CAN CITYWIDE MUNICIPAL WIFI BE A FEASIBLE SOLUTION FOR LOCAL BROADBAND ACCESS IN THE US?

AN EMPIRICAL EVALUATION OF A TECHNO-ECONOMIC MODEL

Ph.D. Dissertation

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Submitted to the Graduate Faculty of

the Department of Information Science and Telecommunications in

partial fulfillment

of the requirements for the degree of

Doctor of Philosophy

University of Pittsburgh

2008

UNIVERSITY OF PITTSBURGH

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University of Pittsburgh 2008

Citywide wireless fidelity (WiFi) offers an opportunity for municipalities and BISPs to break through the duopoly broadband market structure that is prevalent in the US. Although municipal WiFi offers low deployment cost, short building time, high capacity, and wide coverage, the competition from the local broadband market makes it difficult to be self–sustainable from public Internet access revenues. Therefore, it is interesting and useful not only to discuss the demographic features of existing WiFi projects but also to evaluate what is necessary for them to be economically sustainable. We propose to study these questions by building a techno-economic model to determine features, sustainability, and necessary subsidy of citywide WiFi for local broadband access. We evaluate this model with data from several existing projects.

In order to gain insight from previous experience and to evaluate the feasibility of citywide WiFi, we carried this research out in three steps. The first, we undertook a systematic study to analyze all existing and operating citywide WiFi projects in the US. We were interested in identifying what key geo-demographic differences exist between WiFi cities and non-WiFi cities, and how private ISPs and municipalities implemented citywide projects with various business models and strategies. Next, we built a model linking access point density and network coverage, and used this to build a techno-economic model of municipal WiFi. Finally, we evaluated the effectiveness of the model using existing projects identified in the empirical study and determined how much subsidy could be reasonable from municipality to make WiFi projects sustainable. The outcome of this research is designed to assist policy makers, municipalities, and WiFi ISPs in evaluating, designing and implementing a sustainable project.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

ACKNOWLEDGEMENTS

This dissertation would never have been possible without support from people too many to name. However, I would like to thank the following.

I would like thank to my adviser Dr. Weiss for his guidance, invaluable advice, moral support, and motivation for timely completion of the work. His caring and wonderful personality to encourage me during difficult times in my research kept me going. I am also very grateful to Dr. Thompson, Dr. Krishnamurthy, and Dr. Tomer of University of Pittsburgh and Dr. Bauer of the Michigan State University for their assistance and moral support throughout the course of this work.

I am thankful for the Telecommunication Program of the School of Information Science of University of Pittsburgh and the Ministry of Education of Taiwan for giving me the opportunity and financial assistance to pursue the Ph.D. program.

Finally, I express my deepest gratitude for my wife and son for the emotional, financial and nutritional support. Without their continuous support and encouragement, this work would not have been accomplished.

1.0 INTRODUCTION

Citywide WiFi with its low deployment cost, short building time and high capacity is an appealing approach for improving municipal effectiveness, providing a hospitable environment for businesses, addressing the broadband digital divide, and presenting a potential “third pipe”. However, the mixed results of existing projects have provided limited guidance for further development. For example, the Lompoc project suffers from low subscription numbers, the stock price of the wireless internet service provider (WISP) Mobile Pro has been languishing, and EarthLink was forced to reveal unfavorable operating results and withdraw from its municipal WiFi projects. [1],[2],[3] Articles in BusinessWeek and the Wall Street Journal highlighted these uncertainties.[4],[5] On the other hand, St. Cloud’s and Google’s Mountain View municipal WiFi systems have won praises through their free citywide public access, and Wireless Minneapolis has shown positive cash flow.[6],[7], [8]

According to information from muniwireless.com, there are over 400 municipalities have evaluated or engaged in wireless projects for internal or external broadband access.[9] Why did WiFi become a prominent solution for local broadband access in the US? This chapter provides a brief background of the broadband market status and driving forces, with leads to the motivation and problem statement that guides this dissertation proposal.

1.1 BACKGROUND

1.1.1 Macro perspective: Broadband market structure, coverage, and penetration rates in the US

This section provides a brief macro-perspective to explain why municipal involvement may be necessary to spur local broadband access. The duopoly market structure of the broadband market in the US has not led to pervasive broadband coverage and satisfying penetration rates on par with our major trading partners. Though asymmetric digital subscriber line (ADSL) and cable modems operators have been upgrading their networks to increase transmission rates and extend service coverage for a few years, the broadband coverage for both services, compared with other developed countries are not considered satisfactory.[10]

Figure 1:1 shows that DSL and Cable Modems have been competing in each other's territory by expanding their network from 2000 to 2003. There have been, however, very few cases of broadband deployment in the area where there was no broadband service since 2000. It is clear that Cable and DSL service providers have adopted a strategy of offering broadband service only in profitable areas.

According to data from the Organization for Economic Co-operation and Development's (OECD) Broadband Portal in Dec 2007, the broadband penetration rate of the US lags behind other developed countries, ranking 15 out of the 30 member states. (Figure 1:2) Municipalities, who face competition from around the globe have a clear motivation to get involved in broadband provisioning to create and secure local jobs, enhancing education, quality of life, and narrowing the so-called digital divide.

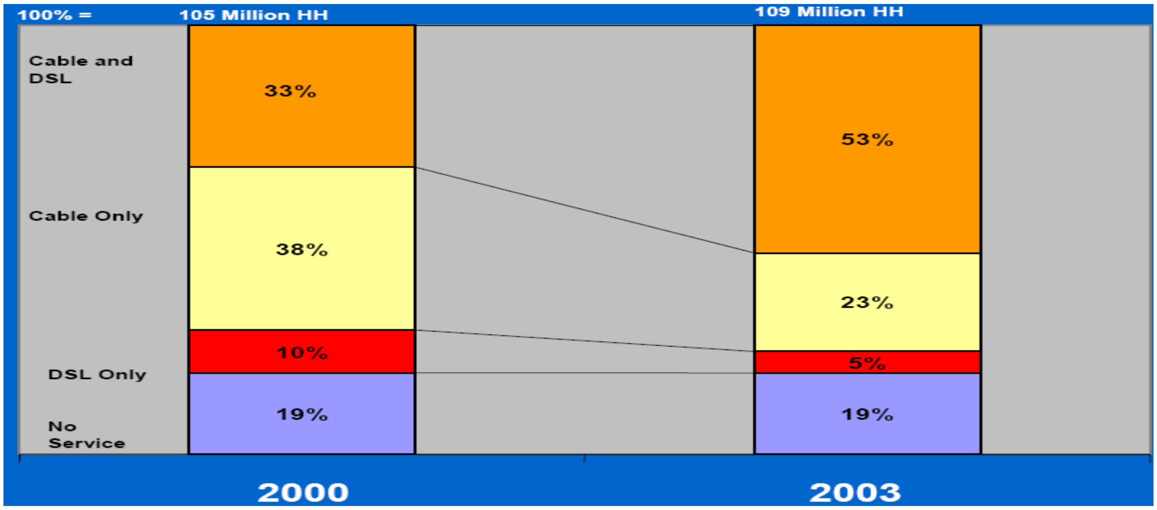

Figure 1:1 Overlap between DSL and Cable broadband in 2000 and 2003

Source: [11]

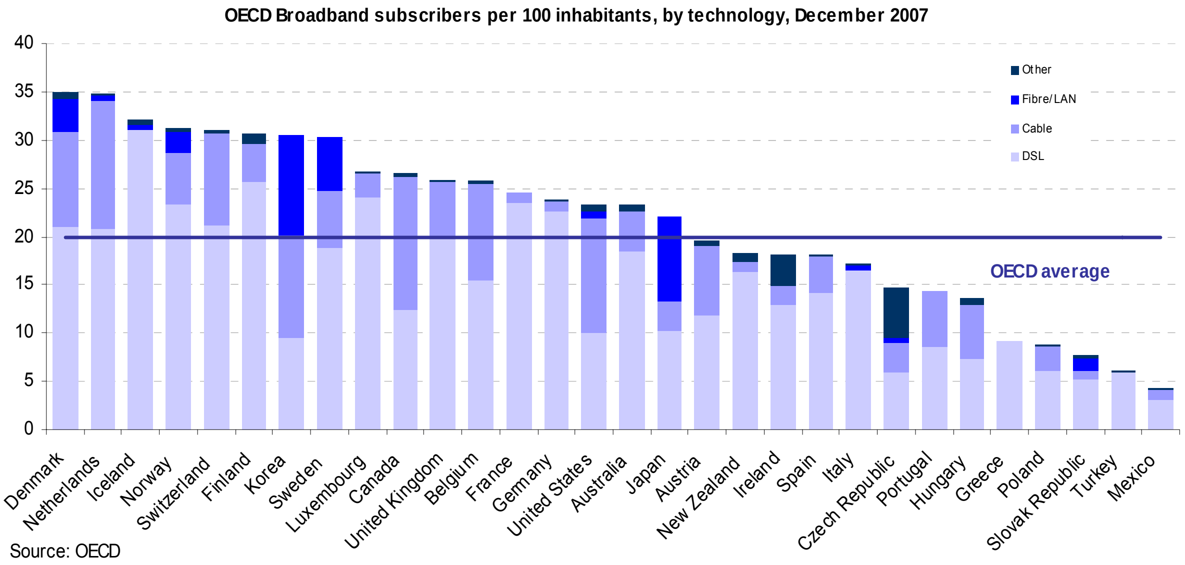

Figure 1:2 Broadband penetration rates of OECD Dec 2007

Source: [10]

1.1.2 Micro perspective: Driving forces for implementing municipal broadband

In general, the objective of elected municipal decision makers is to maximize the welfare of municipal residents. There are three reasons why municipal broadband implementation can contribute to the welfare of municipal residents. First, broadband stimulates municipal economic development. According to Lehr, Osorio, Gillett and Sirbu's measure of broadband's economic impact,[12]

> …between 1998 and 2002, communities in which mass-market broadband was available by December 1999 experienced more rapid growth in (1) employment, (2) the number of businesses overall, and (3) businesses in IT-intensive sectors. In addition, the effect of broadband availability by 1999 can be observed in higher market rates for rental housing in 2000.

Gillett, Lehr and Osorio (2004) offer a second reason why broadband is beneficial to municipal residents: the municipal broadband means a new source of revenue based on an expansion of the existing utility infrastructure (electricity, cable TV, gas or telephone). [13] WiFi provides an avenue for a municipality to enter the broadband market. The third reason why municipal broadband improves the welfare of municipal residents is that most municipal residents are users or potential users of broadband services

1.1.3 The trend of municipal WiFi development

From a historical perspective, municipal WiFi may be treated as a successor to municipal fiber. According to Balhoff and Rowe's survey from the late 1990's to 2005 "approximately 23 municipally-sponsored fiber networks providing commercial telecommunication services in the US".[14] Even though a fiber optics network can offer high transmission capacity and is regarded as a future-proof technology, its high construction cost makes municipal fiber network risky and thus deters its proliferation. On the other hand, WiFi has low deployment cost and uses unlicensed spectrum along with widely adopted WiFi enabled devices. Muniwireless.com's 2004 report identified only 58 municipal wireless deployments in the US as of mid-2004; this number doubled in its 2005 report.[15],[16] Fleishman estimated that almost 200 municipalities have announced plans for a citywide wireless network in 2006 and the Wireless Internet Institute reported "about 300 early adopters have formulated municipal broadband projects in 2007". [17], [18]

Owing to the great potential of citywide WiFi, participants include not only municipalities but also BISPs. Originally, municipalities had to undertake the financial responsibilities of network construction and operation. BISPs were eager to join citywide municipal WiFi projects and willing to bear the uncertainty and take on investment risks. EarthLink, MetroFi and MobilePro were the three main WiFi ISPs. They cooperated with local governments on eleven, nine and five municipal WiFi projects, respectively. However, subscription rates were below expectations, which forced these major players to adjust their business strategies to survive. EarthLink withdrew from San Francisco, Chicago, Houston and Philadelphia. Similarly, MetroFi deferred its network construction and required municipality to act as the anchor tenant. Without positive response from the city of Portland, MetroFi may find it necessary to shutdown its Portland WiFi network. Finally, MobilPro has sold its Arizona WiFi projects to Gobility Inc.[19],[20] The roller coaster experience of citywide WiFi shows that the citywide WiFi projects with no financial responsibilities on the part of municipalities no long exist. However, it is to soon to draw the conclusion that WiFi projects are dead. If we take a look at the cases of Minneapolis and Riverside, we see that projects with anchor tenancy model are operating smoothly and that several cities are using this business model to bring up WiFi networks for public safety and public access. The important issue for citywide WiFi is shifting from selecting a suitable business model, but to determining a reasonable subsidy for the network as its anchor tenant.

1.2 MOTIVATION

During 2004 to 2007, municipal wireless experienced rising deployments proliferated in the United States. Several hundred local governments have evaluated or were engaged in the deployment of wireless technology for internal or external usages. When approaching this research area, some questions that come to mind are: Who has constructed and operated municipal WiFi at the citywide scale for public access? In addition, what distinguishes these cities from those that have not constructed or operated this network?

The disappointing news that a major ISP, EarthLink, withdrew from several noteworthy WiFi projects in Aug 2007 and that the shutdown Philadelphia projects was expected in June 12 2008, exposed the risks of citywide WiFi. It has slowed down the investments in municipal WiFi from private sector and ended the possibility of citywide WiFi projects with no financial commitment from the municipalities.

How could this prominent technology with its many advantages become infeasible so quickly? If subscription rates were over-estimated, then more accurate estimates of actual network coverage and a better understanding of the price differences between WiFi service and existing Internet services are necessary. If the construction cost was under-estimated, it is important to evaluate access point (AP) density is necessary to provide reliable WiFi services, since the costs of APs can occupy over 50% of total construction cost and affect network coverage considerably.[21],[22]

Therefore, we plan not only to analyze existing projects but also to evaluate the feasibility of citywide WiFi from technical and economic perspectives. In addition, we will apply data from existing projects into the techno-economic model to evaluate it. In addition, our model can evaluate a reasonable subsidy for municipalities and ISPS to build sustainable WiFi projects. Our goal is to perform an integrated study of existing projects and to build a simulated model that will capture the key features of citywide municipal WiFi to assist policy makers in project design.

1.3 PROBLEM STATEMENT

The theme of this dissertation is to evaluate whether citywide municipal WiFi is a feasible solution for local broadband access in the United States. With hundreds of municipal wireless projects throughout the United States, there are no uniform criteria to decide which cities can be treated as having citywide municipal WiFi. Thus, the first part of the task is to identify who can be considered to have has implemented citywide WiFi, what the municipal roles and business models are and what the key differences between WiFi cities and non-WiFi cities are.

The next part is to build an appropriate model to evaluate the sustainability of WiFi projects, because we have not found a suitable model to assess citywide WiFi from both the engineering and economic perspectives. The first step in this is to understand the relationship between access point (AP) density and WiFi network coverage. The second step is to build an assessment model.

The last part is to verify the effectiveness of the model and to compute a reasonable subsidy to assist the deployment of sustainable citywide WiFi projects. The outcome of this dissertation should aid municipalities and BISPs to evaluate the feasibility of WiFi project and to compute reasonable subsidy levels for these projects.

1.4 DISSERTATION OUTLINE

The reminder of this dissertation is organized as follows: Chapter 2 presents an overview of citywide WiFi development including regulations and policy, SWOT analysis and classification of citywide WiFi users. Chapter 3 illustrates technical issues of a two-layer citywide WiFi network structure. Chapter 4 elaborates the research design, research questions, and details of the techno-economic model. Chapter 5 performs a quantitative comparison of demographic factors between WiFi cities and non-WiFi cities and analyzes main features of citywide municipal WiFi projects. The development of the relationship between access point density and network coverage and a baseline model for suitable access point density are presented in chapter 6. Chapter 7 compares the result of our simulated model and empirical data and uses this information to compute the necessary subsidy for municipal WiFi projects. Finally, Chapter 8 concludes this dissertation and discusses the future research.

2.0 CITYWIDE MUNICIPAL WIFI: AN OVERVIEW

This chapter addresses citywide municipal WiFi from three perspectives to present an overview. Section 2.1 describes legal and policy issues related to municipal wireless. Section 2.2 provides a SWOT analysis. Section 2.3 offers classification of citywide WiFi users. Section 2.4 summarizes the legal issues and business potential of citywide municipal WiFi.

2.1 LEGAL AND POLICY ISSUES RELATED TO MUNICIPAL WIRELESS

In general, this discussion is guided by: (1) the Supreme Court's decision on state's legislation rights, (2) the states' statues about municipal wireless, and (3) the implications for municipal wireless policy.

2.1.1 The Supreme Court's decision on state's legislation rights

The Supreme Court's decision in March 2004 affirms that states can enact statutes to forbid or restrict municipalities from engaging in the provision of communications services[1].

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[1] Details See Supreme Court, Nixon, Attorney General of Missouri V. Missouri Municipal League et Al. Certiorari to the Unite States Court of Appeals for the Eight Circuit No. 02-1238 argued Jan 12, 2004 – Decided Mar 24, 2004.

However, the Supreme Court did not stipulate whether municipal broadband should be prohibited or whether municipal wireless would cause a negative impact on economic development.

2.1.2 State's statutes about municipal broadband and legal risk

After winning the legislative right from the Supreme Court, 23 states have enacted or are considering legislation related municipal communication services. [14],[23] Twelve of these states[2] limit future municipal communications projects by law. Two[3] of them basically support municipal communications projects with some safeguards.

Restrictions of the states' statues can be classified as follows:

- A "safeguard procedure" requirement for communications projects that may include public hearings (with a certain period between consecutive hearings), feasibility studies, majority approval by referendum, and financial evaluation of the project.
- Anti-competition provisions that may include several conditions: (1). Separate accounting for communications projects, (2). Publication of financial reports, (3) Forbidding public funding that produce below market access charges, regulatory preference and cross-subsidy.

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[2] Arkansas, Florida, Minnesota, Missouri, Nebraska, Nevada, Pennsylvania, South Carolina, Tennessee, Texas, Utah, and Washington.

[3] Maine and Virginia

- Outright prohibition, which excludes municipal involvement on communications projects with some exceptions. The exceptions may include permission of the local exchange carriers[4] or dark fiber leasing on a non-discrimination basis.[5]

Uncertainties in the results of referenda and the time of required for safeguard procedures are major sources of legal risk for municipal broadband. If state's statute does not impose these requirements, a municipality can reduce expected legal risk and accelerate the broadband project.

2.1.3 Implications on municipal broadband policy

Municipal broadband is a new development in telecom policy. It takes f time to observe its development and consequences. At the moment, 27 states have not imposed regulations related to municipal broadband.[14] The policy stance of these states is neutral on whether municipalities should compete with private BISPs. With no regulatory requirement, municipalities can speed up the development of their broadband project.

Most of the 23 states that enacted statutes for municipal broadband focus on safeguard procedures and anti-competition prevention rules. Very few states impose a strict prohibition on municipality involvement. There are two clear policies: First, strong opposition to unfair competition through cross-subsidy; and second, municipalities have to offer more broadband project information for further discussion of their broadband project. In addition, residents should have the final decision on their broadband project.

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[4] Section H of Pennsylvania house Bill 30 available at http://www.legis.state.pa.us/WU01/LI/BI/BT/2003/0/HB0030P4778.HTM

[5] Texas Code 54.2025

2.2 SWOT ANALYSIS

The advantages and disadvantages of citywide WiFi are intermingled. For example, the use of unlicensed spectrum results in the absence of radio band acquisition costs which decreases operations costs, but the interference from these shared radio bands can lead to unstable Internet connections. SWOT analysis helps us decompose these entangled features so that we can see a citywide WiFi project's strengths, weaknesses, opportunities and threats more clearly. With the result of SWOT analysis, we propose a two-dimensional model to summarize the options for the strategic positioning of citywide WiFi.

2.2.1 Strengths

- *Low cost WiFi chipsets have been embedded into most new laptops, PDAs and other electronic devices*. This provides a large potential user base, because users with WiFi enabled device do not need to spend extra money for hardware.
- *Lower network deployment cost than other broadband technologies*. Compared with fixed broadband service, WiFi has cost advantages in network deployment since there is no digging to reach the user's premises.
- *WiFi adopts unlicensed 2.4 GHz and 5.8 GHz radio bands for communication*. This results in short deployment times and no spectrum fees.
- *Ubiquitous and pervasive service:* Compared with other fixed Internet services, such as DSL, cable modem and dial up, WiFi can support ubiquitous service. Students, sales people, tourists can be target customers for WiFi service. In addition, ubiquitous and high transmission rates can provide improved convenience and productivity for municipal employees, such as police, firefighters, building inspectors, etc.
- Compared with 3G data services, WiFi offers higher throughput at lower cost. [24]

2.2.2 Weaknesses

- *Low reliability and stability.* WiFi service is a best effort service, so it is difficult to guarantee service quality, because a lot factors can cause interference and decrease service coverage and throughput. Although WiFi uses unlicensed spectrum, it has to follow FCC's Part 15 regulations limit its transmit power. In addition, other electronic devices that use the same radio band can cause interference. Further, in a dense urban area, it is quite likely that more than three different WiFi systems exist, so that non-overlapping channels cannot be guaranteed, so quality service level would be affected due to inter-channel interference.
- *Less sensitive antennas and weaker transmission power for laptops and PDAs.* With interference from other wireless device and limited transmission power from end user laptops or PDA, the link quality between access point and end user device fluctuates and a reliable connection cannot be maintained.
- *Outdoor access.* The coverage of citywide WiFi is for outdoor access, but most residents and business users need indoor access, so a WiFi bridge may be necessary to boost wireless signal power may be necessary. With a bridge installation, the actual indoor WiFi subscription cost could be close to Cable Modems or DSL, both of which require a modem. In addition, a free DSL modem or cable modem is common for DSL and cable service (with a service contract) but WiFi operators, without strong financial support, do not plan to promote their service with a free bridge. Furthermore, the installation of a WiFi bridge requires a knowledgeable technician, which means that a "truck roll" may be necessary for installation.
- *Security is a weakness for wireless service.* Security in a wireless connection is not as robust as on a wired connection. To set up a well protected WiFi connection requires some security knowledge. In addition, some WiFi projects offer open access, such as Google's Mountain View service, do not offer security mechanisms on their network; so end users have to set up a VPN or other security methods to protect private Information.[25]

- *High churn rate of WiFi service.* WiFi can not offer the same level quality of service as DSL and cable modems, which may cause high churn rates by customers whose expectations have not been met. [26]

2.2.3 Opportunities

- *Duopoly broadband market structure.* Municipal WiFi may be a viable alternative to the ILEC and CATV duopoly in internet access that exists in many areas.[27],[28],[29] As such, it may serve as a "third pipe" that can put price pressure on the other facilities-based providers. In addition, it can be as an access medium for areas that private service providers do not serve.
- *Broadband availability.* Several early municipal WiFi systems (in 2003 and 2004) were undertaken mainly because of the lack of broadband availability.[30] If the broadband market is competitive and customers are satisfied with service, there is little opportunity for citywide WiFi to enter residential and business market.
- *Charge for broadband service.* Compared with wireline regular broadband service, which costs about $25 to $50 per month, WiFi is inexpensive at $17 ~$25 per month. These fees are comparable to dialup service fees, so that they are (presumably) affordable.
- Municipal WiFi stimulates municipal economic development and brings positive impact for local economy. [12]
- Wireless broadband technology will enable local governments to be more proactive in the last mile broadband landscape than they have been before.[31]
- The municipal WiFi means a new source of revenue based on an expansion of the existing utility infrastructure (electricity, cable TV, gas or telephone), or street light and utility pole leasing. [31]
- *Many applications services can piggyback on the WiFi platform* to send either one-way or two-way communications to a municipal control center. For example, one-way communications might be radio frequency identification (RFID), surveillance camera for security, automatic meter reading for utilities and parking.

- *Maturity of mesh technology* and other fiber backhaul technology can minimize backhaul connections and expenses to enable large scale WiFi coverage. Some under-served areas can enjoy broadband without fixed broadband ISP involvement. WiFi is an entry technology for the broadband market not just for municipalities but also for some BISPs.
- Municipalities can also take advantages for economies of scale and scope for existing municipal utilities and fiber optical infrastructure. [32]
- *Geo-location*: WiFi can provide some location-based services to attract advertising, which may provide additional revenues.

2.2.4 Threats

- *Even though pervasive and ubiquitous broadband connection is appealing, the quality of service between fixed broadband and citywide WiFi network is different.* There are many factors that can affect WiFi quality. If customers are familiar with fixed broadband, it may be difficult to encourage them to stick with WiFi service even if the price is lower. The competition between cable modem and DSL offers competitive prices that dilute the attractiveness of WiFi service.
- *Threat from WIMAX.* WiMax is a potential competing technology for WiFi networks. Even though its CPE (chipset) cost is higher at this stage, its potential for longer distance and higher transmission rates cannot be ignored.[33]
- *Competition from wireless broadband.* An increase in wireless ISPs in the market can squeeze the broadband market share of citywide WiFi.
- *Competition from 3G services.* The transmission of 3G service is about 200 kbps, which is much slower than WiFi's 1 Mbps. The emerging 3.5 G services can offer more comparable transmission rates and more reliable service. Even with their higher monthly charges, business customers may choose a high priced, reliable service instead of low priced, and limited covered area service.[24]

- High potential of losing money from public access revenue alone. For the municipal owned model, both the municipality and its residents, however, have to bear the responsibility of high deployment costs and high financial risks. [34]

2.2.5 Strategic Position of Citywide WiFi services for indoor Internet access

Through the SWOT analysis, the main strength becomes clear: WiFi can offer a low cost, nomadic broadband service that covers a large area. Its main weakness is that the reliability of WiFi is worse than fixed broadband for indoor access, where many potential users would find the greatest utility[6]. The main opportunity for municipal WiFi is that many municipal services would benefit from portable broadband access. Finally, the main threat is in the form of competition from existing broadband services. If these are taken together, it seems clear that low cost outdoor portable data transmission service is the main target market for citywide WiFi. With stable revenue sources coming from outdoor portable data transmission service, citywide WiFi can provide free public access for whole municipality.

Under this scenario, the future indoor broadband market has four tiers of service (Figure 2:1). Fiber to the home (FTTH) is located upper-right and positioned in the first tier with a high price and the highest transmission rates. DSL, cable modem or WiMAX service are positioned in the second tier with moderate price and transmission rates. Citywide WiFi is positioned in the third tier with low reliability but low (or free) access prices. Dial-up is located at the bottom-left and is the lowest tier of indoor Internet access. According to the strategic position of indoor Internet access technologies, if the provision of Internet access through citywide WiFi is reliable, its high speed connectivity can appeal to dial-up users and

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[6] Outdoor access is attractive for some applications and uses, but is not a good alternative for regular use due to lack of electrical power for portable devices and exposure to potentially extreme weather conditions.

its affordable subscription rates can attract some broadband users from DSL and Cable Modem services. In addition, with free or low cost indoor broadband access, people may have more incentive to install a WiFi bridge at home to strengthen the wireless signal and enhance WiFi service quality.

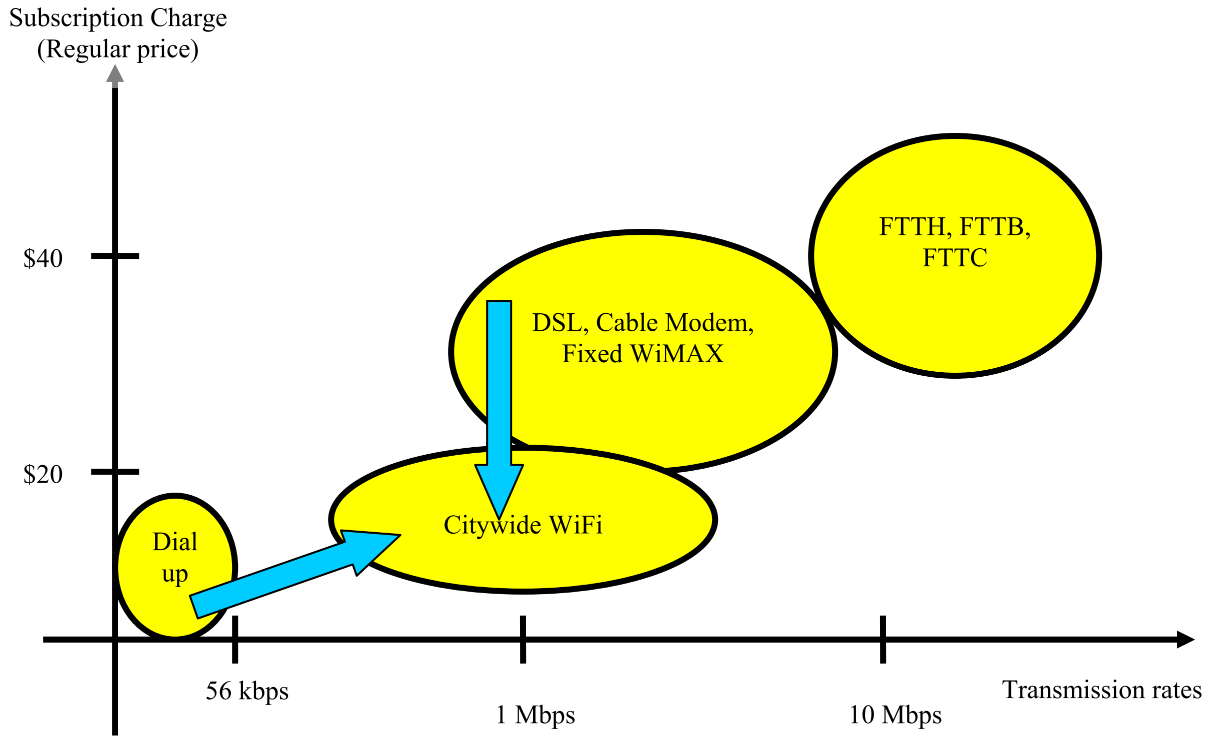

Figure 2:1 Strategic position of indoor citywide WiFi

2.3 CLASSIFICATION OF CITYWIDE WIFI CUSTOMERS

Citywide WiFi supports not only indoor and outdoor users but also fixed and portable applications due to its wireless connectivity, pervasive coverage and high capacity. We classified applications and users into following types: (Table 2-1)

- Fixed indoor users: Major users are business, municipal offices and residential users with requirement for high data transmission rates. Its client devices may be desktop computer, laptop computers and personal digital assistant (PDA). Depending on the quality of the access environment, users or WiFi ISPs can install an indoor WiFi bridge with high transmission power, receive sensitivity, and high gain antenna to expand network coverage. Compared with business users, residential users are willing to pay medium price for broadband access, but they are also sensitive to service price and quality.
- Fixed outdoor users: Main applications are automatic utility meter reading (AUMR) with low transmission rates requirement and surveillance cameras for crime and traffic monitoring with a high data rate requirement to support video transmission. According to the different applications in this service type, client devices can be a combination of several RFID devices and a WiFi enabled hub for AUMR or a video camera with a high gain outdoor WiFi bridge. Both applications require a significant investment in equipment and a willingness to pay premium access charges. Their sunk costs make them price insensitive with respect to other Internet technologies.
- Portable indoor users: Real estate inspectors and students are main users in this category. Both users require high transmission rates for downloading image or multimedia content. The primary client device is a WiFi enabled computer. Students may have a low willingness to pay for Internet access but an employer of real estate inspectors may have a high willingness to pay because of their increased productivity.

- Portable outdoor users: Public safety services, such as police patrol cars, fire engine and emergence medical service (EMS) are the three main users of public safety communications. Wireless connectivity can enable these applications to retrieve and send critical data more conveniently. The installation of high gain WiFi bridges on the top of the vehicles enhances service quality and they may be willing to pay premium access charges.

Table 2-1 Classifications of Citywide WiFi Users

Classification	Fixed indoor	Fixed outdoor	Portable indoor	Portable outdoor
Application / User	1.Business 2.Municipal offices 3.Residential users	1.AUMR 2.Surveillance camera	1.Real estate inspector 2. Students	1.Police patrol car, 2.fire engine 3. EMS
Willing to pay	1.2. High 3.Medium	High	1.High 2. Low	High
Data transmission rates requirement	High	1.low 2. High	High	Medium or high
Client Device plus Customer Premise Device (CPE)	WiFi enabled computer, video game console, PDA plus high gain WiFi bridge	1.RFID plus WiFi enabled hub 2.Camera plus high gain WiFi bridge	WiFi enabled handheld computer	Laptop computers and PDA plus high gain WiFi bridge

2.4 SUMMARY

This chapter reviews the regulations and the business potential of citywide municipal WiFi from different analytical perspectives. Through a two-tier legal analysis structure, regulations and restrictions on municipal wireless are subject to state governments. In addition, we found that most restrictions are focused on safeguard procedures. A clear evaluation of citywide WiFi market is critical for designing network and estimating revenue sources. The SWOT analysis and classification of WiFi users was designed to assist municipalities and WiFi ISPs to assess services, users and the market to develop a practical implementation plan.

3.0 TECHNICAL ISSUE OF CITYWIDE WIFI SYSTEM

We are interested systems in which municipal WiFi covers most of the municipality's population. The network structure for these systems is more complex than small and medium WiFi networks, such as hot-spots and hot-zones. In our survey, all citywide WiFi networks could be decomposed into an access layer and a backhaul layer structure, with WiFi for the access layer and traffic aggregation for backhaul layer. Although this two-layer network structure can provide an economical solution by decreasing the necessary backhaul links for each access point, the structure also brings challenges in network design and deployment. In this chapter, we describe the access layer and IEEE802.11 in Section 3.1and backhaul layer with aggregation tier and transport tier in Section 3.2 to provide a clear profile for a large scale citywide WiFi network.

3.1 ACCESS LAYER AND IEE802.11

3.1.1 Access layer

The access layer provides a wireless link between an end user's WiFi enabled device and a network's access point using IEEE802.11 specifications. Due to the weak transmission power and a low sensitivity antenna on some client devices, the number and location of access points in this layer is critical in determining whether WiFi users can have high speed Internet connections, especially indoors.

Owing to the varying quality of broadband access, the geography of WiFi coverage and interference from other wireless devices, it is difficult to determine precisely how many access points are needed for a system. In general more access points bring higher WiFi performance; this has been verified by a metro WiFi testing firm's survey.[7][35] Thus, the average number of access point per square mile can serve as an index to estimate network quality. In the qualified citywide municipal WiFi projects, the number of access point per square mile has increased from 10~ 20 access point per square in 2004 to 25~35 in 2006. In an extreme case, Toronto Hydro installed more than 100 access point per square mile to achieve a 5 Mbps service rate.[8][36] To achieve a more accurate index to measure the quality of WiFi service by AP density, we will link the AP density and WiFi network coverage as described in Section 4.2.

Location is the other important factor can affect the quality of WiFi service. There may be some dead spots with poor wireless quality. In addition, sufficient and suitable locations for access point attachment are critical for network deployment. In citywide projects, street lights, utility poles and rooftops of municipal buildings are common places for access point attachment. Since some municipalities do not own street lights and utility poles, network deployment can be challenging. In addition, the power supply for access points from street lights and utility poles can be an obstacle because some street lights only power up from dusk to dawn. [37]

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[7] From Novarum's website, Toronto, ON is the top one with highest access point density and Tempe, AZ is the 10th ranked network with lowest access point density in its list. http://www.novarum.com/MetroWi-FiRankings.htm

[8] We convert the average access points per square mile is 104 from its announcement "Toronto Hydro installed 225 access points in 6 square kilometer area" http://www.novarum.com/MetroWi-FiRankings.htm

The evolution of wireless in commercial access points has improved service quality, although the relatively weak transmission power and less sensitive antennas on client devices can result in a poor experience by the WiFi user. It is difficult to require customers to upgrade their equipment for a better WiFi connection. Nor is it easy for the customer to determine whether the quality problems are due to their devices or the municipal network infrastructure. Thus, it is generally more practical to install a high-gain WiFi bridge on the customer location (by WiFi ISPs) to enhance wireless connectivity. Besides, WISP also can improve service quality by upgrading the access points through the use of multi-input and multi-out (MIMO) antennas, higher transmission power and sensitive antenna arrays.

3.1.2 IEEE802.11

WiFi uses radio technology to provide broadband service between an access point (AP) and WiFi enabled equipment within a certain transmission range. WiFi is a group of specifications based on the IEEE 802.11 wireless local area network (WLAN) standard. Access Points transmit RF over the unlicensed spectrum (2.4 GHz and 5.8 GHz) with a maximum speed of 54 Mbps. The widely deployed standard is 802.11b with 11 Mbps transmission speed, because it has been available since 1999 with relative cost advantages in access points and WLAN cards. Other standards are 802.11a and 802.11g. They use OFDM for channel access control and throughput can reach 54 Mbps. Using the same frequency band at 2.4 GHz, 802.11g can be backward compatible with 802.11b. The emerging standard is 802.11n, which has not been ratified yet, but pre-N AP equipment is already being sold in the market. 802.11n adopts multiple-input and multiple-output (MIMO) technology to alleviate multi-path fading and enhance network coverage and transmission rates.[38] Table 3:1 summarizes these four WiFi standards.

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Table 3-1Summary of IEEE 802.11 and Highlights

Attributes	802.11a	802.11b	802.11g	802.11n
Range (feet)	60	300	300	>300
Maximum data rate (Mbps)	54	11	54	>100
Through (Mbps)	23	4	19	>50
Frequency band (GHz)	5.8	2.4	2.4	2.4
Modulation	OFDM	DSSS	OFDM	OFDM
Compatibility	802.11a	802.11b	802.11 b & g	802.11 b and g
Availability	2001	1999	2003	June 2009 (expected)
Highlights	Short transmission range and poor wall penetration ability	Most widely deployed standard	Backward compatible with 802.11 b and higher throughput	With MIMO technology against multi-path fading

Source: Adapted from [39], [40]

3.2 BACKHAUL LAYER

3.2.1 Point to multi-point topology for the aggregation tier

There are two steps of traffic aggregation in this tier. The first step is the aggregation of access points to a gateway node, and the second step is the aggregation of gateway nodes to an aggregate node.

The first step is supported by a dynamic mesh network, which can support traffic hopping through several access points. This reduces the cost of connection to the fixed network and can be used to realize both hot-zone and citywide WiFi projects. Typically, separate radio bands are provisioned for the end user to access point links (2.4 GHz) and the access point to gateway node links (5.8 GHz). This helps prevent packet collisions and transmission bottlenecks. Even though the mesh network can provide multi-hop transmission and intelligent packet routing, a star topology is commonly used in to minimize the number traffic hops for shorter packet delay and higher throughput. [41]

The second step is supported by WiMAX or similar wireless technology, which provides high capacity backhaul links between the gateway nodes and an aggregator node. Although the mesh network can minimize the backhaul requirements from all access points to gateway nodes, it is still cost-prohibitive to prove a separate wired connection to each gateway node. Thus, the second tier aggregation is necessary and cost reduction is achieved by other high capacity point to multi-point technologies. Google’s Mountain View citywide WiFi project uses a 6 to 1 ratio for APs to a gateway node and a 20 to 1 ratio for gateway nodes to an aggregation node. [41]

3.2.2 Technologies of aggregation tier

There are two main technologies for the aggregation tier. One is fixed WiMAX technology based on 802.16d with a sectoring antenna and a TDMA sharing scheme. Theoretically, it can support 15 Mbps transmission rates over a 5 MHz channel and reach 35 miles. The other is Motorola Canopy with propriety technology. It also adopts a TDMA sharing scheme and communicates in the 5.8 GHz with a simulated capacity of 10 Mbps and a 2 mile distance.

Table 3-2 Technologies of Aggregation Layer

Vendor	Alvarion / Redline 802.16d	Motorola Canopy
Physical Layer	OFDM	Proprietary
Radio band	UNII 5.8 GHz or 3.5 GHz or	UNII 5.8 GHz
Base station antenna	Sectoring	Sectoring
Sharing	TDMA	TDMA
Theoretical Capacity	15 Mbps for 5 MHz channel 35 Mbps for 10 MHz channel	10 Mbps
Reach	35 miles	2 miles

Source: Adapted from [42],[43]

3.2.3 Point-to-Point wireless or fiber ethernet for transport tier

High volume traffic from each aggregation node requires a reliable and high capacity link to an Internet Data Center (IDC). In this layer, a fiber network is the first choice. Otherwise, wireless is the solution. In spite of high transmission rates and low loss, the build costs for the fiber network cannot easily be absorbed by a citywide WiFi project. A high capacity point to point wireless connection between aggregation nodes and the IDC is used if no fiber connection is available. However, the quality of this wireless transmission is apt to be affected by weather, geography and other interference factors.

3.2.4 Technology of transport tier

The transport tier technology requires high capacity to deliver the aggregated traffic over 20 gateway nodes or a hundred access points to prevent them from being a network bottleneck.[41] Table 3.3 describes four high speed transmission technologies for the transport tier. If municipalities have deployed a fiber loop for its internal usage it can be a suitable solution for a reliable backhaul connection. If a fiber loop is unavailable, copper wire can be a wired alternative with some limitations in capacity and distance. If wired solutions are infeasible, free space optics (FSO) or ultra-high radio band transmission can offer a cost-effective solution. However, fog can hinder FSO connectivity significantly and rain can impede ultra-high radio band transmission dramatically. Each transport technology has its tradeoff between cost and performance. Citywide WiFi needs to evaluate suitable transport tier technology by considering its weather, geography and resources carefully to ensure a reliable end-to-end wireless connection.

Table 3-3 Technologies of Transport Tier

Technology	Fiber wired	Copper Wired	FSO wireless	GigaBeam wireless
Capacity	>1Gbps	Up to T3	1 Mbps to 2.5 Gbps	100 Mbps to 2.5 GHz
Distance	No significant restriction	3 miles	0.7 to 2.5 miles	1 mile+
Radio Band	NIL	NIL	Visible light	71-76 GHz 81-86 GHz 92-95 GHz
Features	High cost Long deployment period	Limited capacity T3	Affected by Fog	Affected by Rain

Source: Adapted from [44],[45]

3.3 SUMMARY

The citywide network structure is much more complicated than hotspot or hotzone architectures and needs to integrate different wireless technology to reduce backhaul costs as well as prevent potential network bottleneck. According to the project requirement and the geographic environment, the design of the access and backhaul layers for each citywide WiFi project is different. Figures 3:1 integrates layers and tiers together to present a clear profile of a large scale citywide WiFi network.

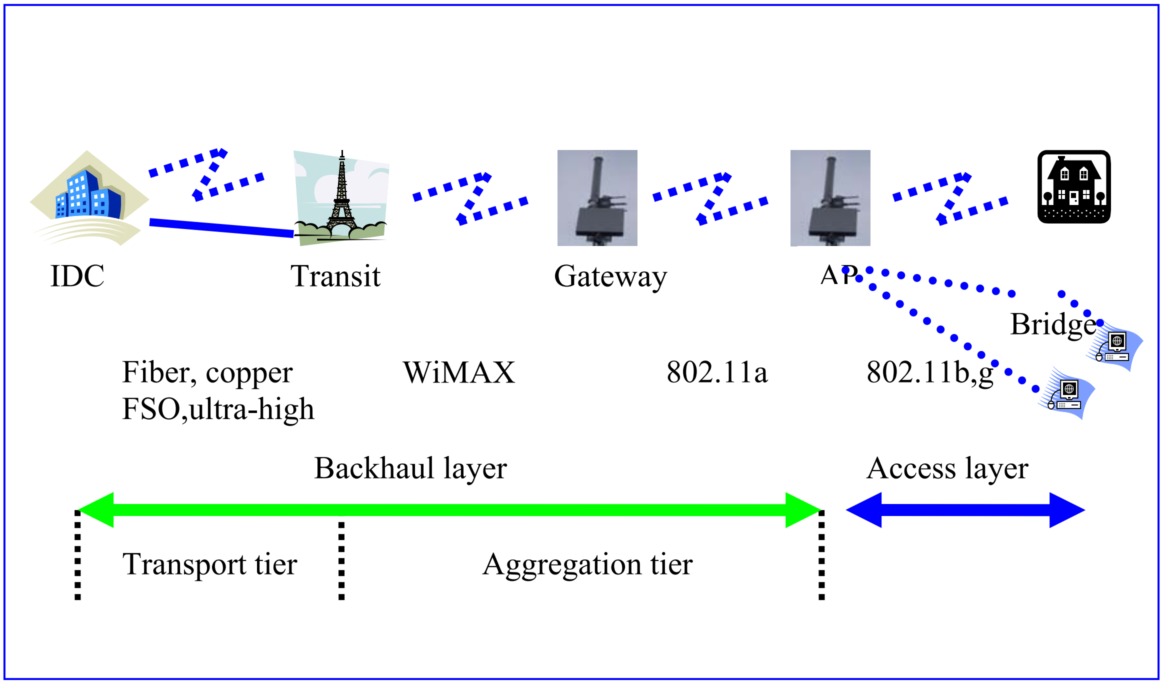

Figure 3:1 Infrastructure of a large scale citywide WiFi network

4.0 RESEARCH DESIGN AND RESEARCH QUESTIONS

The purpose of this dissertation is to evaluate whether municipal WiFi can be a feasible solution for local broadband access and if ubiquitous coverage of the WiFi project is not sustainable from public access revenue alone, how much subsidy is necessary. We undertake a systematic study of existing citywide WiFi projects in the US, build a techno-economic model, assess the effectiveness of the model using empirical data, forecast the sustainability of ongoing projects, and evaluate the amount of subsidy needed if the for network deployment is to achieve ubiquitous coverage. The research outcome can provide a foundation to explain the wisdom of safe-guard regulations on citywide WiFi, and what kinds of conditions can make a feasible and sustainable operation, and how much subsidy is necessary from municipality to achieve target network coverage. Owing to difficulties of data collection and criteria formulation, there is limited research that focuses solely on citywide WiFi and the geo-demographic features of municipalities with citywide WiFi and those without.[46] In addition, a few papers perform a techno-economic analysis of citywide WiFi projects, although some determine the density of access point heuristically.[21],[22] With the result of analysis of empirical projects and a simulated model of citywide WiFi projects that considers network design, business model and market structure, we can examine why many projects have withdrawn, suspended and shut-down. This dissertation is guided by following research questions:

- Are municipalities that have built municipal WiFi systems different in measurable ways from those that have not?
- How do the roles of municipalities and business models affect the development of WiFi service?
- What is the relationship between network coverage and the density of access points?
- How can network coverage, construction costs, local competition, and revenue sources be integrated to analyze why many projects failed?
- If ubiquitous coverage WiFi project can not survive from public access revenue, how much subsidy in deployment to achieve target network coverage?

In order to provide a clear picture of the development of citywide municipal WiFi empirically and theoretically, this research will use a dual analysis. The empirical part consists of the following:

(1) Investigate municipal wireless projects and develop the criteria by which municipal citywide WiFi can be assessed
(2) Identify the predominant social-demographic and geo-demographic differences (if any) between municipalities with and without citywide WiFi
(3) Analyze the business models and municipal roles in citywide WiFi projects.

The simulated part requires the construction of a techno-economic model. There are four stages of this analysis.

(1) Build a relationship between access point density and network coverage by considering the role of attenuation and fading in the size of a WiFi cell.
(2) Build a techno-economic model by integrating a variety of market factors and decision variables to evaluate the sustainability of a WiFi project.

(3) Build revenue flow equation to estimate WiFi public access revenue from survey of local broadband access prices and the FCC's statistical subscription rates.

(4) Build cost flow equation to estimate network implementation and operating cost for a WiFi project.

The validation and policy implications part compares the simulated data from our techno-economic model and real data from existing citywide WiFi projects. We will analyze not only operating projects but also projects under construction to discuss policy implications and business suggestions. This application part includes the following steps.

(1) Collect required market data from empirical projects and apply the data into the techno-economic model for simulation.

(2) Compare simulated outcome and empirical result to validate the effectiveness of the model.

(3) Evaluate municipal subsidy of network deployment cost and business operating cost for achieving target WiFi network coverage.

The proposed research framework with carry out steps is depicted in Figure 4.1.

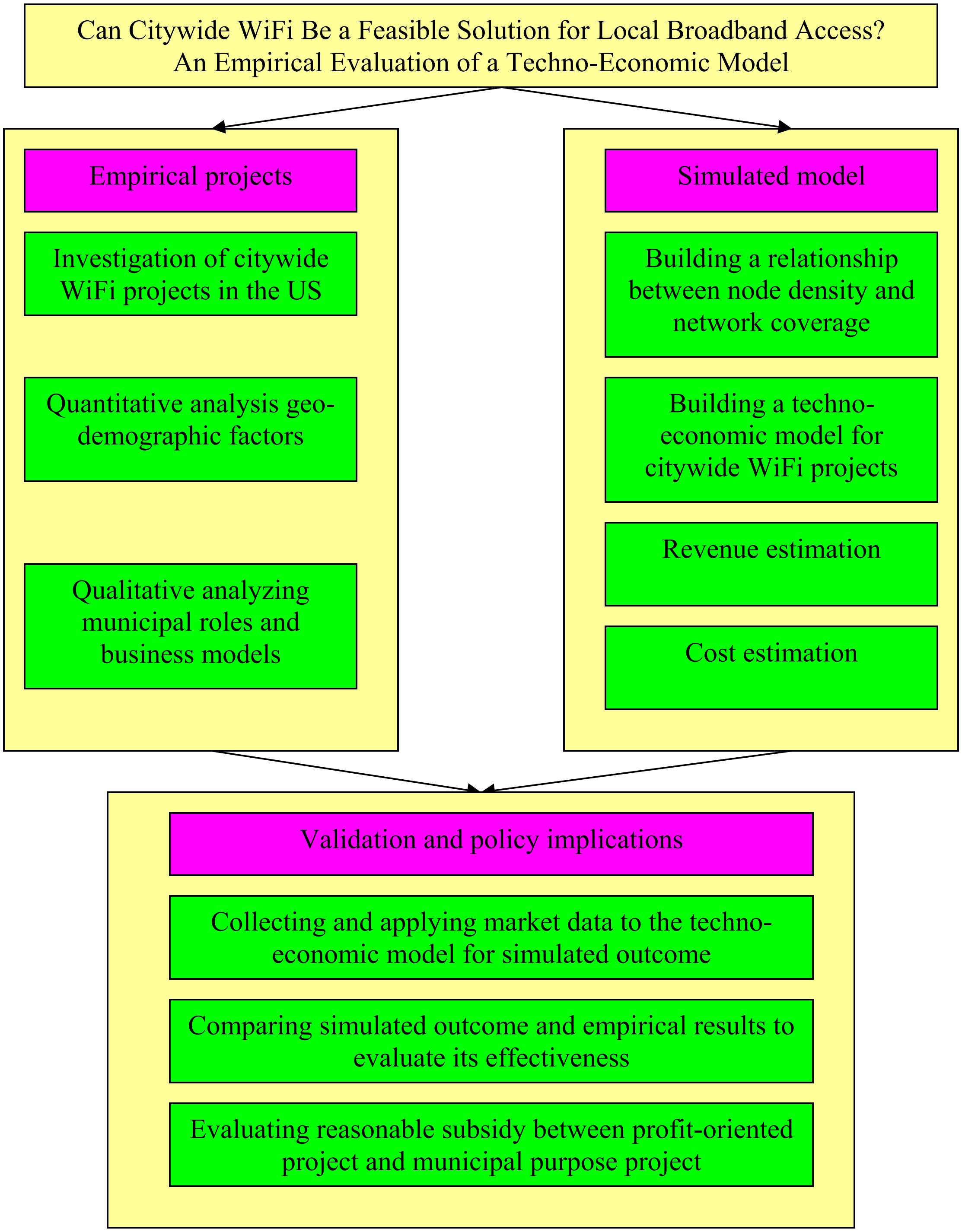

Figure 4:1 Research framework

4.1 EMPIRICAL STUDY OF CITYWIDE WIFI PROJECTS

Based on the proposed framework, an empirical study was conducted as described above. The comparison of WiFi and non-WiFi cities consists of social-economic and geo-demographic data collection for both kinds of municipalities. The analysis of the existing citywide municipal WiFi projects includes municipal roles, business models, service charges and transmission rates.

4.1.1 Investigation of citywide WiFi projects

Although several research and commercial papers analyze municipal wireless projects, there is limited systematic research of existing citywide WiFi projects in the US.[47],[42],[48],[49] We follow the three stage model described above.

(1) Criteria:

- *The project adopted WiFi as the access technology for client devices*: There are several wireless technologies that can be used for citywide broadband access, such as satellite, local multimedia distribution system (LMDS), 3G and WiMAX. We examined only 802.11-compliant systems.

- *The municipality is involved in the WiFi project*: Municipalities have multiple roles in citywide WiFi projects, including facilitator, investor, anchor user, operator, and supervisor.[9]
- *The project offers public broadband access*: Without public access, the impact of a citywide project is limited. We require a public access component.
- *WiFi coverage has to reach approximately to 55% of land area or 90% of population at a minimum*: There are many difficulties in fully covering a municipality, so 100% geographic coverage is unreasonable. For example some dead spots inevitably exist or the municipality may not own all street lights and utility poles. Many municipal WiFi projects post a network coverage map instead of publishing actual covered percentage of their networks. We collected the publishing data and network coverage maps and determined that the 55% area or 90% of population coverage was reasonable threshold so that we could obtain 20 qualified cases for statistical comparison without compromising too much on the idea of "citywide" coverage, as opposed to hot zones . For example, Google's Mountain View project intended to achieve 100% coverage, but because of private land and multiple unit apartment areas, Google's project only covers 80% to 90% of the area.
- *Completion of WiFi project deployment:* Numerous WiFi projects have been delayed in planning, tender, and deployment by political or financial obstacles. It is hard to know whether or when these obstacles will be overcome and the project can be finished. We chose to focus on projects that have been largely implemented and are operating.

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[9] To avoid confusion, we define municipality as a political subdivision of a state in the US. The actual definition of municipality depends on each Country.

- *The project has a minimum of 10 access points per square mile:* This figure is the minimum access point density needed to support pervasive access.

(2) Data collection:

The data for potential citywide municipal WiFi projects came from a variety of sources, including MuniWireless[10], WNN WiFi Net News and other broadband survey reports[11]. Then, each case was evaluated by abovementioned criteria from relevant municipal and WiFi ISP websites, white papers from equipment vendors[12], case studies and presentations from W2i Digital Cities.[50],[51],[52] Cases that were included are referred to as "qualified municipal WiFi projects". The list of the twenty qualifying cities is in appendix 1

4.1.2 Comparing social-economic and geo-demographic factors

This research uses three steps to compare WiFi and non-WiFi cities: Data collection, hypothesis testing, and further statistic analysis.

(1) Data collection of social-economic and geo-demographic factors for WiFi and non-WiFi cities

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[10] *The 2005 Municipal Wireless State of the Market Report and* update of wireless cities and counties 2006 Dec, June 2007, and Aug 2007

[11] Shamp, S. "A Survey of Municipal Wireless Initiatives" Mobile Media Consortium University of Georgia, White papers and case studies from W2i Digital Cities

[12] Main AP equipment vendors for citywide WiFi are Tropos http://www.tropos.com/, BelAir http://www.belair.com/, Skypilot http://www.skypilot.com/, Nortel http://www.nortel.com/, and Motorola http://www.motorola.com/

After generating a list of qualified citywide WiFi projects from Section 4.1.1, we gathered geography, demographics, education and economic data of each city from Federal Census Bureau's 2000 census.[53] We focused on seven aspects: geography, race, age, education house occupation, income, and poverty. The geographic, demographic, and social-economic data for cities without WiFi also came from the Federal Census Bureau's Census 2000. We chose this as the most reliable data source despite the age of the data.

For comparison, we generated a list of non-WiFi cities. There are only seven states with qualified citywide projects. To develop a comparative data set, we used a random number generator to select two sets of 80 cities without WiFi projects. Set A came from these seven states and Set B came from all fifty states. This resulted in a 1:4 ratio of WiFi cities to non-WiFi cities and produced a data set that was sufficiently large for regression analysis. For Set A, these cities were distributed across the states containing municipal WiFi system in the same proportion. For example, California has nine qualified cities, so we picked 36 cities at random without WiFi in California for comparison. For Set B, the population of each state as a weight factor to determine the number of from that state. For example, the population of California is approximate 10% of the US, so we picked eight cities at random without WiFi in California for comparison. The geographical, demographic, and socio-economic data for cities without WiFi also came from the Federal Census Bureau's Census 2000. We chose this as the most reliable data source despite the age of the data.

(2) Hypotheses

We developed hypotheses for seven aspects of social-economic and geo-demographic factors as listed below. Each hypothesis accounts for one or several factors.

H1: The population, land size, and population density of the municipalities influence the implementation of citywide municipal WiFi.

Population, land size are available factors obtained from 2000 Census database to determine whether the size of the municipality affects WiFi implementation.

H2: The racial profile of the municipalities influences the implementation of citywide municipal WiFi.

The race of municipalities includes five factors as white, black, American Indian, Asia, and Hispanic

H3: The medium age of the municipal residents influences the implementation of citywide municipal WiFi.

H4: Housing factors of the municipalities influence the implementation of citywide municipal WiFi.

The house factors include number of occupied house, percentage of occupied house and homeownership.

H5: The education levels of the municipalities influence the implementation of citywide municipal WiFi.

There are two education levels can be found from 2000 Census, one is high school and the other is bachelor's degrees.

H6: The income factors of the municipalities influence the implementation of citywide municipal WiFi.

In the Census database, we chose household income, capita income and house value as income factors to determine whether they can affect the implementation of citywide WiFi.

H7: The poverty factors of the municipalities influence the implementation of citywide municipal WiFi.

In the Census database, we chose family below poverty and individual below poverty as poverty factors to determine whether they can negatively affect the implementation of citywide WiFi.

(3) Statistical methods

A total of 19 variables have been selected to test for differences between WiFi and non WiFi municipalities. The first step is to perform two sided t-tests for means at 5% and 1% significance levels on both groups. The next step is to conduct a stepwise selection to eliminate non-significant variables using the 5% criterion. The last step is to perform a logit regression of the selected variables. All statistical processes are conducted by SAS version 9.1

4.1.3 Analyzing existing citywide WiFi projects

With the qualified citywide municipal WiFi data set in hand, the research further classifies the municipal roles, business models, service fees and transmission rates for each qualified city.

- **Municipal roles:** Municipal involvement is critical for a citywide WiFi project to provide necessary support and remove project obstacles. After analyzing all citywide municipal WiFi projects, we determined that there were five major roles of a municipality: investor, operator, anchor user, facilitator, and supervisor. In some cases, a municipality can play multiple roles in a citywide WiFi project. For example, it can be a facilitator and a supervisor, because a municipality can act dual-role as supporter monitor at the same time. However, if a municipality is an operator, it cannot also be a supervisor, because the roles conflicts with each other.
- **Business model:** The business model for citywide municipal WiFi can change dynamically. In order to emphasize the defining characteristic of citywide municipal WiFi, we propose a 2 by 2 matrix with free or fee as the first index to distinguish among citywide municipal WiFi business models. The use of unlicensed spectrum and low deployment cost can enable WiFi project to provide free Internet access. Free broadband access is so unique and has not been found in other fixed and mobile broadband service.
- **Free service:** Free broadband access is a unique characteristic for citywide WiFi. It does not, however, mean, all free WiFi services have no restrictions. We conduct further analysis to distinguish free WiFi services into following types: No restriction, time restriction, location restriction, transmission rate restriction, and advertisement restriction.

- **Service fee and transmission rates:** service fee means regular monthly Internet access charge instead of a promotion price for the lowest-tier public access service. Transmission rates indicate the maximum transmission rates from access point to client device at the lowest-tier monthly WiFi access charge.

4.2 THEORETICAL ANALYSIS OF A TECHNO-ECONOMIC MODEL

The methodology to design a techno-economic model for citywide WiFi is based on the notion of a forward-looking economic model. The type of model has been adopted by the Federal Communications Committee (FCC) for assessing cost-based interconnection and unbundled network elements charges and access prices.[54] In addition, this method is also widely adopted to evaluate emerging telecommunication technology for new service and new market opportunities.

This techno-economic model assumes a green-field deployment, building the network from bottom up with no preexisting WiFi network infrastructure. Since late 1990s, there have been various techno-economic models that analyze telecommunication infrastructures from a variety of perspectives.[55],[56],[57] As for the analysis of citywide WiFi project, Gunasekarun et al., proposed a financial analysis to evaluate the viability of a WiFi/WiMAX infrastructure to cover Philadelphia with 30 access points per square mile.[22] Peha et al., developed a techno-economic analysis by building a two-tier citywide WiFi project in Pittsburgh to explain various business models.[21] However, the analysis did not evaluate the relationship between access point density and coverage and chose arbitrarily 19 access points per square mile to build up the model.

Since the expense of access point procurement and installation is the main source of citywide WiFi construction cost, a heuristically determined the number of access point per square does not present a useful linkage between network deployment cost and network coverage. For example, it does not enable us to examine why certain node density is necessary to ensure reliable service. Therefore, we use two stages to construct a techno-economic model for a citywide WiFi project. The first stage is a technological analysis to build the relationship between access point density and network coverage by considering transmission power, receive sensitivity, antenna gains, path loss, and other fading factors for outdoor and outdoor to indoor environments. The second stage is an economic analysis based on the finding of previous section with reasonable assumptions on market factors and decision variables to construct a techno-economic model for project sustainability assessment

4.2.1 Relationship between access point density and network coverage percentage

Constructing the relationship between access point and network coverage requires information from two sources. The first is a path loss formula to determine the link budget from client device to access point. The second is the definition of WiFi coverage by regular hexagonal cells to cover a whole city. With the information from link budget and the side length of a (hexagonal) WiFi cell, we can link node density, the length of cell radius and network coverage all together to estimate the percentage of network coverage. Thus, it becomes possible to explicitly link access point density with an estimate of network coverage.

(1) The path loss function decides the link budget from client device to access point.

According to the analysis of section 3.1, the upstream connection from the client device to the access point is more challenging than the downstream connection. Although the receiver sensitivity of an access point can reach 100 dBm for a 1 Mbps transmission rate, the transmission power and antenna gain from the client device is not designed for long distance transmission. The effective isotropic radiated power (EIRP) from a client device is as low as 15 dBm[13], too weak to provide a reliable connection over longer distances. Therefore, the link budget must be based on the upstream connection from client device instead of the downlink connection. The following discusses the wireless specifications for both the access point and the client device.

- Transmission power, receive sensitivity and antenna gain for the access point and the client device

Originally, WiFi was designed for short-distance coverage, so the transmission power, receive sensitivity and antenna gain are limited to reducing interference and to increase spectrum efficiency. Therefore, 15~50 mW transmission power, 94~97 dBm receiver sensitivity for 1 Mbps transmission rate and 0 to 3 dBi antenna gain are commonly found on the specification sheet of WiFi enabled client devices.[14] In addition, a WiFi ISP can not certify a client device as cellular operators can certify their mobile handsets to ensure reliable service. A WiFi ISP can, however, choose a carrier-class access point with suitable combination of transmission power and antenna gain to reach the upper bound of EIRP, 36 dBm, based on

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[13] The transmission power of client device is between 15 ~50mW with zero to two dBi antenna gain by a dipole antenna, so the EIRP of a client device is approximately 12-19 dBm

[14] See Table 5-9

FCC Part 15 regulation for point to multi-point transmission, and 100 dBm receive sensitivity with 1Mbps transmission rate to expand the WiFi coverage as wide as possible.

- Link budget between client device and access point

Camp et al., measured the outdoor WiFi throughput of a Houston neighborhood to estimate the path loss exponent, shadow fading and multi-path fading of its simulated model for a two-tier WiFi mesh network.[58] The mean of path loss exponent found in this paper is 3.7 (with a standard deviation 4.1), shadow fading of 8 dB and multi-path fading of 7 dB. Arjona et al., assessed Google's citywide WiFi project to determine whether voice service over the WiFi network could compete with cellular voice.[41] It assumed that a path loss exponent of 3.3 with SNR > 25 as the requirement to measure whether WiFi can support high throughput and low delay for VoIP service. Liechty et al., proposes an outdoor WiFi propagation model that a direct ray, single path loss exponent, Seidel-Rappaport model can balance model complexity and prediction accuracy for a campus environment.[59] Although it supports a direct ray, single path loss exponent model to predict signal propagation in 2.4 GHz, it also requires a regression analysis of onsite measurements for path loss exponent, building footprint and foliage boundary to obtain model parameters.

The covered radius of a WiFi circle can be obtained by integrating the allowable link budget (L_{path}) into an outdoor radio attenuation model. The allowable link budget for path attenuation can be computed from the client device transmission power (P_{tx}), access point receive sensitivity (P_{rx}), the antenna gain for the transmission client device and receiving access point (G_{tx} and G_{rx}), shadow fading (F_{shadow}) and multi-path fading ($F_{multipath}$):

$$L_{path} = P_{tx} - P_{rx} + G_{tx} + G_{rx} - F_{shadow} - F_{multipath} \quad \text{........(1)}$$

The attenuation model for outdoor WiFi path loss can be calculated by equation (2), where the radius is the distance between an access point and the border of the covered cell, *f* is the radio band of 802.11 b and 802.11g and C is the speed of light:

$$L_{path} = 10 \times \alpha \times \log(radius / d_{ref}) + 20 \times \log(f) - 20 \times \log(4\pi / C) \text{......(2)}$$

Because the frequency band of access is fixed to 2.4 GHz, speed of light is 3 X 10^8 (meter/second) and d_{ref} is one meter, the equation (2) of the allowable link budget can be simplified as formula (3)

$$L_{path} = 10 \times \alpha \times \log(radius) + 40 \text{...........(3)}$$

Moving the radius to left hand side and the other components to right hand side, the equation (3) can be rewritten as follows:

$$radius = 10^{\frac{L_{path} - 40}{10 \times \alpha}} = Power[10, (L_{path} - 40) / 10 \times \alpha]\text{........(4)}$$

Applying the allowable link budget of path loss (L_{path}) of equation (1) into equation (4), the radius of the WiFi circle can be obtained as follows.

$$radius = Power[10, (P_{tx} - P_{rx} + G_{tx} + G_{rx} - F_{shadow} - F_{multipath} - 40) / 10 \times \alpha]\text{........(5)}$$

(2) The side length of a WiFi cell

We define the coverage of a WiFi network to be the percentage of a municipal area that a client device can expect to receive 1 Mbps transmission rate both upstream and downstream. For clear explanation WiFi coverage, we assume the shape of all hexagonal cells is a regular hexagon where the length between the center point of a hexagonal cell to its vertex is the same as the length of its side. Although the shape of WiFi cell does not affect the relationship between access point density and network coverage, the shape of cell could be a circle or a regular polygon. However, if the WiFi coverage is close to 100%, the regular hexagonal assumption is convenient to explain the location of access point and the network coverage.

If the coverage of a city is 90%, it means that WiFi enabled devices send and receive at least 1 Mbps transmission over of the city's WiFi area theoretically. There are several factors such as interference from other devices operating in the unlicensed spectrum, foliage, buildings, and packet loss that can affect the actual throughput.

Following the tradition in cellular communications systems, this research assumes that the shape of WiFi cell's coverage is regular hexagonal because the shape makes efficient use of the space.[60] A square mile of area is covered by regular hexagonal WiFi cells shown on Figure4.2. If the node density of a WiFi project is ten access points per square mile, the side length of a hexagonal cell is 313.9 meters and the distance between two access points is 543.7 meters. If the node density is increased by a factor of four to 40 access points per square mile, the side length of the hexagonal cell and the distance between two nodes can be shortened by 50% to 157 meters and 271.8 meters, respectively.

The number of access point per square mile determines the size of a regular hexagonal cell, which is represented as equation (5). On the other hand, the area of a hexagonal cell can be calculated by the length of its side in equation (6). The details are shown on Figure 4.3. Integrating equation (5) and (6), we can find the inverse relationship between the side's length of a regular hexagonal cell and square root of access point density, which is shown as follows:

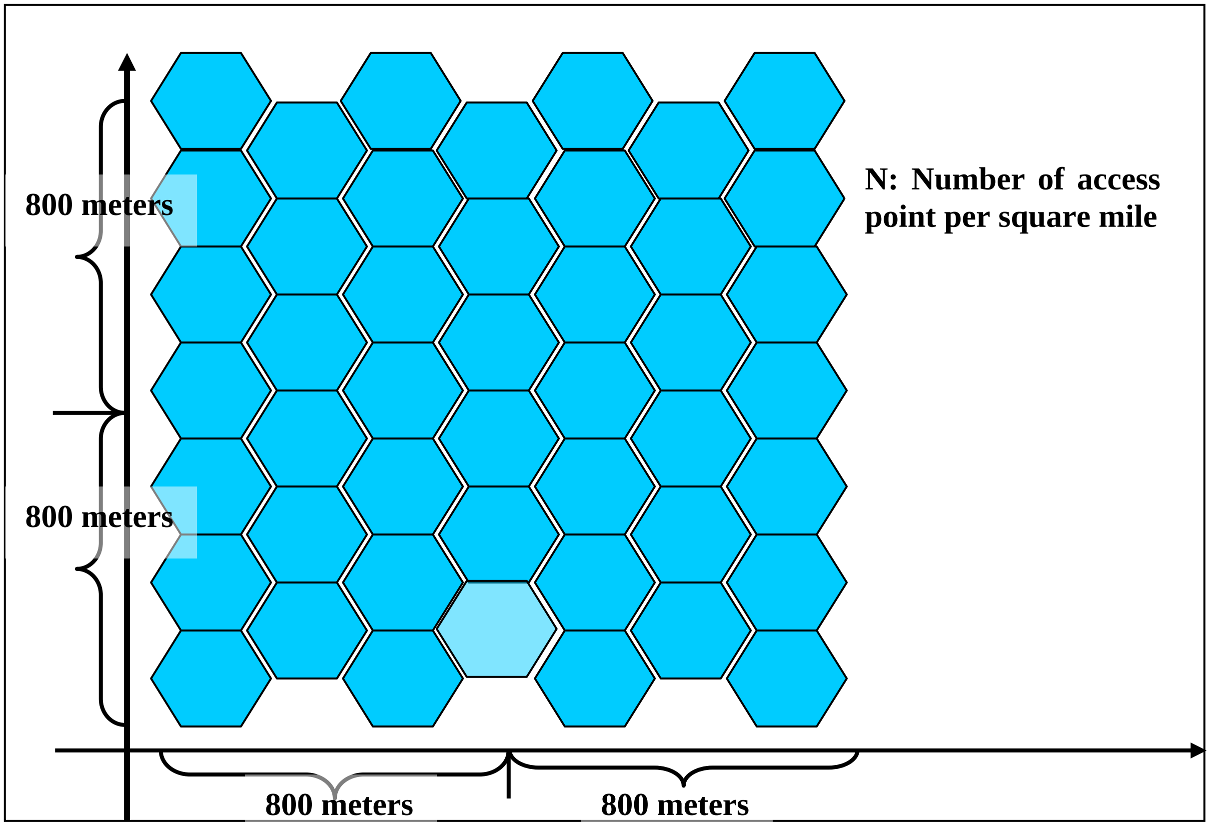
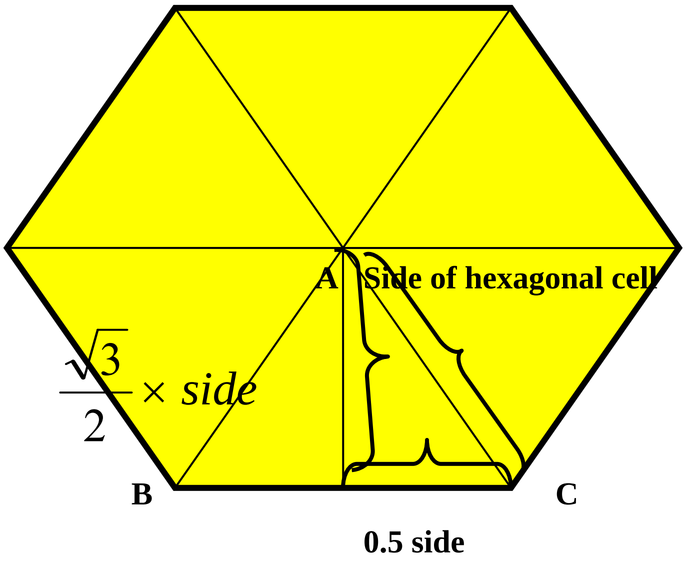


Figure 4:2 A Square mile is covered by N hexagonal cells

$$Size(hexagonal\_cell) = \frac{1600^2}{N} \ldots..(5)$$

$$Size(hexagonal\_cell) = \frac{3\times\sqrt{3}}{2}\times(side)^2 .....(6)$$

$$Side_{(meter)} = \sqrt{\frac{2\times1600^2}{3\times\sqrt{3}\times N}} \propto 1/\sqrt{N} ....(7)$$



Triangle (ABC) =

$$\frac{\sqrt{3}}{4}side^2$$

Area of a hexagonal cell = six triangles =

$$\frac{3\times\sqrt{3}}{2}\times side^2$$

Figure 4:3 Size calculation of a hexagonal cell by its side

(3) Linkage among node density, side length of hexagonal cell, and network coverage

The covered percentage of a WiFi circle and a hexagonal cell can be computed by dividing their sizes as shown in following, which is described in Figure4:4. Applying the formulas for the area of a circle and of a hexagonal, we can determine the network coverage percentage as shown in equation (8). We assume that the access point is located in the center of the WiFi circle and the hexagonal cell. The circle with a sky-blue color is the area covered by sufficient WiFi signal strength and the portion in yellow color is outside of the WiFi coverage area. Client devices A, B, and C are inside the covered WiFi area, and client device D, E, and F are outside the covered area.

$$Network\_Coverage_{percentage} = \frac{(\pi \times radius^2)}{(3 \times \sqrt{3} \times side^2 / 2)} ....(8)$$

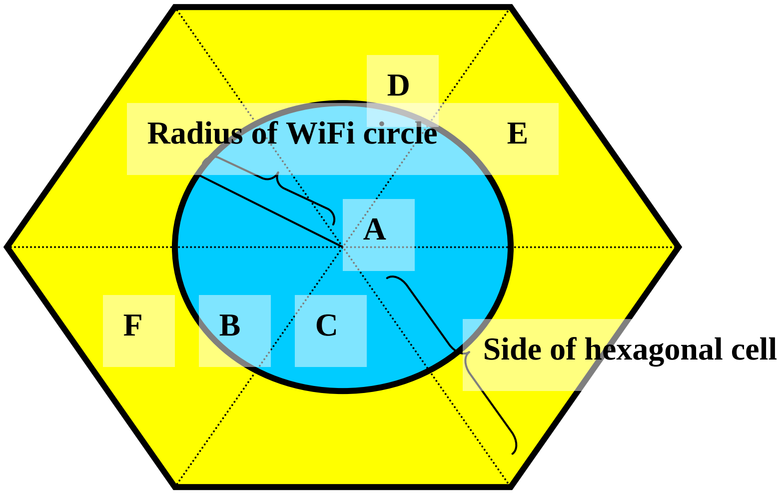


Figure 4:4 The concept of network covered percentage. A, B, C are inside WiFi coverage with reliable connection, D, E, F are outside WiFi coverage without reliable connection

Then, applying the radius and the side length from equation (4) and equation (7) into equation (8), the network coverage percentage can be rewritten as shown in equation (9). The equation indicates that network coverage has positive relationship with access point density. If Lpath and α are fixed, K becomes a constant as equation (10).

$$Network\_Coverage_{percentage} = \frac{N \times \pi \times (Power[10,(L_{path} - 40)/(10 \times \alpha)])^2}{1600^2} \propto N \times K \ldots\ldots(9)$$

$$K = \frac{\pi \times (Power[10,(L_{path} - 40)/(10 \times \alpha)])^2}{1600^2} \ldots.(10)$$

4.2.2 Overview of techno-economic model of citywide municipal WiFi and NPV for cash flow estimates

The main purpose of building the techno-economic model is to analyze WiFi network deployment strategies, service provisioning, and market competition in an integrated way. Based on the results of previous section, the model structure is built by integrating OPTIMUM[15] and Mobile Network Evolution model with modified components to address the citywide WiFi infrastructure.[61],[62]

In order to understand the interaction of market factors, decision variables, and output mentioned in the techno-economic model of Figure 4.5, we use a three-tier structure. The yellow boxes in the first tier represent market factors, which can be obtained from the market study and site survey but can not be decided by the municipality or WiFi ISP.

The blue circles in the second tier represent decision variables with two layers, which can be controlled by the municipality and the WiFi ISP. The upper layer includes the service provisioning plan and the network deployment plan, which are affected by market factors. The

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[15] OPTIMUM is a tool for techno-economic assessment of telecommunication network. The detailed information is available from http:// www.telenor.no/fou/prosjekter/tera/publication/guide.htm

lower layer consists of access charges for each service type, covered area, access point density, backhaul capacity and volume discount, which are influenced by market factor and the upper layer decision variables.

The green boxes of the bottom tier are outputs of the computation of market factors and decision variables to obtain project costs, revenues and financial outputs. The first layer of output contains interim outputs such as network construction cost, service penetration rates, number of subscribers for each service, average revenue per user (ARPU) from service types, which are decided by the lower layer of decision variables. The second layer comprises network OA& M cost, revenue from each service type and cash flows, which is decided by the upper layer of this output tier, to determine the profit and loss of the project. The lower layer of bottom tier contains final outputs calculated by NPV financial tool to achieve better understanding of WiFi project sustainability.

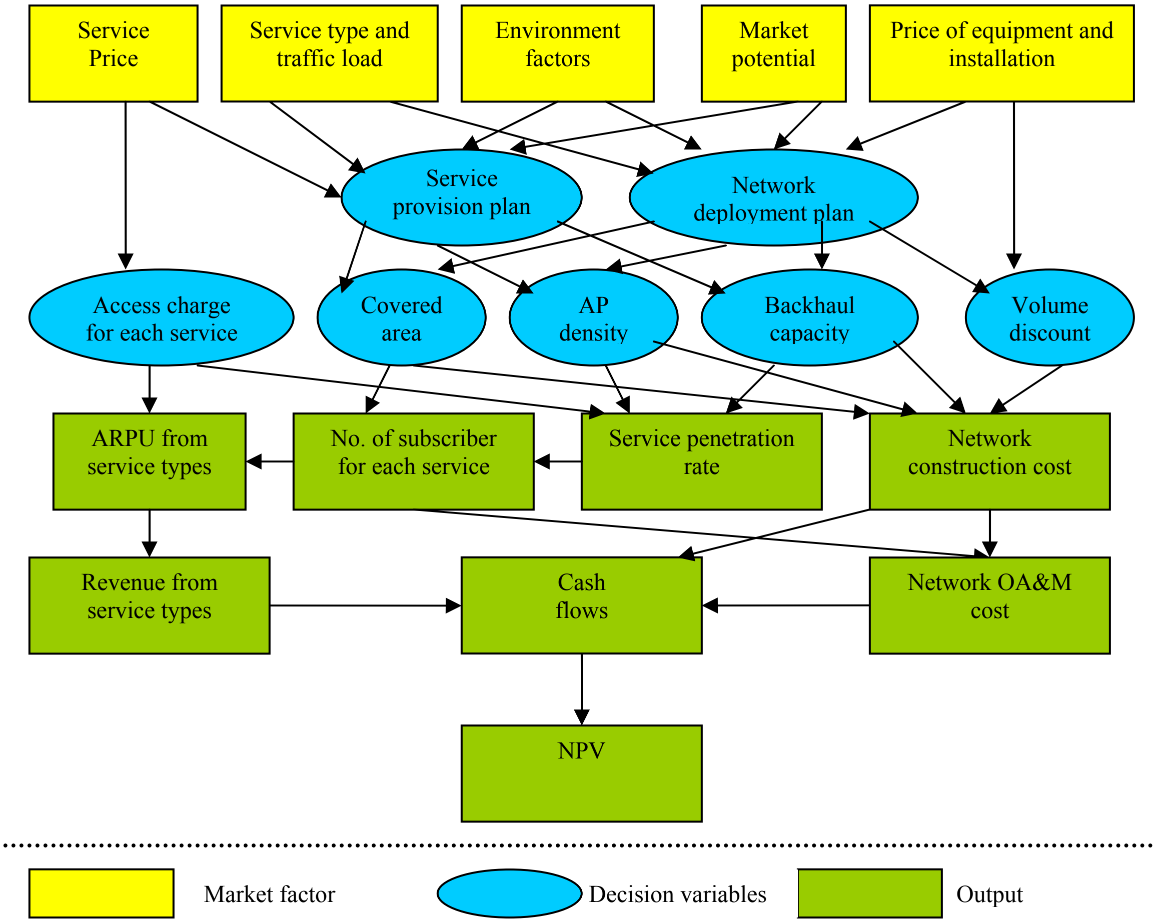

Figure 4:5 Flow chart of citywide WiFi techno-economic model

We use net present value (NPV) is the traditional method to compare total project costs for WiFi projects in our simulated model. We assume that there is no residual value of the WiFi equipment at the end of project, so the NPV of the WiFi project can be expressed as in equation (11). In addition, the impractical assumption that households and businesses are distributed equally in a municipality is removed to consider population density and distribution in real cases. Revenues and cost estimations are taken from published data and empirical information from existing WiFi projects and consider all kinds of major factors; the compiled population distribution of municipal WiFi cities is embedded into our model, so that we can examine the relationship between NPV and project scale. More details of the revenue flow (RE) estimation are given in Section 4.23 and the cash flows (CO) in Section 4.2.4.

$$NPV = \sum_{t=0}^{n} \frac{CF(t)}{(1+r)^t} = \sum_{t=0}^{n} \frac{RE(t) - CO(t)}{(1+r)^t} \quad \ldots.(11)$$

Where

n : the total time of a WiFi project(year)

t : the time of cash flow (year)

r : the discount rate of a WiFi project (%)

CF : the net cash flow at time t

RE : Revenue flow at time t

CO : Cost flow at time t

4.2.3 Revenue flow estimation

The core of our model is to determine whether a citywide municipal WiFi can survive on public access revenues, because the market structure of the other revenue sources, e.g. public safely and other municipal access, is a monopsony and the revenues coming from these municipal related applications are highly variable and difficult to estimate. Therefore, the model considers revenue source from residential WiFi subscriptions and business WiFi subscriptions. Other revenue resources are only counted when the empirical data is provided from existing projects.

There are some basic assumptions about the revenue estimation. The first assumption is connected to the fixed access charge per month, because WiFi access charges have been stable since 2005. The second assumption is the five years life time of the WiFi network, because the technology progress makes a five-year old WiFi network out of date and loses its subscribers. If the contract period of WiFi service between a municipality and a private ISP is ten years, we assume that the network will be overhauled and upgraded at the end of the fifth year. The last assumption is fixed population and land size of a municipality. Though population is dynamic and land size can be changed by the expansion of a municipality, we assume land size and population are fixed to simplify the model because both the change of the parameter is difficult to predict. Although the above assumptions could assist us to build the model, they cause some limitations. The dynamics of market competition for WiFi access charge and network life time and the growth and decline of a municipality's population are not discussed in this research. However, these basic assumptions can assist us to evaluate the sustainability of a citywide WiFi project in a fixed environment clearly without a lot of extra parameters in a dynamic environment.

The revenue flow can be stated in equation (12), and can be calculated by multiplying the WiFi access charges by the subscriptions for residential users and business users, respectively, and adding monopsony revenues and other revenues.

$$RE(t) = Pw \times Hu \times Sr(t) + Pb \times Bu \times Sb(t) + M(t) + O(t) \ldots .(12)$$

Where

Pw: Monthly WiFi access charge for residents

Pb: Monthly WiFi access charge for businesses

Hu: Household number of a municipality

Bu: Business number of a municipality

Sr(t): Residential subscription rate of WiFi service at time t

Sb(t): Business subscription rate of WiFi service at time t

M(t): Monopsony revenue sources from municipality at time t

O(t): Other revenue sources at time t

We use collected monthly WiFi access charges for residents and businesses from operational projects and found there is little price variation for WiFi services, so WiFi access charges are assumed to be fixed for the project life. The household (Hu) and number of businesses (Bu) is obtained from the Census Bureau. However, it is difficult to estimate the number of WiFi subscriptions for residential and business access, so we adopt a two-layer structure to estimate the subscriber numbers for residential access and business access, respectively. The first layer addresses main factors which can affect the subscription rate and second layer discusses subscriber switching rates from different Interent access technologies.

(1) Number of residential subscribers:

The first layer: There are five main factors to consider: price, service availability, service quality, Internet technology penetration rates, and operating time.

- We assume WiFi does not cause non-Internet users to become Internet users, so all WiFi subscribers need to switch from some other Internet access technology.[16] Therefore, the price difference between WiFi's and competitors' monthly charges is the main factor in estimating subscriber switching rates between these services. However, price difference is not sufficient for all subscribers to switch from other

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[16] Although some projects provide free computers and training courses for low income families to access Interent, the volume of free computers are limited.

Interent technologies to WiFi. We add a factor (α) to recognize that some Internet users are price insensitive and they will not change Internet access technology due to differences in the monthly access charge.

- Based on the outcome of Section 4.2.2, AP density can determine the percentage of WiFi households and businesses that have reliable WiFi signals for Interent access. We choose population percentage (Popu%) instead of land percentage to represent how many households and businesses are covered by a WiFi network, because most WiFi projects do not cover 100% of the land area. For example 80% of population may live in 40% of land area. Therefore, population percentage is a better estimator for how many residents and businesses can be covered. However, stucco exterior of building can affect wireless signal penetration for indoor access and tilt of WiFi antenna for outdoor access can cause poor wireless signals for households and businesses located above the 3rd floor, so we add an actual penetration factor to estimate existing WiFi projects more precisely.
- There are several tiers of service quality for DSL and cable modem services. We only compare the bottom tier service with the lowest transmission rates because WiFi is a best-effort service, sharing wireless resources with subscribers and thus doesn't compete with other wired high transmission rate services.
- Internet penetration rates by different technologies are provided by the FCC's broadband report[17]. Although the report provides Internet technology penetration rates at the state level only, its more precise figures are more useful than national level figures. In addition, there are other broadband technologies, such as BPL,

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[17] High-speed services for Internet access: Status as of June 30,2007 from the Wireline Competition Bureau of the FCC

fixed wireless and FTTH in the FCC's report, but they only occupy a small portion of total penetration rates, so we don't consider subscribers who shift from these broadband technologies. Even mobile wireless subscribers occupy a large portion of the total broadband subscribers, but most of its services are accessed from mobile handsets like SMS and MMS for 2.5G and 3G services. Therefore, we treat mobile wireless access and WiFi access differently and assume that subscribers will not shift to WiFi services from mobile wireless. Penetration rates of dial up and the bottom tier of DSL and cable modem are the three key penetration rates to estimate WiFi residential subscription rates.

- Owing to the one year or two years contract, that many existing Internet subscribers have; we have to assign a time lag factor, T(t), to the switching rates into our revenue estimation. Therefore, we assume there will be 50% of price sensitive subscribers switching to WiFi at the end of the 1st year and 100% of WiFi subscribers at the end of the 2nd year.

With the above mentioned data and assumptions, the subscription rate can be expressed as the sum of subscriber switching rates from different internet technology multiplied by the covered population percentage and network coverage percentage as shown in equation (13). After applying an estimate of subscriber switching rates from different Internet access technologies into equation (13), we can write a mathematical expression as shown equation (14) for WiFi subscription rates.

$$Sr(t)= F(\text{prices, service availability, service quality, penetration rates, operating time})$$

$$= Popu\% \times Net\% \times Ac\% \times (S_{dialup}(t) + S_{DSL}(t) + S_{cable}(t)) \; \ldots.(13)$$

$$= Popu\% \times Net\% \times Ac\% \times \sum_{j=1}^{m} (Pe_j \times P\%_{botj} \times (1-\alpha_j) \times (1 - \frac{Pw}{PI_{botj}}) \times T_{shift}(t)) \; \ldots.(14)$$

Where

Sr(t): Total WiFi subscription rate for residential users at time t

Popu%: Percentage of WiFi covered population of a municipality

Net%: Percentage of reliable indoor WiFi access, which is based on equation (9)

Ac%: Percentage of actual indoor WiFi access caused by building material and location

S_{dialup}(t): Subscriber switching rates from dial up service to WiFi service

S_{DSL}(t): Subscriber switching rates from DSL service to WiFi service

S_{cable}(t): Subscriber switching rates from cable modem service to WiFi service

j : type of Internet access technology

Pe_j : Penetration rate of Interent access technology j

$P\%_{botj}$: Percentage of technology j users who subscribe the bottom tier

α_j: Percentage of user of technology j, who will not shift from technology j to WiFi

PI_{botj}: Price of the bottom tier monthly access charge for technology j

T_{switch}(t): time lag factor for subscription switching rate at time t

The second layer: Subscriber switching rate from different Interent technologies.

We assume there is linear relationship between price sensitive subscriber and WiFi access price to estimate subscriber switching rate. Although the relationship between subscribers and WiFi access price can be either linear or nonlinear, we think the linear assumption is enough to build the relationship clearly and prevent the complex computation of nonlinear assumption.

This assumption means that higher WiFi access charge brings fewer switching subscribers. If WiFi access charge is free, all price sensitive subscribers will move to WiFi service. However, some portions of Internet subscribers won't switch to WiFi service because of price difference, triple-play bundling services from cable TV operators or telephone companies, and higher transmission rates for peer to peer applications. With assumptions for the percentage of price insensitive subscribers for different Internet access technologies (α_j), we can build the basic relationship between subscriber switching rate and the price factor $(1-\frac{Pw}{Pj})$, shown in equation (15). The percentage of subscriber switching rate can be determined easily from Figure 4:6. If free WiFi access, all price sensitive subscriber will move to WiFi server and its subscriber switching rate is equal to $Pe_j \times (1-\alpha_j)$, because its price factor $(1-\frac{0}{Pj})$ is equal to 1. If WiFi service charges the same price as its competitive broadband service, none subscriber switches from its competitive broadband service, because its price factor $(1-\frac{Pj}{Pj})$ is zero and makes its subscriber switching rate also zero. Subscriber switching rates from different Interent access technologies, which are expressed from equation (16) to (18), can be determined by the equation (15) with different penetration rates, percentage of bottom tier subscribers, monthly access charges, time factor, and percentage of price insensitive subscribers. Because of no suitable price we can use to measure dial-up switching rate, we use the lower price between the bottom tier DSL and cable modem monthly charges as the benchmark price to determine the switching rate of dial up users, because most dial up users have to make the decision to upgrade their Internet access either to DSL or cable modem service. If dial up subscribers can afford the WiFi monthly access charge as the same level as fixed broadband monthly charge, most of them have switched to DSL or cable modem already. Therefore, the lower price between both of them would be more suitable to be a substitute price for dial up users.

$$\text{Subscriber switching rate } = Pe_{tech\_j} \times (1-\alpha_{tech\_j}) \times (1-\frac{Pw}{P_{tech\_j}}) \ldots.(15)$$

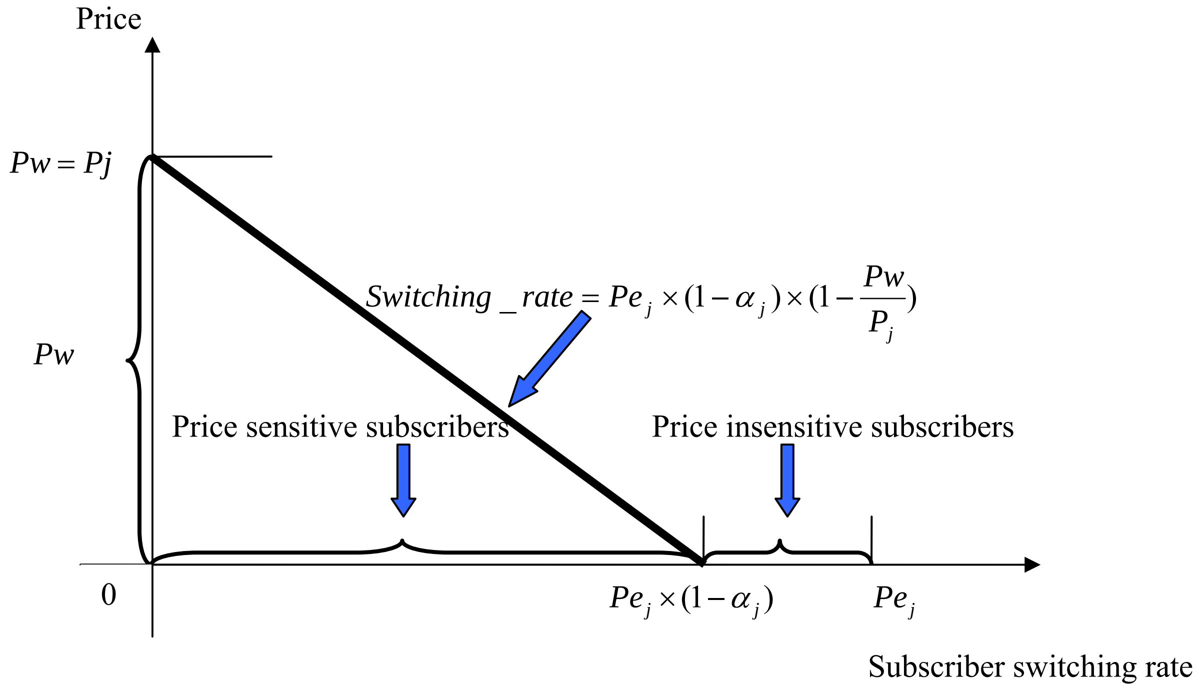

Figure 4:6 Subscriber switching rate versus WiFi access charge

$$S_{dialup} = Pe_{dialup} \times (1-\alpha_{dialup}) \times (1-\frac{Pw}{P_{lower}}) \times T_{shift}(t) \ldots.(16)$$

$$S_{DSL} = Pe_{DSL} \times Pe_{DSL\_bot} \times (1-\alpha_{DSL}) \times (1-\frac{Pw}{P_{DSL}}) \times T_{shift}(t) \ldots.(17)$$

$$S_{cable} = Pe_{cable} \times Pe_{cable\_bot} \times (1-\alpha_{cable}) \times (1-\frac{Pw}{P_{cable}}) \times T_{shift}(t) \ldots.(18)$$

Where

P_{lower}: The lower price between of the bottom tier DSL and cable monthly access fee

P_{DSL}: The bottom tier of monthly DSL access fee

P_{cable}: The bottom tier of monthly cable modem access fee

Pe_{dialup}: Dial up penetration rate

Pe_{DSL}: DSL penetration rate

Pe_{cable}: Cable modem penetration rate

α_{dialup}: Percentage of die hard dial up user who will not switch from dial up to WiFi

α_{DSL}: Percentage of die hard DSL user who will not switch from DSL to WiFi

α_{cable}: Percentage of die hard dial up cable modem user who will not switch from cable modem to WiFi

Pe_{DSL_bot}: Percentage of DSL users who subscribe the lowest tier of DSL service

Pe_{cable_bot}: Percentage of cable modem who subscribe the lowest tier of cable modem service

(2) Number of subscribers for business access:

It is hard to obtain the penetration rates and percentage of bottom tier subscribers with different access technologies for business users. In addition, business users may be price insensitive more reluctant to change ISP, so we assume that WiFi switching rate for business users is the sum of DSL and cable modem subscriber switching rates without considering dial-up subscriber switching rate. With this assumption, WiFi subscription rate for business users can be expressed as the percentage of covered business users multiplied by the network coverage percentage and multiplied by the switching rate shown in equation (19).

Sb(t)= $Busi\% \times Net\% \times (S_{DSL}(t) + S_{Cable}(t))$ ….(19)

4.2.4 Cost estimation

There are two main reasons that can explain why citywide WiFi projects are prone to under-estimate their cost. One is that they implement an outdoor access WiFi network with insufficient AP density for indoor WiFi access. The other is that WiFi isn't the only broadband choice for residents and businesses in most projects; WiFi service has to compete with DSL, cable modem and dial-up service. Therefore, sufficient AP density, reasonable customer acquisition cost, decent customer service, sufficient backhaul capacity and intelligent network management system are necessary to survive. We tried to consider all these factors when we estimate the actual WiFi project cost. As before, we adopted a two-tier hierarchy. The first layer introduces the main components of cost and the second layer discusses the detailed items of each main cost component.

There are two basic assumptions for the cost estimation. The first assumption is about WiFi network construction time. Swift network construction is an advantage of WiFi technology, so we assume network construction is finished in the first year. The second assumption is fixed cost of network equipment and implementation. It is reasonable because the network is assumed to be finished in the first year with little price variance. The hidden limitation of both assumptions is that WiFi ISPs do not build their network step by step, but expand network coverage by market responses. Therefore, WiFi ISPs will bear higher investment risks in our model to complete whole network construction in the first year.

- The first cost layer:

The cash flow of cost estimation is expressed in equation (20) and is composed of network deployment cost and operating cost. Network deployment cost is described in equation (21), and consists of equipment acquisition cost, network design and implementation cost. Operating cost, shown in equation (22), is composed of customer acquisition cost, quality service expenses, business administration expenses, and network operation expenses.

$$Co(t) = Nd(t) + Op(t)\ldots.(20)$$

$$Nd(t) = Ea(t) + Ni(t) + Ndm(t)\ldots.(21)$$

$$Op(t) = Ca(t) + Ch(t) + Sq(t) + Ba(t) + No(t)\ldots.(22)$$

Where

Co(t): Cost flow at time t

Nd(t): Network deployment cost at time t

Op(t): Network operating cost at time t

Ea(t): Equipment acquisition cost at time t

Ni(t): Network implementation cost at time t

Ndm(t): Network design and construction monitoring cost at time t

Ca(t): Customer acquisition cost at time t

Ch(t): Customer churn rate at time t

Sq(t): Service quality expenses at time t

Ba(t): Business administration expenses at time t

No(t): network operation expenses at time t

- The second cost layer:

Network deployment cost: Equipment acquisition cost, network implementation cost and network design cost are three main components of the network deployment cost.

(1) Equipment acquisition cost is the function of network covered land area, AP density per square mile, AP price, gateway node price, aggregate node price, and volume discount rate for equipment. With the information from our network design in Section 3.2.1, a 6 to 1 ratio for APs to a gateway node and a 20 to 1 ratio for gateway nodes to an aggregation node, we can express equipment acquisition cost in equation (23). From our demographical statistics, 15% to 30% land area of a city with no people lives over there, so AP density for populated areas and unpopulated areas is calculated by indoor access requirement and outdoor access requirement, respectively. Even the list price for an AP is about $3,500 but Tropos's AP might cost Earthlink under $1,000 for its Philadelphia project.[18][63]Therefore, we also assume that equipment discount rate has positive relationship with procurement volume. The equation of equipment discount is expressed in equation (26). The related equipment cost and installation cost are shown in appendix 4. b

(2) Network implementation cost is related to installation expenditures for an AP or a gateway node and base station construction cost for an aggregate node. It can be expressed in equation (24). We assume that installation discount rate also has positive relationship with installation volume. Installation discount rate is smaller than equipment discount rate, because labor expenses do

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[18] Information is based from http://wifinetnews.com/archives/007973.html

normally not receive the same discount rate as equipment cost. The equation of equipment discount is expressed in equation (26).

(3) Network design and construction monitoring cost is related to other miscellaneous work from initial network design to complete network construction. It consists of site survey, location selection for AP, gateway node, and aggregate nodes, logic network design, operating and support system installation, and network construction monitoring. We assume it is equal to 15% of total equipment acquisition cost and network implementation cost.

$$\text{Ea(t)} = \sum_{k=1}^{2} land_{size}(k,t) \times AP_{density}(k) \times (P_{Ap} + \frac{P_{gateway}}{6} + \frac{P_{aggregate}}{120}) \times R_{equip} \ldots.(23)$$

$$\text{Ni(t)} = \sum_{k=1}^{2} land_{size}(k,t) \times AP_{density}(k) \times (E_{install} + \frac{E_{install}}{6} + \frac{E_{aggregate}}{120}) \times R_{Install} \ldots.(24)$$

$$\text{Ndm(t)} = 15\% \times [Ea(t) + Ei(t)] \ldots.(25)$$

$$\text{R}_{\text{equip}}\% = 1 - \frac{\sum_{k=1}^{2} land_{size}(k,t) \times AP_{density}(k)}{8{,}000} \ldots.(26)$$

$$\text{R}_{\text{install}}\% = 1 - \frac{\sum_{k=1}^{2} land_{size}(k,t) \times AP_{density}(k)}{15{,}000} \ldots.(27)$$

Where

$\text{Land}_{\text{size}}$: The size covered land area in square mile at time t

$\text{AP}_{\text{density}}$: The amount of AP number per square mile for 100% coverage

k: parameter for land area, k=1 means covered land area with population and k=2 means covered land area with no popluation

P_{ap}: Price of an access point

$P_{gateway}$: price of a gateway node

$P_{aggregate}$: price of an aggregate node

R_{equip}: volume discount rate for equipment

$R_{Install}$: volume discount rate for labor

$E_{install}$: Installation expenditures for an AP or a gateway node

$E_{aggregate}$: Construction cost for an aggregate node

Operating cost: Operating cost is composed of four major components.

(1) Customer acquisition cost: The main cost for a WiFi ISP is to acquire Internet users and related to WiFi bridge subsidy, advertisement and promotion cost. We assume the customer acquisition cost is about 15 times the monthly WiFi access charge, because the positive relationship between acquisition cost and monthly access charge can justify how much WiFi ISP would be willing to pay for soliciting a new customer. The rough broadband user acquisition cost is $600 in the US[19] and the average broadband access charge is about $42.5 dollars[20]. [64],[65] Therefore, we choose 15 months as the basis for estimating WiFi customer acquisition cost. In addition, the cost for churn rate is included in customer acquisition cost. We assume that 10% of WiFi customer churn rate

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[19] APS customer acquisition cost http://isp-lists.isp-planet.com/isp-asia/0106/msg00027.html

[20] The average broadband access price of Comcast, AT&T, Qwest, Comcast and Time Warner cable. The information is based on US broadband comparisons http://www.dslreports.com/shownews/83886

each year, because the average of cable ISP churn rates is 2.5% per quarter, approximately.[21][66]

(2) Service quality cost: It is related to quality of customer service level and shared backhaul Internet capacity per user, and is a function of WiFi subscribers.

(3) Business administration cost: It consists of business administration overhead and accounting and billing expenditures and related to the number of WiFi subscriber.

(4) Network operating and management cost: It is the function of WiFi network size with positive relationship between network operation cost and network size. We assume 9% of network deployment cost to support a well-mannered network operation.

After applying the assumptions for four main factors of operation cost into equation (21), we can express operating cost as equation (28).

$$
\begin{aligned}
Op(t) &= Ca(t) + Ch(t) + Sq(t) + Ba(t) + No(t) \\
&= (15 \times Pw + Pq1 + Pq2) \times [Hu \times Sr(t) + Bu \times Sb(t)] \times (1 + ch) + 9\% \times Nd(t) \ldots\text{.(28)}
\end{aligned}
$$

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[21] Cable ISP churn rate is about 2.5 per quarter. The information is based on “Broadband pickup seen next quarter” http://www.multichannel.com/article/CA6469967.html

4.3 VALIDATION, SUBSISDY CALCULATION, AND POLICY IMPLICATIONS

This section validates the techno-economic model using empirical data and draws preliminary conclusions from the results. We performed three steps to achieve this goal. Section 4.3.1 describes the data collection of operating citywide municipal WiFi projects from model simulation. Section 4.3.2 compares simulated results and current operation outcomes to verify the effectiveness of the model. Section 4.3.3 analyzes how much subsidy for network deployment and project operations would be necessary for a profit-oriented ISP. We also discuss the implications of the results.

4.3.1 Data collection

The required data for the simulation includes not only the decision variables for the project itself but also market information. Decision variables of project data consist of service provision and deployment plans, backhaul capacity, access point density, network covered area, volume discount of network equipment, and revenue sources for each application and service. Projects led by a municipality are more willing to publish those data, however, private ISPs projects treat those data as confidential. Market factor information contains access price from other ISPs, service type and traffic loads, geographic characteristics, market potential, and equipment price. Some market information can be accessed readily (such as access price from other ISPs, geographic characteristics, and service types) but some of them are not. If municipalities did not survey their local market, Internet penetration rates by technology for estimating its market potential may be difficult to obtain in this moment[22]. [67] For these projects, we adopt state and national penetration rates from FCC, OECD and Pew instead of local data.[10],[68] Other market information can be attained from the Internet. For example, Internet access charges for local market can be obtained from the websites of the local DSL and Cable Modem service providers, and equipment prices can be accessed from online equipment sales channels.[69] If some data is unavailable, we make some reasonable assumptions and use national data for the model simulation.

4.3.2 Comparison citywide WiFi projects between simulated data and real data

The goal of this section is to compare simulated outcome with actual data from a project to evaluate the effectiveness of our model. Although there are difficulties in obtaining project and market data for the simulation, some projects publish their construction plans, market survey and the performance of their operations. These are useful input and output data for validating our model. If there is a significant difference between the simulated outcomes and real result, the actual input and output data from operating projects can assist us to discuss some parameters have to be adjusted for enhancing its effectiveness.

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[22] The FCC changes data collection of wireline competition of broadband Interent access since 2008. BISPs have to report subscriber number, transmission rates, and service availability by census block level.

4.3.3 Evaluation of municipal Subsidy between profit-oriented project and municipal-target project

The simulated model with empirical data enables us to analyze the feasibility of citywide WiFi solutions from different points of view. The NPV outputs from the simulation model provide valuable information to determine whether a project is sustainable. In addition, our techno-economic model can be a useful tool to not only explain why many projects were withdrawn or suspended but also calculate the required subsidy from the municipality to make them sustainable. If the municipal subsidy has become necessary to support citywide WiFi projects, determining the size of subsidy would be a useful question to answer. We take following steps to estimate the subsidy amount for network deployment and business operations to make a WiFi network breakeven.

(1) Draw a chart with population percentage versus land percentage: Divide each census block's population by its land size, each census block's population by city's population and each census block's land size by city's land size to obtain population density, population percentage and land percentage of each census block. Sort population density of each census block to draw a chart with population percentage versus land percentage.[23] The purpose of creating the chart is to understand the degree of population aggregation for existing WiFi cities, because most people live in a small portion of the land area. The information is critical to build the relationship between population and network size. Figure 4:7 is an example of ths kind of cumulative graph (for Minneapolis MN). The degree of

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[23] From the US Census Bureau's 2002 data

population aggregation in Minneapolis, MN is significant, where 60% of population lives in less than one-fourth of the land area and 100% population lives in three-quarters of the land. The figure shows that more than 75% land coverage WiFi project would be impossible for a profit-oriented WiFi project without municipal subsidy.

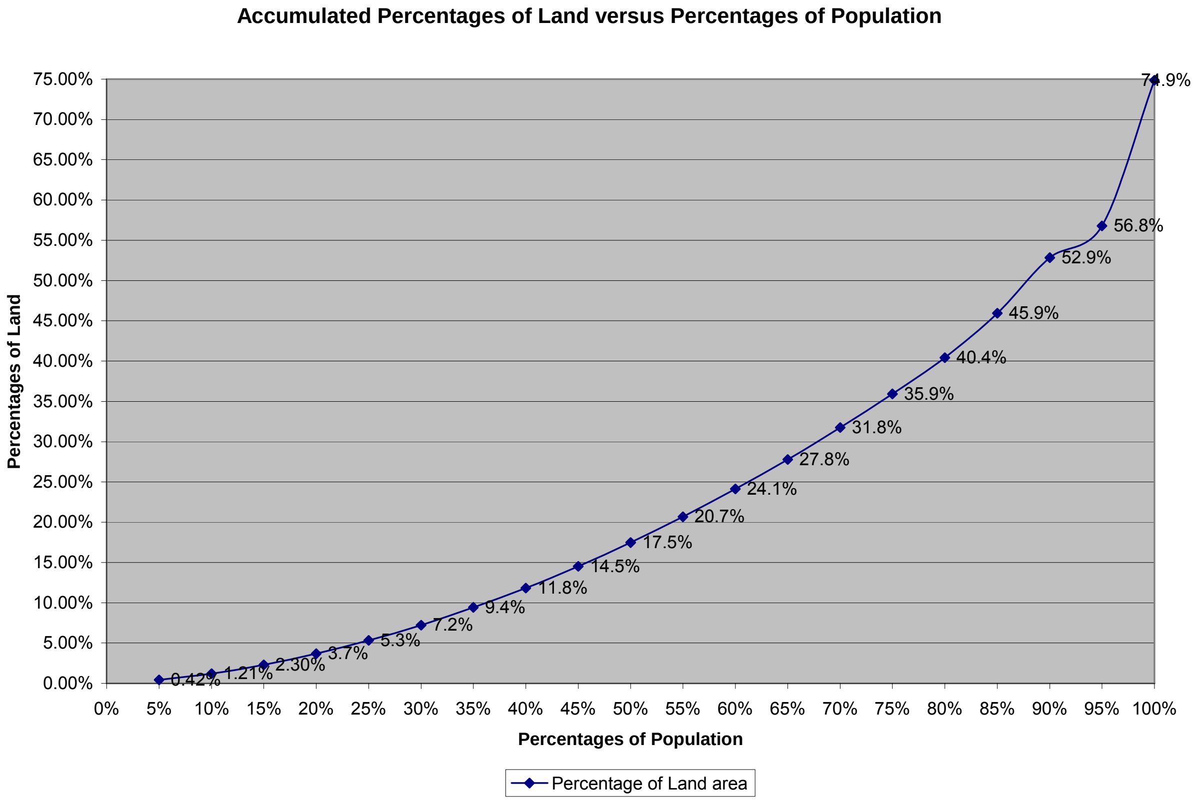

Figure 4:7 Accumulated Land Percentages versus Population Percentages in Minneapolis

(2) Find an optimal network size: After applying data for population percentage and land size from step1 into the techno-economic model, we can compute the optimal network size is for a profit-oriented project. Optimal network size means the minimal network area, covering the dense population areas that maximize profit.

(3) Evaluate the subsidy for a 100% land coverage project: A citywide municipal WiFi project providing public safety service and other municipal applications usually require 100% land coverage. The estimated NPV value, NPV(100%land), for a 100% land coverage project can be calculated using our techno-economic model with different AP density requirements for populated and unpopulated areas. The estimated number is the benchmark for municipalities to determine how much subsidy for a 100% land covered project is needed to achieve breakeven.

(4) Evaluate a reasonable subsidy for a private WiFi ISP to participate in 100% land coverage project: The sum of NPV value obtained from step (2) and step (3) is the reasonable value to encourage private WiFi ISPs to be a partner to build and operate a 100% land coverage WiFi network, because its expected profit from limited land coverage and potential loss from 100% land coverage are fully compensated in the subsidy, shown in equation (27).

$$NPV(subsidy) = NPV(\max) + |NPV(100\% land)| \ldots.(27)$$

5.0 COMPARISON BETWEEN CITIES WITH AND WITHOUT CITYWIDE MUNICIPAL WIFI

This chapter presents the results of the first part of our research. Section 5.1 performs a quantitative comparison of social-economic and geo-demographic data collection between WiFi cities and non-WiFi cities. Section 5.2 discusses roles, business model, location, price and service, and free service for citywide municipal WiFi projects.

5.1 QUANTITATIVE COMPARISON OF SOCIAL-ECONOMIC AND GEO-DEMOGRAPHIC DATA

In this section, we compare cities with qualifying municipal WiFi networks to cities that do not have them. The objective of this study is to test the research hypotheses described in Section 4.1.2 This section adopts three statistical procedures to determine what factors might be useful in explaining the presence of WiFi in some cities and not in others. The first step is to compute the mean of each variable for WiFi cities and Non-WiFi cities. Then, we perform two sided t-tests for means on both groups. The next step is to conduct a stepwise selection to eliminate non-significant variables using the 5% criterion for a logit regression.

5.1.1 Data characteristics

The descriptive statistics of each variable for WiFi cities and non-WiFi cities with Set A and Set B are shown in Table 5.1, Table 5.2 and Table 5.3, respectively. We will compare both groups using a two-sided t-test at 5% and 1% significant levels.

Table 5-1 Descriptive Statistics of WiFi cities

Aspects	*Variables*	*With citywide WiFi*				
		Median	*Mean*	*S.D.*	*Max*	*Min*
Geographic	Population	43,436	84,081	102,983	382,618	4,531
	Land size(sq mile)	12.75	20.78	19.27	73	3.76
	Population density(per sq mile)	3,422	3,836	2,178	7,664	709
Racial profile	White	70.6%	71.9%	17.4%	94.5%	26.9%
	Black	2.4%	3.6%	4.2%	18.0%	0.3%
	American Indian	.6%	.9%	.7%	2.4%	0.1%
	Asia	4.3%	11.6%	15.4%	58.4%	0.5%
	Hispanic	17.0%	18.8%	12.3%	46.8%	4.5%
Age	Median age	33.7	33.7	3.4	41.7	28.7
Housing	# of occupied house	14,225	31,419	39,249	162,352	2,165
	% of occupied	96.3%	92.8%	12.7%	98.6%	40.2%
	Homeownership	58.4%	59.0%	15.4%	83.5%	20.7%
Education	High school	87.3%	85.6%	7.3%	96.2%	69.3%
	Bachelor degree	31.7%	34.4%	15.0%	60.9%	13.8%
Income	Household income	49,870	53,654	16,029	95,279	34,781
	Capita income	24,068	26,409	9,368	45,754	15,509
	House value	169,450	243,535	173,038	575,000	83,600
Poverty	Family below poverty	5.1%	5.8%	2.9%	12.6%	1.7%

	Individual below poverty	7.8%	8.7%	3.9%	16.3%	2.9%

Table 5-2 Descriptive Statistics of Non-WiFi Cities Set A

Aspects	*Variables*	*Without citywide WiFi*				
		Median	*Mean*	*S.D.*	*Max*	*Min*
Geographic	Population	6,370	28,672	47,775	247,057	62
	Land size(sq mile)	2.8	14.5	29.2	203.6	0.2
	Population density(per sq mile)	1,501	2,496	2,695	14,779	3
Racial profile	White	82.3%	77.1%	20.6%	100.0%	21.3%
	Black	1.0%	5.4%	12.2%	67.8%	0.0%
	American Indian	0.7%	1.2%	1.9%	14.1%	0.0%
	Asia	1.1%	4.8%	10.2%	61.8%	0.0%
	Hispanic	14.2%	20.9%	22.6%	93.6%	0.0%
Age	Median age	36.1	36.9	7.0	60.4	22.7
Housing	# of occupied house	2,354	10,016	16,468	83,441	26
	% of occupied	93.4%	91.0%	8.1%	98.4%	56.4%
	Homeownership	66.9%	67.3%	13.2%	97.1%	29.8%
Education	High school	77.0%	76.5%	12.5%	98.8%	39.5%
	Bachelor degree	15.8%	19.7%	14.9%	75.4%	0.0%
Income	Household income	34,920	42,288	19,752	130,796	20,625
	Capita income	17,264	21,280	14,144	113,595	9,524
	House value	99,100	162,191	173,137	1,000,001	10,000
Poverty	Family below poverty	8.1%	10.1%	6.8%	34.1%	0.0%
	Individual below poverty	12.6%	13.6%	7.2%	35.2%	2.0%

Table 5-3 Descriptive Statistics of Non-WiFi Cities Set B

Aspects	*Variables*	*Without citywide WiFi*				
		Median	*Mean*	*S.D.*	*Max*	*Min*
Geographic	Population	2,108	7877	13,933	78452	14
	Land size(sq mile)	1.935	4.84	7.5	45.84	0.03
	Population density(per sq mile)	1,176	1,938	2,611	16,018	19.6
Racial profile	White	92.3%	84.2%	16.9%	100.0%	32.8%
	Black	0.9%	8.3%	16.6%	89.6%	0.0%
	American Indian	0.3%	0.7%	1.3%	8.5%	0.0%
	Asia	0.4%	2.1%	0.6%	44.8%	0.0%
	Hispanic	3.15%	9.4%	18.1%	97%	0.0%
Age	Median age	36.6	37.69	5.42	52.3	23.4
Housing	# of occupied house	766	2,756	5,256	33,509	2
	% of occupied	92.5%	88.1%	14.9%	99%	21.2%
	Homeownership	70.5%	69.8%	13.4%	98.1%	17.3%
Education	High school	81.2%	78.9%	12.9%	98.6%	33.2%
	Bachelor degree	15.8%	20.4%	15.1%	77.5%	0.02%
Income	Household income	37,660	44,159	26,524	192,037	14,500
	Capita income	17,986	23,985	22,358	137,382	7,078
	House value	92,650	148,621	169,673	1,000,001	16,300
Poverty	Family below poverty	7.7%	10.59%	9.2%	40.4%	0.0%
	Individual below poverty	9.8%	13.6%	10.4%	44.3%	0.0%

5.1.2 T-tests

We separated the collected data into “WiFi cities” and “non-WiFi cities” with Set A and Set B, and performed two-sided t-tests for all 19 variables for both sets. The two-sided t-test is widely used to determine whether sample means are statistically different. Along with the t-values of each variable, SAS converts these values into two-tailed probability values for each variable and the degrees of freedom. The results of the t-test, p-value, and 5% and 1% statistical significance of each variable are shown in Table 5.4 and Table 5.5, respectively. They also offer evidence to determine whether the hypotheses of Chapter 4 can be accepted or rejected.

The outcome of the two-side t-tests for Set A shows that population and population density, median age, number of occupied houses and home ownership, high school graduates and bachelor degrees, household income, and family below poverty and individual below poverty are different at 5% level. In addition, age, education level, and poverty are different at 1% level. According to the results, there are ten variables in six categories with 5% significance and five variables in three categories with 1% significance. The racial profile is the only category without significance. Therefore, H2 is rejected (that racial profile of municipalities does not influence citywide WiFi implementation). At the 1% level, H3, H5 and H7 are accepted (that age, and education level have positive influence and poverty has negative influence on citywide WiFi implementation).

The outcome of two-side t-tests for Set B shows that only American Indian, percentage of house occupied, and income have no difference at 5% level. In addition, the geographic hypothesis and the racial profile hypothesis are rejected in Set A but are accepted in Set B. There are two reasons to explain the differences in geography variables and racial profile variables. The great differences of geographic variables of Set B might be caused by different definitions of a municipality from each state, because cities without WiFi in Set B are sampled from 50 States which brings more of small cities into Set B. The statistical differences of racial profile in Set B for White people and Hispanic people might be a result of the fact that 70% of citywide WiFi projects coming from California, Texas, Arizona, and Florida, which have higher percentages of Hispanic people than other states. At the 1% level, H3, H5 and H7 are accepted in both Set A and Set B. It means that these hypotheses are robust and can be verified through different sample methods. Therefore, municipalities with citywide WiFi have younger median age, higher education level and fewer families below the poverty level than municipalities without citywide WiFi.

Table 5-4 Result s of Two-side t-tests (Set A)

Aspects	Variable	Two-side t-tests			
		t-value	P-value	5%	1%
Geographic	Population	2.344	0.029	Yes	No
	Land size	1.166	0.2499	No	No
	Population density	2.34	0.0251	Yes	No
Racial profile	White	-1.149	0.2585	No	No
	Black	-1.08	0.2829	No	No
	American Indian	-1.046	0.2984	No	No
	Asian	1.871	0.0739	No	No
	Hispanic	-0.585	0.561	No	No
Age	Median age	-2.896	0.0056	Yes	Yes
Housing	Number of occupied house	2.387	0.0266	Yes	No

	Percentage of occupied house	0.602	0.5534	No	No
	Homeownership	-2.218	0.0353	Yes	No
Education	High school graduates	4.218	0.0001	Yes	Yes
	Bachelor or higher degrees	3.902	0.0005	Yes	Yes
Income	Household income	2.7	0.0106	Yes	No
	Capita income	1.954	0.0571	No	No
	House value	1.88	0.0701	No	No
Poverty	Family below poverty	-4.389	0.0001	Yes	Yes
	Individual below poverty	-4.115	0.0001	Yes	yes

Table 5-5 Result s of Two-side t-tests (Set B)

Aspects	Variable	Two-side t-tests			
		t-value	P-value	5%	1%
Geographic	Population	3.301	0.0037	Yes	Yes
	Land size	3.631	0.0016	Yes	Yes
	Population density	3.34	0.002	Yes	Yes
Racial profile	White	-2.853	0.008	Yes	Yes
	Black	-2.268	0.0256	Yes	No
	American Indian	0.983	0.3532	No	No
	Asian	2.731	0.0132	Yes	No
	Hispanic	2.737	0.009	Yes	Yes
Age	Median age	-4.074	0.0002	Yes	Yes
Housing	Number of occupied house	3.259	0.0041	Yes	Yes
	Percentage of occupied house	1.435	0.1607	No	No
	Homeownership	-2.878	0.0078	Yes	No

Education	High school graduates	3.077	0.0033	Yes	Yes
	Bachelor or higher degrees	3.694	0.0009	Yes	Yes
Income	Household income	2.041	0.0467	Yes	No
	Capita income	0.743	0.4597	No	No
	House value	2.041	0.0467	Yes	No
Poverty	Family below poverty	-3.994	0.0001	Yes	Yes
	Individual below poverty	-3.375	0.0011	Yes	yes

5.1.3 Stepwise variable selection of Logit regression

According to the result of previous section, there are ten variables with 5% significance of a total of 19 variables. In order to eliminate superfluous variables, we performed a stepwise variable selection to figure out the best combination of variables. This method starts with a single variable, and then increases the number of variables step by step. After a new variable has been inserted, all selected variables are also tested to verify whether their contribution for the dependent variable is significance. The criterion is 5% to decide whether a variable is selected or not.

After stepwise variable selection, median age, bachelor degree and family below poverty are the only three variables remained. Based on the result of t-tests, all three selected variables have 1% significance. The linear relationship between implementing citywide WiFi municipalities and three significant variables is described in the following Logit regression.

$$Y(citywide\_WiFi) = 10.38 - .33 \times age_{median} + 5.96 \times education_{bachelor} - 33.25 \times poverty_{family}$$

5.2 FEATURES OF CITYWIDE MUNICIPAL WIFI

This section addresses roles of municipality, business model, location, price and service, and free service, respectively, to provide a comprehensible description for the features of citywide municipal WiFi projects.

5.2.1 Roles of municipalities

Municipal involvement is critical for the citywide WiFi projects in this study by definition. After analyzing all citywide municipal WiFi projects, we determined that there were five major roles of the municipality: investor, operator, anchor user, facilitator, and supervisor. In some cases, a municipality can play multiple roles in a citywide WiFi project. For example, it can be a facilitator and a supervisor, because a municipality can support and monitor a WiFi support at the same time. On the other hand, if a municipality is an operator, it cannot also be a supervisor, because the roles of player and a referee conflict. The taxonomy of local government roles from previous literature in municipal broadband was classified as stimulator of demand, rule-maker, source of funds, and developer of infrastructure.[31]

(1) *Investor* The municipality provides financial support for its WiFi project. The types of financial support can be direct funding by tax money, issuing municipal bonds, and/or indirect funding by asking its municipality utility to invest, guaranteeing the project's liability, etc.. Municipalities can mix several funding sources to sponsor WiFi projects. In the 20 qualifying municipal WiFi projects, only five municipalities act as investor. In addition, these municipalities act as investors in small WiFi

projects, because the coverage of these WiFi cities is less than 15 square miles and funding requirement is lower.

(2) *Operator* The municipality manages the WiFi network by assigning municipal employees or employees of its public utility to the project. Municipalities do not have expertise in wireless network operation and management, so this is an uncommon role. Only Granbury in Texas acts as operator for its WiFi network. This town is small with land area less than 5.5 square miles and population less than 6,000. In another case, St Cloud provided customer service by itself in early in their project's operating period, but since then it has out-sourced its operation to HP.

(3) *Anchor user* Some municipalities trade the right of street lights attachment to WISP for WiFi accounts with no payment. It seems that the municipality as anchor user is more apt than the municipality as anchor tenant to characterize its role in the WiFi system. There are 13 cities that act as an anchor user for WiFi network, which amounts to 65% of all cases.

(4) *Facilitator* The process of taking a citywide WiFi project from an idea to an operating WiFi service can take several years. There are numerous political, financial and technical challenges to be solved[24]. In our research, only Mountain View and Galt in California projects required minimal municipal support; other projects need some financial and non-financial support from the municipality. Actually, municipalities are a key stakeholder in citywide WiFi projects in all business models. The outcome of WiFi project affects not only its mayor's political credibility but also

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[24] Details see http://www.wi-fiplanet.com/tutorials/article.php/3620836

the social welfare of its residents and its business development. In our analysis, we separate the municipal role of facilitator into two stages.

- *Planning and evaluation stage* Citywide municipal WiFi does not have any model to follow that guarantees success. Although the free service model of St. Cloud, FL is attractive, other municipalities may not have enough resources to emulate it. To take a citywide WiFi from an idea to a workable project requires that municipalities consider the details of network deployment and operation and evaluate all possible business models and their risk.
- *Assistance in problem solving in deployment and operation stage* It is difficult to predict all possible difficulties during design period. Each WiFi project may confront different problems in planning, deployment and operation. Even in a franchise business model, where the municipality does not bear financial risk in the WiFi project, the municipality must still do its best to help the WISP overcome obstacles for the project to progress. Delay or failure of the WiFi project causes not only the loss of social welfare but also political risk to the municipality.

In our survey, 18 cities acted as facilitator for a WiFi project. Google's project in Mountain View and Softcom project in Galt are exceptions, because Google initiated and fully sponsored the project to provide purely free WiFi service. The main municipal relationship between Mountain View municipality and Google is the leasing contract for municipality-owned streets lights. Softcom installed access point on the roof of subscribers' house instead of leasing utility poles from municipalities.

After providing Internet access for the residents, this WiFi ISP collaborates with local government to offer public service for the municipality.

(5) *Supervisor* Either the municipality has to invest in WiFi project or has to offer the franchise right to a BISP to build and operate the network. If the network is built and operated by a municipality, the role of the municipality cannot be a supervisor, because the roles pose a conflict of interest. However, municipalities can out-source their network operation and focus on its role as supervisor. Lompoc in California, St Cloud in Florida and Chaska in Minnesota are three cities that out-sourced their operation.

In the franchise projects, even though there was no capital investment, municipalities also have responsibility to monitor the network operation and service quality. Its supervisory roles for franchise WiFi project can be separated into five stages.

- *The first stage* Evaluating potential WISPs to select the most suitable one for awarding the franchise right.
- *The second stage* Negotiating the content of contract with the awarded BISP to determine municipal usage, location and the leasing fee for access point attachment, warranty amount, and the contract period.
- *The third stage* Testing the coverage, transmission rates, and reliability of the trial site. After all requirements have been accepted, the municipality approves that the BISP can deploy other parts of the WiFi network.
- *The fourth stage* Monitoring the deployment schedule of citywide network and testing the whole network to make sure the quality of service can match the requirement depicted in the contract.

- *The fifth stage* Monitoring the financial capability and customer service of the BISP. If the connection quality and transmission rates are lower than expected, the municipality can require BISP to improve and upgrade the network. If the BISP cannot match the requirement form the contract in required period, the municipality can terminate the contract.

Granbury in Texas is the only city that operates their network and cannot act as supervisor. All other municipalities have to allocate resources to monitor the performance of WiFi project.

Table 5-6 Roles of Municipalities

	Facilitator	Investor	Anchor user	Operator	Supervisor
Number of yes (percentage)	18 (90%)	5 (25%)	13 (65%)	1 (5%)	19 (95%)

5.2.2 Business models

The business model for citywide municipal WiFi can change dynamically. For example, even if the ownership of the WiFi project was decided before network deployment, a municipality and a private WISP can reach an agreement to change the ownership and operation of the system. This can happen at any stage of system deployment. This is illustrated by the cases of Granbury, Texas, which bought its network back from its WISP for $225,000.[70]

Previous literature classified municipal broadband into different business models by various characteristics and features. Gillett et al., proposed four business models for municipal fiber network as retail service, wholesale service, franchise model, real estate, coordination model. [71] Tapia et al., classified business models as community, public utility, private consortium, cooperative wholesale by ownership and cooperation relationship. [49] Although the FTC categorizes municipal wireless into six operating models: non-profit, cooperative, contract out, public-private partnership, municipal and government loan-grant, some of them cannot be found in qualified citywide WiFi projects.[72] Bar proposes nine business models of municipal WiFi to cover all kinds of possibilities comprehensively, but they are too many to reveal the key features of citywide WiFi projects obviously.[29]

We find another 2 by 2 matrix classification by access charge and ownership to be useful for our purposes. In order to emphasize the characteristic of free broadband service of citywide municipal WiFi, we adopt free or fee as the first index to distinguish among citywide municipal WiFi business models, because the advantages from unlicensed spectrum and low deployment cost can enable WiFi project to provide free Internet access. Free broadband access has not been found in other fixed and mobile broadband service.

While all citywide municipal WiFi projects can be separated into a free or fee model, there is a significant variance in what constitutes "free" service. Most citywide projects offer some limited free service. Thus, we define the free model as one which offers free public access without restrictions in location and usage time.

Within the free model, there are two types of business models depending on the ownership of network. One is the community model with free public access provided by its municipality. St Cloud in Florida is the representative case, which owns the network and has provided free Internet access since 2005, with excellent user satisfaction.[35] The other type is free franchise model with service provided by a private WISP. Google's Mountain View is one of the cases to provide pure free WiFi access. MetroFi's free Internet access with advertisement is other case in free franchise model. Although free WiFi with advertisement support has not been proved feasible yet, MetroFi offered this option for free broadband access.

In the fee model, there are also two types of business models. One is the municipal utility model with affordable Internet access provided by the municipality. In most cases, municipalities can not fully absorb the WiFi deployment, operation, and upgrade costs. Thus, revenue coming from public access is a critical part of the citywide project. Chaska, Minnesota is a representative case that has offered affordable broadband service since 2004 to reach its goals of availability and affordability.[73] The other is business model is franchise model with fee-based Internet access provided by a private WISP. EarthLink and MobilePro are two representative WISPs in this business model.

In our survey, there are six cities that chose the free model. Only one of them uses the community model and five use the free-franchise model. In the fee model, five use the public utility model and ten the fee-franchise model. It is clear that free public Internet access with no limitation in location and time is not common at this moment. In addition, over 71% of citywide project adopted a fee model to use public access as one of main revenue sources.

Table 5-7 Business Models

Ownership Access Charge	Public	Private
Fee Number (percent)	Public Utility 4 (20%)	Fee Franchise 10 (50%)
Free Number (percent)	Community 1 (5%)	Free Franchise 5 (25%)

5.2.3 The distribution of citywide municipal WiFi

There are 20 qualified citywide municipal WiFi projects in our data set, and they are concentrated in seven states. Nine of these projects are located in California, three projects in Texas, and three in Minnesota. The dispersion of citywide WiFi is not balanced through the U.S., because there are 16 citywide WiFi projects locate in southwest states, three projects in plains states and one projects in south east. There are two factors that might explain the location imbalance. First, major citywide WISPs as EarthLink, MobilePro, and MetroFi invested twelve cities in California and Texas. This might have been a matter of corporate policy. But it can be much easier to build a citywide project in neighboring cities, because some potential problems have been solved and WiFi networks have the possibility to be connected together to create some synergy. This remains a question to be researched further.

Table 5-8 The Distribution of Citywide Municipal WiFi

States	Number of Citywide Municipal WiFi
Arizona	1
California	9
Colorado	2
Florida	1
Minnesota	3
New Mexico	1
Texas	3

5.2.4 Public access price and service level

With low deployment cost and unlicensed spectrum, WiFi has an advantage in providing affordable broadband service for public access. In our survey, the average charge for regular broadband connections verifies this assumption. There are six projects with free public access and the average WiFi monthly fee is $22.38 per month for lowest transmission service. In addition, only three projects charge more than $20 per month. One is a resort town (Vail, Colorado) and the other two are Cerritos and Galt, California. In our survey, we compare the lowest download speed of WiFi service. There are 15 projects that provide 1 Mbps download as their basic service. More generally, we find that the speed is between 0.3 Mbps to 4 Mbps with average rate 1.1 Mbps.

Table 5-9 Service Price and Transmission Rates of Citywide WiFi

	Median	Mean	Standard deviation	Maximum	Minimum
Service price (per month)	$19.95	$22.38 (free service excluded)	$12.68 (free service excluded)	$59.95	$0
Transmission rates (Mbps) downstream	1 Mbps	1.11 Mbps	0.77 Mbps	4Mbps	0.3 Mbps

5.2.5 Free Service

There are different kinds of limited free service supported by citywide municipal WiFi. Limited free service can be free access for the municipal portal, limited time free access, downtown, park and library free service, limited transmission rate free access, and advertisement-supported free access. Nearly all citywide municipal WiFi projects provide some limited free broadband access. Compared with the other broadband technology, WiFi has a clear advantage in providing some kind of free public access.

Table 5-10 Type of Free Service

Type of Free Service	No Restriction	Time Restriction	Location Restriction	Transmission Rates Restriction	Advertisement sponsor
Number of yes (percentage)	2 (10%)	5 (20%)	6 (30%)	5 (20%)	4 (20%)

6.0 ACCESS POINT DENSITY AND NETWORK COVERAGE

This chapter performs the technological calculation of our simulated model to identify the equipment investment and decide the suitable access point density with different path loss factor for a medium city. Section 6.1 discusses the relationship between access point density and network coverage for both outdoor and outdoor to indoor access environments. Section 6.2 performs a techno-economic analysis to evaluate profit and loss of a WiFi project with different access point density and marketing strategies.

6.1 THE RELATIONSHIP BETWEEN ACCESS POINT DENSITY AND NETWORK COVERAGE

6.1.1 Basic information of WiFi access equipment and wireless environmental factors

To link access point density and network coverage, we conducted a survey to understand the specifications of transmission power, receive sensitivity, and antenna gain for these basic components of access layer. The survey results show that AP and CPE manufacturers adopt the combination of high transmission power and high gain antenna for outdoor commercial WiFi access point to extend the WiFi cell as well as enhance connection quality, the design of WiFi enabled client devices, however, are targeted for short distance access with limited transmission power, antenna gain, and receive sensitivity. (Table 6-1) Environment factors of WiFi access are based on the research described in Chapter 4 and summarized in Table 10. We used the upstream connection, from client device to AP, to calculate the relationship between AP density and network coverage, because the upstream connection with weak transmission power and low antenna gain from the client device is more challenging than downstream connections with high transmission power and antenna gain.

Table 6-1 WiFi System Information

	Transmission Power	Receive Sensitivity (1 Mbps)	Antenna Gain (Omni antenna)
Access Point (dBm)	200~400mW (23~26dBm)	100 dBm	10~13 dBi
Client Device	15~50mW (11.7~17dBm)	93~95 dBm	0~3 dBi
WiFi bridge (CPE)	100~400mW (20~26dBm)	98~100 dBm	10~13 dBi

Source: [74] , [75] ,[76], [77], [78]

Table 6-2 Environment Parameters of WiFi Access

Environment Factor	Path Loss Factor	Shadow Fading	Multi-path Fading	Outdoor to Indoor power Reduction
Value	3.3~3.7	7 dB	8dB	6~9 dB

Source: [58], [41], [59], [79]

6.1.2 Outdoor WiFi network coverage

In the outdoor scenario, link budget is determined by the fixed parameters mentioned in Table 6-1 and Table 6-2. According to equation (9) in Section 4.2.1, K becomes a constant as link budget and the path loss factor are fixed. The linear relationship between network coverage and AP density is described below.

By holding all parameters constant and increasing the path loss factor from 3.3 to 3.7, Figure 6-1 and Figure 6-2 show the relationship between AP density and network coverage with different path loss factor for household client device and public safety client device with a high gain antenna, respectively. In this figure, the path loss factor is the slope of each line and affects the required AP density to reach 100% network coverage. As the path loss factor tends towards 3.7, 100% network coverage for outdoor access requires 65 APs per square mile. In addition, Figure 6.2 presents the tradeoff between network coverage and AP density, Municipalities and WiFi ISPs can build a one square mile WiFi trial site to measure path loss and fading factors to determine the required AP density for achieving a specific network coverage requirement.

$$Network\_Coverage_{percentage} = \frac{N \times \pi \times (Poewer[10,(L_{path} - 40)/(10 \times \alpha)])^2}{1600^2} \propto N \times K \ldots (9)$$

Table 6-3 WiFi Equipment parameters for Outdoor Access

	Transmission Power	Receive Sensitivity (1 Mbps)	Antenna Gain
Access Point (dBm)	200mW (23dBm)	100 dBm	13 dBi
Client Device	30mW (15dBm)	94 dBm	2 dBi
Client Device Public safety	30mW	94 dBm	12 dBi

Source: Average value of Table 5-9

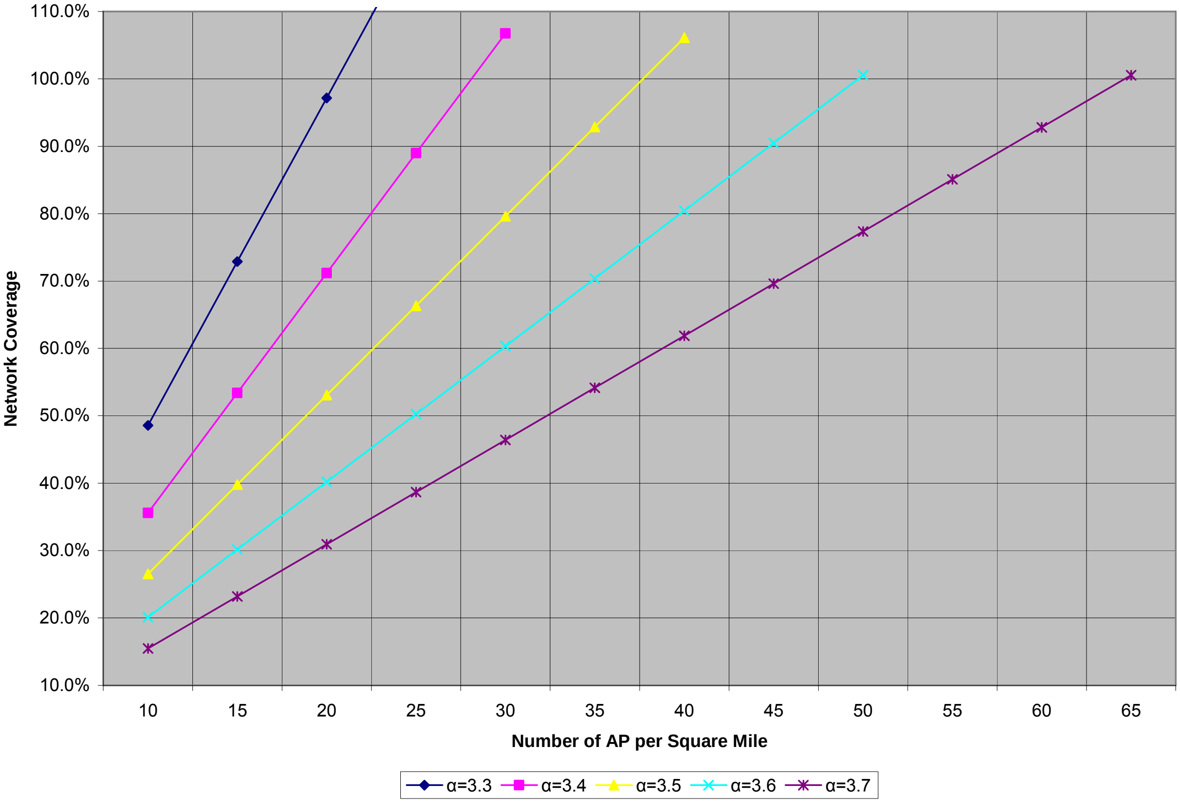

Figure 6:1 Outdoor WiFi network coverage

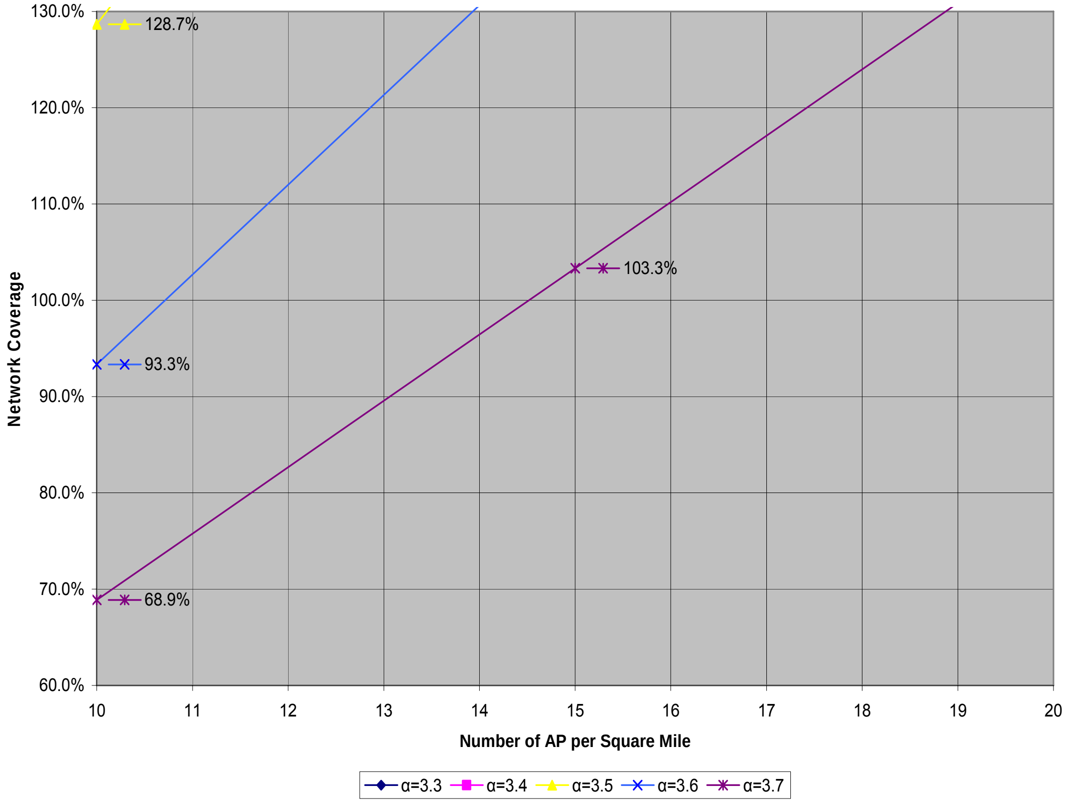

Figure 6:2 Outdoor WiFi Coverage for Municipal Applications with High Gain Antenna

6.1.3 Outdoor to indoor WiFi Network Coverage

We perform a further analysis to evaluate an outdoor to indoor access environment. Potential WiFi customers, residents and small or medium business, access the Internet in the home or office. It can be inconvenient to move WiFi enabled devices close to a window or yard for a better WiFi connection. The signal strength reduction, however, cannot be avoided when the signal passes through walls, windows and other obstructions. In this section, we compare the difference of required AP density between outdoor access and outdoor to indoor access (indoor). Because of the high AP density requirement for attaining 100% indoor network coverage, we also discuss outdoor to indoor access with assistance from WiFi bridge (customer premise equipment, CPE).

(1) Comparison between outdoor access and indoor access

The path loss increases by 7.5 dB[25] for indoor access, because we believe the advantage of wireless ubiquitous access from WiFi should enable subscribers to access the Internet anywhere from their home or office.[79] Therefore, a 7.5 dB power reduction should be a reasonable assumption to ensure WiFi signal can cover most places inside a building. The parameters for AP and CPE are described in table 5-12. According to Figure 6-2, by keeping other parameters constant and increasing the indoor path loss from zero to 7.5 dBm, the required AP density for 100 percent coverage is over 55 AP per square mile using path loss factor 3.3. If the path loss factor moves towards 3.6 and 3.7, even 100 APs per square mile can not achieve 100% indoor coverage. Comparing Figure 6.1 and Figure 6.2, even though the AP density doubles, the indoor network coverage is still less than the outdoor network coverage. For example, 60% indoor network coverage requires 100 APs per square mile with path loss factor 3.7, however, 60% outdoor network coverage only needs 40 APs per square mile.

(2) Comparison between outdoor to indoor access with and without CPE

According to Figure 6-3, with a high path loss factor, 100% network coverage is hard to realize only by increasing AP density. The common solution is to install customer premise equipment (CPE) to enhance transmission power, receive sensitivity, and antenna gain. Therefore, we analyze how much network coverage can be expanded by a high-end CPE to

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[25] http://www.connect802.com/wcu/2005/newsletter_051101.htm#tech_eng "In our experience, in a typical indoor residential or office building with drywall construction, an increase in power of roughly 6 to 9 dB is required before you see a significant increase in coverage" So we choose the middle point 7.5 dBm between 6 to 9 dB as the power loss for indoor coverage.

determine the relationship between AP density and network coverage for indoor access. The parameters of a high-end CPE are depicted in Table 6-4.

Figure 6.4 shows that network coverage can be enhanced by CPE. If path loss factor is as low as 3.3, ten APs per square mile can attain 100% indoor coverage. If path loss factor moves up to 3.7, 35 APs per square mile also can reach 100% coverage. It sheds some light that CPE can offer effective expansion of network coverage instead of boosting AP density. Therefore, we will discuss two WiFi marketing strategies "with free CPE" and "without free CPE" in our baseline model.

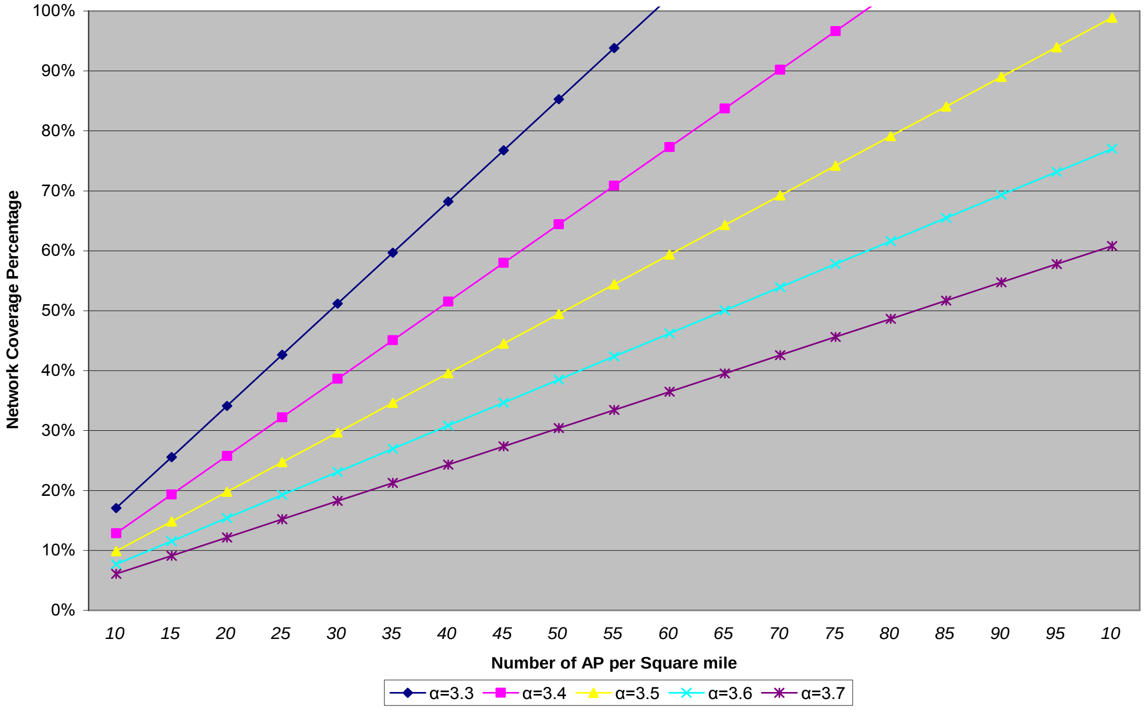

Figure 6:3 Outdoor to indoor WiFi network coverage with 7.5 dB power reduction

Table 6-4 WiFi Equipment Assumptions for Outdoor to Indoor Access

	Transmission Power	Receive Sensitivity (1 Mbps)	Antenna Gain
Access Point (dBm)	200W (23dBm)	100 dBm	13 dBi
WiFi Bridge(CPE)	200mW (23dBm)	100 dBm	12 dBi

Source: Based on major AP and WiFi bridge vendors [77, 78, 80],

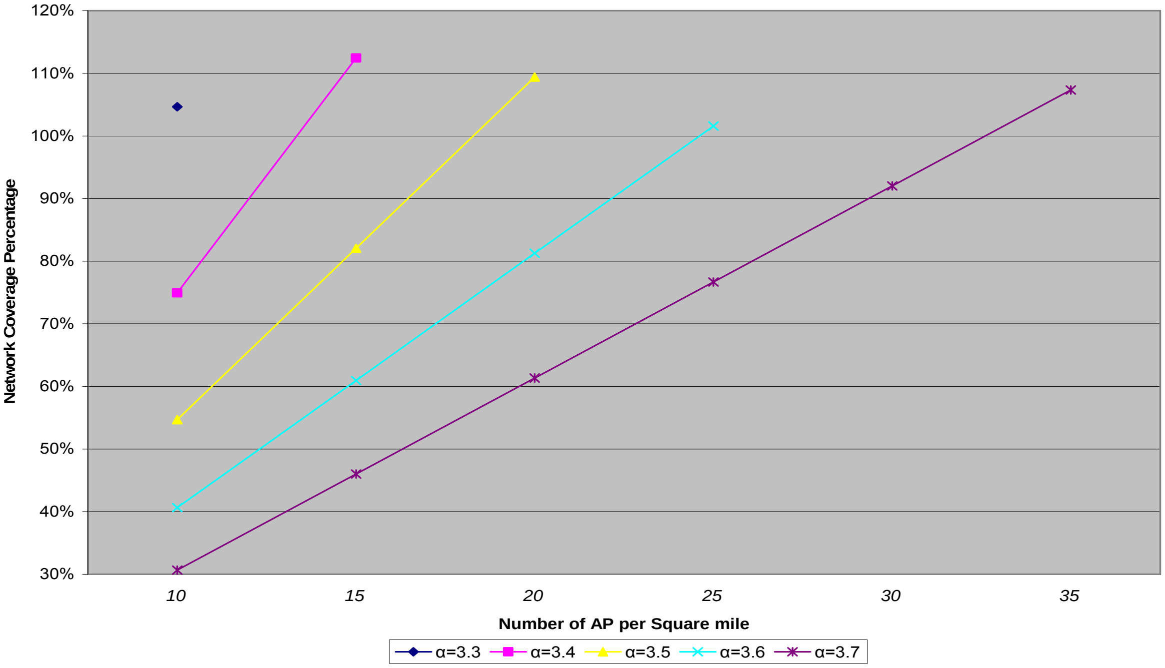

Figure 6:4 Outdoor to indoor WiFi network coverage with 7.5 dB power reduction and a CPE

6.2 A BASELINE TECHNO-ECONOMIC MODEL FOR A MEDIUM CITY

6.2.1 Model Description

This techno-economic model presents an end to end WiFi network, covering backhaul hub, aggregate node, gateway node, access point, and CPE. In order to design a robust WiFi network, the assumptions of two-layer network design are based on Chapter 3 with following equipment ratios: the ratio between assess points and gateway nodes is 6 to1, and the ratio between gateway node to aggregate node is 20 to 1. The oversubscription rate of Internet access subscriber is 6 to1[26].[81] Each aggregate node connects a fiber loop to the backhaul hub for Internet transit. The network design fee and cost for OSS are treated as 3% and 4% of the total construction cost, respectively. In addition to the one time cost of the 1st year network construction, marketing, customer service, administration, accounting, billing, pole and office leasing, Internet transit of backhaul, and network maintenance and management costs are calculated each year. The time frame of a WiFi network is five years with 10% discount rate.

The unique feature of the revenue estimation of this techno-economic model is to quantify network design, price competition and types of potential subscribers. In order to simulate the actual WiFi market and access environment, this model adopts two parameters to estimate subscription rates of four groups, non-Internet access, dial-up, broadband, and small

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[26] A T1 circuit usually can support a WiFi network around 100-200 users depending on their bandwidth requirements. Most WISPs over subscribe their network on a 6:1 ratio. “How Much Internet Bandwidth Does My Town Really Need to Build a Wireless ISP” http://www.bbwexchange.com/howto/4_how_much_bandwidth.asp

and medium business, by access point density and price differences between WiFi and fixed broadband.

We choose a medium sized city with 250,000 people and a 50 square mile land area to build a baseline model for evaluating the sustainability of a WiFi project. The model considers two marketing strategies: One is WiFi service with no free CPE, the other is WiFi service with free CPE and installation, because the previous section indicates that 100% network coverage for reliable indoor Internet connection is hard to achieve by increasing the number of access point per square mile without assistance from CPE. Parameters of geo-demographic parameters are mentioned in Appendix 2, estimations of subscription rates from different customer types are described in Appendix 3, and parameters of network construction cost and operation cost are depicted in Appendix 4 and Appendix 5, respectively. The relationship between access point density and network coverage is adopted from previous section.

6.2.2 Results

According the results from previous section, 100% network coverage with reliable indoor Internet connection can be achieved by 35 AP per square mile with CPE, so we only calculate its AP density from 10 to 35 nodes per square mile. WiFi service without CPE requires more than 100 APs per square mile to achieve reliable indoor Internet connection, so the calculation goes from 10 nodes to 100 nodes. Figure 6:4 shows this comparison. There is a significant difference in total costs for ten APs per square mile but the difference in total costs is reduced as the density of AP increases. The revenues of the two types of WiFi service are widely different (Figure 6:5). With 35 nodes, the revenue of service with free CPE is over $25 million but service without free CPE is less than $10 million because CPE can extend the network coverage from 35% to 100% and increase the subscription rate. Based on the profits of two services (Figure6-5 and Figure 6-6), no matter how many access points per square mile, WiFi service without CPE is not profitable. WiFi service with free CPE can make a profit from 30 nodes to 35 nodes, but the project is still risky. We assume WiFi is priced at $20 per month and fixed broadband at $40 per month to make WiFi service attractive. If fixed BISPs launch a price war for the local access market, the advantage of WiFi service could evaporate and can make the project infeasible.

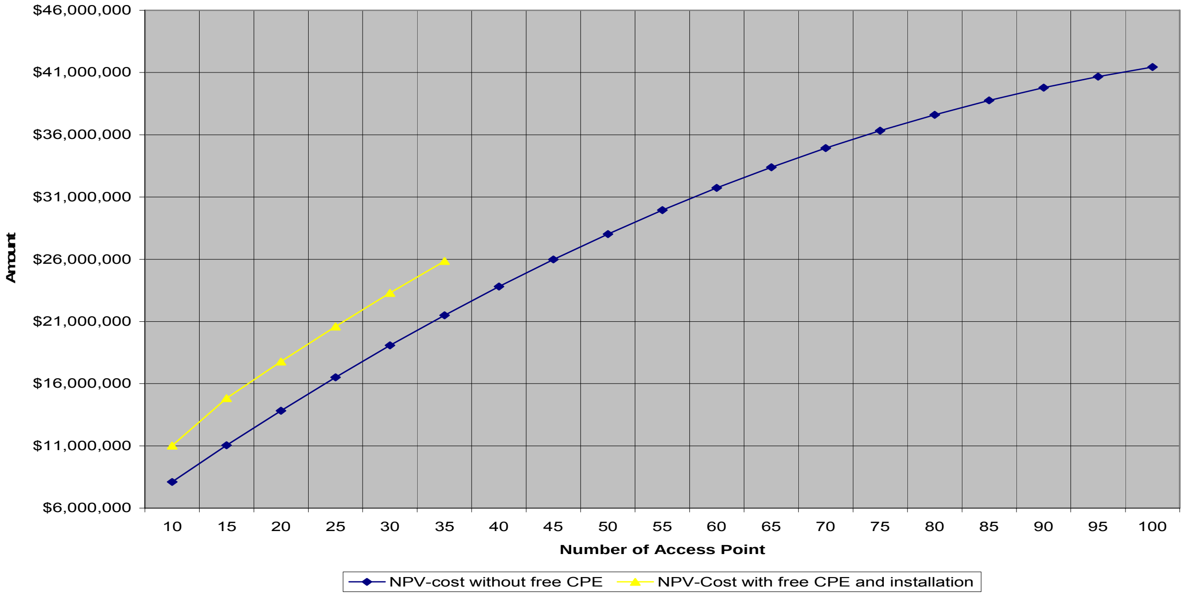

Figure 6:5 Cost Comparisons with different AP density and marketing strategies

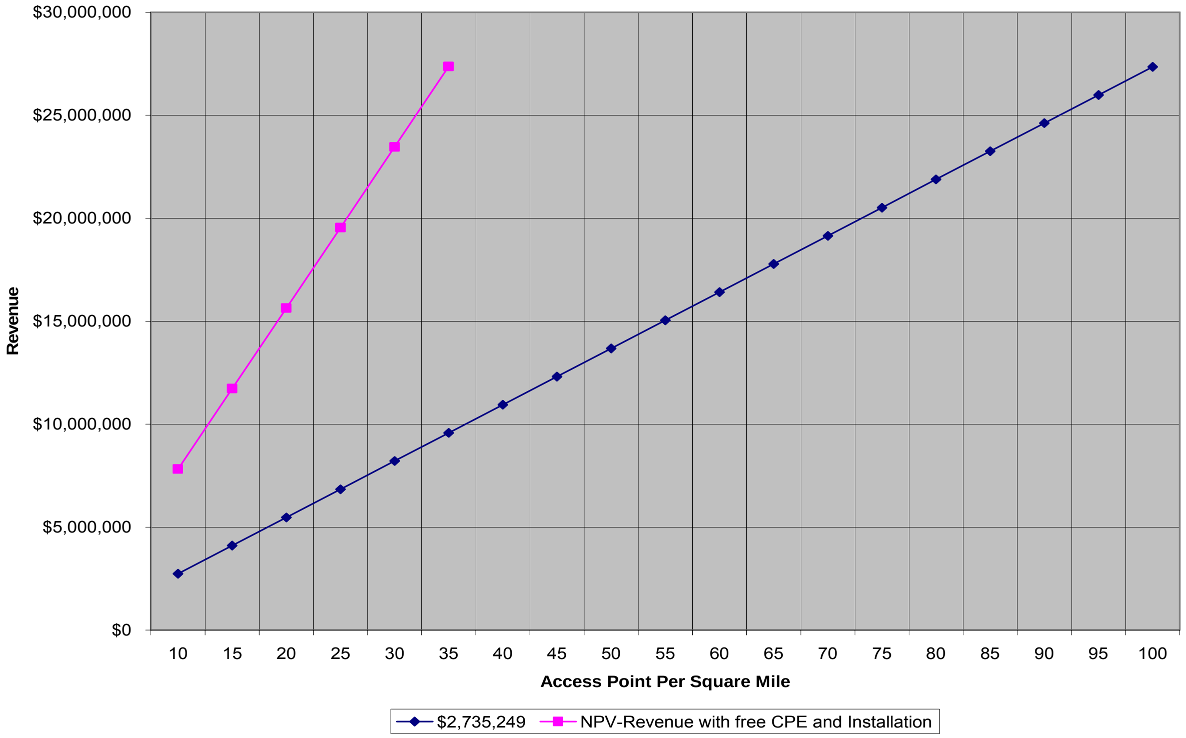

Figure 6:6 Revenue comparisons with different access point density and marketing strategies

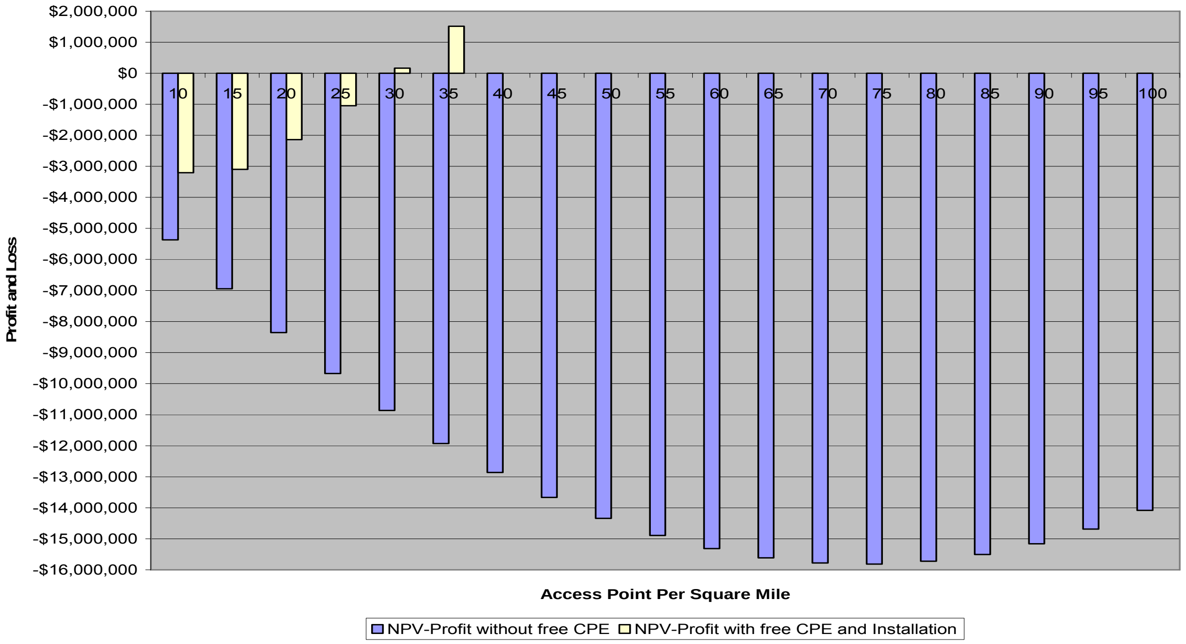

Figure 6:7 Profit and loss with different AP density and marketing strategies

7.0 MODEL VERIFICATION AND SUBSIDY CALCULATION

This chapter presents the results of the application of empirical WiFi project data into the techno-economic model and the associated subsidy. Owing to the disappointed outcomes from Earthlink, MetroFi and MobilePro, it is much easier to say that citywide WiFi is dead. However, if we look deeper into WiFi projects, we found that an old business model with no commitment from municipalities is longer feasible, but WiFi projects with subsidy are developing smoothly and several municipalities are using the anchor tenancy model to bring WiFi to their residents. Therefore, our analysis tries to further study this trend of citywide WiFi development by classifying the existing projects into three groups by subsidy and anchor tenancy. Table 7-1 shows the classification of the groups. Subsidy is the first index to classify all projects, and anchor tenant is the second index to separate the subsidy projects into anchor tenancy model or full subsidy model.

Owing to relative scarcity of available capital expenditures data from existing WiFi projects, we selected two projects with similar features in each group to provide some confidence in results. For each project, we verified the effectiveness of our model by comparing the simulated results and current operation outcome and computed a reasonable subsidy to sustain WiFi operation of anchor tenancy group and non-subsidy group. Section 7.1 describes the key features of six selected WiFi projects in three groups. Then, Section 7.2 ~7.4 presents the verification between the simulated results and the operating outcome of WiFi projects, the feasible range of network coverage for profit-oriented projects, and reasonable subsidy to sustain smooth operation for metropolitan, medium and small group, respectively. Finally, Section 7.5 provides a summary of systematical comparison between the simulated results and current operating outcome of all selected projects.

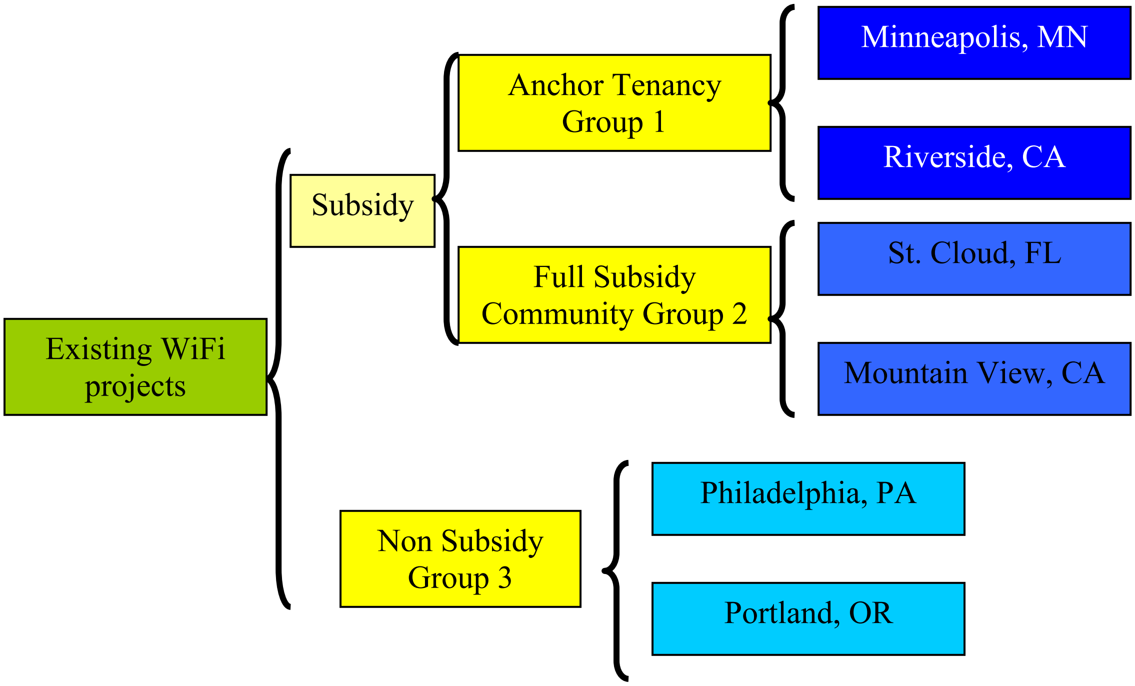

Figure 7:1 The Classification of Existing WiFi Projects by Subsidy and Anchor tenet

7.1 KEY FEATURES AND CALSSIFICATION OF SELECTED WIFI PROJECTS

There are different business models of citywide municipal WiFi projects, each having unique features. There are six selected six projects in our analysis. Two projects of each group have similar network deployment scale to have a reasonable comparison, shown in Table 7-1. Group

1 has the most well-known tenancy model in Minneapolis and Riverside, because of the value of their anchor tenant commitments. For the full subsidy model of Group 2, we selected St Cloud and Mountain View by their unique feature of true-free WiFi service and similar network coverage. For non-subsidy model in the Group 3, Philadelphia and Portland are most representative projects because of their metropolitan deployment scale.

Table 7-1 Key Features of WiFi Cities

Group	Municipality	Deployment Scale Square mile	Subsidy	Ownership	Free Service
1	Minneapolis, MN	54.8	Anchor tenant	USI Wireless	No
1	Riverside, CA	55/85 [27]	Anchor tenant	AT&T	Yes
2	St Cloud, FL	15	Full subsidy	Municipality	Yes
2	Mountain View, CA	11.5	Full subsidy	Google	Yes
3	Philadelphia, PA	134	No subsidy	Earthlink→ NAC	No
3	Portland, OR	135	No subsidy	MetroFi	Yes with AD

7.2 GROUP 1: ANCHOR TENANT PROJECTS

Minneapolis and Riverside are two representative projects in which municipalities act as anchor tenants to subsidize WiFi network development. There are similarities in their populations and network coverage, but their subsidy amounts and partners are different.

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[27] Current network coverage of Riverside, CA

Minneapolis made a commitment of $1.25 million for ten years, but Riverside's commitment is only $4 million for five years. Minneapolis chose a local ISP to build and operate the network, but Riverside selected its incumbent DSL ISP. Nonetheless, we applied the empirical data for both projects into the techno-economic model to determine their cost, revenue, cash flow and discuss whether the subsidies are sufficient.

7.2.1 Minneapolis, Minnesota

(1) Background:

Minneapolis issued a request for a proposal (RFP) in April, 2005 to solicit proposals from private ISPs to design, build, and operate a 100% land coverage WiFi network. US Interent Wireless was selected by the municipality in 2006 with a long-term contract to provide wireless Interent access service using WiFi technology. The City of Minneapolis invested a $1.25 million per year subsidy for ten years as an anchor tenant to provide a stable revenue sources for municipal applications. This project is different from other municipal citywide WiFi projects in that the private ISP owns the network but the municipality provides a sufficient subsidy to enable a smooth operation.

(2) Analysis of the simulated result:

We applied empirical data shown in Appendix 6 into our techno-economic model to calculate cash flow, distribution of revenue sources, distribution of network deployment cost and operating cost, and distribution of operating cost components. From the information in Figure 7-2, the positive cash flow starts in the third year, because network deployment cost and customer acquisition cost result in negative cash flow in the first three years. In the contract between the City of Minneapolis and US Internet Wireless, the WiFi network is expected to be overhauled at the end of the fifth year, so the cash flow in the fifth year is about $4.7 million. We assume the expenses of the network upgrade and improvement costs 60% of original network deployment cost.

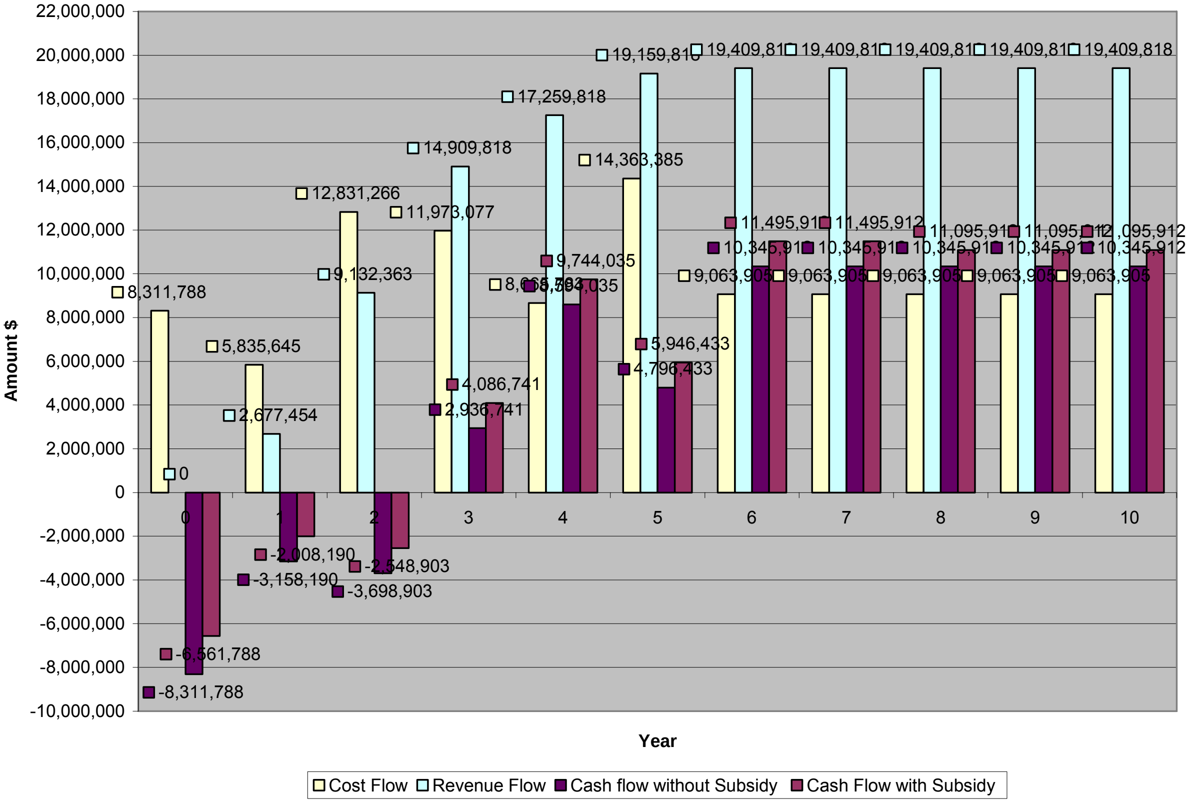


Figure 7:2 10-Year Cash Flow, Subsidy Flow, Cost Flow and Revenue Flow

From the distribution of revenue sources in Figure 7-3, the NPV of the 10 year subsidy was only 9% of total revenue; residential and business access revenues are the main portion of revenue source and consist of 59% of the total revenue. The revenue from municipal applications was the smallest portion at 9%. Other revenue sources, such as fixed wireless, wholesale, visitor usage, and application service, comprise 32% of the total expected revenue.

Although we believe that 15% visitor revenue is probably an over-estimated, (from the Business Cases of Minneapolis Wireless), we included it and it makes the net present value of the whole project over $2 million.

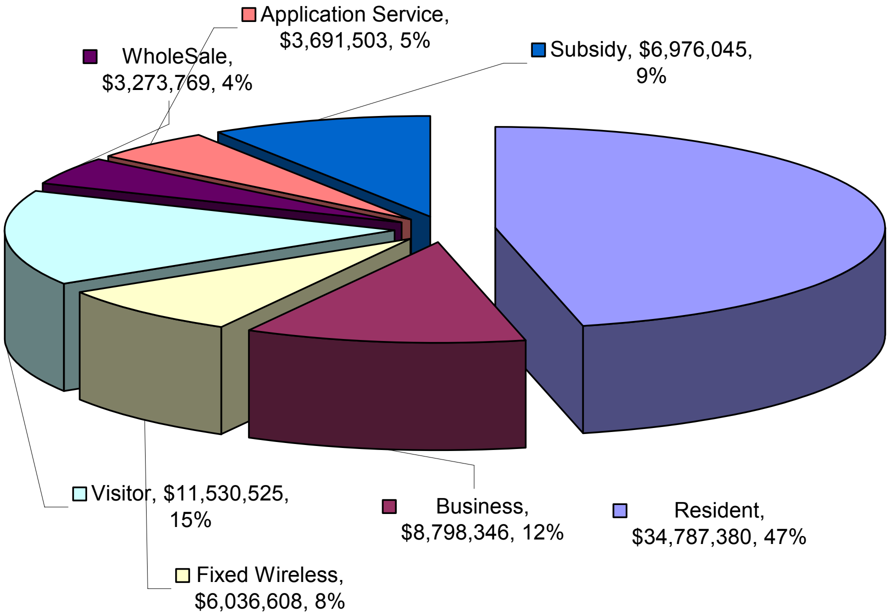


Figure 7:3 The Distribution of Revenue Sources

Figure7-4 shows that the network operating cost is more than four times the network deployment cost. Since a reliable WiFi network needs to install high density access points, the network deployment cost only occupies 17% of the total cost. The operating cost analysis (Figure 7-5), shows that customer acquisition cost occupies close to 40% of the total operating cost with service quality cost, business administration and billing cost, and network operating and management cost making up the remainder.

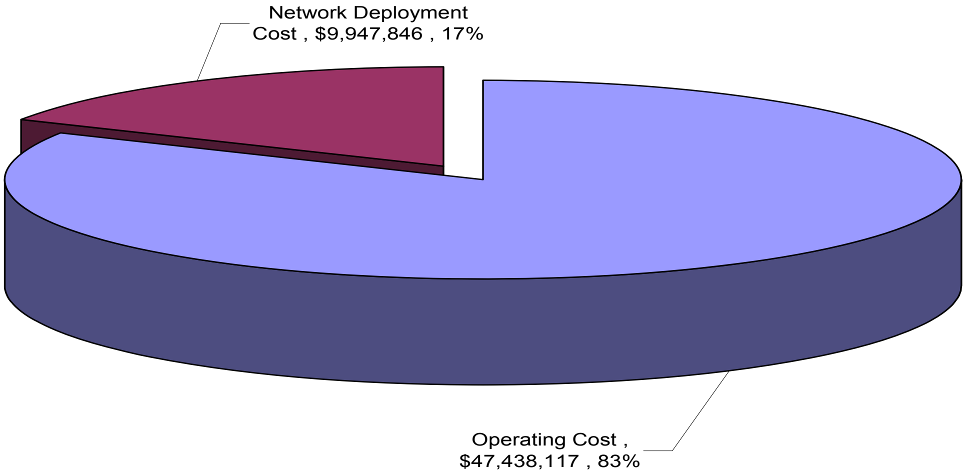


Figure 7:4 The Distribution between Network Deployment and Operating Cost

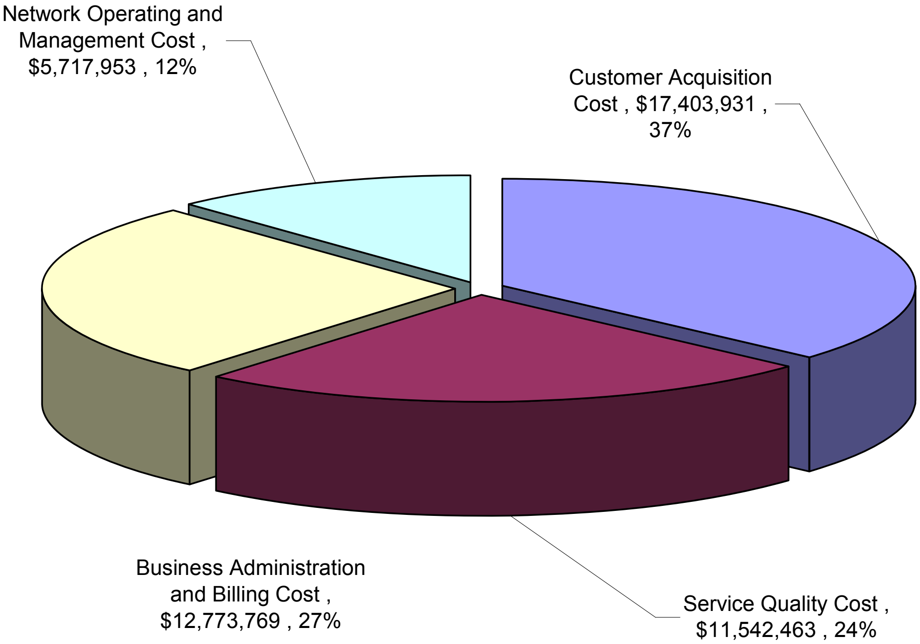


Figure 7:5 The Distribution of Operating Cost Components

(3) Feasible network coverage of a profit-oriented project:

The degree of population aggregation, obtained from Section 4.3.3, is an important index for private ISPs to identify the priority location for network deployment. Based on the cumulative land percentage versus population percentage, we can calculate the NPV values of WiFi project with different percentages of land or population coverage. Figure 7-6 shows that, in the absence of a subsidy, the feasible range of covered population percentages is from 0% to 26% with positive NPV values, because the NPV value becomes negative beyond 26% of population percentage. Figure 7-7 shows that feasible range of covered land percentages is from 0% to 5.7% with positive NPV values, because the NPV value also becomes negative beyond 5.7% of land percentage. Therefore, without sufficient subsidy and extra revenue sources from the municipality, private WISPs have no incentive to extend the scope of WiFi network. In the Minneapolis case, a private WISP might be willing to build a hotzone instead of citywide WiFi to cover less than 26% population or 5.7% of land area but it is can not match the expectation and the goal from the City of Minneapolis.

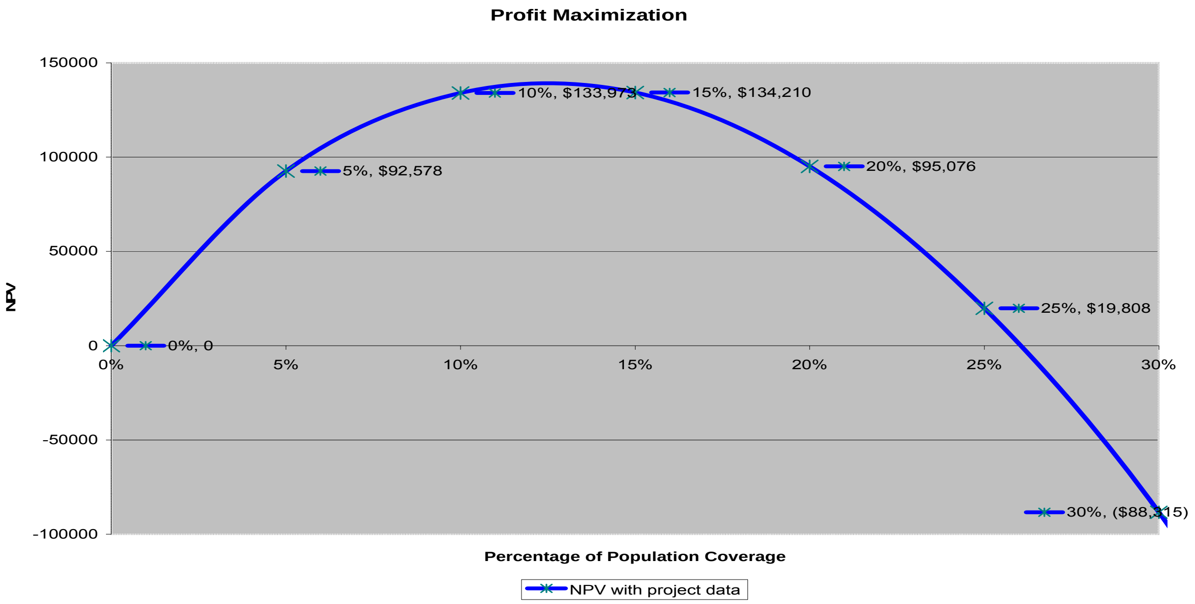


Figure 7:6 The Feasible Range of Population Percentage for a Profit-Oriented WiFi Project

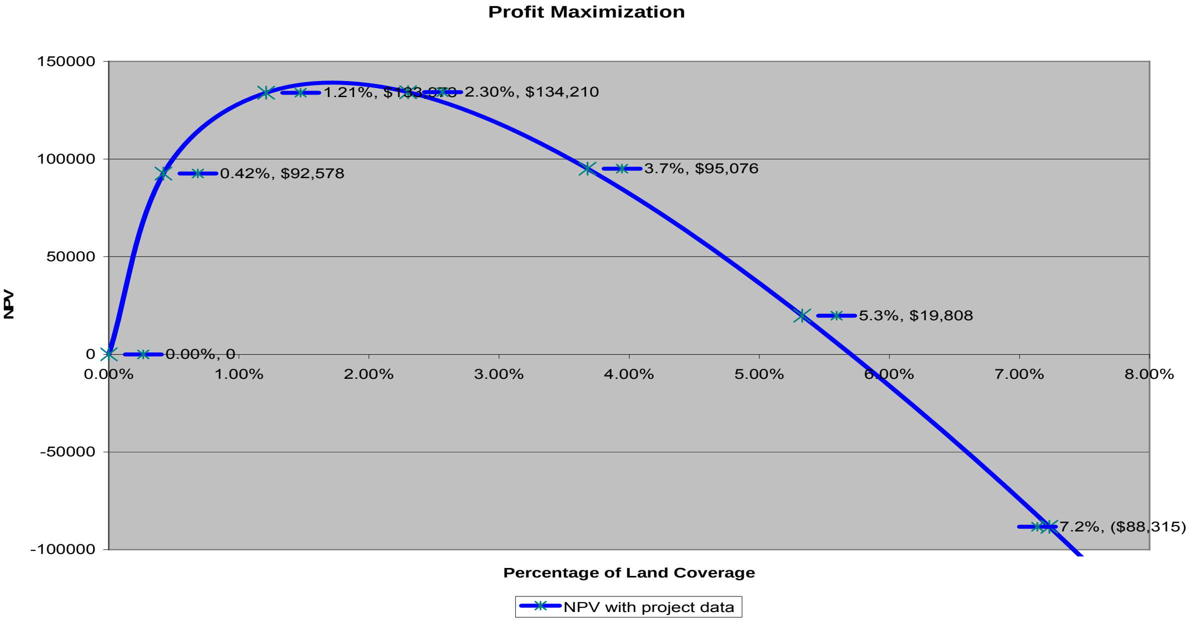


Figure 7:7 The Feasible Range of Land Coverage for a Profit-Oriented WiFi Project

(4) Subsidy for Minneapolis:

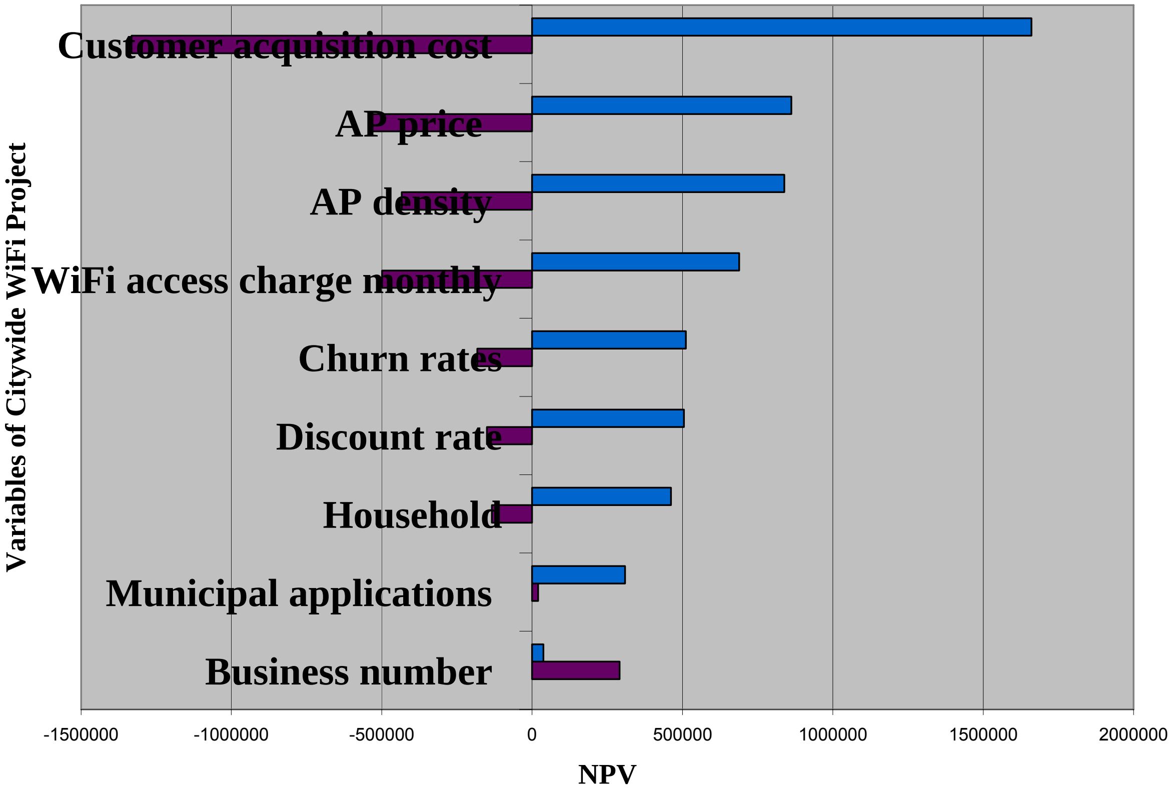
The Minneapolis case is different from other WiFi projects, because the city has signed the contract with USI Wireless that included a ten year subsidy to provide 100% area coverage. Therefore, we must add the municipal subsidy and the other expected revenue sources from the Wireless Minneapolis Report into the model to determine whether the subsidy from the municipality is sufficient.[82] With the 10 year subsidy and the other revenue from fixed wireless, the simulated result of WiFi project NPV is just negative, at -$0.164 million. Given cost and revenue estimation uncertainties, this means that subsidy from the municipality is reasonable to support the operation of the network. If adding other possible over-estimated revenue sources from visitor usage and wholesale, we found that the simulated result of WiFi project NPV can jump to $2.18 million. However, even thought the subsidy makes up only 9%

of total revenue, the subsidy is more than $1 million per year for ten years. Municipalities have to consider seriously whether it is an affordable commitment to go for 100% land coverage WiFi network.

(5) Sensitivity analysis and tornado diagram

Minneapolis project is a useful case for further sensitivity analysis, because it has many input variables and stable revenues from municipal applications. We adopted one way sensitivity analysis to evaluate, holding other variables fixed, which variable makes a significant difference of NPV output. In addition, we used a tornado diagram to show the simulation results graphically in Figure 7-8. In this figure, each input variable in the sensitivity analysis has positive or negative 10% difference. We found that customer acquisition cost is the most salient variable that affects the NPV. With same difference, the project NPV can be changed from breakeven to $1.5 million or from breakeven to -$1 million. Access point price, access point density, WiFi monthly charge, churn rates, discount rates, and household number have significant effect on project NPV. However, municipal applications have little effect on NPV and 10% difference only affect the amount of positive net present values.

Figure 7:8 Tornado Diagram of One-Way Sensitivity Analysis



7.2.2 Riverside, California

(1) Background:

WiFi project in Riverside is interesting and unique. The City of Riverside not only acts an anchor tenant having signed a renewable five year contract in which it pays $4 million for municipal application services but also selected a local incumbent DSL ISP, AT&T, to build and operate the network. The municipality issued a RFP in April, 2006 and selected AT&T from three bidders in October, 2006. [83] The contract requires AT&T to build a network, which covers 85 square miles and supports 90% indoor access and 95% outdoor access, and offers free public Internet access with 512 kbps download and 256 kbps upload.[84] The Riverside project might be a showcase for AT&T, so it may less sensitive to the total costs and revenues of the network. Nonetheless, we estimate a subsidy that is sufficient to support the WiFi network providing municipal applications and free service for its residents.

(2) Analysis:

We applied the expected revenues from the municipal applications in the Table 7-2 into our techno-economic model and modified the customer acquisition cost, network operating cost to match the project's estimates.[84] The City of Riverside is the only customer who pays for this WiFi network, so AT&T does not incur other customer acquisition costs and the churn rate is zero. AT&T also can pool its DSL facilities with the WiFi network, so the network operating cost is only 4.5% of its network deployment cost. In addition, the contract between the city and AT&T is renewable for another five years, so the life time of the WiFi network is assumed to be ten years. In the model, we assume that the $4 million from the municipality is composed of 15,000 low speed accounts, 500 2.4 GHz high speed accounts, 500 4.9GHz accounts, and 50 high-speed 5.8 GHz accounts. Using the empirical data, shown in appendix 7, demographic data in appendix 8, and other revenue data from the contract, and modified parameters of operating cost components, we computed the project's cash flow, distribution of revenue sources, distribution of network deployment cost and operating cost, and distribution of operating cost components. As shown in Figure 7-9, without the expense of customer acquisition cost, the positive cash flow starts in the second year. Without the requirement from the contract for extra municipal services and network upgrade, the cash flow keeps stable for the second year to the tenth year.

Municipal Service	Price	Volume	Remark

Low Speed 2.4GHz	$3/month $2/month $1.5/month	Under 5,000 5,001 to 10,000 Over 15,000	Remote metering
High speed 2.4GHz	$27.95/month $24.95/month	Under 250 Over 250	Public safety
High speed 4.9GHz	$49.95/month $41.95/month	Under 250 Over 250	Public safety
High Speed 5.8 GHz	$180/month $160/month	Under 25 Over 25	Public safety

Table 7-2 Revenue Sources from Municipal Applications of Riverside Municipality

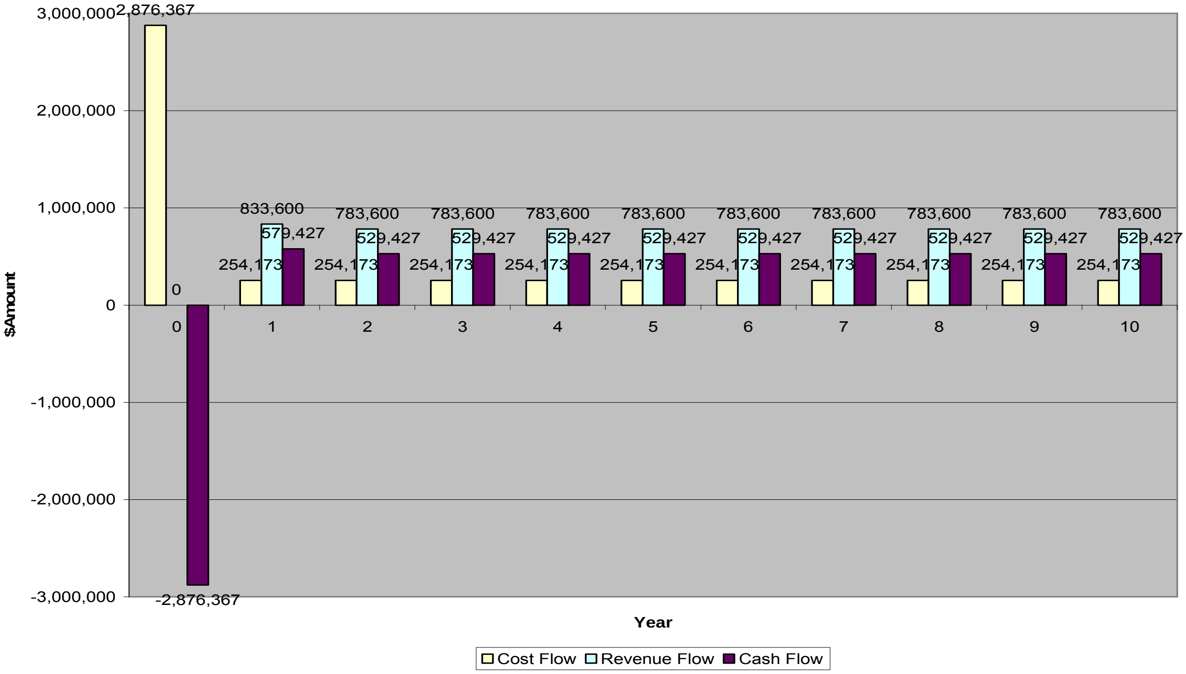


Figure 7:9 10-Year Cost Flow, Revenue Flow and Cash Flow

From the distribution of revenue sources in Figure 7-10, the NPV of low-speed account for remote metering is about 40% of the total revenue, other public safety and video camera service, requiring high–speed transmission, makes up the remaining revenue.

Without customer acquisition cost and lower network operating and maintenance cost, the ratio between network deployment cost and network operation cost is 7:3, shown in Figure 7-11. This is different from the Minneapolis project, because the operator of the Riverside project, the local incumbent DSL provider, has a cost advantage from pooling backhaul facilities and network management. In addition, main cost components in Minneapolis, customer acquisition cost and churn cost, do not apply to this project. As shown in Figure 7-12, the NPV values of the three cost components are similar.

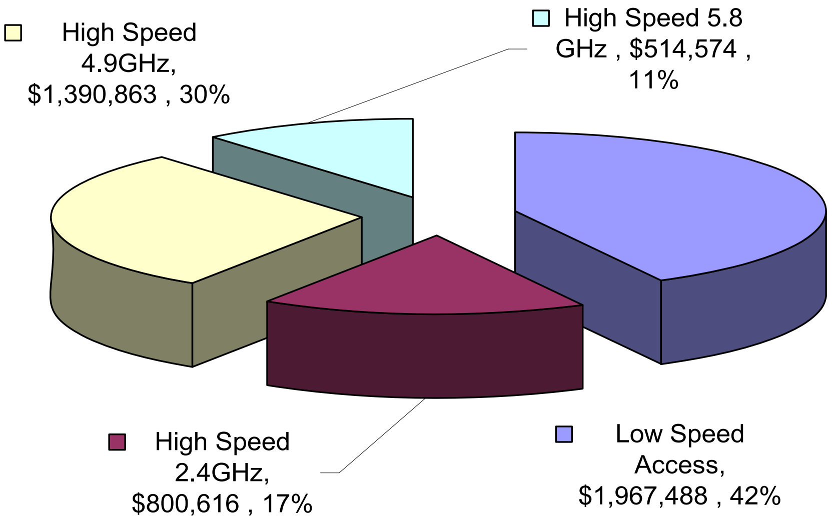


Figure 7:10 Distribution of Revenue Source

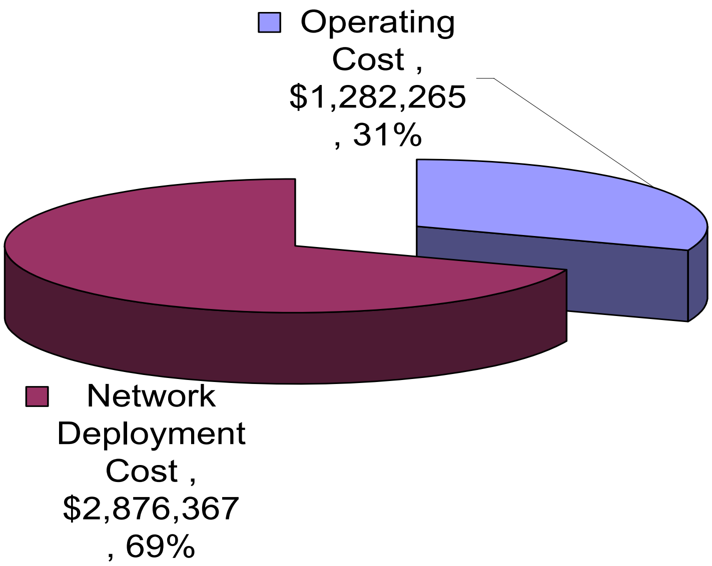


Figure 7:11 Distribution between Network Deployment Cost and Operating Cost

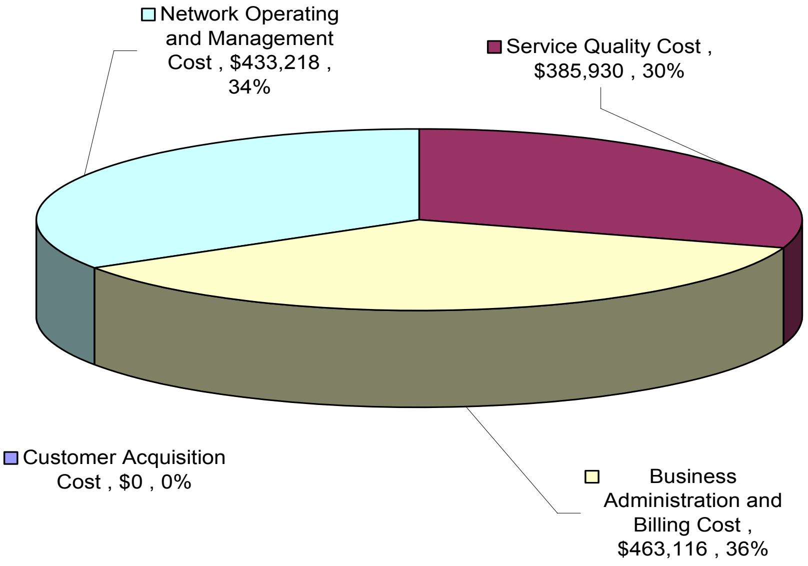


Figure 7:12 Distribution of Operating Cost Components

(3) Feasible network coverage of a profit-oriented project

If we assume a pure profit-oriented project in Riverside with no municipal involvement and compute the feasible ranges of the network coverage, we can see that the NPV values are negative in any scope of network coverage (Figures 7-13 and 7-14). The results are caused by low population density, 3,267 people per square mile in Riverside and 6,970 people per square mile in Minneapolis. Therefore, the municipal subsidy is necessary for WiFi network deployment in Riverside.

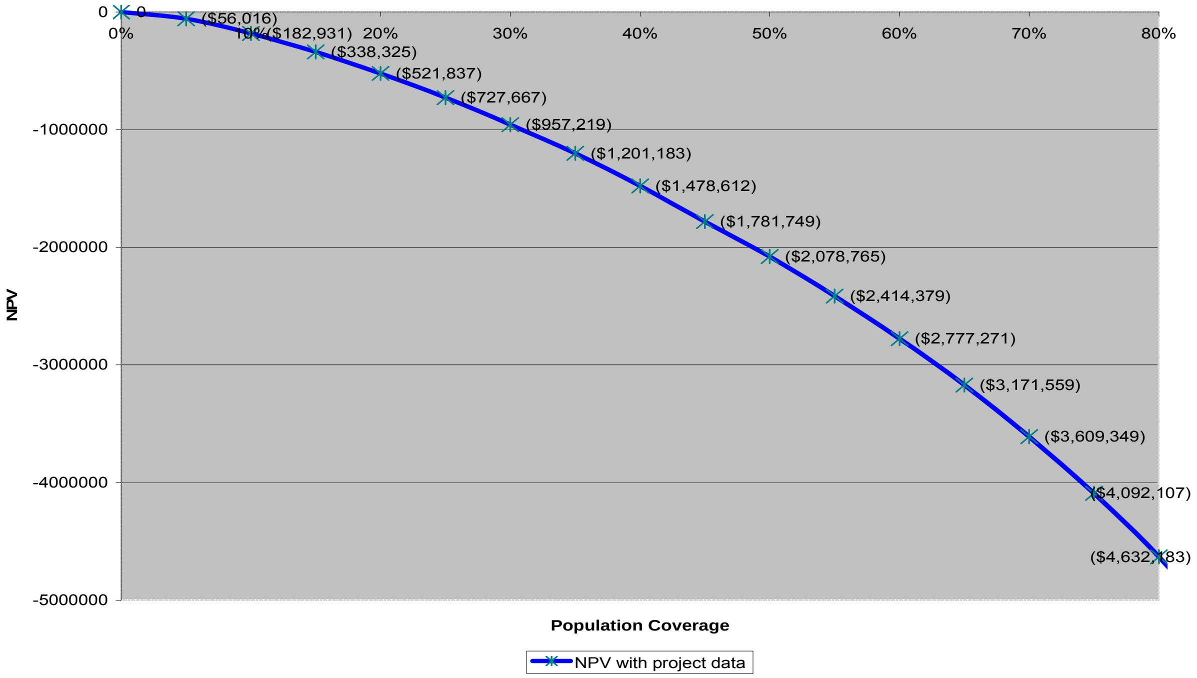


Figure 7:13 The Feasible Range of Population Coverage for a Profit-Oriented WiFi Project

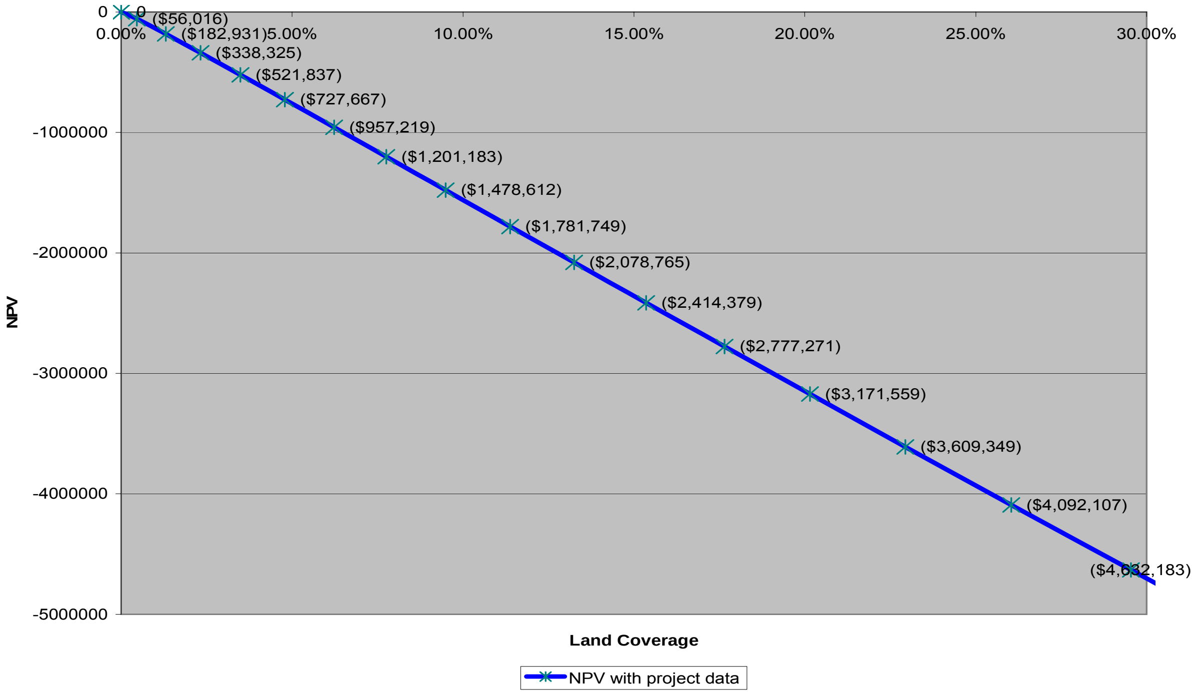


Figure 7:14 The Feasible Range of Land Coverage for a Profit-Oriented WiFi Project

(4) Subsidy for Riverside project:

We doubt whether the subsidy coming from the City of Riverside is sufficient, because Minneapolis has higher population density and a small land area but offers more than three times the subsidy. Our model shows that the 10-year network present value of Riverside project has a negative value with $1.929 million. Therefore, the sole revenue source from its municipality is insufficient to support the operations. If the simulation result from our model is correct, there are three reasons why AT&T remains willing to build and operate the WiFi network.

(a) *Complementary service* - The network provides free WiFi service for AT&T's DSL subscribers. WiFi can be a marketing tool to make AT&T's broadband service more attractive to compete with Comcast's cable modem service.

(b) *Public relations* - The project is a showcase for AT&T to prove its capability in telecom engineering and to keep a close tie with the local municipality.

(c) *Strategic preemption* - Although AT&T provides free WiFi service with no advertisement to interfere user's access, the service is outdoor-oriented with no customer service. It would affect AT&T's existing DSL service but could block potential WiFi ISP to enter the local broadband market.

Clearly, AT&T can justify the loss from the WiFi. In contrast, US Internet Wireless has as many other WiFi revenue sources as compared with AT&T but none outside of the wireless project, so it needs a sufficient subsidy from the City of Minneapolis.

7.3 GROUP 2: FULL SUBSIDY COMMUNITY PROJECTS

Full subsidy projects are those where the municipalities or private companies fully sponsor the citywide WiFi network and provide free service with no advertising support. Compared with the WiFi projects in Section 7-2, St Cloud in Florida and Mountain View in California have a much smaller population and land area. This feature makes free service more affordable. Because the service is free, the focus of full-subsidy projects is not to achieve positive NPV values but to provide free WiFi access for their communities. Therefore, the main purpose of this section is to verify our model. We applied the published data of both projects into the model and compared our estimated results and the empirical data to find out the differences in residential subscription rates, deployment cost, and operating cost.

7.3.1 St. Cloud, Florida

(1) Background:

The city of St. Cloud locating suburban of Orlando, Florida has a population of 28,000 in 15 square miles. The municipality outlined its free WiFi plan in 2005 and built and offered free citywide WiFi service in 2006. It outsourced customer service and network monitoring and management to HP, because it did not have the expertise to operate a WiFi network. This is a well-known project, because it is the first citywide WiFi project providing free high speed access with no advertising.

(2) Comparison between the simulated result and current operating outcome

The published data of the St. Cloud WiFi project are as follows: its start-up costs are about \$2.6 million, including the initial operating cost about \$400,000.[85] The initial project installed 300 access points and 45 gateway nodes. Appendix 9 shows the empirical data for our simulation.

According to the analysis of our techno-economic model, if the path loss factor is greater than 3.7, a density of 20 APs per square mile only can achieve 60% indoor coverage with aid from a wireless bridge to boost its signal power. After applying the related broadband penetration rates from the FCC report, the estimated subscription household is 18.26%.[86] However, the initial household registration rate for WiFi is about 77%, but new information, provided by its mayor six month later, estimated that only 25% of St. Cloud citizens are using its free WiFi service regularly. [87] The new subscription rate is much closer to our estimate. If we adjust the originally assumed path loss factor from 3.7 to 3.6, the estimated residential subscription rates would be increase from 18% to 25%.

The estimated network deployment cost is about $1.6 million. Although our estimated deployment cost is much lower than St. Cloud's $2.6 million start-up costs, we think our simulated result is reasonable, because the start-up costs covers the first year operation cost, consulting service fee and some expenses for WiFi training courses

We don't need to consider customer acquisition cost and churn rate cost for a free service, so our operating cost only consists of two components: one is estimated service quality cost and network management and operating cost. However, our estimated number is only $200,000, which is 50% lower than the actual annual operating cost, that the city paid for HP. If HP has to charge a competitive service expense to maintain the outsource relationship with the City of St Cloud, it is highly possible that we under-estimated the operating costs of small scale projects. Because a small scale project, as St Cloud, is difficult to achieve operation efficiency without economies of scale, we need to adjust the operating cost parameters of the techno-economic model to estimate a small scale project.

The comparison outcomes of subscription rates, network deployment cost, and operating cost can verify that the techno-economic model is capable of estimating subscription rates and network deployment cost with reasonable accuracy, but it needs to adjust some cost parameters to accommodate outsourcing.

7.3.2 Mountain View, California

(1) Background:

Google provides free WiFi access to its headquarters in Mountain View, California. It received approval from the city for its proposal in Nov of 2005 and offered free Internet access in Aug of 2006 as a community service for residents. The network covers 11.5 square miles land size and 70,000 people. The transmission rates are 1 Mbps for upload and download.[28] The giant search engine company is treating the WiFi network as a gift for the residents and also as a large-scale test bed for various WiFi enabled devices and applications. [29]

(2) Comparison between the simulated result and current operating outcome:

Google's website does not disclose the number of installed access point or the budget of the network, but it mentioned that Google is continuing to improve the quality of the WiFi service. The density of access point varies, depending on the different information source. The reported access point density ranges from 30 to 35 per square mile and the total installed APs from 350 to 380.[88] The information about the network deployment budget from different sources is consistently about $1 million. In addition, Google offers online customer support through its online help center and Google Groups WiFi forum, which are more economical than traditional telephone-based customer service.[89] Appendix 9 shows the empirical data for our simulation.

We applied the average number of AP density into our model to estimate the reliable network coverage, subscription rates and network deployment. The simulated results show that the WiFi service is mainly designed for outdoor access. If the path loss factor is smaller than

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[28] http://gigaom.com/2006/08/15/google-launches-wifi-network-in-mountain-view/
[29] http://www.google.com/support/wifi/bin/answer.py?answer=30794&topic=8330

3.4, the outdoor coverage is 100%, but the outdoor coverage decreases to 50% with 3.7 path loss factor. Indoor access requires a WiFi bridge to boost the wireless signal. With the density of 33 APs per square mile, a high-gain WiFi bridge can improve indoor coverage from 20% to 100% with a stringent path loss factor of 3.7. The estimated network deployment for the model is $2.23 million, which is much higher than Google's reported deployment cost. Google might have better bargain power to negotiate the price with its network equipment vendor; because the equipment vendor, Tropos, might expect future cooperation projects with Google for other possible projects.[30]. If we applied the similar access point price, which Tropos offered for Earthlink, the network deployment cost can be lowed down to $1 million.

There is no published operating cost of the network, but it is free service with cheaper online help customer service and no customer acquisition cost and billing expenses. Our estimated operating cost is close to $190,000 per year.

The comparison outcomes of network coverage and network deployment cost can demonstrate that our techno-economic model needs some calibration of the equipment discount for small projects, because the cost of AP takes a large amount of total network deployment cost.

7.4 GROUP3: NO SUBSIDY PROJECTS

In this section, we discuss two well citywide WiFi projects in the "Non-Subsidy" group. Philadelphia WiFi owns the largest network in the US and Portland WiFi is well-known for its

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[30] Google decided to cooperate with Earthlink to build a citywide WiFi network in San Francisco together.

free basic Internet access with advertising support. These projects had high expectations in the beginning that the low deployment cost of WiFi would not only provide reliable wireless Interent access service to spur local broadband competition but also contribute to the elimination of the digital divide. But the reality of network building cost and the competition from local BISPs proved fatal for both of these projects. We use our model to simulate both projects, comparing the model results to the operations outcome, and estimate reasonable subsidies required to support continuous WiFi operations.

7.4.1 Philadelphia, Pennsylvania

(1) Background:

The story of WiFi project in Philadelphia case has gone from hope to despair. Originally, Wireless Philadelphia, a non-profit institution organized by the City of Philadelphia, planned to build a citywide WiFi network across its 135 square miles by itself to enhance broadband coverage, offer affordable broadband service, and narrow the digital divide.[90] Eventually Earthlink was selected and signed a contract with Wireless Philadelphia to build and operate a WiFi network in 2006. After two years of operations, Earthlink announced that they would discontinue operating in Philadelphia in May of 2008 because the subscription rates were lower than expectation, making it difficult for them to recover their investment.[91] Wireless Philadelphia announced that the ownership of the WiFi network was transferred to Network Acquisition Company, a temporary name for a local investor, on June 17 2008.[92] It is not clear what the future holds for this the biggest WiFi project in the US, but some information sources mention that no funding will come from the city of Philadelphia and that basic free service for outdoor access with no customer support will be provided.[93] [94]

(2) Analysis of the simulated results and existing project operating outcome:

After applying the empirical and demographic data (in appendix 11 and 12) into our techno-economic model to calculate its NPV value with different network coverage, we found that all of our estimated NPV values, shown in Figure 7-15, are negative. In addition, the larger the network scope the larger the loss. Basically, low subscription rates for Philadelphia WiFi were caused by insufficient AP density, given no customer premise equipment to enhance indoor access. If we assume that the network covers the 95% of population, the model estimates that network deployment cost is \$9.83 million and the five years loss of the project is \$24 million. Therefore, with no subsidy from the municipality to overhaul the network and pay for customer acquisition costs, a reasonable business strategy for Earthlink would be to quit the WiFi Philadelphia project as early as possible.

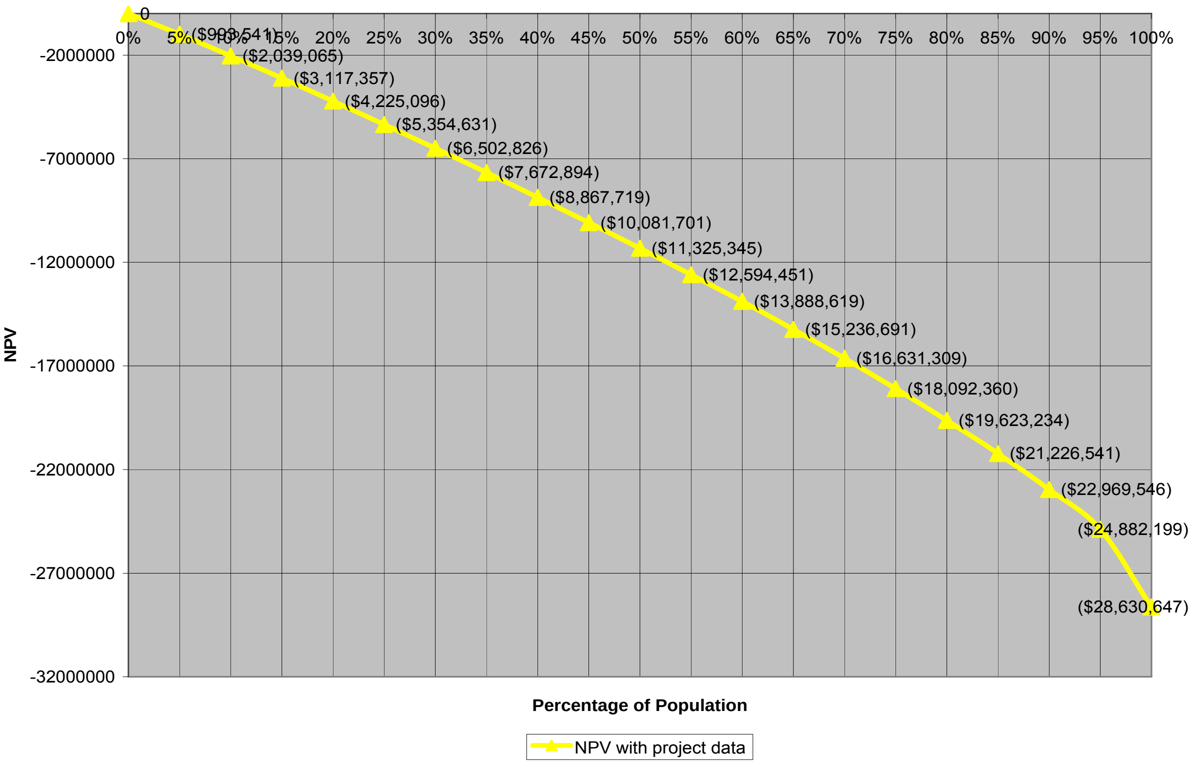

Figure 7:15 NPV Value with Different Population Coverage

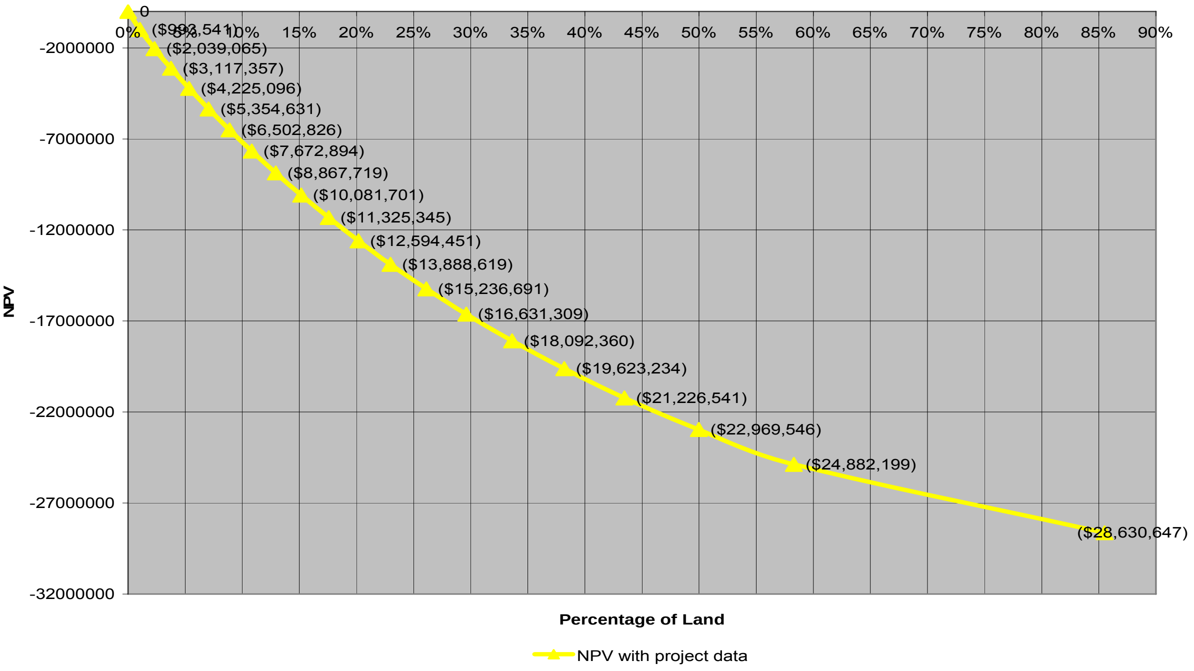

Figure 7:16 NPV Value with Different Land Coverage

(3) Feasible network coverage of a profit-oriented project:

We assume a pure profit-oriented project in Philadelphia with no municipality involvement and compute the feasible ranges of the network size in terms of percentage of population and land area. We estimate a reasonable subsidy for a 100% land coverage project in the next paragraph. The degree of population aggregation in Philadelphia, shown in Figure 4-7, enables us to estimate the NPV values of the Philadelphia WiFi project. Figure 7-16 shows that the feasible range of covered population percentages is from 0% to 61% with positive NPV values, and that the NPV value becomes negative beyond 60% of population percentage. Figure 7-18 shows that feasible range of covered land area is from 0% to 24% with positive NPV values, because the NPV value also becomes negative beyond 24% of land percentage. Therefore, without sufficient subsidy and extra revenue from municipality, private WISPs have no incentive to extend the scope of WiFi network. In the Philadelphia case, a private WISP might be willing to build a hotzone instead of citywide WiFi to cover less than 60% population or 24% of land area but it is can not match the expectation and goal from the City of Philadelphia to have a fully covered network across 135 square miles.

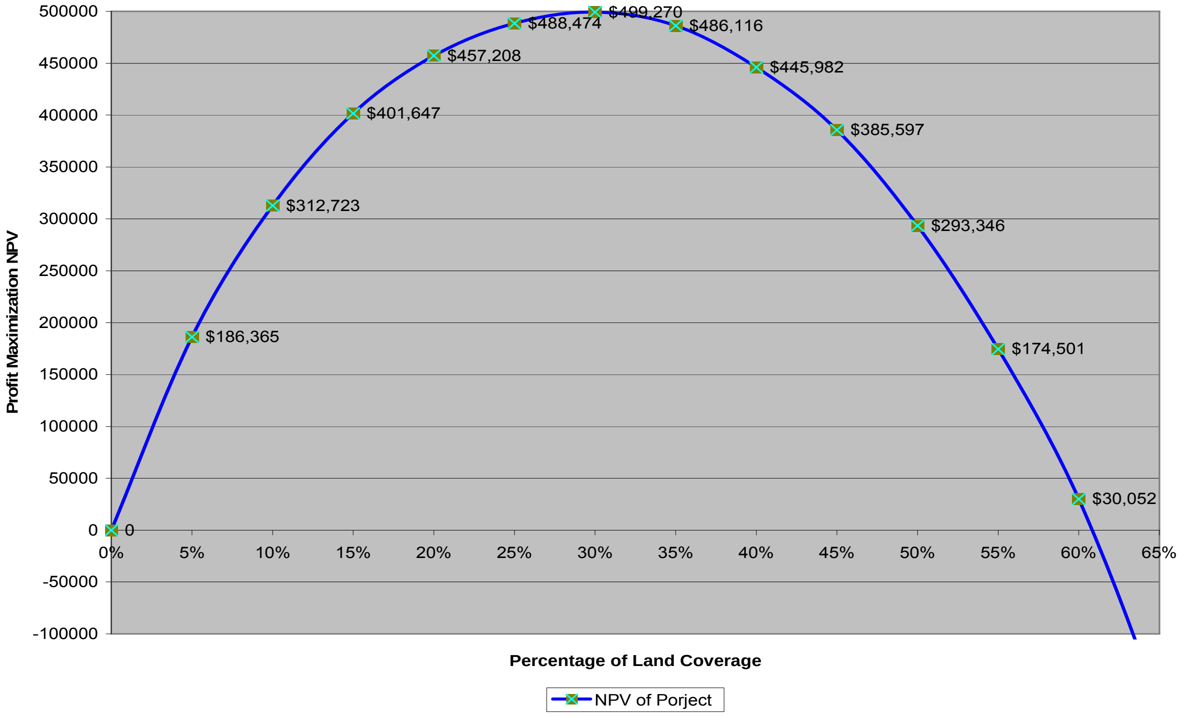

Figure 7:17 The Feasible Range of Population Coverage for a Profit-Oriented WiFi Project

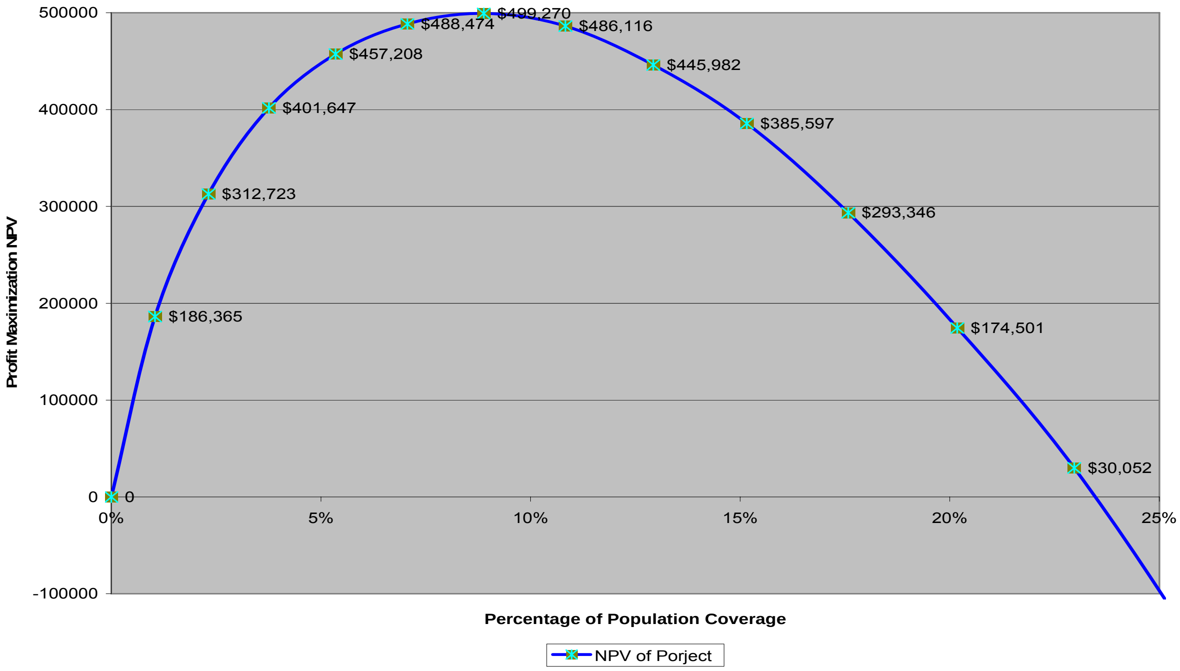

Figure 7:18 The Feasible Range of Land Coverage for a Profit-Oriented WiFi Project

(4) Subsidy for Philadelphia:

It is difficult to estimate the necessary cost to upgrade the infrastructure of the existing Philadelphia network for providing reliable wireless Internet access, so we assume a totally new network with 100% land coverage requirement to estimate its possible loss from the techno-economic model. From the simulation results, the NPV value for 100% land coverage network is -\$6 million. Figure 7-18 shows that the maximum profit of the feasible range of profit oriented project in Philadelphia is about a half million dollars and its network coverage is about 9% of land area. Thus, the reasonable subsidy is \$6.5 million, the sum of the maximum profit in the feasible range and potential loss of the 100% land coverage project, because the WISP can be compensated for cost and the original expected profit in a small scale WiFi network. The financial incentive might be enough for a WISP to expand the network from 9% land coverage to 100% land coverage.

7.4.2 Portland, Oregon

(1) Background:

The story of the WiFi project in Portland is similar to Philadelphia. It also was full of hope for free WiFi service but ended with a possible network shutdown in the end of June, 2008.[31] MetroFi initiated the network deployment in the end of 2006 and offered advertisement-supported free basic WiFi service in April of 2007. The City of Portland agreed to act as anchor tenant to support the network, though this was not executed in the form of a

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[31] http://www.muniwireless.com/2008/06/23/metrofis-portland-network-to-shut-down/

contract as in the Minneapolis's case.[32] MetroFi tried to negotiate with the City of Portland to commit to be an anchor tenant or to provide a $9 million subsidy to continue network expansion and operations, else they would halt network deployment in Oct, 2007. Without a positive response from the municipality, MetroFi announced that if no third party is willing to take over the network, the network in Portland is going to shutdown at the end of June, 2008. [33] [34]

(2) Analysis of the simulated results and existing project operating outcome:

After applying the empirical and demographic data (in appendix 13 and 14) into our techno-economic model to calculate its NPV value with different network coverage, we found all of our estimated NPV values, shown in Figure 7-20, are negative. In addition, the larger the network scope the larger the loss as before. Basically, the low subscription rates for Portland wireless service, as in Philadelphia, were caused by insufficient AP density to provide reliable WiFi connections.

Although it is difficult to calculate the land area of WiFi coverage from its WiFi coverage map, the article in muniwireless.com mentioned that the network coverage is only 30%[35]. In Figure 7-20, if we assume that the network covers 30% of population, our model estimates that network deployment cost is $2.378 million and the loss over the five years of the project is about $3.755 million. If we assume that the network covers 30% of land area, our model estimates that network deployment cost is $6.564 million and the loss over the five

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[32] http://wifinetnews.com/archives/007967.html

[33] http://www.muniwireless.com/2008/06/23/metrofis-portland-network-to-shut-down/

[34] http://blog.oregonlive.com/siliconforest/2007/10/mayors_office_portland_wifi_ne.html

[35] http://www.muniwireless.com/2008/06/23/metrofis-portland-network-to-shut-down/

years of the project is about $9.8 million (Figure 7-21). Therefore in the absence of a subsidy or stable revenues from the City of Portland, a reasonable business strategy for MetroFi is to shutdown the project quickly.

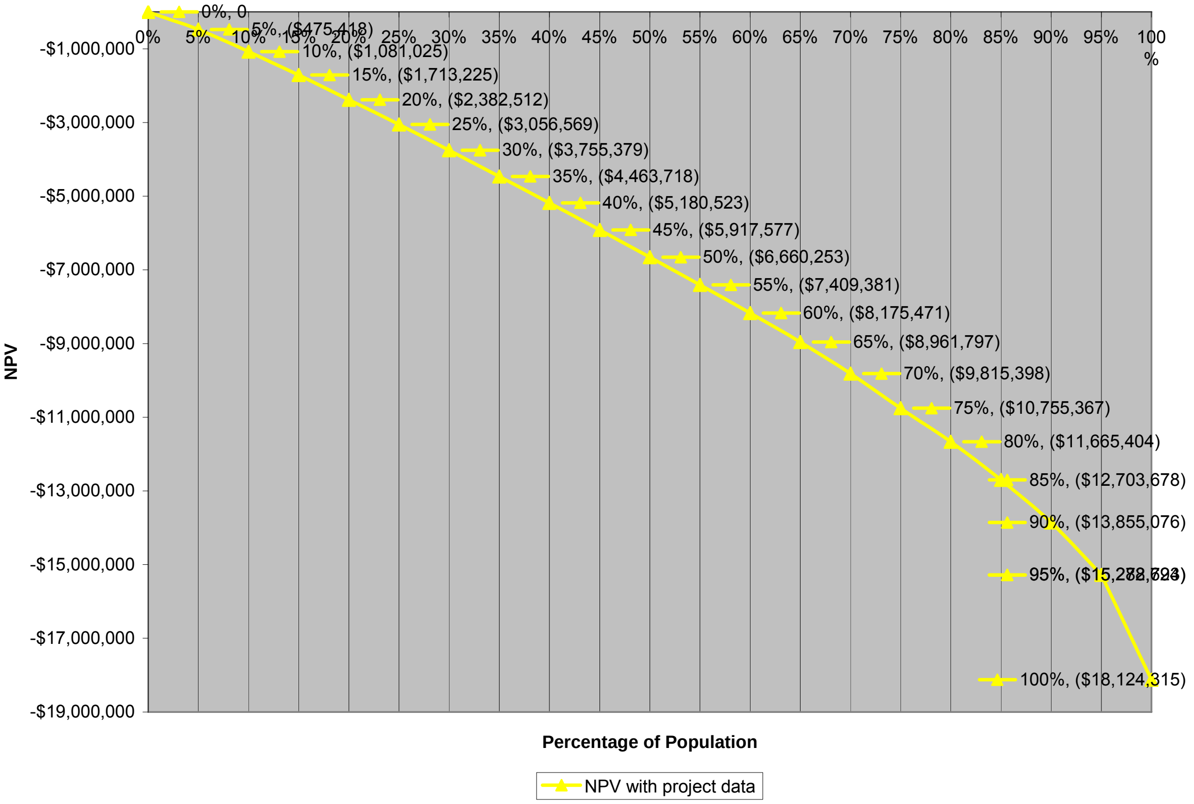

Figure 7:19 NPV Value with Different Population Coverage

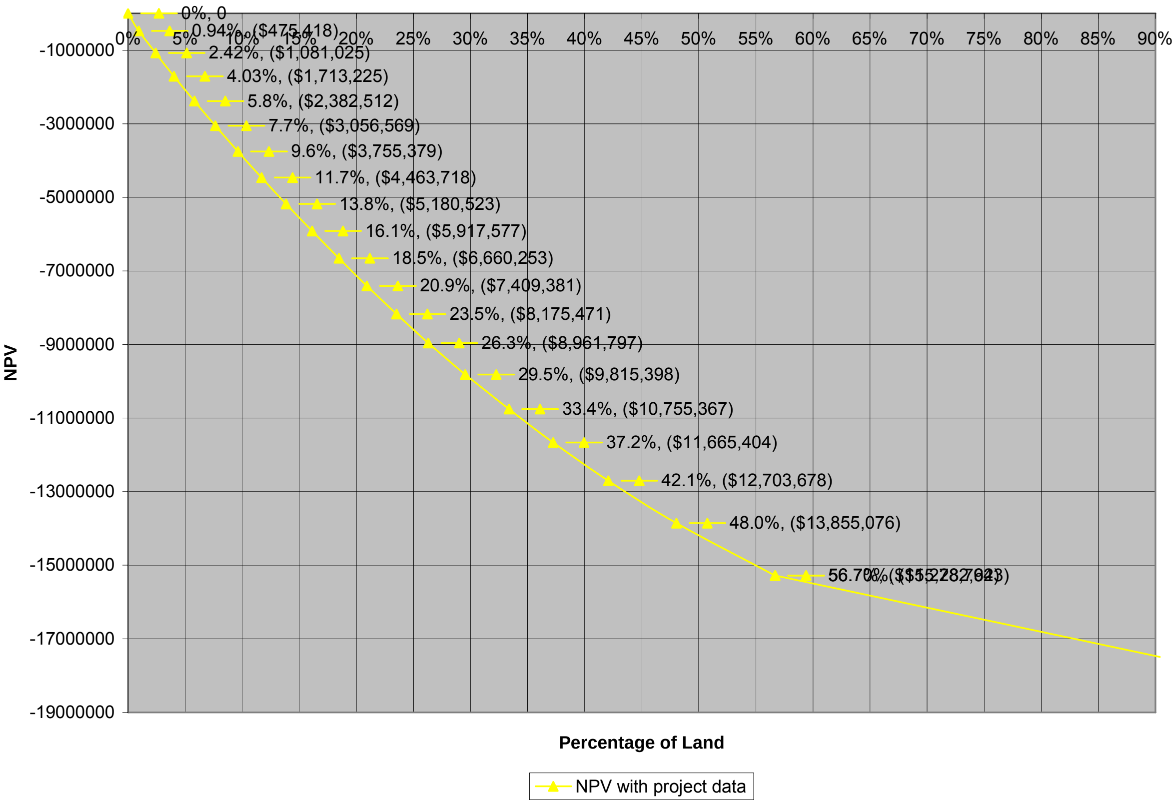

Figure 7:20 NPV Value with Different Land Coverage

(3) Feasible network coverage of a profit-oriented project:

With the assumption of $3 per subscriber per month revenue from advertising-supported service, our model estimates that the free service cannot make the project breakeven under any circumstance. Here, we assume a profit-oriented operator in Portland providing reliable WiFi Internet service for residents and businesses instead of free service. Then, we compute the feasible range of network coverage. The degree of population aggregation in Portland assists us to estimate the NPV values of Portland WiFi project. Figure 7-22 describes that feasible range of covered population percentages is from 0% to 21% with positive NPV values, because the NPV value becomes negative beyond 21% of population percentage. Figure 7-23 shows that the feasible range of covered land area is from 0% to 6% with positive

NPV values, because the NPV value also becomes negative beyond 6% of land percentage. Therefore, without sufficient subsidy and extra revenue from the municipality, private WISPs have no incentive to extend the scope of WiFi network over feasible range of network coverage. In the Portland case, a private WISP that relies on monthly WiFi access revenues from residents and businesses might be willing to build a hotzone to cover less than 21% population or 6% of land area.

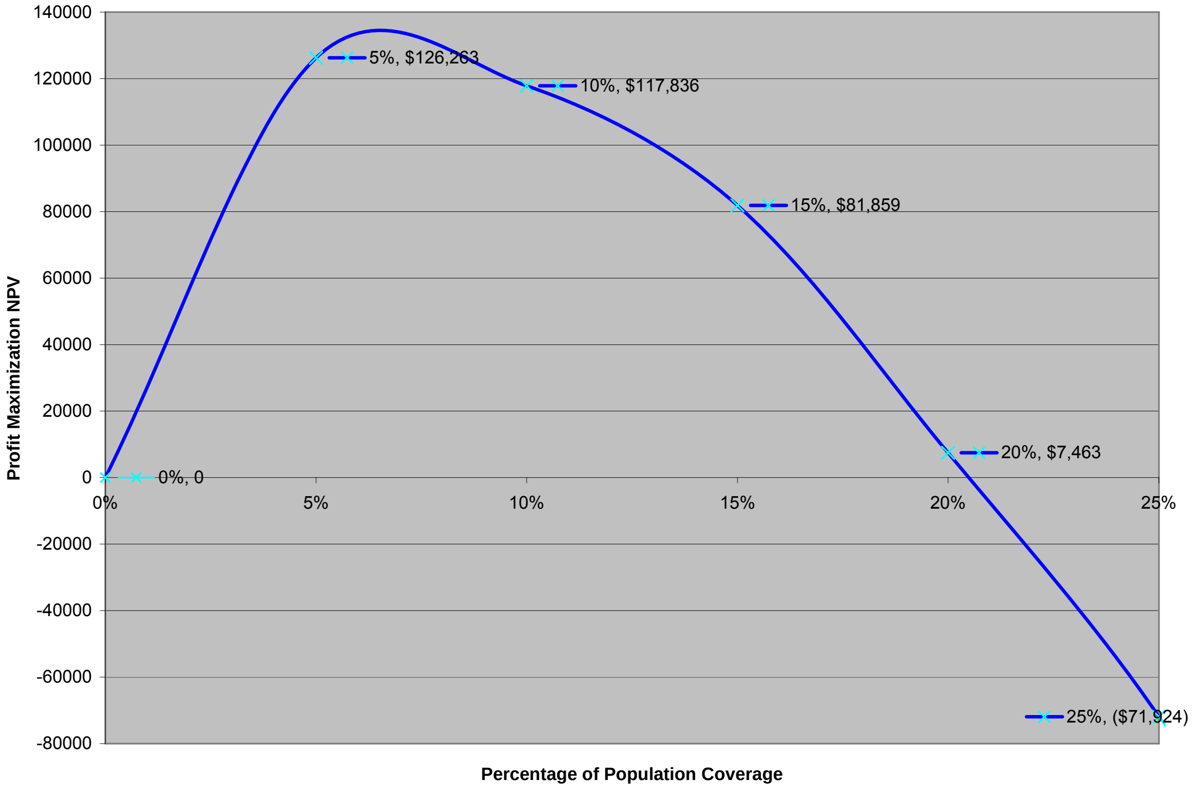

Figure 7:21 The Feasible Range of Population Coverage for a Profit-Oriented WiFi Project

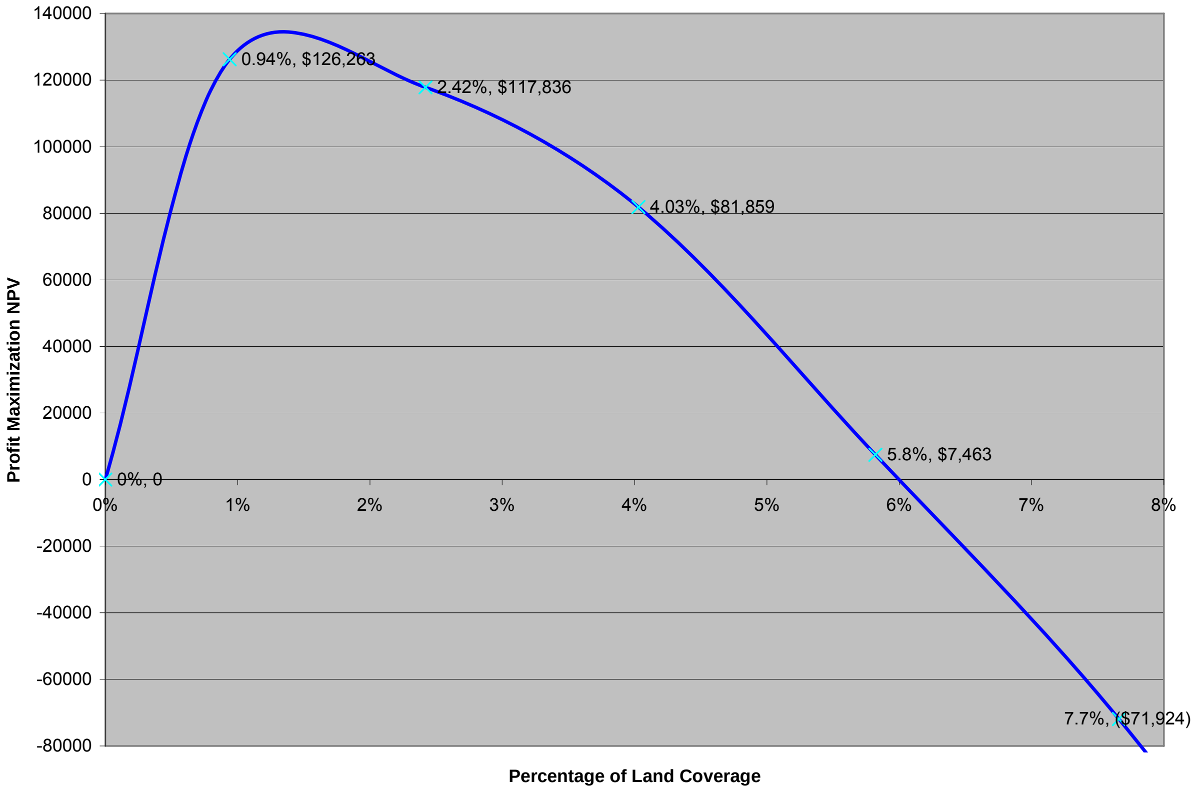

Figure 7:22 The Feasible Range of Land Coverage for a Profit-Oriented WiFi Project

(4) Subsidy for Portland:

It difficult to estimate the necessary cost to overhaul the infrastructure of the existing Portland network and change the business service from free service to fee service, so we assume a new network with 95% population coverage and estimate the possible loss of the project by the model. The City of Portland is less aggressive than Minneapolis and Philadelphia, which sought to achieve 100% land coverage, so we adjust the network deployment requirement from 100% land coverage to 95% population coverage. From the simulation results, the NPV value of 95% population coverage network is -$4 million. Figure 7-23 shows that the maximum profit of the feasible range of profit oriented project in Portland is about $0.13 million and its network coverage is about 6% of land area. The reasonable subsidy therefore is $4.13 million dollars, the sum of the maximum profit in the feasible range and potential loss of 95% population coverage project, this level of financial support would encourage a WISP to expand coverage from 6% population to 95% population.

7.5 SUMMARY WITH SYSMEMATIC COMPARISON

We provided a summary of previous analysis for each project and made a systematic comparison between simulated results and current operating outcome to verify the effectiveness of the techno-economic model, shown in Table 7-3. For anchor tenant group, our simulated results illustrate that the subsidy of Minneapolis is sufficient to maintain a smooth operation but the subsidy of Riverside is insufficient. Although AT&T's WiFi project in Riverside could not fully recover from its investment from municipal application revenues, it could have other strategic reasons to build and operate the network, even if they lose money doing so. For full subsidy projects in Group 2, their small scale projects enable municipalities and private companies to build and provide a free citywide WiFi network. Some differences between our simulated results and their available Internet data, we think it is reasonable to have some differences between estimated and actual numbers. In addition, it is difficult to use the same model to estimate small and large scale WiFi projects. If economies of scale of network operations can not achieve from small WiFi projects, we need to adjust cost parameters to estimate small projects more effectively. For non-subsidy projects with metropolitan scale, our simulated results match with the current operation outcomes. The results also demonstrate that Earthlink and MetroFi had better shutdown their WiFi business quickly to prevent extra loss.

Through the comparison outcomes, we show that our model can provide useful information to estimate related engineering and financial information. In addition, it can determine a reasonable subsidy for municipalities and WiFi ISPs to enable a sustainable citywide WiFi operation.

Table 7-3 The Comparison Table between the Simulated Results and Current Operating Outcomes

Group	Deployment Scale Square mile	Project	Simulated result and subsidy	Current operation outcome
Anchor tenant	54.8	Minneapolis, MN	10-year $1.25 million per year commitment of an anchor tenant payment can support a range of NPV value from -$0.16 million to $2.18 million of the project	Operating smoothly[95]
Anchor tenant	55/85 [36]	Riverside, CA	5 year $4 million commitment is insufficient to sustain a citywide WiFi network The simulated NPV is $-1.929 million	Network deploying[96]
Full subsidy	15	St Cloud, FL	The simulated network deployment cost is closed to actual building cost with some difference in network operating cost	Service is continuing[97]
Full subsidy	11.5	Mountain View, CA	There estimated results can estimate reliable network coverage, network deployment cost and operating cost.[37]	Service is continuing[89]
No subsidy	134	Philadelphia, PA	The simulated results show that original network deployment for 95% population coverage would cause $24 million loss in five years, but reasonable subsidy as Minneapolis project is about $6.5 million	Earthlink notified its customer to discontinue operation and the ownership shifted to

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[36] Current network coverage of Riverside, CA

[37] With calibration of AP discount for network deployment cost

				NAC[91]
No subsidy	135	Portland, OR	The original business model can not breakeven at any circumstance without municipal subsidy. With 30% coverage, 5 years loss is $-3.755 million and a reasonable subsidy is $ 4.13 million	Is going to shut down on June 30 2008 [38]

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[38] http://blog.oregonlive.com/breakingnews/2008/06/portlands_wifi_network_coming.html

8.0 CONCLUSION AND FUTURE WORK

The development of citywide WiFi, which began in 2004 and boomed in 2005, encountered serious roadblocks by the middle of 2007. Focusing only on disappointments from Earthlink, MetroFi and MobilePro, it is easy to draw the conclusion that citywide municipal WiFi projects were built with hype and are dead because of a faulty business model. However, deeper analysis of existing WiFi projects shows a more subtle result, that, *without municipal subsidy*, these projects are infeasible. Citywide projects with subsidy from municipalities are operating smoothly and several cities are engaging in anchor tenancy model to fully exploit WiFi capabilities for both public access and municipal applications. Municipalities and ISPs are still learning their lessons in this market through trial and error. The results of this research can assist them to evaluate WiFi effectively, prevent potential loss, and seize the opportunities to add local broadband choice.

Therefore, the development of citywide WiFi in the US is in transition from a non-subsidy model to an anchor tenancy model. This research thus is arriving at the right time to contribute useful information for municipalities, WiFi ISPs and policy makers. This dissertation makes three major contributions

First, our work makes several findings in the domain of socio-economic factors and business models. More than 400 municipalities have been involved in municipal wireless projects in the US, but only 20 qualified as citywide municipal WiFi for our study. The relationship between socio-economic features of municipalities and implementation of citywide WiFi shows that residents of WiFi cities are younger with higher education level; they need not be rich but cannot be poor. The analysis of empirical projects also demonstrates that municipalities do not have expertise in managing WiFi networks. They can invest and own networks but need to outsource the operations.

Second, the linkage between access point density and network coverage indicates that depending on the path loss factor, that 100% outdoor coverage may require the AP density up to 100 nodes per square mile. In addition, without assistance from CPE, 100% outdoor to indoor coverage is cost prohibitive. The baseline model of a medium city reveals that a WiFi project with pure Internet access revenue source is not feasible without free CPE, because the network coverage is limited for reliable connections. Even though a strategy with free CPE can make the project profitable, it is still risky and the price advantage of WiFi could evaporate in a price war.

Third, our techno-economic model is not only good for estimating cash flow, distribution of revenue sources and distribution of cost components but also useful to determine a reasonable subsidy to sustain a WiFi project with target network coverage. Through the comparison between the simulated results and current operating outcomes from six representative projects, the effectiveness of the techno-economic model has been verified. Since anchor tenancy model has become the dominant business model for sustainable WiFi networks, a method to estimate a reasonable subsidy is necessary for municipalities and WiFi ISPs to compute prospective profit from the feasible range of network coverage and possible loss from the targeted network coverage.

Although the two troubled projects in Philadelphia and Portland have not caused substantial financial loss for their municipalities, the valuable opportunities to build a multi-purpose WiFi network and spur local broadband competition were wasted. With the aid from our techno-economic model, both public and private sectors can negotiate the conditions and terms of their contract directly with clear number to reach a win-win solution.

Our simulated outcome shows that the Earthlink project in Philadelphia is risky and could lose $ 24 million dollars from a five-year operation, which begs the question as to why Earthlink was willing to invest on citywide WiFi projects in 2005. It could be hindsight speculation that WiFi was the last resort for Earthlink to survive in the Interent access market, because its dial-up market was withering and low profit margins coming from reselling DSL broadband services. In addition, other broadband technologies, BPL and WiMAX, were immature. With lower broadband network coverage and a less competitive broadband market at that time, they perhaps originally forecasted that the WiFi project should be profitable. Therefore, Earthlink's strategy was to offer favorable terms and conditions for the municipality in order to win projects. This could explain why Earthlink was willing to bear all projects risks and contributed money into the digital divide fund before the network were operated. However, DSL and cable operators expanded their network coverage aggressively from 2005 to 2007 and offered competitive access rates to attract dial-up users. In addition, they encountered lower than expected outdoor WiFi subscribers, because of the increase in free WiFi access locations from coffee shops, fast-food restaurants, and libraries. Indoor WiFi access requires higher access point density and wireless bridges, which means higher deployment cost and marketing cost to provide reliable WiFi access. These factors are possible reasons why Earthlink's original forecasting and ultimately forcing them to withdraw from their Philadelphia project in June, 2008.

There are three interesting directions for future research. The first one is in improving the effectiveness of our model with more accurate data. The new broadband penetration data from the FCC can provide more precise information to estimate the subscriber switching rates of our model, because the FCC has published a *Report and Order* to improve broadband data collection on June 15, 2008. ISPs have to report subscriber number by census tract and break down the number of subscribers based upon broadband speeds. With the improved data from future Broadband Report from the FCC, we should be able to estimate switching rates by using penetration rates of different broadband access technology and the percentage of subscribers of different service tiers inside a specific city instead of approximate penetration rates of different broadband access technology from state-level and percentage of subscriber number of different service tiers from national-level.

The next is to relax the assumption of WiFi network construction time. Our model assumes that WiFi ISPs complete network deployments in the first year to simplify their investment strategies, but they can build WiFi network step by step in metropolitans to limit their risks and increase operating flexibility. Without the assumption, a new model can simulate real projects more closely, because WiFi ISPs can build and operate wireless broadband services in profitable areas only in the first stage. Then, based on market responses, they can decide whether to expand their networks and provide municipal applications gradually.

The last is the further evolution of the techno-economic model. The current model uses NPV as the economic metric and assumes that technology remains static over the duration of the project. NPV as a project selection tool is known to have shortcomings, so it would be interesting to consider the use of real options in its place. Also, it would be interested to expand the model to explicitly account for the inevitability of technology progress, for what is costly or infeasible today may be feasible in five years. Improvements such as these to the model would aid municipalities and WiFi ISPs to evaluate their WiFi projects from three strategic dimensions: timing, selected technology, and required investment. It will also be interesting to observe the long term effects of sustainable WiFi projects and take the lessons into account as policymakers consider a national broadband policy.

APPENDIX

Appendix 1Qualified Citywide Municipal WiFi Projects

City		Total Population	Land Area	Density	Median age	White %	Black %	American Indian %	Asian %	Hispanic Latino	occupied Housing
Tempe	AZ	158,625	40.00	3966	28.8	77.5%	3.7%	2.0%	4.7%	17.9%	63,602
Anaheim	CA	328,014	48.94	6702	30.3	54.8%	2.7%	0.9%	12.0%	46.8%	96,969
Cerritos	CA	51,844	8.68	5974	39.3	26.9%	6.7%	0.3%	58.4%	10.4%	15,390
Concord	CA	121,780	31.31	3889	35.1	70.7%	3.0%	0.8%	9.4%	21.8%	44,020
Foster City	CA	28,803	3.76	7664	38.1	59.3%	2.1%	0.1%	32.5%	5.3%	11,613
Galt Softcom	CA	19472	5.9	3300	30.6	70.5%	1.2%	1.0%	2.8%	33.2%	5974
Lompoc	CA	41,103	11.60	3543	32.2	65.8%	7.3%	1.6%	3.9%	37.3%	13,059
Mountain View	CA	70,708	12.06	5861	34.6	63.8%	2.5%	0.4%	20.7%	18.3%	31,242
Santa Clara city	CA	102,361	18.39	5566	33.4	55.6%	2.3%	0.5%	29.3%	16.0%	38,526
Sunnyvale	CA	131,760	21.94	6007	34.3	53.3%	2.2%	0.5%	32.3%	15.5%	52,539
Longmont	CO	71,093	21.80	3261	34.0	84.8%	0.5%	1.0%	1.8%	19.1%	26,667
Vail town	CO	4,531	4.50	1007	31.9	94.1%	0.3%	0.5%	1.7%	6.2%	2,165
St. Cloud	FL	20,074	9.20	2182	36.8	90.3%	2.1%	0.5%	1.0%	13.4%	7,716
Chaska	MN	17,499	13.70	1277	32.2	93.7%	1.0%	0.3%	1.7%	5.8%	6,104
Minneapolis	MN	382618	54.9	6969	31.2	65.1%	18.0%	2.2%	6.1%	7.6%	162352
Moorhead	MN	32,177	13.44	2394	28.7	92.1%	0.8%	1.9%	1.3%	4.5%	11,660
Rio Rancho	NM	51,765	73.00	709	35.1	78.4%	2.7%	2.4%	1.5%	27.7%	18,995
Addison	TX	14,166	4.40	3220	31.6	67.8%	9.6%	0.4%	7.8%	24.0%	7,621
Farmers Branch	TX	27,508	12.00	2292	34.7	78.4%	2.4%	0.5%	2.9%	37.2%	9,766
Granbury	TX	5,718	6.10	937	41.7	94.5%	0.4%	0.7%	0.5%	7.3%	2,391

City		Occupied housing units percent	Owner-occupied housing percent	High School Graduate percent	Bachelor's degree or higher percent	Median Household Income	Per Capita Income	Families below Poverty Level	Individuals below Poverty Level	Median House Value
Tempe	AZ	94.8%	51.0%	90.1%	39.6%	$42,361	$22,406	7.5%	14.3%	$132,100
Anaheim	CA	97.2%	50.0%	69.3%	19.6%	$47,122	$18,266	10.4%	14.1%	$213,800
Cerritos	CA	98.6%	83.5%	90.7%	43.7%	$73,030	$25,249	4.0%	5.0%	$281,000
Concord	CA	97.6%	62.6%	84.7%	25.9%	$55,597	$24,727	5.2%	7.6%	$233,700
Foster City	CA	96.7%	61.5%	95.6%	59.8%	$95,279	$45,754	1.7%	2.9%	$566,500
Galt	CA	96.2%	79.5%	75.2%	14.0%	$45,052	$16,620	8.5%	10.6%	$135,300
Lompoc	CA	95.9%	51.6%	74.4%	13.8%	$37,587	$15,509	12.6%	15.4%	$148,300
Mountain View	CA	96.3%	41.5%	89.0%	55.3%	$69,362	$39,693	3.6%	6.8%	$546,900
Santa Clara city	CA	97.2%	46.1%	86.9%	42.4%	$69,466	$31,755	4.5%	7.8%	$396,500
Sunnyvale	CA	97.7%	47.6%	89.4%	50.8%	$74,409	$36,524	3.7%	5.4%	$495,200
Longmont	CO	97.3%	65.6%	86.5%	31.3%	$51,174	$23,409	5.9%	7.8%	$177,900
Vail town	CO	40.2%	52.3%	96.2%	60.9%	$56,680	$42,390	1.8%	6.6%	$575,000
St. Cloud	FL	89.7%	71.7%	79.1%	13.8%	$36,467	$17,031	6.2%	8.1%	$89,800
Chaska	MN	97.9%	75.2%	91.6%	32.1%	$60,325	$25,368	3.4%	4.7%	$161,000
Minneapolis	MN	96.3%	51.4%	85.0%	37.4%	$37,974	$22,685	9.2%	12.4%	$113,500
Moorhead	MN	95.7%	63.7%	87.7%	29.5%	$34,781	$17,150	8.2%	16.3%	$86,100
Rio Rancho	NM	94.0%	81.5%	91.2%	24.8%	$47,169	$20,322	3.7%	5.1%	$112,900
Addison	TX	92.9%	20.7%	90.5%	44.6%	$48,566	$38,606	6.2%	7.7%	$222,400
Farmers Branch	TX	96.5%	68.0%	76.2%	27.2%	$54,734	$24,921	4.0%	6.3%	$99,200
Granbury	TX	87.7%	55.2%	82.5%	20.5%	$35,952	$19,801	5.0%	9.6%	$83,600

Appendix 2 Parameters of Geo-Demographic Factors for the Baseline Model

Geo-demographic Assumptions	Size	Population	Average number per household	Number of Small & Medium Business
	50 sq miles	250,000	2.5	25000

Appendix 3 Parameters of Market Potential and estimated subscription rates and numbers for the Baseline Model

Customer Type	Non-Internet access	Dial-up	Broadband (DSL & Cable Modems)	Small & Medium Business
Distribution (percentage)	30%	28%	42%	10% of population
Market Internet access charge	NIL	$20/Month	$40/Month	$40/Month
WiFi access charge	$20	$20	$20	$30
Price difference ratio	NIL	0%	100%	33.3%
WiFi subscription factor	5%	50%	35%	35%
WiFi subscription rates	1.5%	10.8%	12.6%	10%
1st year potential subscription number (40%)	180	5,600	5,880	1,166
2nd year potential subscription number (100%)	4,50	14,000	14,700	2,914

Appendix 4: Parameters of Construction Cost for the Baseline Model and Techno-Economic Model

Item	Price
Access Point with volume	$3,500
Gateway Node with same discount as access point	$3,500
Aggregate Node	$25,000
Power supply, cabling, mounting, fine-tune	$600
Intermediate Site for aggregate node	$50,000
Backhaul Hub	$100,000
Network Design	5% of construction cost
OSS (software and hardware)	5% of construction cost

Appendix 5: Parameters of Operation Cost for the Baseline Model and Techno-Economic Model

Item	1st Year Cost	2nd Year to Fifth Year Cost
Marketing (awareness) baseline model	15% of construction cost	8% of construction cost
Customer Service $7 per call Baseline model	two calls for new subscribers	two calls for new subscribers and one call for old subscribers
Network Maintenance and Management Baseline model	10% of construction cost	15% of construction cost
Churn rate cost	10% of total subscribers with extra customer acquisition cost	10% of total subscribers with extra customer acquisition cost
Service quality expenses	$36 per subscriber per year	$36 per subscriber per year
Business administration expenses	$30 per subscriber per year	$30 per subscriber per year
Pole attachment leasing and electricity	$36 per pole per year	$36 per pole per year
Aggregation Node Space leasing	$5,000 per node per year	$5,000 per node per year
Fiber loop leasing for aggregate node	$5,000 ($1,000 per mile and five mile per node)	$5,000 ($1,000 per mile and five mile per node)
Internet Transit Fee (backhaul cost)	OC3 $20,000 per month T3 $8,000 per month T1 $1,000 per month	OC3 $20,000 per month T3 $8,000 per month T1 $1,000 per month
WiFi Bridge (CPE)	$100	$90
CPE Installation	$150	$150

Appendix 6 The Empirical Data for Minneapolis, MN

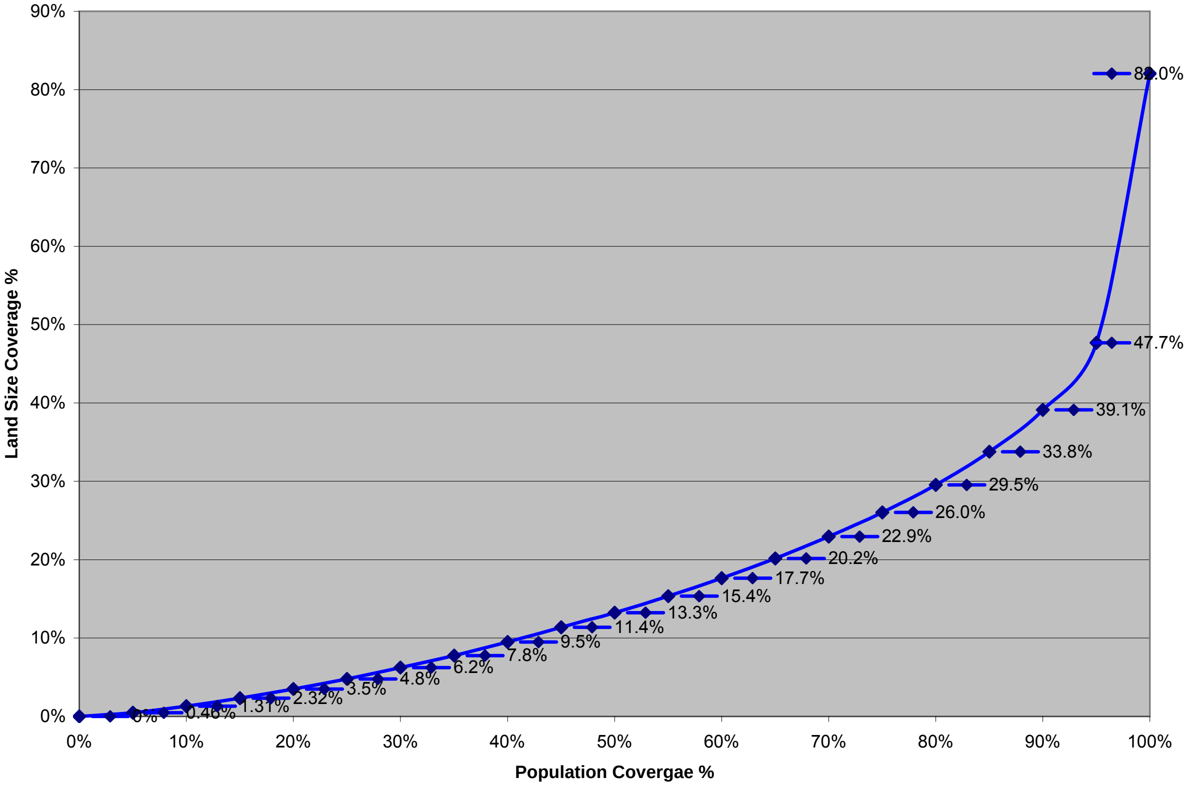
DSL ISP Qwest			Cable Modem ISP ComCast		
Penetration rate	**Bottom tier %**	**Monthly charge ($)**	**Penetration rate**	**Bottom tier %**	**Monthly charge ($)**
41.50%	62.37%	$31.99 (S) $39.99 (NS)	52.68%	90.54%	$59.95 (S) $42.95 (NS)

WiFi ISP US Internet Wireless		Price insensitive subscribers %		
Residential access	**Business access**	**Dial up**	**DSL**	**Cable Modem**
$20	$30	45%	15%	25%

Appendix 7 The Empirical Data for Riversidel, CA

<table>
<tr><th colspan="6">DSL ISP
AT&T</th><th colspan="6">Cable Modem ISP
ComCast</th></tr>
<tr><th colspan="2">Penetration rate</th><th colspan="2">Bottom tier %</th><th colspan="2">Monthly charge ($)</th><th colspan="2">Penetration rate</th><th colspan="2">Bottom tier %</th><th colspan="2">Monthly charge ($)</th></tr>
<tr><td colspan="2">54.38%</td><td colspan="2">62.37%</td><td colspan="2">$19.99 (S)
$25 (NS)</td><td colspan="2">40.49%</td><td colspan="2">90.54%</td><td colspan="2">$59.95 (S)
$42.95 (NS)</td></tr>
<tr><th colspan="6">WiFi ISP
AT&T</th><th colspan="6">Price insensitive subscribers %</th></tr>
<tr><th colspan="3">Residential access</th><th colspan="3">Business access</th><th colspan="2">Dial up</th><th colspan="2">DSL</th><th colspan="2">Cable Modem</th></tr>
<tr><td colspan="3">$0</td><td colspan="3">$0</td><td colspan="2">45%</td><td colspan="2">15%</td><td colspan="2">25%</td></tr>
</table>

Appendix 8 Accumulated Land Percentage Versus Population Percentage in Riverside, CA



Appendix 9 The Empirical Data for St Cloud, FL

DSL ISP **AT&T**			**Cable Modem ISP** **Bright House**		
Penetration rate	**Bottom tier %**	**Monthly charge ($)**	**Penetration rate**	**Bottom tier %**	**Monthly charge ($)**
41.50%	**62.37%**	**$19.99 (S)** **$25 (NS)**	**52.68%**	**90.54%**	**$29.95 (S)** **$44.95(NS)**
WiFi ISP **CyperSpot**			**Price insensitive subscribers %**		
Residential access	**Business access**		**Dial up**	**DSL**	**Cable Modem**
$0	**$0**		**45%**	**15%**	**25%**

Appendix 10 The Empirical Data for Mountain View, CA

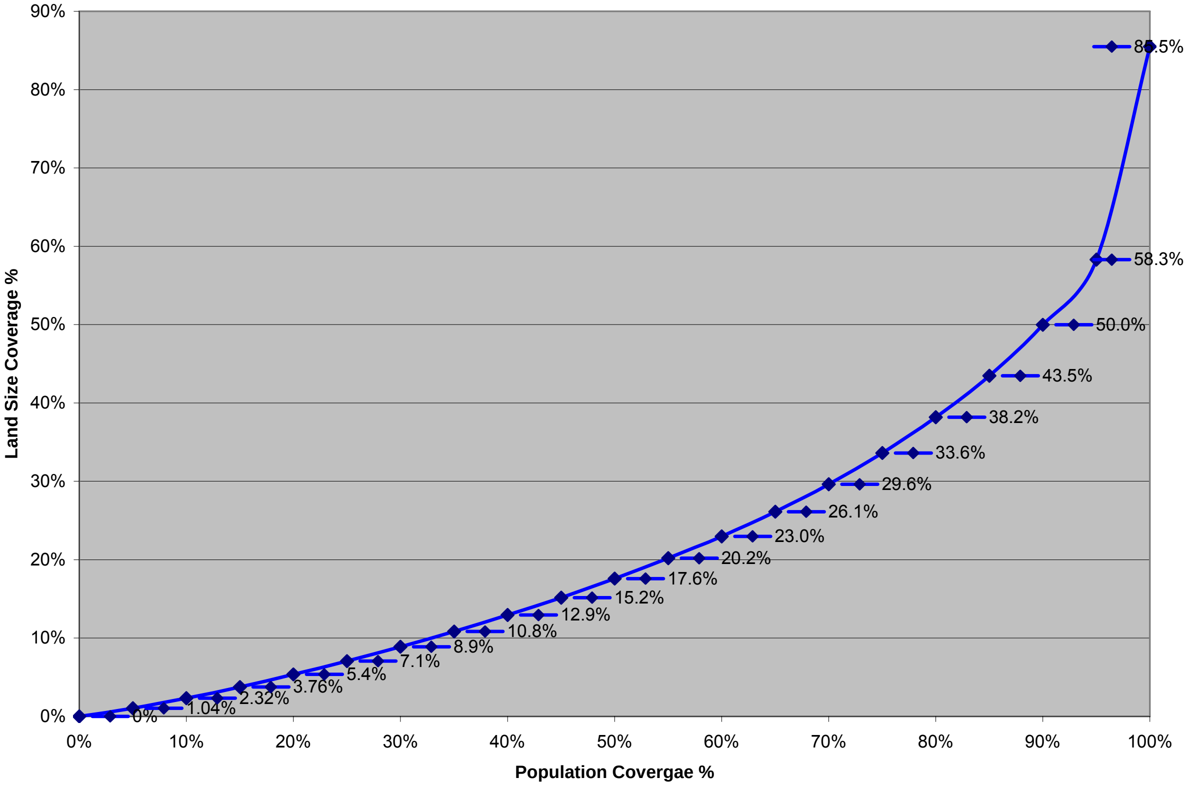
DSL ISP AT&T			Cable Modem ISP ComCast		
Penetration rate	**Bottom tier %**	**Monthly charge ($)**	**Penetration rate**	**Bottom tier %**	**Monthly charge ($)**
54.38%	62.37%	$19.99 (S) $25 (NS)	40.49%	90.54%	$59.95 (S) $42.95 (NS)

WiFi ISP Google		Price insensitive subscribers %		
Residential access	**Business access**	**Dial up**	**DSL**	**Cable Modem**
$0	$0	45%	15%	25%

Appendix 11 The Empirical Data for Philadelphia, PA

<table>
<tr><th colspan="6">DSL ISP
Verizon</th><th colspan="6">Cable Modem ISP
ComCast</th></tr>
<tr><th colspan="2">Penetration rate</th><th colspan="2">Bottom tier %</th><th colspan="2">Monthly charge ($)</th><th colspan="2">Penetration rate</th><th colspan="2">Bottom tier %</th><th colspan="2">Monthly charge ($)</th></tr>
<tr><td colspan="2">46.22%</td><td colspan="2">62.37%</td><td colspan="2">$17.99 (S)
$25.99 (NS)</td><td colspan="2">52.19%</td><td colspan="2">90.54%</td><td colspan="2">$59.95 (S)
$42.95 (NS)</td></tr>
<tr><th colspan="6">WiFi ISP
Earthlink to NAC</th><th colspan="6">Price insensitive subscribers %</th></tr>
<tr><th colspan="3">Residential access</th><th colspan="3">Business access</th><th colspan="2">Dial up</th><th colspan="2">DSL</th><th colspan="2">Cable Modem</th></tr>
<tr><td colspan="3">$21.95</td><td colspan="3">$21.95</td><td colspan="2">45%</td><td colspan="2">15%</td><td colspan="2">25%</td></tr>
</table>

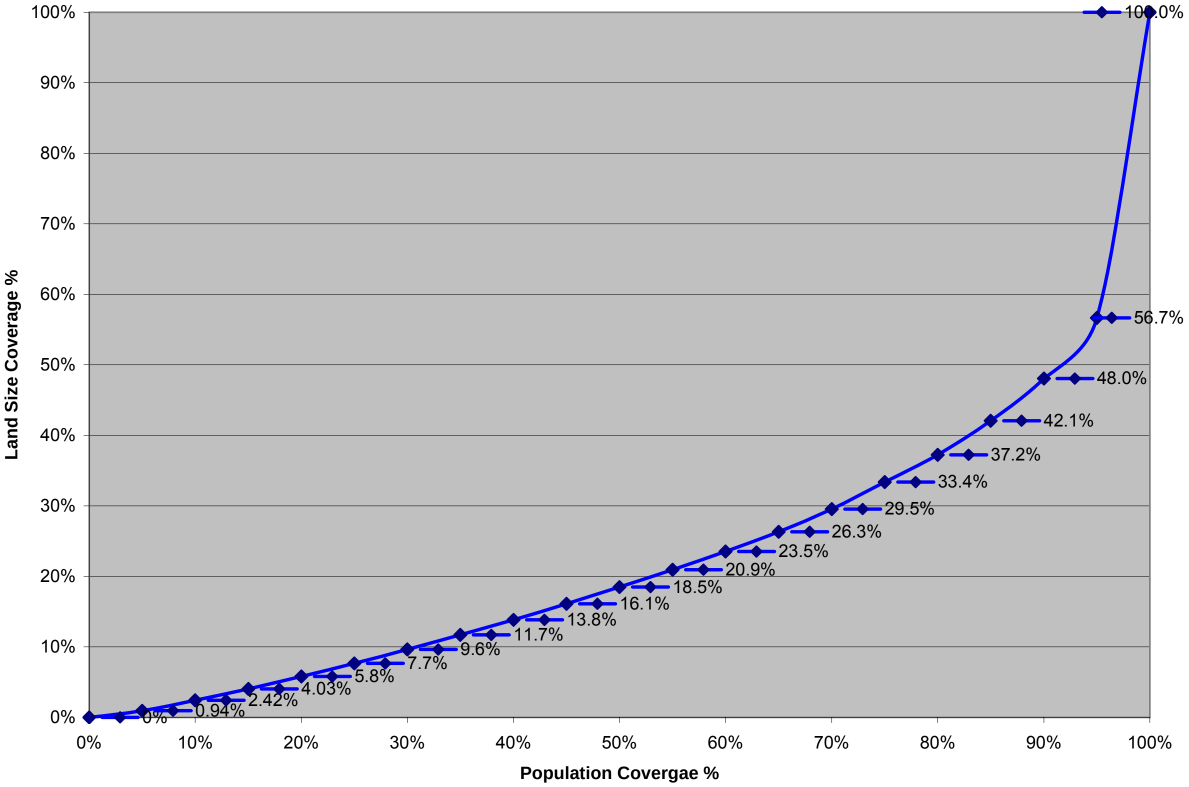
Appendix 12 Accumulated Land Percentage Versus Population Percentage in Philadelphia, PA



Appendix 13 The Empirical Data for Portland, OR

<table>
<tr><th colspan="6">DSL ISP
Qwest</th><th colspan="6">Cable Modem ISP
ComCast</th></tr>
<tr><th colspan="2">Penetration rate</th><th colspan="2">Bottom tier %</th><th colspan="2">Monthly charge ($)</th><th colspan="2">Penetration rate</th><th colspan="2">Bottom tier %</th><th colspan="2">Monthly charge ($)</th></tr>
<tr><td colspan="2">37.57%</td><td colspan="2">62.37%</td><td colspan="2">$31.99 (S)
$39.99 (NS)</td><td colspan="2">56.88%</td><td colspan="2">90.54%</td><td colspan="2">$59.95 (S)
$42.95 (NS)</td></tr>
<tr><th colspan="6">WiFi ISP
MetroFi</th><th colspan="6">Price insensitive subscribers %</th></tr>
<tr><th colspan="3">Residential access</th><th colspan="3">Business access</th><th colspan="2">Dial up</th><th colspan="2">DSL</th><th colspan="2">Cable Modem</th></tr>
<tr><td colspan="3">$0 (with AD)
$20 (No AD)</td><td colspan="3">$0 (with AD)
$20 (no AD)</td><td colspan="2">45%</td><td colspan="2">15%</td><td colspan="2">25%</td></tr>
</table>

Appendix 14 Accumulated Land Percentage Versus Population Percentage Portland, OR



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