subscribers who adopt Licensed Networks. The Bold line represents the adopters in the base case, when White Space is not available. The dotted line (overlapped) represents the licensed network adopters when TVWS is available for unlicensed networks. As it can be seen the addition of TVWS for unlicensed usage does not affect the licensed adoption.

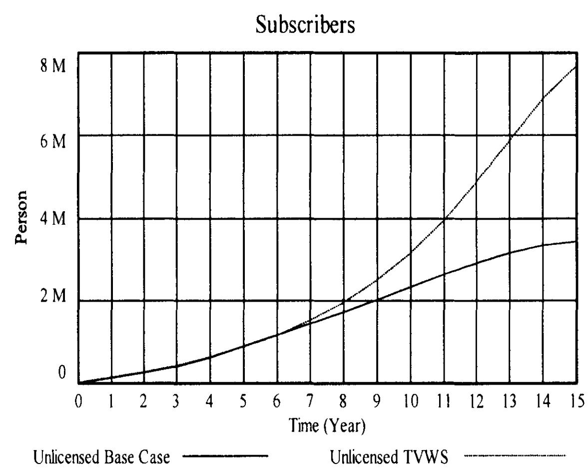

Figure 5-5: The bold line represents the unlicensed networks adopters when TVWS is not available for unlicensed purposes. The dotted line represents the unlicensed network adopters when the TVWS frequencies are available for unlicensed use. As it can be seen adoption is two-folded.

5.2.3 Coverage

White space introduces a substantial change in the unlicensed networks coverage, this causes more user adoption. However, the white space introduced coverage enhancement is still very low compared with the licensed network deployment, which provides licensed operators a source of competitive advantage in terms of network attractiveness. See in Figure 5-6 and Figure 5-7, the comparison between coverage in licensed and unlicensed networks, for the Base and white space case.

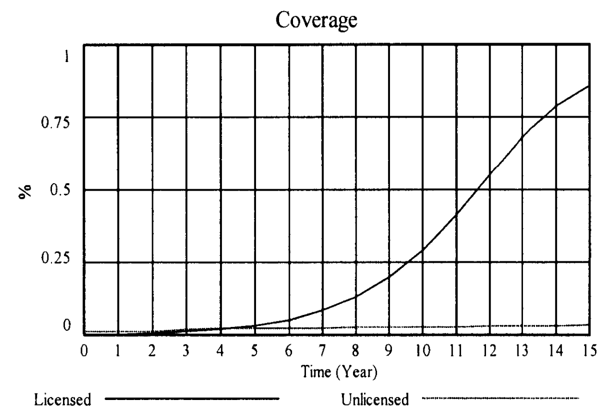

Figure 5-6: Bold line represents coverage of licensed networks and dotted line represents coverage of unlicensed networks. Both "coverages" refer to the base case, where TVWS is not available.

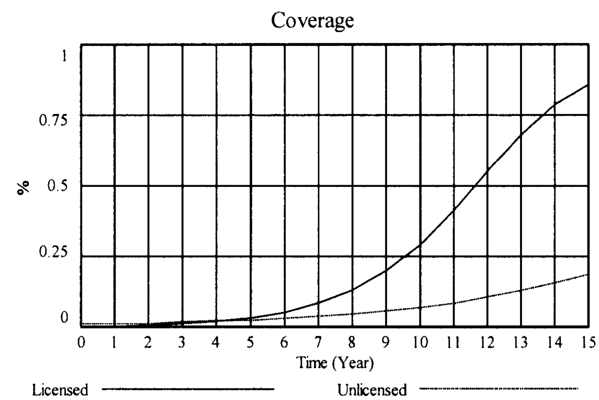

Figure 5-7: Bold line represents coverage of licensed networks and dotted line represents coverage of unlicensed networks. Both "coverages" refer to the TVWS case, where TVWS is available for unlicensed networks . As it can be observed unlicensed networks coverage increases considerably with respect to the base case in the figure 5-6 on the left.

5.2.4 Service Prices

See in Figure 5-8 the two model outcomes for the service price in the base case and after white space is introduced Figure 5-9. As can be observed, licensed Operators Pricing strategy does not get affected by the introduction of the white space. However, the new frequency has better propagation characteristics and requires less equipment in order to cover the same area, this allows having less costs per user. Moreover, because of more coverage, more users adopt, see Figure 5-5, and as a result of less costs and more users, the unlicensed operators can reduce more their service price when white space is introduced. See Figure 5-9. Finally, this will allow more affordable prices and a more attractive network that will capture more customers.

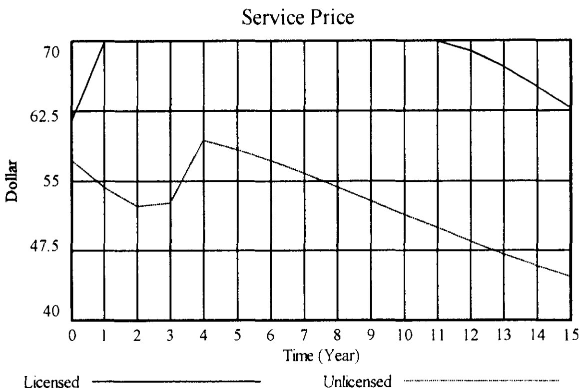

Figure 5-8: The bold line represents Service Price evolution of licensed networks and the dotted line represents Service Price evolution of unlicensed networks. Both Service Price evolutions refer to the base case, where TVWS is not available

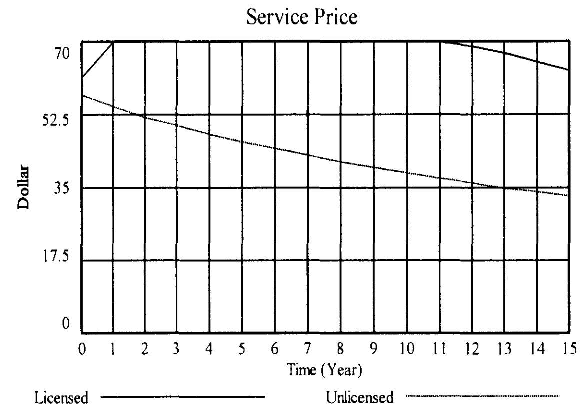

Figure 5-9: The bold line represents Service Price evolution of licensed networks and the dotted line represents Service Price evolution of unlicensed networks. Both Service Price evolutions refer to the TVWS Case, where TVWS is released for unlicensed purposes.

5.2.5 Conclusion on the Impact of the TV White Space in the Wireless Industry Competition

In this chapter, the business impact of the TV frequencies in the wireless industry has been studied. Two general assumptions have been made: first, that the technology implemented in the white space will bring a noticeable difference in infrastructure costs for unlicensed operators; second, that there will be real competition between licensed and unlicensed operators, which may well bring about increased adoption of the unlicensed networks. Results of this study show that, with the actual technology and level of services, the effect of white space will be a faster user adoption of unlicensed wireless networks without a significant impact on the traditional licensed operators. Figure 5-4 shows the stock of users who have not yet subscribed to either of the two kinds of networks. As adoptions take place, the potential users decrease. When white space is introduced as a factor, the number of potential users decreases faster as users adopt unlicensed networks earlier.

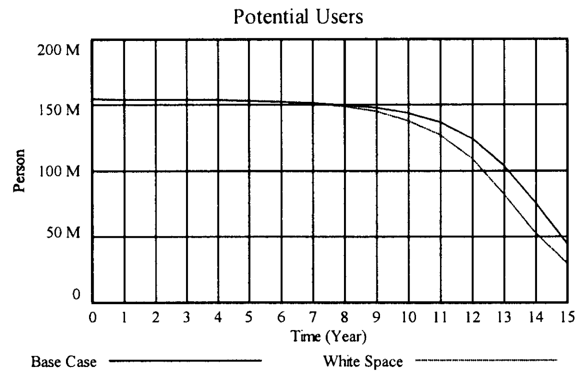

Figure 5-10: Both lines represent the stock of users that have not adopted any network, either licensed or unlicensed. The bold line represents the non-adopters stock for the base case, when no TVWS is available for unlicensed devices. The dotted line represents the non-adopters stock when TVWS is available for unlicensed use. As can be seen, the dotted line (non-adopters when TVWS is released) decreases faster, which can be translated in a faster adoption of wireless technologies.

In the next chapter, a general overview of external factors that can enhance the White Space effects on the unlicensed networks will be modeled and analyzed in order to illuminate changing circumstances that, when combined with the white space release, could affect the course of the wireless industry.

6 Factors that can enhance the Impact of TV White Space in the Wireless Industry Competition

In this section, two scenarios that can improve the potential of TVWS will be represented. First, hypothetical improvements in the TVWS technology will be implemented in the model, and interesting outputs will be shown. Second, a sensitivity analysis of the relative value of external versus internal services will show the real potential of the TVWS. The main purpose of these two studies is to find out whether the combination of white space with the development of potential external factors could be so great as to increase unlicensed adoption patterns and thus remove customers from licensed networks.

6.1 TV White Space Technology Improvement

In this section the model will be used to assess whether TVWS could reduce the infrastructure of WISPs networks to such an extent that a substantial change in the user adoptions would occur and cause a real change in the competition between licensed and unlicensed operators.

As a base case, the white space is assumed to introduce a five-fold increase in the area covered by the backhauling links in the unlicensed infrastructure. In this section a sensitivity analysis with the number of site reductions indicates how much of an improvement must be made by white space introduction to enable new unlicensed networks to capture customers from licensed networks

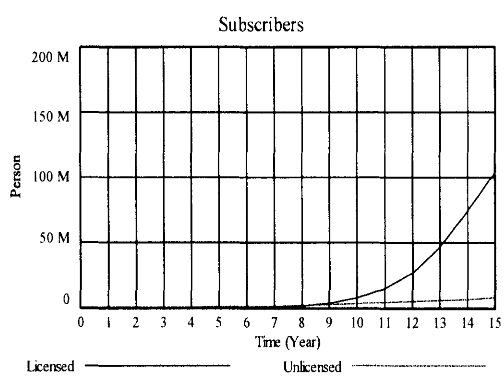

Figure 6-1: Bold line represents Subscriber Adoption of licensed networks and dotted line represents Subscriber Adoption of unlicensed networks. Both Adoptions represent the TVWS were TVWS is available for unlicensed use. The TVWS technology improves coverage in 5 times the actual unlicensed networks coverage (This is the expected range). As can be seen the adoption for unlicensed networks is really low.

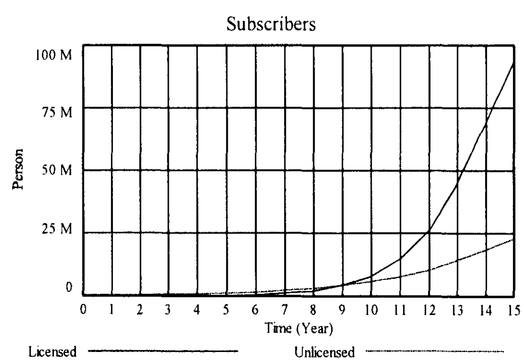

Figure 6-2: Bold line represents Subscriber Adoption of licensed networks and dotted line represents Subscriber Adoption of unlicensed networks. Both Adoptions represent the case in which TVWS technologies could improve by a factor of 10 the coverage assumed for unlicensed networks in the base case. This improvement in TVWS networks coverage is interpreted as an enhancement in the TVWS Technology. As it can be observed, if the TVWS technology improves, the adoption in unlicensed networks increases substantially compared with case assumed for TVWS. See figure 6-1

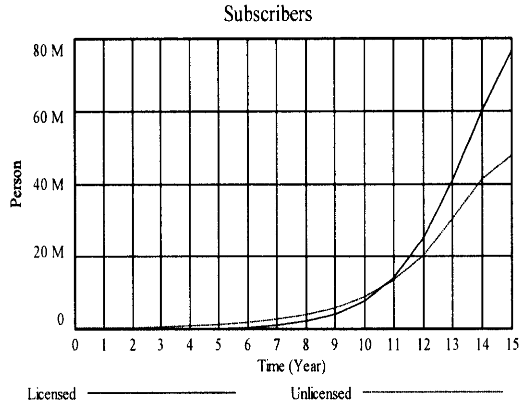

Figure 6-3:Bold line represents Subscriber Adoption of licensed networks and dotted line represents Subscriber Adoption of unlicensed networks. Both adoptions represent the case in which TVWS technologies could improve by a factor of 15 the coverage assumed for unlicensed networks in the base case. As can be observed, thanks to this technology improvement the unlicensed networks would represent a real threat for the licensed operators. Compare dotted line in this Figure, with Figure 6-1, the base TVWS case.

As can be seen, only if the TVWS technology improvement allows a reduction by fifteen-fold of the backhauling links, would the white space be a real threat to licensed networks (see Figure 6-3). User adoption will be enhanced by cost reductions enabled by the use of the white space; this, in turn, will allow lower user prices (see Figures 6-7 to 6-9), as well as improved coverage due to the better propagation features of the white space (see Figures 6-4 to 6-6).

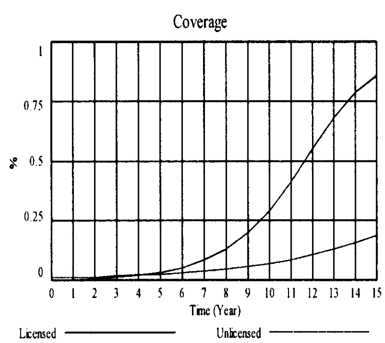

Figure 6-4: Bold line represents Coverage of licensed networks and dotted line represents Coverage of unlicensed networks. Both Coverages represent the TVWS case, were TVWS is available for unlicensed use

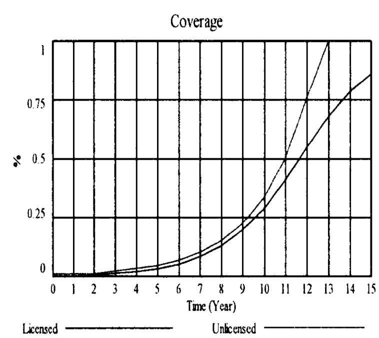

Figure 6-5: Bold line represents Coverage of licensed networks and dotted line represents Coverage of unlicensed networks. Both Coverages represent the case where TVWS technology improves by a factor of **10** the coverage, with respect to the base case.

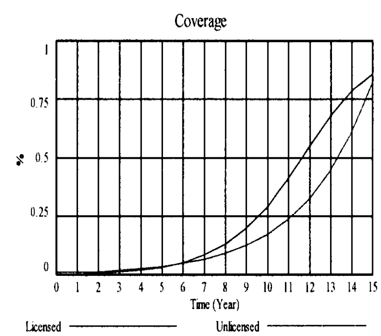

Figure 6-6: Bold line represents Coverage of licensed networks and dotted line represents Coverage of unlicensed networks. Both Coverages represent the case where TVWS technology improves by a factor of **15** the coverage, with respect to the base case.

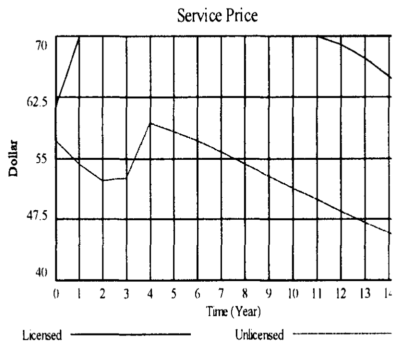

Figure 6-7: Bold line represents Service Price for licensed networks and dotted line represents Service Price of unlicensed networks. Both Service Prices represent the TVWS case, were TVWS is available for unlicensed use

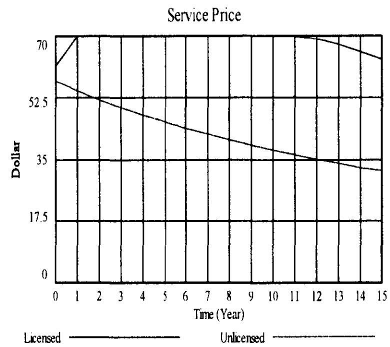

Figure 6-8: Bold line represents Service Price for licensed networks and dotted line represents Service Price of unlicensed networks. Both Service Prices represent the case where, with respect to the base case,TVWS technology improves the coverage by a factor of **10**.

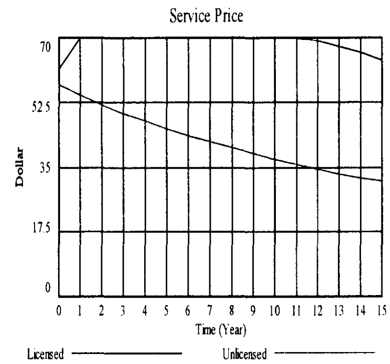

Figure 6-9: Bold line represents Service Price for licensed networks and dotted line represents Service Price of unlicensed networks. Both Service Prices represent the case where, with respect to the base case,.TVWS technology improves the coverage by a factor of **15**.

6.2 A Potential Increase in External Services Availability

This section will show how a growth of external services provided by telecom networks can enhance the business case for white space operators. First, a brief introduction about the implementation of services in the model will be provided. Then a sensitivity analysis will be performed in order to study how an increase in the external services availability can enhance the white space impact in the wireless industry licensed vs. unlicensed competition.

6.2.1 Services Implementation

The model will implement the dynamics of service generation and pricing in an access network. A very brief summary of the service implementation is provided here; however, a thorough explanation can be found in chapter 4.

- There is a variable representing service availability, which is an additional factor that influences the user adoption and network switching.
- The service availability will have two components: internal services, representing the service availability due to services generated by operators in the network, and external services, which is a subjective variable representing the level of services provided by companies which are not operators.
- The creation of new internal services will be adjusted to the excess of capacity, with a delay representing the time needed by operators to develop internal capabilities to offer the new services.
- It will be assumed that services generated internally will be adopted by existing subscribers, and this will bring to the platform an increase in the average income per customer. However, new internal services will also mean new costs. This is shown in the model as a percentage increase in the Network Management System Operating Costs.
- The sensitivity that will define the creation of services that are dependent on excess capacity will be different in both industries. It will be assumed that licensed operators, because of their greater infrastructures, will be more willing to create internal services, whereas small operators, limited by their size and capacity, will be more limited to offer external services through their basic connectivity.
- Internal Service Availability will be an endogenous variable that will depend on the internal services generated. This variable, in combination with an exogenous variable, External Service Availability, will represent the level of services offered by the two access wireless infrastructures. The external services, represented in the model as an exogenous variable, will not generate any increase in revenues or costs, but will have an impact on the attractiveness of the platform and thus to user adoption. Likewise, when the internal level of services increases, user adoption will increase.

In the next section, in order to represent the increase in the external services, different values have been assigned to the exogenous variable representing them.

6.2.2 TV White Space and External Services Dependence

In this section, a sensitivity analysis shows how the competitive advantage of licensed networks can be overtaken by a substantial improvement in the level of external services. The reason behind this is that the services availability variable has an impact in user adoption, which is dependent upon the user's elasticity to either adopt or switch to a network whose service availability has enough attractiveness. In principle, the licensed networks have an extensive advantage over the unlicensed, due to the former's high coverage and high internal service availability. However, if external service availability increases enough to have more weight in the user's decision than coverage itself, both networks will be on a par in terms of capturing customers. The figures below represent a sensitivity analysis of the external Services variable. The analysis shows that when external services grow to certain degree, the unlicensed networks will capture customers from the licensed see Figure 6-11.

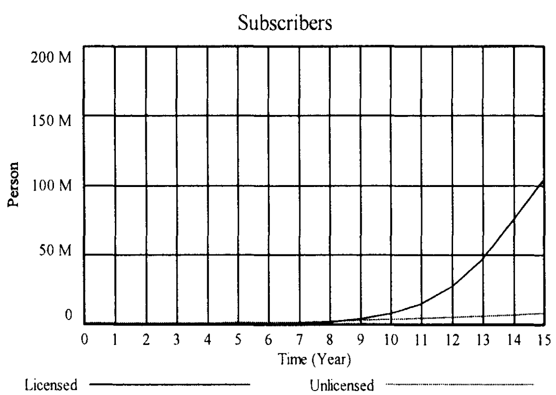

Figure 6-10 Bold line represents Subscriber Adoption of licensed networks and dotted line represents Subscriber Adoption of unlicensed networks. Both Adoptions represent the case in which TVWS is available for unlicensed use. Variable External Services corresponds to 50% (half of the total services).

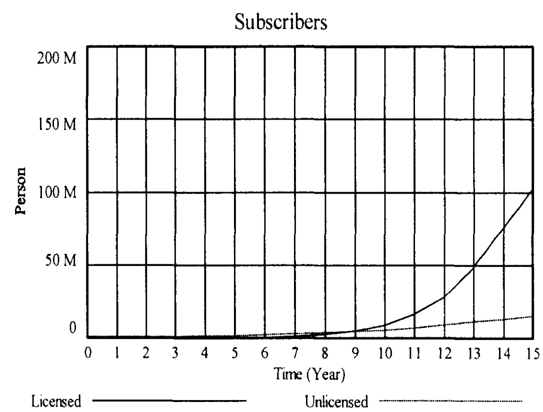

Figure 6-11 Bold line represents Subscriber Adoption of licensed networks and dotted line represents Subscriber Adoption of unlicensed networks. Both adoptions represent the case in which TVWS is available for unlicensed use. Variable External Services is increased to 100%, which corresponds to two thirds of the total services. The users for unlicensed networks increase considerably compared with Figure 6-10.

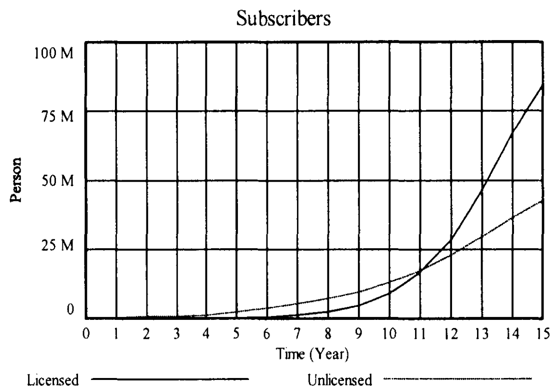

Figure 6-12 Bold line represents Subscriber Adoption of licensed networks and dotted line represents Subscriber Adoption of unlicensed networks. Both Adoptions represent the case in which TVWS is available for unlicensed use. Variable External Services is increased by 150% representing three fourth of the total generated services. If external services availability increases enough, the adoption of TVWS networks will capture customers from established operators.

6.3 Conclusions

In this section, a sensitivity analysis has shown that only a major improvement in the technology that could increase by fifteen-fold the area covered by an Access Point site in the licensed networks[53] would allow the white space to significantly change the WISPs' performance. Increased performance could improve the attractiveness of their networks and therefore increase the number of users preferring WISPs to other national licensed operators (who would obviously lose customers).

Later in this chapter, a second study about external services has shown that big national operators such as ClearWire, AT&T, or Verizon have a unique competitive advantage—coverage which makes them more attractive than WISPs networks. However, if WISPs are able to leverage a hypothetical external services growth[54] enabled by the TVWSs, then these networks will be able to better leverage their less expensive white space infrastructure and will perform better in terms of operator benefits. This will permit them to offer more affordable

[53] Although it sounds like a huge improvement, the increase in the area covered by a 5GHz cell (0.72 Square Km) by 15 (10.8 Km2) is equivalent to decrease from frequency 5GHz to 1.225 GHz according to the Hata Model. This means that the assumption of increasing the area by 15 of a TVWS Access point is physically possible since the TVWS are still lower around (50-600 MHz), however, other issues such as interferences, frequency availability and other protocol requirements make experts think that the TVWS area increase to 5GHz cells is still 5.

[54] Interview with WISP owner: Q What services would TVWS allow that you cannot provide at the moment? A: In some places where smart meters are in use, the utility has to build an entirely new network to support the communications. It would be efficient use of spectrum and equipment if the utilities could deploy a meter reading device that could communicate either through a WISPs existing network or through the customer's broadband connection. Meter reading is very low bandwidth and it is easy to do a secondary verification in the event that the traffic is lost for some reason. TVWS spectrum would be good for this because it would be less dependent on LOS, which is a problem for many unlicensed WISP deployments.

services and therefore gain more user adoptions. Given these dynamics, WISPs can become real competitors for traditional licensed access networks.

7 How can TV White Space best contribute to the Social Welfare?

Thus far in this research, the main conclusion to be drawn is that, under ordinary circumstances, white space will benefit unlicensed operators without any significant impact on licensed networks and that under extraordinary circumstances, white space can substantially benefit unlicensed networks to the detriment of the licensed. This section will propose that white space used in a cooperative scenario, in which both licensed and unlicensed operators collaborate, can be beneficial not only for incumbent and operators but also for subscribers.

7.1 TV White Space benefits in a Cooperative Scenario

Under a cooperative scenario, TVWS would provide an opportunity for Wisp operators to reach many places that cannot profitably be covered by incumbents. In other words, the Wisps would be providing a means of reaching places now generating losses for big operators.

Heretofore, a coverage-driven strategy has been assumed for licensed operators in rural areas. Some of these regions, however, are sparsely populated, which means very expensive network deployments for those licensed operators. Unlicensed networks have much more cost effective operations than their licensed counterparts and are therefore better suited for these areas. Thus, if licensed operators could confine the areas they cover to the more densely populated regions, leaving the less populated areas to the White Space operators, both industries should benefit.

To verify this assertion, the model below represents a scenario in which traditional operators and unlicensed operators accommodate each other, adopting conservative strategies. (Later in this section, the outputs of this scenario, "conservative" vs. "conservative strategies with white space", will be contrasted with the base case scenario, "coverage" versus "conservative strategies and no white space.")

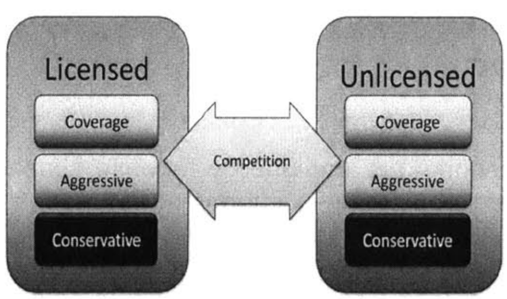

Figure 7-1: Cooperative scenario

As in chapter 5, the variables chosen for analysis represent the main modules in the model. First, Net Present Value will contrast the cost structure and financials for the actual case and the white space cooperative scenario. Then the number of subscribers is compared in order to see whether there is any substantial change in adoption patterns. Subsequently, the variable coverage highlights the network dimensioning and capacity deployment. Finally, the service price is used to represent how a cooperative could potentially benefit the user.

7.1.1 Subscribers

Figure 7-2 shows the competition output for the base case, Figure 7-3 shows the same output scenario when white space is introduced for coverage in less profitable areas. It is clear that white space operators are able to capture more customers and optimize the unlicensed networks, while, the licensed networks adoptions still remain without any substantial change.

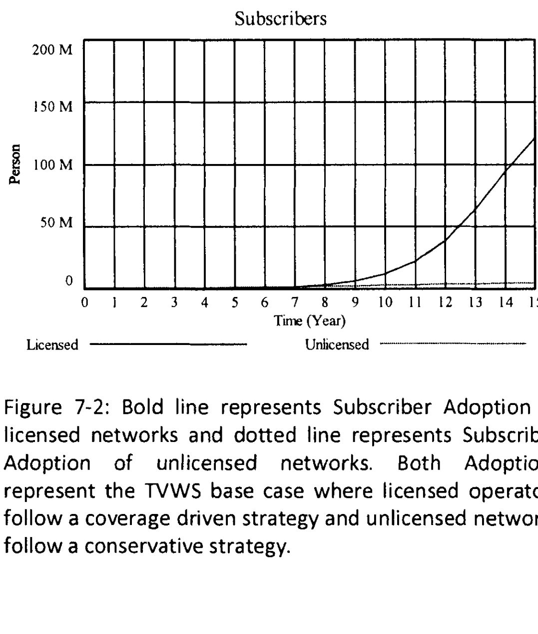

Figure 7-2: Bold line represents Subscriber Adoption of licensed networks and dotted line represents Subscriber Adoption of unlicensed networks. Both Adoptions represent the TVWS base case where licensed operators follow a coverage driven strategy and unlicensed networks follow a conservative strategy.

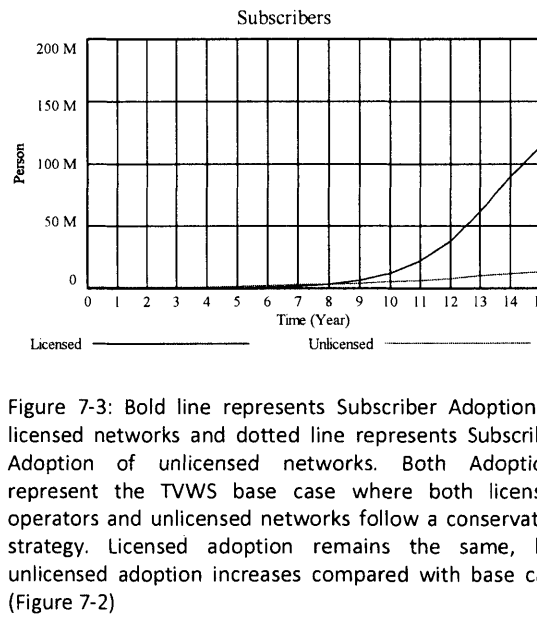

Figure 7-3: Bold line represents Subscriber Adoption of licensed networks and dotted line represents Subscriber Adoption of unlicensed networks. Both Adoptions represent the TVWS base case where both licensed operators and unlicensed networks follow a conservative strategy. Licensed adoption remains the same, but unlicensed adoption increases compared with base case (Figure 7-2)

7.1.2 Net Present Value

When unlicensed networks are equipped with white space, their business case — as well as the case for licensed operators — improves. Figure 7-5 shows how the unlicensed operators are able to offer their new customers better coverage and better prices because of an improved cost-per-customer ratio. When studying these outputs, it is especially important to note the highly positive NPV for both cases and for both operators. This can be explained by the extent of the conservative growth strategy that allows licensed operators to cover only those areas that are reliably profitable; while at the same time white space operators, with their less costly networks, are able to reach areas not profitable for their licensed counterparts.

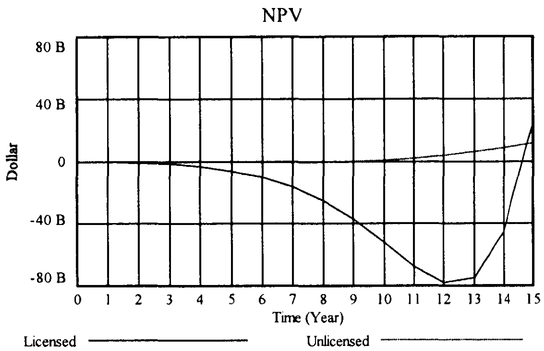

Figure 7-4: Bold line represents NPV of licensed networks and dotted line represents NPV of unlicensed networks. Both Adoptions represent the TVWS base case where licensed operators follow a coverage driven strategy and unlicensed networks follow a conservative strategy.

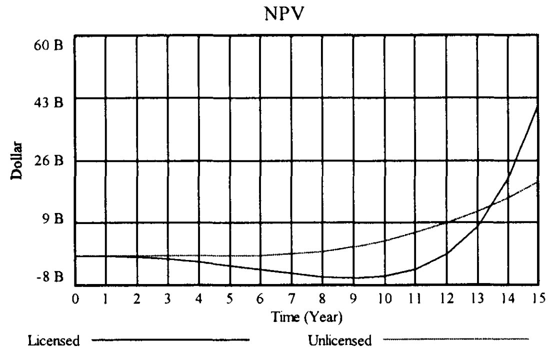

Figure 7-5: Bold line represents Subscriber Adoption of licensed networks and dotted line represents Subscriber Adoption of unlicensed networks. Both Adoptions represent the TVWS base case where both licensed operators and unlicensed networks follow a conservative strategy. The NPV value improves for both licensed and unlicensed operators.

7.1.3 Coverage

The scenario depicted in Figure 7-6 represents the base case in the wireless competition under discussion. As is shown in this figure, the licensed operators incur expenses deploying networks in places where the population density is too low to be profitable for them. But because white space enhanced unlicensed networks are able to be more cost efficient in covering low density areas, they can be profitable, provided that both licensed and unlicensed industries work to accommodate each other — meaning that more populous areas will be covered by licensed operators, while remote and low-density areas will be the realm of the white space unlicensed networks. Figure 7-7 shows the load of coverage when shared by both licensed and unlicensed industries. Any effect of lesser coverage on user adoption goes virtually unnoticed because of the positive effects of service prices and profitability for both networks.

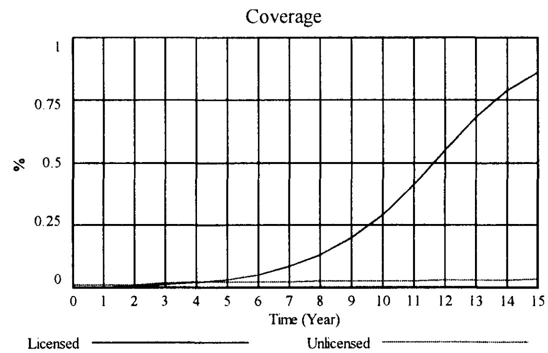

Figure 7-6: Bold line represents Coverage of licensed networks and dotted line represents Coverage of unlicensed networks. Both Adoptions represent the TVWS base case where licensed operators follow a coverage driven strategy and unlicensed networks follow a conservative strategy.

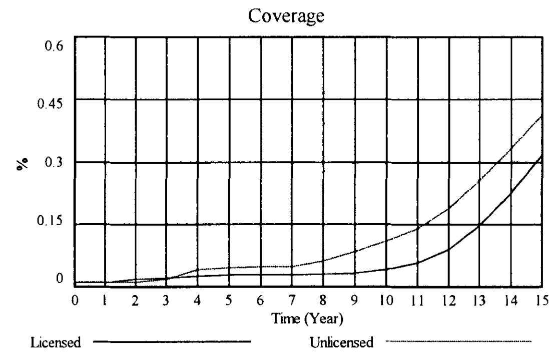

Figure 7-7: Bold line represents Coverage of licensed networks and dotted line represents Coverage of unlicensed networks. Both coverages represent the TVWS base case where both licensed operators and unlicensed networks follow a conservative strategy.

7.1.4 Service Price

In this scenario, prices reach their lowest values. The reason for this lies in the fact that the operators confine their coverage to only those areas needed by the customers as they adopt. Additionally, the coverage effort is split between the two networks, thus allowing both licensed and unlicensed networks to leverage their infrastructures more efficiently and thereby lower their service prices. Lower prices also increase adoption and therefore add to profitability.

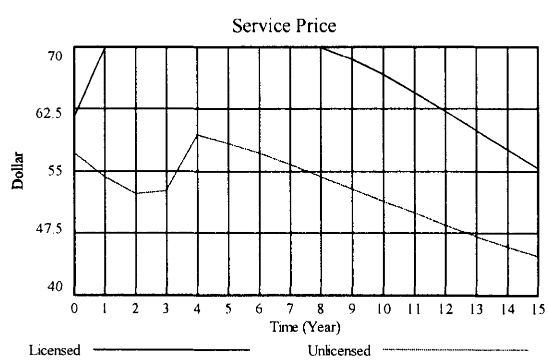

Figure 7-8: Bold line represents Service Price of licensed networks and dotted line represents Service Price of unlicensed networks. Both Service Prices represent the TVWS base case where licensed operators follow a coverage driven strategy and unlicensed networks follow a conservative strategy.

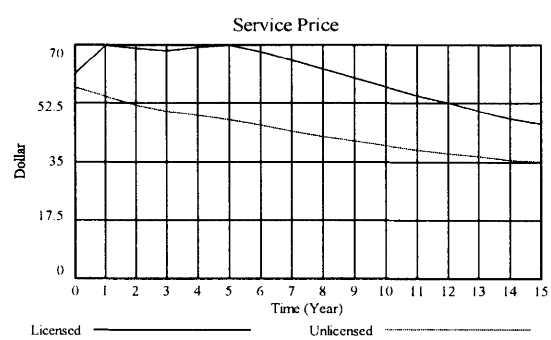

Figure 7-9: Bold line represents Service Price of licensed networks and dotted line represents Service Price of unlicensed networks. Both Service Prices represent the TVWS base case where both licensed operators and unlicensed networks follow a conservative strategy. Service prices are lower than in base case. Compare with (Figure 7-8)

7.2 Conclusions

In the scenario proposed in this section, both licensed and unlicensed networks accommodate each other so that each industry deploys networks only in those areas profitable to it. Coverage is targeted to specific demand in such a way as to optimize the potential and benefits of both networks. The social benefits of this scenario are numerous: not only are incumbent operators released from deployments in the less profitable areas, but also unlicensed operators can now reach more areas and more subscribers, which themselves in turn benefit from lower prices. In other words, the scenario in which there is an accommodation between WISPs and traditional operators represents the most positive Net Present Value for operators *and* the best prices for customers. This use of the white space would bring about a better solution for WISPs as well as the possibility of covering remote areas otherwise unprofitable for the currently existing wireless access industry.[55]

[55] Interview with Matt Larsen (Vistabeam and WISP association webpage owner)

8 Thesis Conclusions and further Research

The research makes clear that operation in the TVWS will have many challenges, primarily because the spectrum is shared, and problems such as interference, channel access, and channel availability detection will be difficult to overcome. Nevertheless, the implementation of white-space-extended Wi-Fi networks will still be truly relevant for the entire Wi-Fi industry value chain: for chip manufacturers who can see a new source of revenue in the sales of a new Wi-Fi chips feature; for Wi-Fi device manufacturers who can increase their sales by declaring a need to replace existing Wi-Fi devices; and of course for the Wi-Fi rural operators, who will improve their network profitability.

In addressing the main question of this thesis, "what is the impact of TVWS in the wireless industry?" it has been necessary to investigate how and who will implement TVWS and to create a model to study the TVWS impact. After analyzing the results of these investigations, it is evident that the TVWS *per se* will increase the adoption of unlicensed networks, but that this will not significantly impact the business of licensed networks (see Figure 8-1). It is also evident that, thanks to the white space, more people will have a connection to an access network. The thesis further demonstrates how a substantial improvement in the TVWS efficiency could change the scenario allowing unlicensed networks to capture customers from incumbent licensed networks (See Figure 8-4). While recent studies on the Wi-Fi white space spectrum efficiency have been used in exploring the topics of this research, there is no question that further research is needed in order to clarify the full nature of future white space technologies efficiencies and opportunities.

That TVWS will not significantly change the wireless access scenario but will improve unlicensed user adoption should be very useful for companies and authorities who can more fully appreciate the potential value of the liberalized spectrum and can engage in more informed speculation about how to capitalize on it. They will have seen in this study how the TVWS can become a great benefit — not only for unlicensed operators but also for incumbent licensed operators and subscribers. They will also have seen that the most effective way to maximize TVWS benefits would be a scenario in which both licensed and unlicensed operators accommodate and deploy networks in those regions that are most profitable for them. Cooperation between WISPs and traditional operators about the coverage area will improve the business case for both industries and generate the best prices for customers— but only if cooperative protocols, common databases and incumbent protection rules are put in place. Existing scenarios of cooperation between 5GHz operators are very interesting, and further research on collaboration drivers and negotiation arrangements would be very useful for applying existing knowledge to potential white space and licensed operator negotiations. Moreover, the study of existing challenges and achievements with Radar Databases in the 5GHz band would help to better deploy white spaces databases and frequency available query processes.

Finally, before politicians and companies attempt to leverage the potential of the new released spectrum with any real-world plans, they should also be aware that the access wireless industry is not isolated, and that knowledge of all the factors that can change the role/importance of the white space is crucial. A hypothetical growth in the services provided through access networks might well enhance the potential of white space unlicensed networks —something especially relevant for non-operator service providers such as Amazon, Google and Microsoft, who are continually increasing the variety of their services and could see the white space networks as a new way to reach their customers without any operator intermediary.

In light of this possibility, traditional operators like ClearWire, AT&T, and Verizon will not remain quiet — and indeed will probably try to protect their direct access to the customer, either by creating internal platforms offering internal services to enhance their benefits or by using the TVWS as traffic offload — overloading this spectrum and in this way preventing the unlicensed operators from leveraging the TVWS. Further study is needed to fully assess the impact of these possible incumbent reactions on the success of the TVWS adoption.

9 Appendix A: Additional Information for TVWS Standards

1. ECMA PHY/MAC FEATURES

1.1. PHY Layer

The Physical Layer (PHY) assumes OFDM-based waveform, and allows adaptive modulation and variable error correction to support different applications and QoS requirements [5]. Normal and burst modes are allowed to support different application types. Finally, the ECMA PHY layer supports multiple antennae that can adapt to different transmission modes. See in Table 3, a summary with the main ECMA 392 PHY Layer features.

ECMA 392 PHY Layer features	
Feature	**Characteristics**
OFDM waveform	Support for addressing multipath
128 FFT	128 subcarriers
Flexible Channel Sizes	Adapts to different TV Channel bandwidths in each area, 6,7 and 8 Mhz.
Adaptive Modulation: 3 modulations (QPSK, 16QAM, 64QAM) and 5 coding rates (1/2,	Multiple Cyclic Prefixes that allow different Channel Conditions
2/3, 3/4, 5/6,7/12)	Data Rates goes from 4.5 Mbs/s to 23.74 Mb/s with 6 Mhz and Spectral efficiency goes from 0.79 to 3.96 depending on selected modulation
Outer Code: Reed-Solomon	Provides error correction to PHY layer
Inner Code: Convolutional	Ensures robust RF link while maximizing the number of bps for each subscriber unit
Enhanced Retransmission	If a packet needs to be retransmitted, a different interleave is used on the retransmission (Ncol= 7 instead of 14)
Multiple Antennae support	Suppress interference and increase system gain.

Figure 9-1: ECMA 392 PHY Layer features

1.2. MAC Layer

The ECMA 392 was designed for different types of architectures, including: master, slave, and peer to peer. The channels access allows two access modes: Contention Based and Reservation based access. The standard specifies a toolbox approach for incumbents' protection, including Dynamic Frequency Selection (DFS), Transmit Power Control (TPC), and spectrum sensing, which may be adapted to the regulatory requirements of any specific region. Although the standard allows the protection of incumbents by an externally provided channel list, geo-location/database access is not implemented in this standard. The standard uses a beacon exchange for coordination with existing networks. See in Table 4, a summary of ECMA MAC Layer features:

ECMA 392 MAC Layer features		
Type	**Feature**	**Characteristics**
Architecture	Unified Super frame Structure	Allows burst transmission
	Different Operation Modes	Master slave and peer operation mode
Channel Access and frame processing	Support Reservation Based Access	Allows different types of reservation of devices: Hard, allows exclusive access to the medium for the reservation order; Soft, allows access but owner has preferential access; Priority Content Access, reserves time but no user has preference
	Contention Based Access	The slots for transmission are reserved by the content identifier. There are four types of content defined: Video, Voice, Best Effort and Backup
	Optimized QoS	Provides support for HDTV
Incumbent protection	Dynamic Frequency Selection	Receives input from an external measurement system or geo-locations database
	Transmission Power Control	Reduces power from 100mW to 40mW when operating in adjacent channel
Self coexistence	Super frame Merge and beaconing promotion (for slave device)	Allows different TVWS network to coexist.

Figure 9-2: ECMA 392 MAC Layer Features

2. IEEE 802.22

2.1. IEEE 802.22 Architecture

The IEEE 802.22 defines the reference architecture for networks and devices that will enable Dynamic Spectrum Access across the functions and interfaces. The scope of the protocol goes from the Base Controller Station (BSC) to the Customer Premises Equipment (CPE). The BSC-CPE Dynamic Spectrum Access provides three functions: Spectrum Sensing, Spectrum Managing and Geo-location.

The 802.22 WRAN standard architecture responds to the need for cognition that will allow the MAC/PHY air interface to be frequency agile. This agility will be used to change frequencies within the fragmented TV bands and will also avoid interference with the TV band incumbent services.

By generating awareness of multiple channels used by TV broadcasters, 802.22 WRAN will be able to discard the channels in use and select an appropriate frequency in which to work without harming incumbents.

The 802.22 architecture (see Figure 2), is defined in two planes — one defining the different interfaces and features across the OSI Layer, and the other defining a cognitive plane.

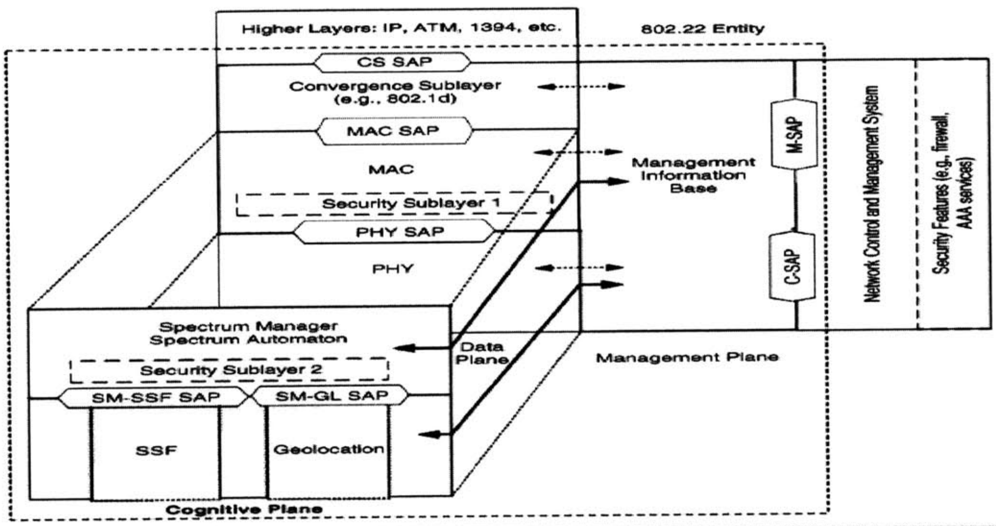

Figure 9-3: 802.22 Cognitive Architecture. Source(Bruce, 2009)

2.2. 802.22 PHY Layer

The PHY Layer uses orthogonal frequency division multiple access (OFDMA) in the air interface. 802.22 is based on the same architecture as Wimax (802.16), except for the frequency ranges, channel bandwidths, and special options[56]. The number of subcarriers is 2048, which will offer more user capacity than the ECMA standard which has only 128. Different modulations can be used according to medium conditions and the distance range extends to 100 km; in fact, the 802.22 provides several mechanisms to allow for the delay spread and the Doppler spread, thus making the standard especially robust in terms of distance coverage. Finally, the 802.22 WRAN standard requires the minimum delivered peak data rate per

[56] Often Telecom Standards offer different configuration possibilities for QoS configurations. For example in Wimax it is possible to adapt the standard to use the channels on a fix data rate basis or to a more opportunistic variable data rate.

subscriber to be 1.5 Mbps forward link and 384 Kpbs return link A summary of the main 802.22 PHY features is provided below.

802.22 PHY Layer features	
Feature	**Characteristics**
OFDM waveform	Support for addressing multipath
2048 FFT	2048 Subcarriers
Flexible Channel Sizes	Adapts to different TV Channel bandwidths in each area, 6, 7 and 8 Mhz.
Adaptive Modulation: 3 modulations (QPSK, 16QAM, 64QAM) and 4 coding rates (1/2,	Spectral efficiency adapts to different Channel Conditions from 0.76 to 3.78
2/3, 3/4, 5/6)	Data Rates
Turbo-block bit interleaver and subcarrier interleaver	Maximize the distance between adjacent samples to achieve better frequency diversity
No Multiple Antennae support	Heavy multiple antennas specs (MIMO or beam forming) are not support due to physical sizes of antenna structures at lower frequencies
Robustness to delay spread	Support wide coverage 100km.

Figure 9-4 802.22 PHY Layer features

2.3. 802.22 MAC Layer

The 802.22 Standard defines a connection-oriented MAC Layer that dynamically allocates connections and services [8]. The standard describes the way a Base Station or a terminal can initiate transmission on the channel. The Customer Premises Equipments (CPEs) must check the channels available before starting the transmission. The 802.22 considers a channel free until an incumbent is detected, and when this happens, the channel and two channels adjacent to it are determined to be busy. Once the user locates a Base Station[57], the authentication and connection setup is accomplished by using the connection setup time at the start of each frame. In the 802.22 networks, the Base Station (BS) controls all downlink traffic, and users must request uplink slots before they transmit. In addition, the BS's control of the CPEs allows them to perform measurements of existing frequencies and power in the area; therefore, a specific period is defined in the frame structure. The Base Station reserves portions of the OFDMA frame to provide a list of channels to monitor. Once all the sensing information is collected, the BS creates a revised list of occupied and unoccupied channel allocations, as well as possible channel candidates. If necessary, the Base Station can ask some of the CPES to move to other channels.

The 802.22 WRAN has a super-frame structure that provides mechanisms to support several cells working in the same channel when enough channels are available. See 802.22 MAC Layer Features below (Table 6).

[57] The checking of a Base Station is done by using the preamble sent at the start of the OFDMA frame.

ECMA 392 MAC Layer features		
Type	**Feature**	**Characteristics**
Architecture	Unified Super frame Structure	Allows burst transmission
	Different Operation Modes	Master slave and peer operation mode
Channel Access and frame processing	Support Reservation Based Access	Allows different types of reservation of devices: Hard, allows exclusive access to the medium for the reservation order; Soft, allows access but owner has preferential access; Priority Content Access, reserves time but no user has preference
	Contention Based Access	The slots for transmission are reserved by the content identifier. There are four types of content defined: Video, Voice, Best Effort and Backup
	Optimized QoS	Provides support for HDTV
Incumbent protection	Dynamic Frequency Selection	Receives input from an external measurement system or geo-locations database
	Transmission Power Control	Reduces power from 100mW to 40mW when operating in adjacent channel
Self coexistence	Super frame Merge and beaconing promotion (for slave device)	Allows different TVWS network to coexist.

Figure 9-5: ECMA 392 MAC Layer features

3. 802.11 af

3.1. PHY Layer

The PHY Layer will use orthogonal frequency division multiple access (OFDMA), in the air interface. 802.11af should be based on the same PHY specifications as Wi-Fi (802.11 y), except for the frequency ranges and channel bandwidths[58]. The number of subcarriers will be defined as in 802.11 y. The distance range and the possible data rate have not been defined yet.

[58] Information provided by Mika Kasslin.

9.1.1 MAC Layer

The access mode will be configurable to be "peer to peer" or "master-slave". Most of the 802.11 af changes will be in the MAC Layer to meet the regulatory requirements. The 802.11af will have to implement mechanisms for incumbent protection and coordination with existing networks.

10Appendix B: Main USA Mobile Market Areas and Demographics

	Area (sq mi)					Population				
MSA Name	Dense Urban	Urban	Suburban	Rural	Total	Dense Urban	Urban	Suburban	Rural	Total
Los Angeles-Long Beach, CA	282	633	479	2,456	3,850	3,378,878	3,166,396	1,915,933	567,055	9,028,263
New York, NY	193	148	349	517	1,207	3,861,026	2,213,178	1,919,806	632,997	8,627,006
Chicago, IL	144	668	1,270	3,051	5,133	1,436,715	3,341,493	2,540,975	444,793	7,763,976
Philadelphia, PA-NJ	77	406	941	2,504	3,928	774,372	2,030,719	1,881,917	360,820	5,047,827
Washington, DC-MD-VA-WV	47	504	753	5,465	6,769	470,273	2,522,419	1,505,089	215,828	4,713,610
Detroit, MI	41	516	682	2,697	3,936	414,894	2,579,807	1,022,255	367,430	4,384,386
Houston, TX	20	494	719	4,727	5,960	199,639	1,975,736	1,437,105	234,567	3,847,047
Atlanta, GA	3	321	1,566	4,319	6,210	13,858	1,292,553	1,566,312	801,377	3,674,100
Boston, MA-NH	48	249	956	845	2,097	475,887	995,560	1,433,392	318,679	3,223,519
Dallas, TX	10	369	722	5,393	6,494	102,120	1,474,084	1,082,570	470,320	3,129,094
Riverside-San Bernardino, CA	4	301	805	26,304	27,413	40,108	1,204,187	1,206,927	546,560	2,997,781
Minneapolis-St. Paul, MN-WI	13	292	600	5,445	6,350	130,069	1,166,184	899,831	642,320	2,838,403
Phoenix-Mesa, AZ	7	393	289	13,917	14,605	68,014	1,572,203	433,071	732,648	2,805,936
Nassau-Suffolk, NY	24	344	344	624	1,337	243,356	1,376,987	860,887	136,369	2,617,599
San Diego, CA	41	286	327	3,618	4,272	411,916	1,144,403	816,582	227,659	2,600,560
St. Louis, MO-IL	13	271	653	5,604	6,541	131,332	1,083,767	979,791	398,290	2,593,180
Orange County, CA	52	292	102	338	784	515,966	1,168,816	152,552	719,966	2,557,300
Pittsburgh, PA	15	210	629	3,819	4,673	148,625	838,836	944,049	479,273	2,410,783
Baltimore, MD	29	220	485	2,009	2,743	293,998	878,845	728,063	497,936	2,398,842
Cleveland-Lorain-Elyria, OH	24	229	478	2,017	2,748	243,765	914,571	716,567	382,957	2,257,860
Oakland, CA	35	224	323	884	1,465	347,740	894,006	807,674	122,664	2,172,084
Seattle-Bellevue-Everett, WA	13	250	436	3,903	4,602	131,433	999,202	653,543	301,660	2,085,839
Newark, NJ	34	161	371	1,046	1,612	337,435	806,272	741,049	85,260	1,970,016
Tampa-St. Petersburg-Clearwater, FL	4	281	415	1,800	2,500	39,695	1,123,031	623,046	159,893	1,945,665
Miami, FL	50	188	130	1,826	2,194	498,017	750,223	195,446	478,650	1,922,337
Denver, CO	7	263	208	3,268	3,746	68,355	1,051,631	519,664	256,783	1,896,432
Portland-Vancouver, OR-WA	5	217	296	4,603	5,122	54,464	866,606	444,748	417,770	1,783,588
Kansas City, MO-KS	4	208	411	4,853	5,475	37,141	830,300	616,792	237,985	1,722,217
San Jose, CA	41	146	154	961	1,301	406,758	727,868	384,565	124,843	1,644,034
Cincinnati, OH-KY-IN	10	151	425	2,807	3,393	96,350	605,475	637,140	293,365	1,632,330
San Francisco, CA	44	87	120	1,147	1,398	437,760	434,879	300,793	398,998	1,572,430
Fort Worth-Arlington, TX	1	221	304	2,455	2,981	5,967	884,908	456,316	210,060	1,557,251
Indianapolis, IN	4	156	389	2,987	3,536	38,687	623,749	584,056	277,318	1,523,810
San Antonio, TX	4	202	240	2,912	3,358	36,437	808,946	360,488	314,226	1,520,098
Sacramento, CA	4	179	250	3,850	4,283	43,440	714,708	374,887	360,984	1,494,019
Columbus, OH	9	147	288	2,722	3,166	87,712	586,843	432,461	373,908	1,480,924
Milwaukee-Waukesha, WI	21	113	314	1,053	1,502	209,003	452,981	471,669	338,751	1,472,404
Norfolk-Virginia Beach-Newport News, VA	5	172	295	1,942	2,415	54,617	689,398	442,685	259,969	1,446,670
Orlando, FL	2	152	453	3,412	4,018	15,214	607,760	678,852	115,933	1,417,758
Fort Lauderdale, FL	5	214	185	811	1,214	49,263	854,923	277,401	202,635	1,384,222
New Orleans, LA	14	104	277	6,220	6,615	143,680	416,578	415,340	370,291	1,345,889
Charlotte-Gastonia-Rock Hill, NC-SC	1	97	459	2,887	3,444	14,502	387,666	688,521	251,639	1,342,328
Bergen-Passaic, NJ	24	141	204	74	443	240,654	563,777	306,493	222,506	1,333,430
Salt Lake City-Ogden, UT	4	164	239	1,692	2,098	37,214	654,434	358,280	213,455	1,263,383
Las Vegas, NV-AZ	9	122	184	39,391	39,705	89,276	487,469	275,560	396,552	1,248,857
Buffalo-Niagara Falls, NY	16	116	200	1,270	1,602	155,828	465,230	300,140	256,476	1,177,673
Hartford, CT	7	76	389	1,242	1,714	68,527	303,587	583,743	209,551	1,165,408
Greensboro-Winston-Salem-High Point, NC	0	54	408	3,459	3,922	3,236	214,701	612,489	318,686	1,149,112

Table 10-1 Information about the main USA Markets used in the Model. Source: Wimax Certification Course (Doceotech) http://www.wimax-industry.com/sp/dct/dcthome.htm

	Area (sq mi)					Population				
MSA Name	Dense Urban	Urban	Suburban	Rural	Total	Dense Urban	Urban	Suburban	Rural	Total
Nashville, TN	2	68	424	3,639	4,133	19,538	272,479	636,064	212,456	1,140,537
Providence-Fall River-Warwick, RI-MA	11	89	286	890	1,276	108,724	355,412	429,493	219,715	1,113,344
Middlesex-Somerset-Hunterdon, NJ	5	133	261	662	1,061	46,375	531,339	392,125	137,748	1,107,587
Memphis, TN-AR-MS	3	140	204	2,694	3,042	34,856	561,681	305,450	194,209	1,096,195
Rochester, NY	7	71	294	3,102	3,474	68,984	283,094	440,883	297,211	1,090,172
Austin-San Marcos, TX	1	86	257	3,941	4,286	14,458	344,339	385,909	328,590	1,073,296
Raleigh-Durham-Chapel Hill, NC	2	77	282	3,194	3,555	22,039	306,444	422,557	293,086	1,044,126
Oklahoma City, OK	0	129	219	3,954	4,302	3,858	516,895	328,124	188,496	1,037,373
Grand Rapids-Muskegon-Holland, MI	2	73	316	2,464	2,856	21,445	292,487	474,351	242,150	1,030,434
Louisville, KY-IN	3	112	242	1,740	2,098	32,892	449,666	363,583	170,205	1,016,346
Monmouth-Ocean, NJ	2	109	322	692	1,125	18,535	436,279	482,755	58,420	995,989
Dayton-Springfield, OH	3	85	312	1,292	1,692	33,216	338,838	467,327	131,481	970,861
Richmond-Petersburg, VA	2	79	316	2,627	3,025	21,646	317,883	474,030	144,412	957,971
Jacksonville, FL	2	81	322	2,428	2,833	20,472	323,345	482,612	116,325	942,753
Greenville-Spartanburg-Anderson, SC	-	41	344	2,898	3,283	-	163,261	516,278	253,338	932,877
West Palm Beach-Boca Raton, FL	2	142	203	1,858	2,205	19,406	566,205	304,742	29,727	920,079
Birmingham, AL	1	75	252	2,911	3,239	7,474	298,445	378,165	235,665	919,749
Albany-Schenectady-Troy, NY	4	58	264	2,952	3,279	44,303	233,748	396,318	213,610	887,979
Fresno, CA	4	71	151	7,941	8,168	44,556	285,847	226,968	303,818	861,189
Tucson, AZ	-	93	144	8,958	9,195	-	371,498	216,718	185,909	774,126
Tulsa, OK	-	74	229	4,860	5,162	-	294,423	342,798	126,400	763,621
Syracuse, NY	5	45	163	3,015	3,227	45,463	180,956	244,173	278,001	748,593
Honolulu, HI	16	41	89	530	676	161,010	163,265	133,888	271,613	729,776
Omaha, NE-IA	1	87	124	2,291	2,503	7,835	349,475	186,557	158,555	702,422
Akron, OH	2	61	231	632	926	21,043	242,031	346,719	90,175	699,968
Ventura, CA	6	59	178	1,766	2,009	64,007	234,018	267,432	126,190	691,647
El Paso, TX	3	87	84	840	1,015	34,520	348,898	126,530	181,376	691,323
Albuquerque, NM	1	75	134	5,684	5,894	5,793	300,646	201,707	165,912	674,058
Knoxville, TN	0	20	279	2,229	2,529	2,824	81,785	418,526	152,885	656,020
Scranton--Wilkes-Barre--Hazleton, PA	4	49	120	2,091	2,263	40,461	194,278	179,868	223,525	638,132
Gary, IN	2	53	241	643	938	16,742	210,368	361,039	47,071	635,220
Tacoma, WA	2	65	173	1,520	1,760	21,433	260,006	260,123	91,628	633,190
Harrisburg-Lebanon-Carlisle, PA	3	50	173	1,799	2,025	31,200	199,966	258,937	132,553	622,657
Allentown-Bethlehem-Easton, PA	4	60	138	911	1,113	37,195	239,312	207,632	137,246	621,384
Toledo, OH	2	68	133	1,146	1,348	20,679	270,388	199,589	127,462	618,118
Bakersfield, CA	2	62	116	7,981	8,161	23,078	247,769	173,993	171,637	616,477
Youngstown-Warren, OH	-	60	212	1,317	1,589	-	241,155	318,254	48,584	607,993
Baton Rouge, LA	0	49	196	1,436	1,682	4	197,276	294,188	93,158	584,626
Springfield, MA	4	54	206	395	659	41,242	215,148	309,155	17,636	583,181
Wilmington-Newark, DE-MD	3	56	142	704	904	30,092	222,612	212,663	97,292	562,658
Little Rock-North Little Rock, AR	0	42	134	2,829	3,005	3,400	167,649	200,724	183,992	555,766
Ann Arbor, MI	2	36	92	1,936	2,066	15,659	145,002	138,645	255,126	554,432
Stockton-Lodi, CA	2	66	51	1,306	1,425	19,158	264,195	76,540	180,254	540,147
New Haven-Meriden, CT	3	45	218	176	443	34,701	180,885	218,358	90,463	524,406
Jersey City, NJ	15	12	16	5	48	181,929	117,280	119,606	102,339	521,155
Wichita, KS	1	56	117	2,820	2,995	13,128	225,744	175,994	105,274	520,140
Columbia, SC	1	48	186	1,296	1,532	10,244	192,498	279,341	26,571	508,654
Mcallen-Edinburg-Mission, TX	1	39	204	1,341	1,586	7,712	156,247	306,697	36,094	506,750
Worcester, MA-CT	4	32	134	713	883	37,402	128,370	200,386	136,147	502,304
Mobile, AL	1	35	142	2,845	3,023	9,420	139,285	213,432	123,809	485,947
Charleston-North Charleston, SC	1	23	198	2,350	2,571	7,718	90,798	297,185	90,128	485,829
Fort Wayne, IN	0	33	116	2,307	2,457	3,742	132,359	174,628	174,669	485,398
Colorado Springs, CO	0	55	98	1,975	2,128	1,500	221,859	146,402	113,485	483,245
Vallejo-Fairfield-Napa, CA	2	61	71	1,526	1,661	20,461	243,473	107,122	98,790	469,846

Table 10-2 Information about the main USA Markets used in the Model. Source: Wimax Certification Course (Doceotech) http://www.wimax-industry.com/sp/dct/dcthome.htm

11 Appendix C: System Dynamics Model Documentation

In this section, the System Dynamics model will be documented. The following sub-sections will first briefly describe each part of the model and then list the variables and formulas used. To better illustrate each part of the model, a graphical view will be also presented. The last section of this chapter will present the parameters used to configure the model in the different scenarios presented in this thesis.

11.1 Bass Diffusion Model

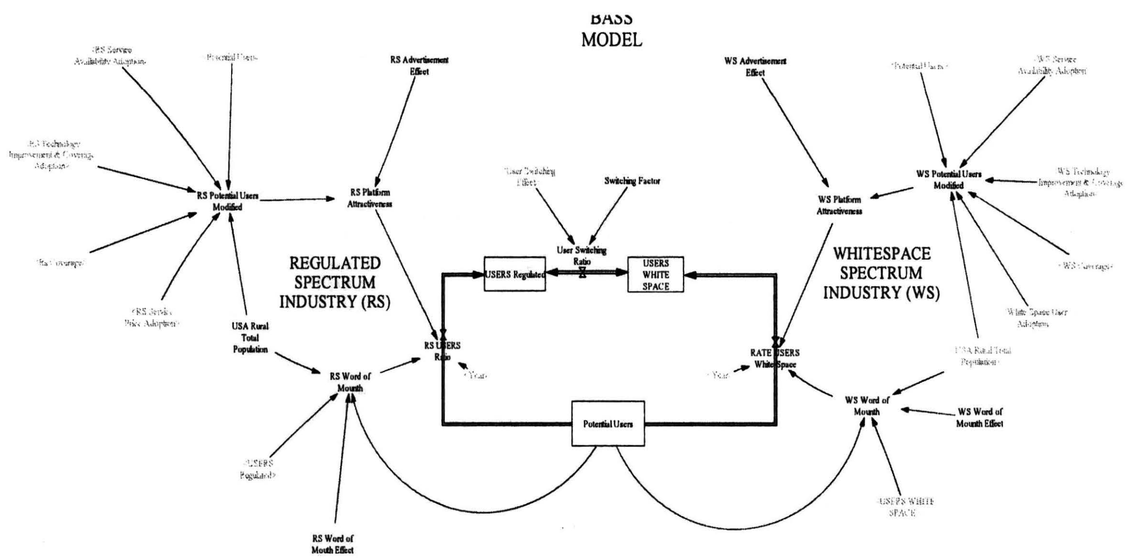

Figure 11-1: Overview of SD Bass Diffusion Model Overview

11.1.1 Bass Model Implementation

This part of the model implements two Bass Diffusion Models that represent the adoption for both types of networks, Regulated and Whitespace. The two adoption models will share the same pool of potential adopters. The heuristics implemented in the model for the network adoption have been inspired by the formulae used in Sterman (2000), page 332.

11.1.2 Bass Model Variables

Potential Users= INTEG (
-RATE USERS White Space-RS USERS Ratio,
USA Rural Total Population)
Units: Person [0,?]
Stock with Potential Users who have not adopted any network

RATE USERS White Space=
MAX((WS Platform Attractiveness+WS Word of Mounth)/Year
,0)
Units: Person/Year
This variable represents the user adoption for Whitespace
Spectrum Industry

RS Advertisement Effect=
0.008
Units: Dmnl
Advertisement Effectiveness

RS Platform Attractiveness=
MAX(0,(RS Potential Users Modified*RS Advertisement Effect))
Units: Person
Part "Adoption from Advertising" from Bass Diffusion Model
Equation

RS Potential Users Modified=
(Rs Coverage*RS Service Price Adoption*"RS Technology Improvement & Coverage Adoption"
*RS Service Availability Adoption
*(Potential Users-USA Rural Total Population*0.05))
Units: Person
The total Potential Users variable modified by effects of
Coverage, Service Availability and Technology

RS USERS Ratio=
MAX((RS Platform Attractiveness+RS Word of Mounth)/Year
,0)
Units: Person/Year
This variable represents the user adoption for Regulated
Spectrum Industry

RS Word of Mounth=
MAX(0,RS Word of Mouth Effect*((Potential Users-USA Rural Total Population
*0.05)*USERS Regulated/USA Rural Total Population))
Units: Person
Part "Adoption from Word of Mouth" from Bass Diffusion Model
Equation

RS Word of Mouth Effect=
0.94
Units: Dmnl
Word of Mouth Effectiveness

Switching Factor=
-0.001
Units: Dmnl/Year
Switch to regulate the churn rate

USA Rural Total Population=
1.54297e+008
Units: Person
Total Population assumed for the model

User Switching Ratio=
User Switching Effect*Switching Factor
Units: Person/Year
This represents flow of users changing networks

USERS Regulated= INTEG (
RS USERS Ratio-User Switching Ratio,
10000)
Units: Person
Stock with Users who have adopted Regulated Spectrum Networks

USERS WHITE SPACE= INTEG (
RATE USERS White Space+User Switching Ratio,
10000)
Units: Person
Stock with Users who have adopted Whitespace Spectrum Networks

WS Advertisement Effect=
0.102958
Units: Dmnl
Advertisement Effectiveness

WS Platform Attractiveness=
WS Advertisement Effect*WS Potential Users Modified
Units: Person
Part "Adoption from Advertising" from Bass Diffusion Model
Equation

WS Potential Users Modified=
MAX(0,(Potential Users-USA Rural Total Population*0.05)*White Space User Adoption
*WS Service Availability Adoption*WS Coverage
*"WS Technology Improvement & Coverage Adoption")

Units: Person
The total Potential Users variable modified by effects of
Coverage, Service Availability and Technology

WS Word of Mounth=
MAX(0,WS Word of Mounth Effect*(Potential Users-USA Rural Total Population
*0.05)*USERS WHITE SPACE/USA Rural Total Population
)
Units: Person
Part "Adoption from Word of Mouth" from Bass Diffusion Model
Equation

WS Word of Mounth Effect=
1e-005
Units: Dmnl
Word of Mouth Advertisement Effectiveness

11.2 Strategy and Growth Strategies

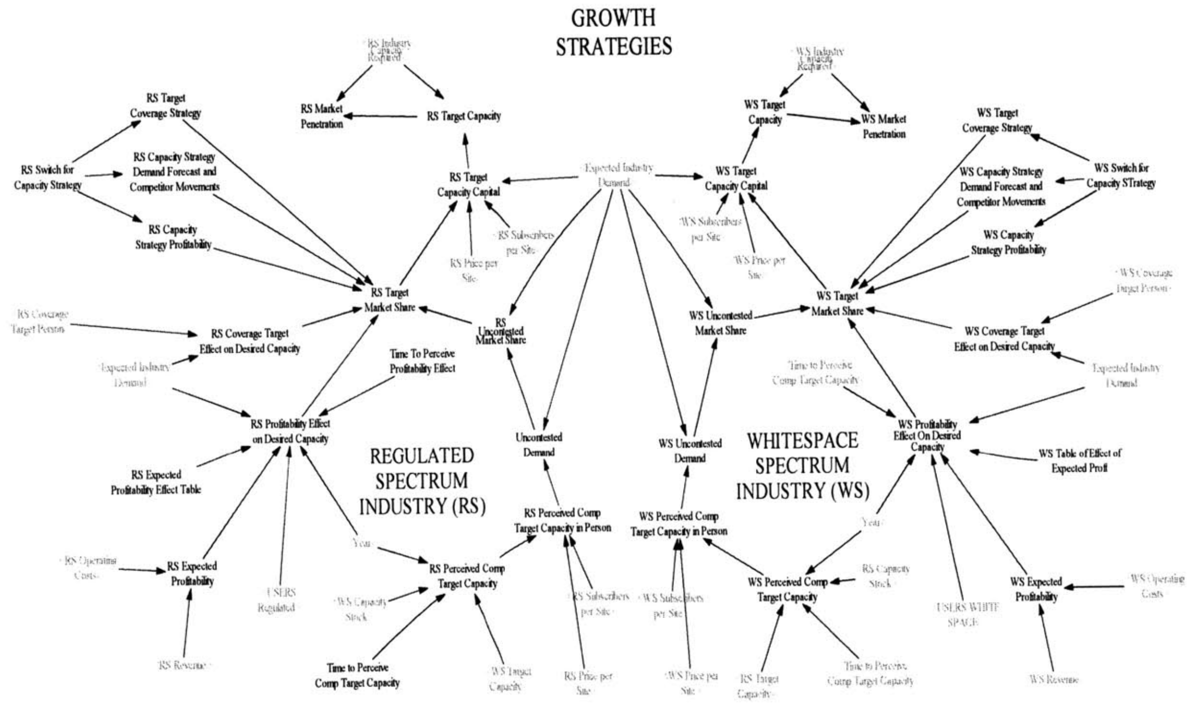

Figure 11-2: Growth Strategies SD Model Overview

11.2.1 Strategy and Growth Drivers Implementation

The growth strategy in both industries will be defined "manually" with the variable Strategy Option. The model will allow for three strategy options:

1. Coverage Strategy: Growth driven by a predefined Coverage. Strategy Option = 1
2. Aggressive Strategy: Growth driven by the coverage of uncontested demand. Strategy Option =2
3. Conservative Strategy: Growth driven by the investment of previous year revenues. Strategy Option = 3

The strategy selection will be an input parameter based on the assumptions made for each scenario in this thesis. This part of the model will calculate the operators' network capacity target for the following year for each wireless industry.

11.2.2 Strategy and Growth Drivers Variables

RS Capacity Strategy Demand Forecast and Competitor Movements=
IF THEN ELSE(RS Strategy Option=2, 1 , 0)
Units: Dmnl
Growth driver switch for capacity growth based on covering
uncontested demand. It will be activated if the strategy is
Aggressive

RS Capacity Strategy Profitability=
IF THEN ELSE(RS Strategy Option=3, 1 , 0)
Units: Dmnl
Growth driver swith for growth based on Profitability It will be
activated if the strategy is Conservative

RS Coverage Target Effect on Desired Capacity=
RS Coverage Target Person/Expected Industry Demand
Units: Dmnl

RS Expected Profitability=
IF THEN ELSE(RS Revenue=0, 0,(RS Revenue-RS Operating Costs)/RS Revenue)
Units: Dmnl
Variable representing the expected profitability. pg 808
Sterman. Long run time price - cost / cost . Effect on Desired
capacity

RS Expected Profitability Effect Table(
[(-1,0)-(1,2)],(-8,0.0263158),(-0.840979,0.114035),(-0.785933,0.131579),(-
0.688073,0.219298),(-0.559633,0.315789),(-0.400612,0.412281),(-0.278287,0.5
),(-0.192661,0.570175),(-0.149847,0.640351),(-0.0825688,0.780702),(-0.0336391
,0.877193),(0.0030581,1),(0.0642202,1.10526),(0.107034,1.19298),(0.155963,1.27193
),(0.211009,1.36842),(0.253823,1.40351),(0.308868,1.46491),(0.400612,1.53509
),(0.449541,1.5614),(0.535168,1.58772),(0.663609,1.62281),(0.737003,1.64035
),(0.828746,1.66667),(0.920489,1.68421),(0.957187,1.69298),(0.969419,1.70175
),(1,1.70175))
Units: Dmnl
Table that represents how the previous year profitability
influences/conditions capacity growth plans for next year

RS Perceived Comp Target Capacity=
SMOOTHI(WS Target Capacity,Time to Perceive Comp Target Capacity
,WS Capacity Stock/Year)
Units: Dollar/Year
Firm's perception of competitor's target capacity

RS Perceived Comp Target Capacity in Person=
(RS Perceived Comp Target Capacity/RS Price per Site)*RS Subscribers per Site
Units: Person/Year

Conversion of Estimated Competitor Capacity in Dollar to Person

RS Profitability Effect on Desired Capacity=
(SMOOTH(0.5*RS Expected Profitability Effect Table(RS Expected Profitability
)*USERS Regulated
/Expected Industry Demand,Time To Perceive Profitability Effect))/Year
Units: Dmnl
Operators will decide their desired capacity based on the last
year profitability.

RS Strategy Option=
1
Units: Dmnl
Manual Switch to set Strategy for the Regulated Spectrum. A
Coverage based strategy =1. And aggressive strategy = 2. A
conservative strategy = 3.

RS Target Capacity=
MAX(RS Target Capacity Capital,RS Industry Capacity Required)
Units: Dollar/Year
The target capacity will be the maximum between the capacity
required by the strategy and the capacity required by adoption

RS Target Capacity Capital=
((Expected Industry Demand*RS Target Market Share)/RS Subscribers per Site
)*RS Price per Site
Units: Dollar/Year

RS Target Coverage Strategy=
IF THEN ELSE(RS Strategy Option=1, 1 , 0)
Units: Dmnl
Growth driver swith for growth based on a coverage target
proposed by the opeator. It will be activated if the strategy
chosen is Coverage.

RS Target Market Share=
RS Capacity Strategy Demand Forecast and Competitor Movements*MAX(RS Uncontested
Market Share
,RS Profitability Effect on Desired Capacity)
+RS Capacity Strategy Profitability*MIN(RS Profitability Effect on Desired Capacity
,RS Uncontested Market Share)
+RS Coverage Target Effect on Desired Capacity*RS Target Coverage Strategy
Units: Dmnl
The demand forecast,adjusted by strategic considerations, used
to determine target capacity.

RS Uncontested Market Share=
Uncontested Demand/Expected Industry Demand

Units: Dmnl
The share of the market the firm expects to be unconstested
based on expected uncontested demand and forecasted industry
capacity

Time to Perceive Comp Target Capacity=
2
Units: Year
Time required to estimate competitor capacity plans

Time To Perceive Profitability Effect=
1
Units: Year

Uncontested Demand=
MAX(0.0001,Expected Industry Demand-RS Perceived Comp Target Capacity in Person
)
Units: Person/Year
Portion of expected industry demand firm believes competition is
not planning to build capacity to serve

WS Capacity Strategy Demand Forecast and Competitor Movements=
IF THEN ELSE(WS Strategy Option=2, 1 , 0)
Units: Dmnl
Growth driver swith for capacity growth based on covering
Uncontested demand. It will be activated if the strategy is
Aggressive

WS Capacity Strategy Profitability=
IF THEN ELSE(WS Strategy Option=3, 1 , 0)
Units: Dmnl
Growth driver swith for growth based on Profitability It will be
activated if the strategy is Conservative

WS Coverage Target Effect on Desired Capacity=
WS Coverage Target Person/Expected Industry Demand
Units: Dmnl
Growth driver swith for growth based on Profitability It will be
activated if the strategy is Conservative

WS Expected Profitability=
IF THEN ELSE(WS Revenue=0, 0,(WS Revenue-WS Operating Costs)/WS Revenue)
Units: Dmnl
Variable representing the expected profitability.pg 808
Sterman. Long run time price - cost / cost . Effect on Desired
capacity

WS Perceived Comp Target Capacity=

SMOOTHI(RS Target Capacity, Time to Perceive Comp Target Capacity
,RS Capacity Stock/Year)
Units: Dollar/Year
Firm's perception of competitor's target capacity

WS Perceived Comp Target Capacity in Person=
(WS Perceived Comp Target Capacity/WS Price per Site)*WS Subscribers per Site
Units: Person/Year
Conversion of Estimated Competitor Capacity in Dollar to Person

WS Profitability Effect On Desired Capacity=
(SMOOTH(0.5*WS Table of Effect of Expected Proft(WS Expected Profitability
)*USERS WHITE SPACE
/Expected Industry Demand, Time to Perceive Comp Target Capacity))/Year
Units: Dmnl
Operators will decide their desired capacity based on the last
year profitability.

WS Strategy Option=
3
Units: Dmnl

WS Table of Effect of Expected Proft(
[(-40,0)-(1,2)],(-40.982,2e-005),(-0.902141,0.0877193),(-0.847095,0.131579
),(-0.749235,0.201754),(-0.663609,0.280702),(-0.59633,0.368421),(-0.565749,
0.429825),(-0.541284,0.473684),(-0.498471,0.561404),(-0.443425,0.631579),(-
0.370031,0.701754),(-0.302752,0.77193),(-0.180428,0.877193),(-0.0825688,0.929825
),(-0.00917431,0.991228),(0,1),(0.149847,1.18421),(0.253823,1.29825),(0.394495
,1.4386),(0.529052,1.5614),(0.724771,1.68421),(1,1.7193))
Units: Dmnl
Table that represents how the previous year profitability
influences/conditions capacity growth plans for next year

WS Target Capacity=
MAX(WS Industry Capacity Required,WS Target Capacity Capital)
Units: Dollar/Year
The target capacity will be the maximum between the capacity
required by the strategy and the capacity required by adoption

WS Target Capacity Capital=
((Expected Industry Demand*WS Target Market Share)/WS Subscribers per Site
)*WS Price per Site
Units: Dollar/Year
The demand forecast, adjusted by strategic considerations, used
to determine target capacity.

WS Target Coverage Strategy=
IF THEN ELSE(WS Strategy Option=1, 1 , 0)

Units: Dmnl
Growth driver switch for growth based on a coverage target
proposed by the operator. It will be activated if the strategy
chosen is Coverage.

WS Target Market Share=
WS Capacity Strategy Demand Forecast and Competitor Movements*MAX(WS Uncontested
Market Share
,WS Profitability Effect On Desired Capacity) +
WS Capacity Strategy Profitability*MIN(WS Profitability Effect On Desired Capacity
,WS Uncontested Market Share)
+WS Target Coverage Strategy*WS Coverage Target Effect on Desired Capacity
Units: Dmnl
The demand forecast, adjusted by strategic considerations, used
to determine target capacity.

WS Uncontested Demand=
MAX(0.0001,Expected Industry Demand-WS Perceived Comp Target Capacity in Person
)
Units: Person/Year
Portion of expected industry demand firm believes competition is
not planning to build capacity to serve

WS Uncontested Market Share=
WS Uncontested Demand/Expected Industry Demand
Units: Dmnl
The share of the market the firm expects to be uncontested
based on expected uncontested demand and forecasted industry
Capacity

11.3 Adoption & Churn Rate

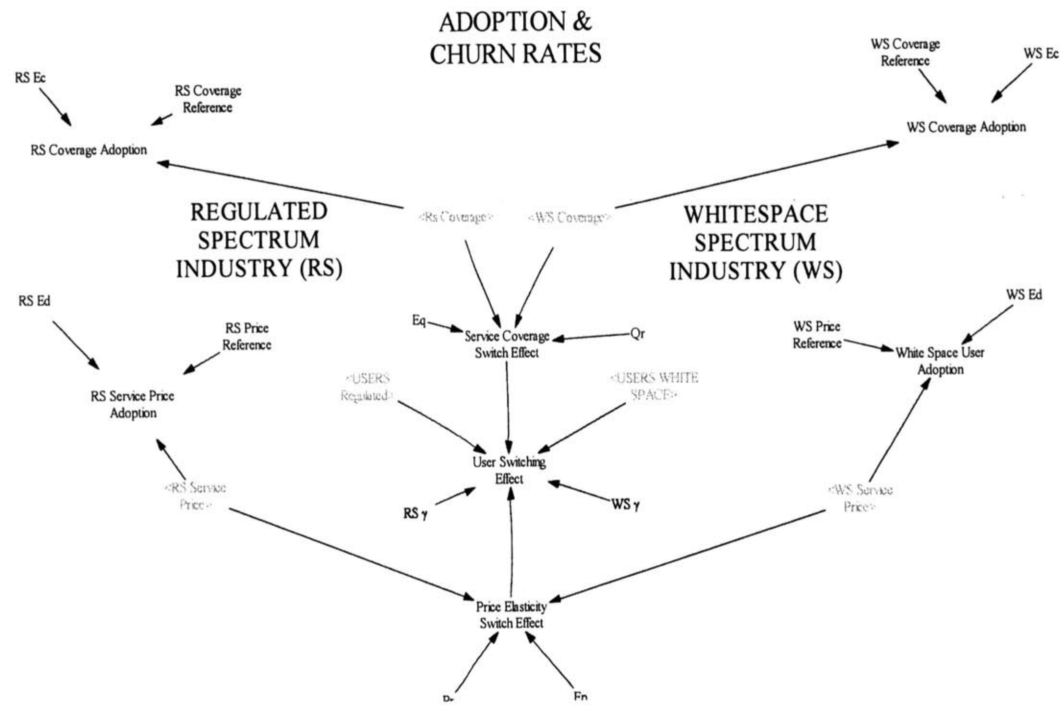

Figure 11-3: Adoption & Churn Rate SD Model Overview

11.3.1 Adoption and Churn Rate Model implementation

Each industry adoption rate will vary according to the relative industry demand. At the same time, this demand will respond to price and coverage relative to a reference representing the price and coverage of the opponent network. For simplicity, a linear demand curve is assumed. The demand curve will be normalized to generate the Reference Industry Demand at the Reference Coverage and Price. Each industry demand calculation will be applied as a variation in the Potential Available population in the Bass Equation, thus modifying the adoption rate. The model has taken as a reference the model found in Sterman (2000), page 812.

The churn rate will be determined by the attractiveness of each industry's network type relative to the attractiveness of its competitor. The formulation for churn rate must meet several criteria. First, churn rate should increase as the difference in attractiveness of the industries' networks rises, and decrease as the same difference decreases. Second, churn rate must be bounded between 0 and 100% as percentage variable that will define the part of the adopters who will decide to switch networks. Finally, when the attractiveness of both networks is equal, the churn rate must be equal to 0. A very useful formulation that meets these requirements is defined in EQ 4-16 in this thesis. This formula is inspired by the formulation for market share defined for product attractiveness in Sterman (2000), page 392.

11.3.2 Churn Rate Variables

Ep=

-0.94722

Units: Dmnl

Elasticity churn rate at the Reference Price

Eq=

-1

Units: Dmnl

Elasticity churn rate at the Reference Coverage

Pr=

40

Units: Dollar/Service

Price Reference at which there is no Churn Rate

Price Elasticity Switch Effect=

exp(Ep*RS Service Price/Pr)/exp(Ep*WS Service Price/Pr)

Units: Dmnl

Churn Rate Effect based on the difference in Prices between Regulated Spectrum and Whitespace Networks

Qr=

0.5

Units: Dmnl

Coverage Reference at which there is no Churn Rate

RS Coverage Adoption=

MAX(0,1+(RS Ec*(Rs Coverage/RS Coverage Reference-1)))

Units: Dmnl

Effect that modifies the standard Adoption Rate (defined by the standard Bass Model) based on the lack or excess of Coverage

RS Coverage Reference=

0.3

Units: Dmnl

Coverage Reference at which adoption rate is defined by the Standard Bass Model Equation

RS Ec=

0.2

Units: Dmnl

Elasticity of the Adoption at the Reference Coverage

RS Ed=

0.2
Units: Dmnl
Elasticity of Service Price at the Reference Price

RS Price Reference=
40
Units: Dollar/Service
Price Reference at which adoption rate is defined by the
Standard Bass Model Equation

RS Service Price Adoption=
MAX(0,1+(-RS Ed*(RS Service Price/RS Price Reference-1)))
Units: Dmnl
Effect that modifies the standard Adoption Rate (defined by the
standard Bass Model) based on the Service Price

RS γ=
0.8
Units: Dmnl
Variable Representing Effort to switch from Regulated Networks
to WhiteSpace Networks

Service Coverage Switch Effect=
exp(Eq*Rs Coverage/Qr)/exp(Eq*WS Coverage/Qr)
Units: Dmnl
Churn Rate Effect based on the difference in Coverage between
Regulated Spectrum and Whitespace Networks.

User Switching Effect=
(1-RS γ)*USERS Regulated*(1/Service Coverage Switch Effect)*(1/Price Elasticity Switch Effect
)-((1-WS γ)*USERS WHITE SPACE*Service Coverage Switch Effect*Price Elasticity Switch Effect
)
Units: Person
Variable that will define Churn Rate based on difference in
Price in both Regulated Spectrum and Whitespace Networks

White Space User Adoption=
MAX(0,1+(WS Ed*(WS Service Price/WS Price Reference-1)))
Units: Dmnl
Effect that modifies the standard Adoption Rate (defined by the
standard Bass Model) based on the Service Price

WS Coverage Adoption=
MAX(0,1+(WS Ec*(WS Coverage/WS Coverage Reference
-1)))
Units: Dmnl
Effect that modifies the standard Adoption Rate (defined by the
standard Bass Model) based on the lack or excess of Coverage

WS Coverage Reference=
0.3
Units: Dmnl
Coverage Reference at which adoption rate is defined by the
Standard Bass Model Equation

WS Ec=
0.2
Units: Dmnl
Elasticity of the Adoption at the Reference Coverage

WS Ed=
0.2
Units: Dmnl
Elasticity of Service Price at the Reference Price

WS Price Reference=
40
Units: Dollar/Service
Price Reference at which adoption rate is defined by the
Standard Bass Model Equation

WS γ=
0.1
Units: Dmnl
Variable Representing Effort to switch from WhiteSpace Networks
to Regulated Networks. Switch from RS to WS is more difficult due to the fact that Regulated Spectrum networks are based on Subscription models which are more suitable to retain customers than ad-hoc access models, commonly used by free spectrum (Whitespectrum) networks.

11.4 Service Price Setting Implementation

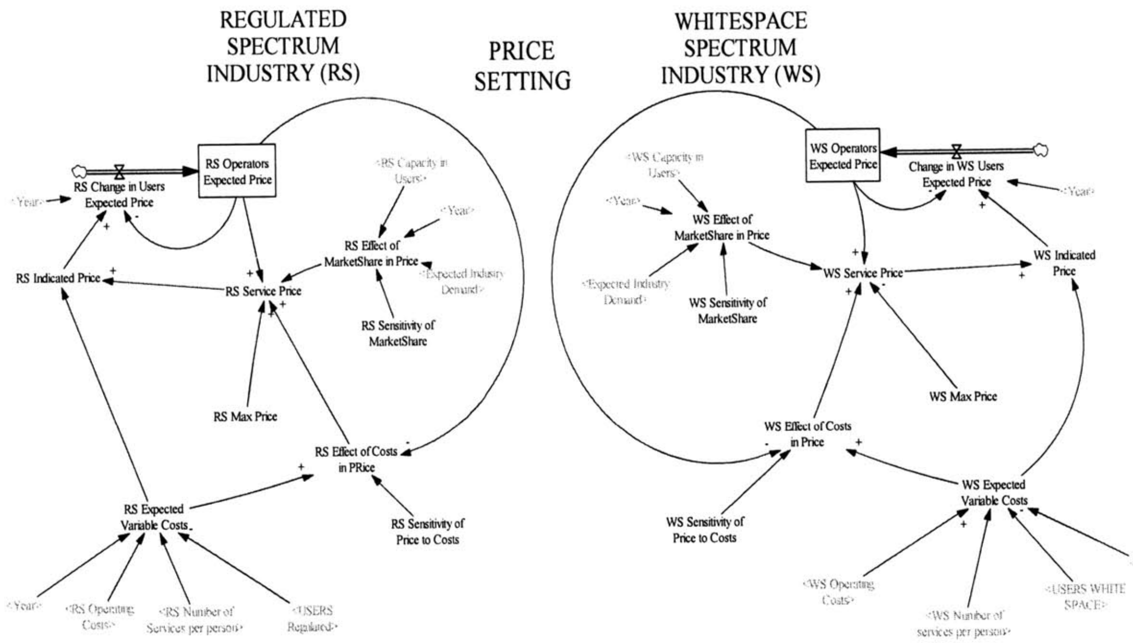

Figure 11-4: Price Setting SD Model Overview

11.4.1 Service Price Setting Implementation

For this economic model, the two network industries will offer a unique service of connectivity with a certain price that will be adjusted over time by two functions: one that will adjust the price according to the demand-and-supply balance and a second that will adjust the price according to the economies of scale in each network type. These two adjustments are represented in EQ 4-4 and have been inspired by the model used in Sterman (2000), page 814.

11.4.2 Service Price Setting Variables

Change in WS Users Expected Price=
(WS Indicated Price-WS Operators Expected Price)/Year
Units: Dollar/Service/Year

RS Change in Users Expected Price=
(RS Indicated Price-RS Operators Expected Price)/Year
Units: Dollar/Service/Year
Change in Operator Expected Price

RS Effect of Costs in PRice=
1+RS Sensitivity of Price to Costs*(RS Expected Variable Costs/RS Operators Expected Price
-1)
Units: Dmnl
Effect of Economies of Scale in Expected Price

RS Effect of MarketShare in Price=
(1+RS Sensitivity of MarketShare*(RS Capacity in Users/Expected Industry Demand
-1))/Year
Units: Dmnl
Effect in Price due to Supply and Demand balance. When Capacity
exceeds Demand price decreases, when demand exceeds capacity,
price rises.

RS Expected Variable Costs=
RS Operating Costs*Year/(USERS Regulated*RS Number of Services per person*
12)
Units: Dollar/Service
Cost of the Service

RS Indicated Price=
MAX(RS Expected Variable Costs,RS Service Price)
Units: Dollar/Service
Variable to keep price above costs

RS Max Price=
70
Units: Dollar/Service
Variable to bound the maximum service price

RS Operators Expected Price= INTEG (
RS Change in Users Expected Price,
60)
Units: Dollar/Service
Stock representing the Operator Expected Price

RS Sensitivity of MarketShare=
-1e-005
Units: Dmnl

RS Sensitivity of Price to Costs=
0.05
Units: Dmnl
Defines how the variation in costs affect the operators expected
service price

RS Service Price=

MAX(0,MIN(RS Max Price,RS Effect of Costs in PRice*RS Operators Expected Price
*RS Effect of MarketShare in Price))
Units: Dollar/Service
Expected Price that will be adjusted over the time with the
supply and demand balance and the economies of scale

WS Effect of Costs in Price=
1+WS Sensitivity of Price to Costs*(WS Expected Variable Costs/WS Operators Expected Price
-1)
Units: Dmnl
Effect of Economies of Scale in Expected Price

WS Effect of MarketShare in Price=
(1+WS Sensitivity of MarketShare*(WS Capacity in Users/Expected Industry Demand
-1))/Year
Units: Dmnl
Effect in Price due to Supply and Demand balance. When Capacity
exceeds Demand Price decreases, when demand exceeds capacity,
price rises.

WS Expected Variable Costs=
WS Operating Costs*Year/(USERS WHITE SPACE*WS Number of services per person
*12)
Units: Dollar/Service
Cost of the Service

WS Indicated Price=
MAX(WS Expected Variable Costs,WS Service Price)
Units: Dollar/Service
Variable to keep price above costs

WS Max Price=
70
Units: Dollar/Service
Variable to bound the maximum service price

WS Operators Expected Price= INTEG (
Change in WS Users Expected Price,
60)
Units: Dollar/Service

WS Sensitivity of MarketShare=
-1e-005
Units: Dmnl

WS Sensitivity of Price to Costs=
0.05
Units: Dmnl

Defines how the variation in costs affect the operators expected
service price

WS Service Price=
MAX(1,MIN(WS Max Price,WS Operators Expected Price*WS Effect of Costs in Price
*WS Effect of MarketShare in Price))
Units: Dollar/Service
Expected Price that will be adjusted over the time with the
supply and demand balance and the economies of scale

11.5 Demand Forecast Model Implementation

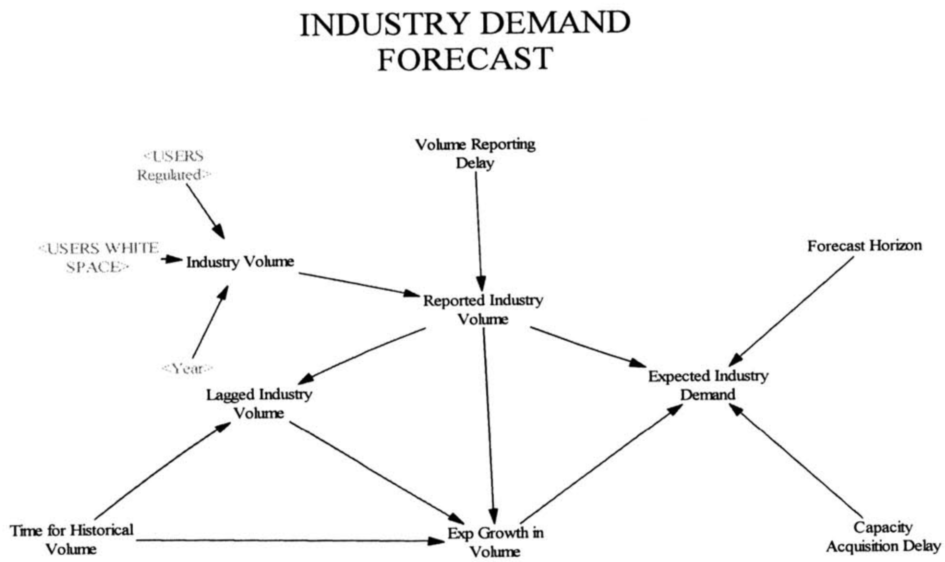

Figure 11-5: Industry Demand Forecast Implementation Overview

11.5.1 Demand Forecast Implementation

Operator aggressive strategic growth will be based on capturing the uncontested forecasted
Operator aggressive strategic growth will be based on capturing the uncontested forecasted demand. The model assumes that the firm extrapolates demand for years ahead assuming that recent growth will continue. The heuristics used and the modeling are inspired by the demand forecast formula used by Sterman and Henderson (2007), page 687. This part of the model has been adapted from the model used for the mentioned paper, which can be found at http://web.mit.edu/jsterman/www/BLC.html.

11.5.2 Demand Forecast Variable

Capacity Acquisition Delay=

1

Units: Year

The average delay in acquiring or discharging capacity

Exp Growth in Volume=

LN(Reported Industry Volume/Lagged Industry Volume)/Time for Historical Volume
Units: 1/Year
Expected growth rate in Industry Volume, based on discrete delay
(compound rate over last 1 year)

Expected Industry Demand=
Reported Industry Volume*exp(Forecast Horizon*Capacity Acquisition Delay
*Exp Growth in Volume)
Units: Person/Year
Firm's forecast of demand

Forecast Horizon=
1
Units: Dmnl
Firm's forecast horizion - how far ahead do they project demand
as a fraction of the capacity acquisition delay?

Industry Volume=
(USERS Regulated+USERS WHITE SPACE)/Year
Units: Person/Year
Estimated industry volume based in network users

Lagged Industry Volume= DELAY INFORMATION (
Reported Industry Volume,Time for Historical Volume
,Reported Industry Volume)
Units: Person/Year
Industry volume lagged by the forecast horizon used to compute
forecasted growth rate

Reported Industry Volume=
SMOOTH(Industry Volume, Volume Reporting Delay)
Units: Person/Year
Reported industry volume is actual volume delayed by the time
required for market researchers to gather and publish data

Time for Historical Volume=
1
Units: Year
Time horizon for smoothing past demand in calculating growth
rate for forecasts

Volume Reporting Delay=
1
Units: Year
Time required to gather and report information on industry volume

11.6 Capacity Estimation

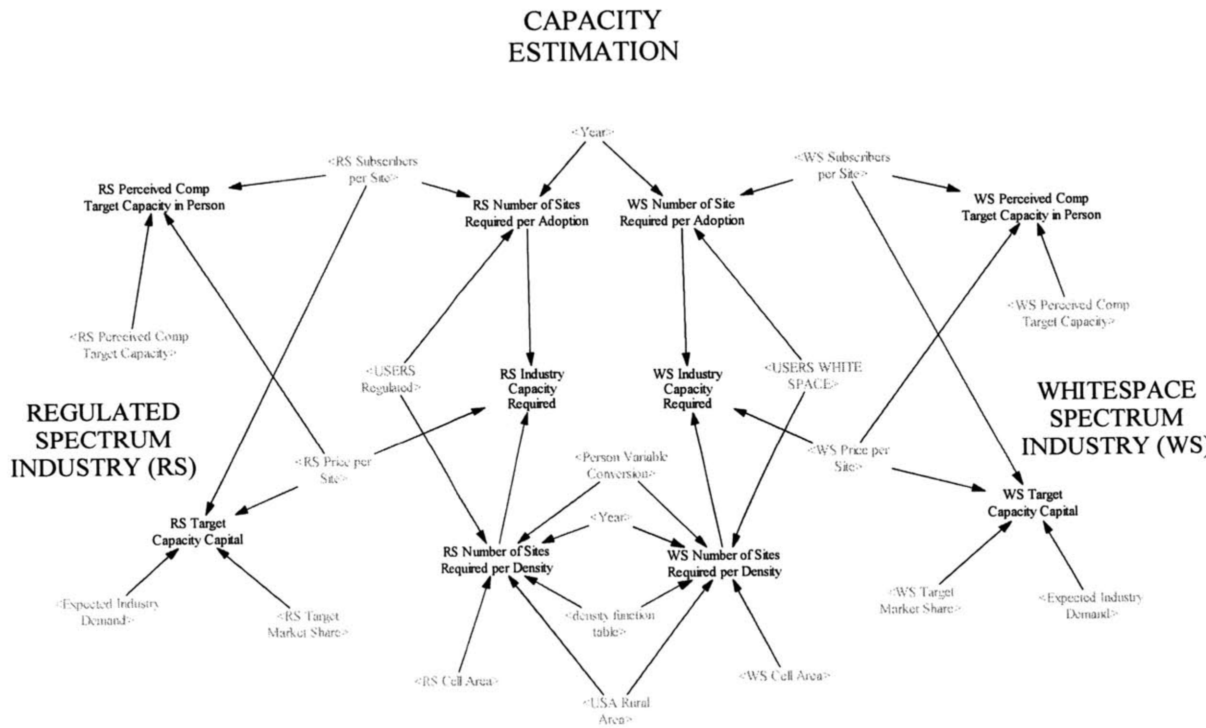

Figure 11-6: Capacity Estimation SD Model Overview

11.6.1 Capacity Estimation Implementation

This part of the model calculates the required network capacity for next year. The calculations are done taking into account the strategic and adoption requirements. Therefore, the strategic growth will define the operators' intentions based on their growth drivers and forecasted demand prospects. The adoption requirements will be derived from the number of network users (capacity required to serve a number of users) and their geographic distribution (capacity required to cover the area where those users reside).

11.6.2 Capacity Estimation Variables

RS Industry Capacity Required=

MAX(RS Number of Sites Required per Adoption,RS Number of Sites Required per

Density

)*RS Price per Site

Units: Dollar/Year

Capacity Required per Adoption in Dollar/year

RS Number of Sites Required per Adoption=
(USERS Regulated)/(RS Subscribers per Site*Year)
Units: Site/Year
Sites required to cover existing network customers/adopters

RS Number of Sites Required per Density=
((density function table(USERS Regulated*Person Variable Conversion)*USA Rural Area
)/RS Cell Area)/Year
Units: Site/Year
Capacity required to cover area ocupied by adopters

RS Perceived Comp Target Capacity in Person=
(RS Perceived Comp Target Capacity/RS Price per Site)*RS Subscribers per Site
Units: Person/Year
Conversion of Estimated Competitor Capacity in Dollar to Person

RS Target Capacity Capital=
((Expected Industry Demand*RS Target Market Share)/RS Subscribers per Site
)*RS Price per Site
Units: Dollar/Year
The demand forecast,adjusted by strategic considerations, used
to determine target capacity.

WS Industry Capacity Required=
MAX(WS Number of Site Required per Adoption,WS Number of Sites Required per Density
)*WS Price per Site
Units: Dollar/Year
Capacity Required per Adoption in Dollar/year

WS Number of Site Required per Adoption=
(USERS WHITE SPACE)/(WS Subscribers per Site*Year)
Units: Site/Year
Sites required covering existing network customers/adopters

WS Number of Sites Required per Density=
((density function table(USERS WHITE SPACE*Person Variable Conversion)*USA Rural Area
)/WS Cell Area)/Year
Units: Site/Year
Capacity required covering area occupied by adopters

WS Perceived Comp Target Capacity in Person=
(WS Perceived Comp Target Capacity/WS Price per Site)*WS Subscribers per Site
Units: Person/Year
Conversion of Estimated Competitor Capacity in Dollar to Person

WS Target Capacity Capital=

((Expected Industry Demand*WS Target Market Share)/WS Subscribers per Site
)*WS Price per Site
Units: Dollar/Year
The demand forecast, adjusted by strategic considerations, used
to determine target capacity.

11.7 Capacity Implementation

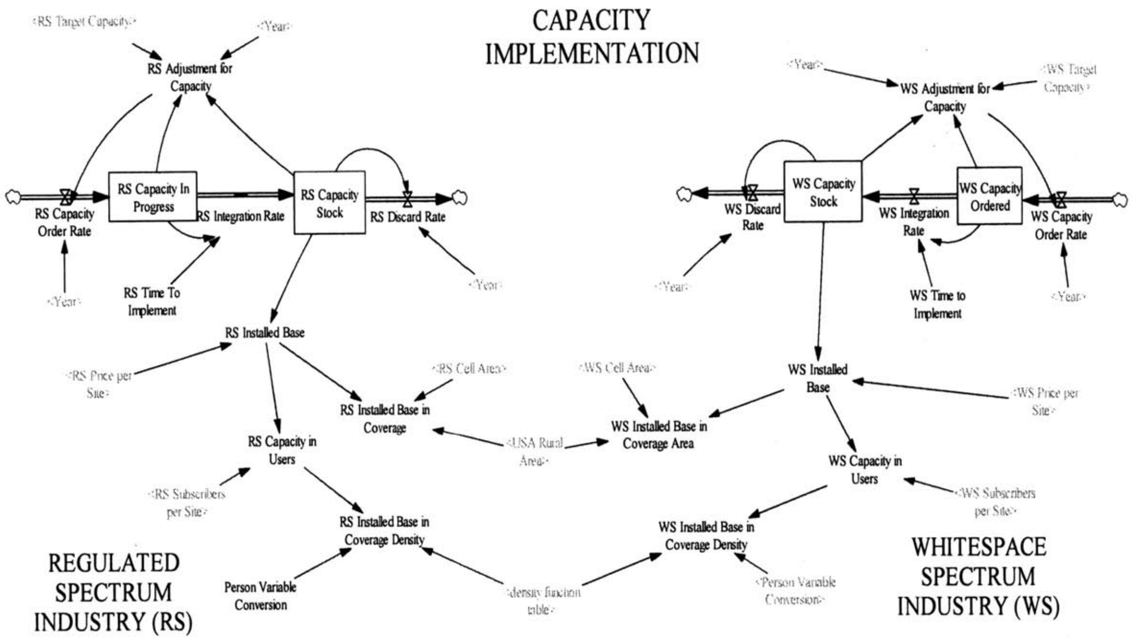

Figure 11-7 Capacity Implementation SD Model Overview

11.7.1 Capacity Implementation

This part of the model represents how the required capacity is first converted in equipment purchase orders and second implemented in the network.

11.7.2 Capacity Implementation Variables

Person Variable Conversion=
1
Units: 1/Person

RS Adjustment for Capacity=
MAX((RS Target Capacity-RS Capacity In Progress)*Year-RS Capacity Stock,0)
Units: Dollar
Capacity Delta between existing Capacity and required Capacity

RS Capacity In Progress= INTEG (
RS Capacity Order Rate-RS Integration Rate,

10000)
Units: Dollar
Ongoing Purchases

RS Capacity in Users=
RS Installed Base*RS Subscribers per Site
Units: Person
Number of Users Covered by Deployed Capacity

RS Capacity Order Rate=
MAX(RS Adjustment for Capacity,0)/Year
Units: Dollar/Year
Equipment Yearly Purchase Rate

RS Capacity Stock= INTEG (
RS Integration Rate-RS Discard Rate,
10000)
Units: Dollar
Capacity Already Available to Deliver Service

RS Discard Rate=
0.03*RS Capacity Stock/Year
Units: Dollar/Year
Obsolete/Damaged Equipment

RS Installed Base=
RS Capacity Stock/RS Price per Site
Units: Site
Number of Sites installed

RS Installed Base in Coverage=
RS Cell Area*RS Installed Base/USA Rural Area
Units: Dmnl
Coverage supplied by the installed base assuming no density
restriction

RS Installed Base in Coverage Density=
density function table(RS Capacity in Users*Person Variable Conversion)
Units: Dmnl
Coverage offered by installed base assuming capacity
restrictions by density

RS Integration Rate=
RS Capacity In Progress/RS Time To Implement
Units: Dollar/Year

RS Time To Implement=
1.5

Units: Year
Tiem to implement the Purchased equipment

WS Adjustment for Capacity=
MAX(((WS Target Capacity-WS Capacity Ordered)*Year-WS Capacity Stock),0)
Units: Dollar
Capacity Delta between existing Capacity and required Capacity

WS Capacity in Users=
WS Installed Base*WS Subscribers per Site
Units: Person
Number of Users Covered by Deployed Capacity

WS Capacity Order Rate=
WS Adjustment for Capacity/Year
Units: Dollar/Year

WS Capacity Ordered= INTEG (
WS Capacity Order Rate-WS Integration Rate,
100000)
Units: Dollar

WS Capacity Stock= INTEG (
WS Integration Rate-WS Discard Rate,
10000)
Units: Dollar

WS Discard Rate=
WS Capacity Stock*0.03/Year
Units: Dollar/Year
Obsolete/Damaged Equipment

WS Installed Base=
WS Capacity Stock/WS Price per Site
Units: Site
Number of Sites installed

WS Installed Base in Coverage Area=
(WS Installed Base*WS Cell Area)/USA Rural Area
Units: Dmnl
Coverage supplied by the installed base

WS Installed Base in Coverage Density=A FUNCTION OF(WS Installed Base in Coverage Density ,density function table, Person Variable Conversion, WS Capacity in Users)
WS Installed Base in Coverage Density=
density function table(WS Capacity in Users*Person Variable Conversion)Coverage offered by installed base assuming capacity restrictions
Units: Dmnl

Coverage offered by installed base assuming capacity restrictions by density

WS Integration Rate=
WS Capacity Ordered/WS Time to Implement
Units: Dollar/Year

WS Time to Implement=
1.5
Units: Year

density function table(
[(0,0)-(1.576e+008,1)],(1,1e-006),(77148.5,0.01),(2.16881e+007,0.171053),(4.28942e+007,0.245614),(7.32575e+007,0.355263),(1.04103e+008,0.47807),(1.27237e+008,0.592105),(1.55672e+008,0.991228),(1.776e+010,0.9935))
Units: Dmnl

11.8 Coverage

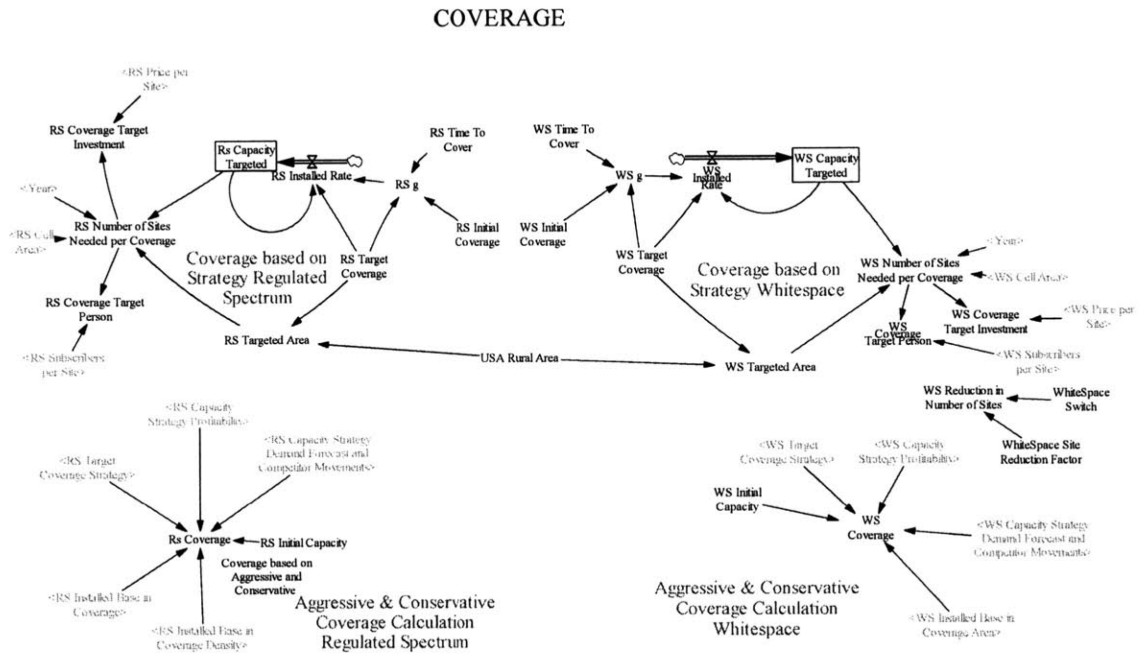

Figure 11-8: Coverage SD Model Overview

11.8.1 Coverage Implementation

This part of the model calculates the coverage assumed for each industry. For the same number of users to cover, the deployed coverage depends on the growth strategy. A coverage-based strategy drives the operators to establish a target coverage that will be deployed over time with a rate defined by a growth logistic (see red labels). For the aggressive and conservative strategies (see green label), the coverage is assumed to be based on the targeted capacity and on a Strategy Factor. For the aggressive strategy, the Strategy Factor is assumed to be bigger than for the conservative one. This heuristic is based on the assumption that the aggressive operators will strategically place their antennas to capture more customers, while conservative operators will try to place their antennas to ensure capacity.

11.8.2 Coverage Variable implementation

Rs Capacity Targeted= INTEG (
RS Installed Rate,
1)
Units: Dmnl
Stock Representing area to be covered by Coverage Strategy

Rs Coverage=

MIN(1,((RS Target Coverage Strategy*RS Installed Base in Coverage) + RS Capacity Strategy Demand Forecast and Competitor Movements
*(RS Installed Base in Coverage
+RS Initial Capacity)
+ RS Capacity Strategy Profitability*(RS Installed Base in Coverage Density
+RS Initial Capacity)))
Units: Dmnl
Regulated Industry Covered Area by Industry based on the
Strategy Growth

RS Coverage Target Investment[i]=
(RS Number of Sites Needed per Coverage*RS Price per Site)
Units: Dollar/Year
Coverage Target for Strategy 1

RS Coverage Target Person=
RS Subscribers per Site*RS Number of Sites Needed per Coverage
Units: Person/Year

RS g=
2*LN(RS Target Coverage/RS Initial Coverage-1)/RS Time To Cover
Units: 1/Years
Used to calculate logistic growth formula for Coverage Based
Strategy

RS Initial Capacity=
0.01
Units: Dmnl
Initial Capacity

RS Initial Coverage=
1
Units: Dmnl
Intial Coverage

RS Installed Rate=
RS g*Rs Capacity Targeted*(1-Rs Capacity Targeted/RS Target Coverage)
Units: 1/Year

RS Number of Sites Needed per Coverage=
(RS Targeted Area*(Rs Capacity Targeted/100)/RS Cell Area)/Year
Units: Site/Year
Number of Sites Required calculated for each Coverage Strategy

RS Target Coverage=
100
Units: Dmnl
Targeted Coverage by Strategy

RS Targeted Area=
USA Rural Area*RS Target Coverage/100
Units: km*km
Area to Cover in Km2

RS Time To Cover=
15
Units: Year
Time Set by the Strategy to Cover the Targeted Area

USA Rural Area=
919728
Units: km*km
Total Area USA

WhiteSpace Site Reduction Factor=
5
Units: Dmnl
Switch activated when Whitespace case is simulated

WhiteSpace Switch=
0
Units: Dmnl
Switch activated when Whitespace case is simulated

WS Capacity Targeted= INTEG (
WS Installed Rate,
1)
Units: Dmnl
Stock Representing area to be covered by Coverage Strategy

WS Coverage=
MIN(1,(WS Target Coverage Strategy*WS Installed Base in Coverage Area + WS Capacity Strategy Demand Forecast and Competitor Movements
*(WS Installed Base in Coverage Area
+WS Initial Capacity)
+ WS Capacity Strategy Profitability*(WS Installed Base in Coverage Area+WS Initial Capacity
)))
Units: Dmnl
Whitespace Industry Covered Area by Industry based on the
Strategy Growth

WS Coverage Target Investment=
(WS Number of Sites Needed per Coverage*WS Price per Site)
Units: Dollar/Year

WS Coverage Target Person=

WS Number of Sites Needed per Coverage*WS Subscribers per Site
Units: Person/Year

WS g=
2*LN(WS Target Coverage/WS Initial Coverage-1)/WS Time To Cover
Units: 1/Years
Used to calculate logistic growth formula for Coverage Based
Strategy

WS Initial Coverage=
1
Units: Dmnl
Intial Coverage

WS Installed Rate=
WS g*WS Capacity Targeted*(1-WS Capacity Targeted/WS Target Coverage)
Units: 1/Year

WS Number of Sites Needed per Coverage=
((WS Targeted Area*(WS Capacity Targeted/100)/WS Cell Area))/Year
Units: Site/Year
Number of Sites Required calculated for each Coverage Strategy

WS Reduction in Number of Sites=
IF THEN ELSE(WhiteSpace Switch=1, WhiteSpace Site Reduction Factor , 1)
Units: Dmnl
Reduction in the number of Site due to the WhiteSpace
introduction

WS Target Coverage=
100
Units: Dmnl
Targeted Coverage by Strategy

WS Targeted Area=
(USA Rural Area*WS Target Coverage)/100
Units: km*km
Area to Cover in Km2

WS Time To Cover=
15
Units: Year
Time Set by the Strategy to Cover the Targeted Area

11.9 Net Present Value Calculations

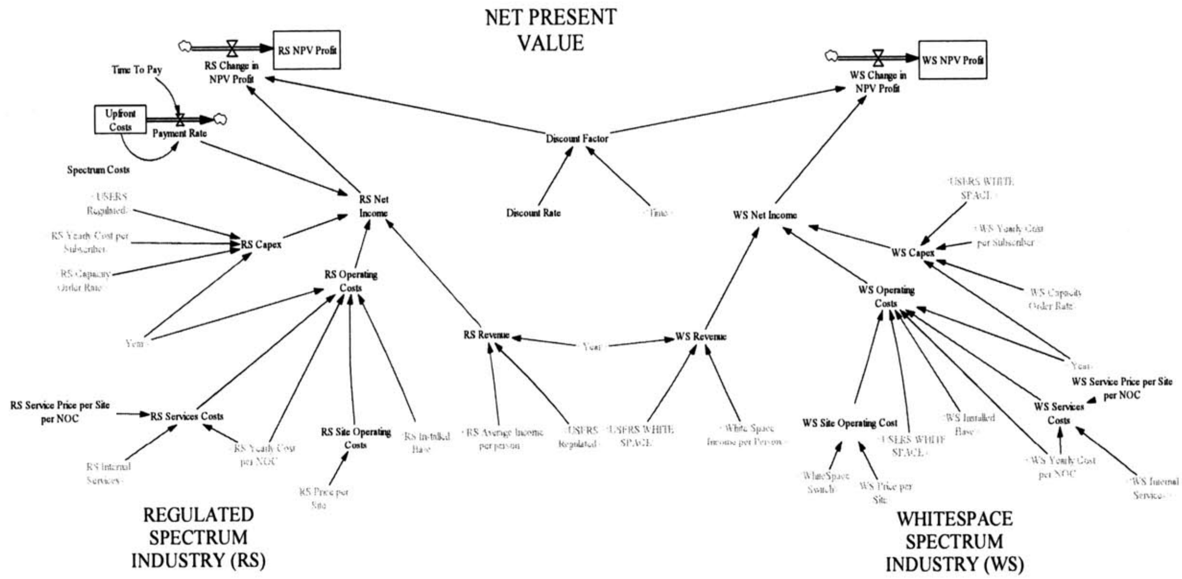

Figure 11-9: Net Present Value SD Model Overview

11.9.1 Net Present Value

The model calculates the net present value for both networks for a running model established period of fifteen years. The net present value is calculated aggregating the cumulative differences between the yearly earnings and expenses. Earnings are calculated by multiplying users per yearly amount paid per user, and the costs are calculated as the addition of the yearly operating cost per site and management systems (Opex) and the costs involved in buying equipment (Capex).

11.9.2 Net Present Value Variables

Discount Factor = exp(-Discount Rate*Time)

Units: Dmnl

The ratio of future value to present value for a cash flow, beginning at time 0 in the simulation.

Discount Rate = 0.04

Units: 1/Years [0,1]

Rate at which profit is discounted.

Payment Rate=
UpfrontCosts/Time To Pay
Units: Dollar/Year

RS Capex=
(USERS Regulated*RS Yearly Cost per Subscriber)/Year+RS Capacity Order Rate
Units: Dollar/Year
Capex Investment Rate

RS Change in NPV Profit=
RS Net Income*Discount Factor
Units: Dollar/Year
Current net income, discounted from the initial time,
accumulates into the NPV of profit over the simulation.

RS Net Income=
RS Revenue-RS Operating Costs-RS Capex-Payment Rate
Units: Dollar/Year
Net Profit per year (Revenues minus Expenses)

RS NPV Profit= INTEG (
RS Change in NPV Profit,
0)
Units: Dollar
Net Present Value of cumulative profits accumulates discounted
net income.

RS Operating Costs=
(RS Installed Base*(RS Site Operating Costs+RS Services Costs)+RS Yearly Cost per NOC
)/Year
Units: Dollar/Year
Operating Costs Rate

RS Revenue=
RS Average Income per person*12*USERS Regulated/Year
Units: Dollar/Year
Yearly Revenue

RS Service Price per Site per NOC=
0.001
Units: 1/(Service*Site)
Percentage of NOC price that will cost and extra service
implemented in each site

RS Services Costs=
IF THEN ELSE(RS Internal Services> 1, RS Yearly Cost per NOC*(RS Internal Services
*RS Service Price per Site per NOC) ,
0)

Units: Dollar/Site
Variable that defines the cost of creating more services.

RS Site Operating Costs=
RS Price per Site*0.05*12
Units: Dollar/Site
Site Operating Costs

Spectrum Costs=
3
Units: Dollar/Person

Time To Pay=
2
Units: Year
Time to pay Spectrum Costs

UpfrontCosts= INTEG (
-Payment Rate,
Spectrum Costs*USA Rural Total Population)
Units: Dollar
Remaining Debt due to upfront Spectrum Costs

WS Capex=
WS Capacity Order Rate+(USERS WHITE SPACE*WS Yearly Cost per Subscriber)/Year
Units: Dollar/Year
Capex Investment Rate

WS Change in NPV Profit=
WS Net Income*Discount Factor
Units: Dollar/Year
Current net income, discounted from the initial time,
accumulates into the NPV of profit over the simulation.

WS Net Income=
(WS Revenue-WS Operating Costs-WS Capex)
Units: Dollar/Year
Net Profit per year (Revenues minus Expenses)

WS NPV Profit= INTEG (
WS Change in NPV Profit,
0)
Units: Dollar
Net Present Value of cumulative profits accumulates discounted
net income.

WS Operating Costs=
(((WS Services Costs+WS Site Operating Cost)*WS Installed Base)+(WS Yearly Cost per NOC

)*(USERS WHITE SPACE/200))/Year
Units: Dollar/Year
Operating Costs Rate

WS Revenue=
USERS WHITE SPACE*12*White Space Income per Person/Year
Units: Dollar/Year
Yearly Revenue

WS Service Price per Site per NOC=
0.001
Units: Person/(Service*Site)
Percentage of NOC price that will cost and extra service
implemented in each site

WS Services Costs=
IF THEN ELSE(WS Internal Services> 1, WS Yearly Cost per NOC*(WS Internal Services
*WS Service Price per Site per NOC)
, 0)
Units: Dollar/Site
Costs Assumed per Generated Service

WS Site Operating Cost=
IF THEN ELSE(WhiteSpace Switch=1, 0.06*WS Price per Site*12 , 0.1*WS Price per Site
*12)
Units: Dollar/Site
Site Operating Costs

11.10 Propagation and Capacity Telecom Equipment Parameters

11.10.1 Radio Parameters used to simulate Network Capacity in Regulated Spectrum Industry

These parameters define the radiation power, frequency, and antenna properties assumed in the Regulated Spectrum networks, which will define the required infrastructure to cover a certain area.

RS Body Loss=
3
Units: Dmnl

RS Building Loss=

7
Units: Dmnl

RS Cell Area=
3.14159*RS RADIUS*RS RADIUS
Units: km*km/Site

"RS EIRP (dBm)"=
23.98
Units: Dmnl

"RS Fade Margin (dB)"=
8
Units: Dmnl

RS Path Loss=
("RS EIRP (dBm)"-"RS Rx Sensitivity (dBm)"-RS Building Loss)-RS Body Loss-"RS Fade Margin (dB)"
Units: Dmnl

RS RADIUS=
8
Units: km

"RS Rx Sensitivity (dBm)"=
-125
Units: Dmnl

11.10.2 Radio Parameters used to simulate Network Capacity in Whitespace Spectrum Industry

These parameters define the radiation power, frequency, and antenna properties assumed in the Unlicensed Spectrum networks, which will define the required infrastructure to cover a certain area.

WS Body Loss=
3
Units: Dmnl

WS Building Loss=
7
Units: Dmnl

WS Cell Area=

(3.14159*(WS RADIUS)^2)
Units: km*km/Site
(3.14159*(WS RADIUS)^2)*WS Reduction in Number of Sites/Number of Sites per Cell

"WS EIRP (dBm)"=
23.98
Units: Dmnl

"WS Fade Margin (dB)"=
8
Units: Dmnl

WS Path Loss=
("WS EIRP (dBm)"-"WS Rx Sensitivity (dBm)"-WS Building Loss)-WS Body Loss-"WS Fade Margin (dB)"
Units: Dmnl

WS RADIUS=
10.2
Units: km
Km Conversion*(10^((WS Path Loss-46.3-33.9*log(WS Carrier Frequency,10)+13.82*log(WS HAAT,10)+(1.1*log(WS Carrier Frequency,10)-0.7)*WS CPE -(1.56*log(WS Carrier Frequency,10)-0.8)-WS Correction Suburban)/(44.9-6.55*log(WS HAAT,10))))

WS Reduction in Number of Sites=
IF THEN ELSE(WhiteSpace Switch=1, WhiteSpace Site Reduction Factor , 1)
Units: **undefined**

"WS Rx Sensitivity (dBm)"=
-125
Units: Dmnl

11.10.3 Telecom Equipment Capacity Parameters

These parameters define the equipment capacity properties assumed in Regulated and Unlicensed Spectrum networks, which will define the required infrastructure to cover a certain area.

RS Price per Site=
140305
Units: Dollar/Site
Site Installation: 3000

RS Subscribers per Site=
300
Units: Person/Site

WS Price per Site=
IF THEN ELSE(WhiteSpace Switch=1, 41040 , 26734)
Units: Dollar/Site
Site Intallation 3000. Equipment (Source: 3745)

WS Reduction in Number of Sites=
IF THEN ELSE(WhiteSpace Switch=1, WhiteSpace Site Reduction Factor , 1)
Units: Dmnl
Reduction in the number of Site due to the WhiteSpace introduction
WS Subscribers per Site=
114
Units: Person/Site

11.11 Parameters used for each scenario

In this section the parameters used to configure the model for each scenario will be shown.

Model Configurable Parameters	**Figure 5-2 Dotted Line**	**Figure 5-2 Bold Line**	**Figure 5 3 Base Case**	**Figure 5 3 White Space**	**Figure 5-4 Dotted Line**	**Figure 5-4 Bold Line**	**Figure 5-5 Dotted Line**	**Figure 5-5 Bold Line**	**Figure 5-6**	**Figure 5-7**	**Figure 5-8**	**Figure 5-9**	**Figure 5- 10 Dotted**	**Figure 5- 10 Bold Line**
RS Strategy Option	1	1	1	1	1	1	1	1	1	1	1	1	1	1
WS Strategy Option	3	3	3	3	3	3	3	3	3	3	3	3	3	3
WhiteSpace Switch	0	1	0	1	1	0	1	0	0	1	0	1	1	0
WhiteSpace Site Reduction Factor	NA	5	NA	5	5	NA	5	NA	NA	5	NA	5	5	NA
External Service Availability	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA

Table 11-1: Parameters used in the Figures showed in Chapter 5

Model Configurable Parameters	Figure 6-1	Figure 6-2	Figure 6-3	Figure 6-4	Figure 6-5	Figure 6-6	Figure 6-7	Figure 6-8	Figure 6-9	Figure 6-10	Figure 6-11
RS Strategy Option	1	1	1	1	1	1	1	1	1	1	1
WS Strategy Option	3	3	3	3	3	3	3	3	3	3	3
WhiteSpace Switch	1	1	1	1	1	1	1	1	1	1	0
WhiteSpace Site Reduction Factor	5	10	15	5	10	15	5	10	15	5	5
External Service Availability	NA	NA	NA	NA	NA	NA	NA	NA	50%	100%	150%

Table 11-2: Parameters used in the Figures showed in Chapter **6**

Model Configurable Parameters	Figure 7-2	Figure 7-3	Figure 7-4	Figure 7-5	Figure 7-6	Figure 7-7	Figure 7-8
RS Strategy Option	1	1	1	1	1	1	1
WS Strategy Option	3	3	3	3	3	3	3
WhiteSpace Switch	0	1	0	1	1	0	1
WhiteSpace Site Reduction Factor	NA	5	NA	5	5	NA	5
External Service Availability	NA	NA	NA	NA	NA	NA	NA

Table 11-3: Parameters used in the Figures showed in Chapter 7

12 Appendix D: Cost Structure Calibration Details

12.1 Capex

Base Station Associated Costs

Costs associated with the antenna and Base Stations. The Base Station Cost is the one associated with equipment; the support equipment refers to the Router, Antenna, Backhaul link and other miscellaneous equipment. "Other", refers to the work invested in planning, site acquisition, license preparation, RF Design, and all the tasks required to prepare a site. The tower construction refers to construction cost of the tower and is calculated as a percentage of the real Tower construction costs. Finally, Spares refers to possible deviations and is calculated as t 10% of the previous costs.

Cost per Site	Wimax	5GHz+Wifi	5GHz+White-Fi
Base Station Cost	50.000	6.000[59]	6000
Support Equipment[60]	11.550	10800[61]	21600[62]
Other (site acq., buildout, RF design, engineering)[63]	35.200	5.200[64]	10400[65]
Tower construction (percentage allocation)[66]	30.400	3040[67]	3040
Spares[68]	13.155	1694	4104
Total	140305	26734	41040

Table 12-1: Costs per Site

Per Market Associated Costs

POP (Point of Presence) costs are associated with the expenses incurred in the construction and materials for the site preparation, BSS equipment and UPS units.

[59] Assumed 3 sector per site
[60] See Appendix
[61] Included 4 Wi-fi APs at price 2700: http://c0000934.cdn2.cloudfiles.rackspacecloud.com/wba_business_case.pdf
[62] White-Fi AP assumed to be twice the price as a normal Wifi AP. 5400 per AP and assumed 4 AP per site
[63] See Appendix
[64] Assumed 10% of Wimax costs
[65] Assumed planning for white-fi will be twice as expensive as the one for standard Wi-fi. Because height requirements and
[66] See Appendix
[67] Assumed 10% of Wimax standard costs
[68] Assumed 10 % of total previous costs

Cost per Market	Wimax	5GHz	5GHz+WhiteFi
POP	180.000	0[69]	0
NOC	330.000		
Total	510.000	0	0

Table 12-2: Cost per Market

Associated Cost per Subscriber

Costs incurred because of customer premises Customer Premises Equipment and marketing.

Cost per Subscriber	Wimax	5GHz	5GHz+White-Fi
CPE Costs	250	895[70]	895
Customer Acquisition Costs (Mktg, Sales)	375	0	0
License Costs	4	0	0
Total	629	895	895

Table 12-3: Costs per Subscriber

12.2 Opex

Monthly Operating Costs per Site

The monthly operating costs per site include the Site Lease expenses and it is assumed that all the Sites will be leased. Maintenance costs include the personnel and material-associated costs to keep the site functional. Utilities, refers to the costs associated with leasing the telecommunications network line and the electricity month consumption.

Monthly Costs per Site	Wimax	5GHz	5GHz+White-Fi
Site Lease (100% of sites leased)	4000	400[71]	400
Maintenance[72]	1096	109	109
Utilities (includes electricity and leased backhaul)	2000	200	200
Total	7096	709	709

[69] See Anaptyx http://www.awdmesh.com/hosted-managed-ubiquiti-aircontrol-server/ they offer AirControl a network management system for ubiquity for 59.99 $ per month. No setup fee.

[70]See http://www.wirelessnetworkproducts.com/5750smmotorolacanopyadvantagesubscribermodulenoresellerdiscounts.aspx

[71] Because of Antenna Size and infrastructure simplicity assumed 10% of Wimax Costs

[72] Technicians required to perform technical operations

Table 12-4: Monthly Cost per Site

Monthly Cost per POP

These costs refer to the office lease, electricity and maintenance., aswell as to the roof rights, and communications lines from the POP to the NOC and from the POP to the Internet.

Monthly Cost per POP[73]	Wimax	5GHz	5GHz+White-Fi
Total	17250	1725	1725

Table 12-5: Monthly Cost per POP

Monthly Cost per NOC

These are the costs associated with the Network Operation Center (NOC). These include the office expenses, equipment maintenance (%25 of Capex per year) and human resources expenses.

Monthly Cost per NOC	Wimax	5GHz	5GHz+White-Fi
Office Maintenance	10000	-	-
SW/HW Maintenance Costs	6875[74]	60[75]	60
24X7 Service	92500[76]	200	200[77]
Total	99375	260	260

Table 12-6: Monthly Cost per NOC

Monthly Cost per Subscriber

These costs refer to the technical service, maintenance, and support and billing and collection expenses associated with every customer.

Monthly Cost per Subscriber	Wimax	5GHz	5GHz+White-Fi
Total	10	1[78]	1

Table 12-7: Monthly Cost per Subscriber

[73] Assumed one POP per 100 sites

[74] This is the 25% percent of the total NOC costs divided by 12 0.25*330/12

[75] See Anaptyx http://www.awdmesh.com/hosted-managed-ubiquiti-aircontrol-server/ they offer AirControl a network management system for ubiquity for 59.99 $ per month. No setup fee.

[76] 11 people earning 90K/ year

[77] Monthly fee external NOC services provider http://www.inoc.com/contact/. By interview prices between 20 and 200 per device, assumed 20 $ per Site

[78] Assumed 10% of Wimax due to less expensive software and less Quality of Service.

12.3 Total Costs Summary

Total Costs	Wimax	5GHz	5GHz+White-Fi
CAPEX			
Cost per Site (Capex)	140.305	26.734	41.040
Cost per Market(NOC)	510.000	0	0
Cost per Subscriber	629	895	895
OPEX			
Monthly Cost per POP+Site	8821(Approx 5 % Site Capex)[79]	881 (Approx 10% Cost per Site Capex)	881 Approx 6% Cost per Site Capex)
Yearly Cost per Noc[80]	11.952.500 (Aprox 80 times Site Capex)[81]	3120 (Approx 12% Cost per Site Capex)	3120(Approx 8% Cost per Site Capex)

Figure 12-1: Table with Costs Summary

[79] Monthly NOC Costs*12. 1192500 Assumed SiteCost*80 NOC Capex will not be included in the model.
[80] It will be assumed

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