A Spatial Decision Support System for Planning Broadband, Fixed Wireless Telecommunication Networks

by

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(ABSTRACT)

Over the last two decades, wireless technology has become ubiquitous in the United States and other developed countries. Consumer devices such as AM/FM radios, cordless and cellular telephones, pagers, satellite televisions, garage door openers, and television channel changers are just some of the applications of wireless technology. More recently, wireless computer networking has seen increasing employment. A few reasons for this move toward wireless networking are improved electronics transmitters and receivers, reduced costs, simplified installation, and enhanced network expandability.

The objective of the study is to generate understanding of the planning inherent in a broadband, fixed wireless telecommunication network and to implement that knowledge into an SDSS. Intermediate steps toward this goal include solutions to both fixed wireless point-to-multipoint (PMP) and fixed wireless mesh networks, which are developed and incorporated into the SDSS.

This study explores the use of a Spatial Decision Support System (SDSS) for broadband fixed wireless connectivity to solve the wireless network planning problem. The spatial component of the DSS is a Geographic Information System (GIS), which displays visibility for specific tower locations. The SDSS proposed here incorporates cost, revenue, and performance capabilities of a wireless technology applied to a given area. It encompasses cost and range capabilities of wireless equipment, the customers' propensity to pay, the market penetration of a given service offering, the topology of the area in which the wireless service is proffered, and signal obstructions due to local geography.

This research is both quantitative and qualitative in nature. Quantitatively, the wireless network planning problem may be formulated as integer programming problems (IP). The line-of-sight restriction imposed by several extant wireless technologies necessitates the incorporation of a GIS and the development of an SDSS to facilitate the symbiosis of the mathematics and geography.

The qualitative aspect of this research involves the consideration of planning guidelines for the general wireless planning problem. Methodologically, this requires a synthesis of the literature and insights gathered from using the SDSS above in a "what-if" mode.

Dedication

I dedicate this dissertation to my beautiful wife and family, without whom I could not have accomplished any of this.

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CHAPTER 1:

INTRODUCTION

Over the last two decades, wireless technology has become ubiquitous in the United States and other developed countries. Consumer devices such as AM/FM radios, CB radios, cordless and cellular telephones, pagers, satellite televisions, car alarm signalers, garage door openers, and television channel changers are just some of the applications of wireless technology. More recently, wireless computer networking has seen increasing employment, including applications meeting the Institute of Electrical and Electronic Engineers (IEEE) 802.11 standard for local area networks (LAN) and local multipoint distribution service (LMDS), another wireless technology using higher frequencies and providing greater data transfer rates. A few reasons for this move toward wireless networking are improved electronics transmitters and receivers, reduced costs, simplified installation, and enhanced network expandability.

In an op-ed piece in the *New York Times*, Kornbluh (2001, p. 21) describes the hundreds of thousands of miles of fiber-optic cable buried in the United States as the "digital equivalent of fallow farmland." She points out that although investors plowed $90 billion into a cross-continental fiber-optic broadband network, today merely 3% of that backbone is in use. The problem, she states, is that entrepreneurs failed to foresee the enormous cost of upgrading the "last mile – copper telephone wires that connect individual homes and small businesses to the broadband backbone" (p. 21). She then encourages both Congress and the president to subsidize sparsely populated regions of the country, low-income users or both, suggesting that an ambitious broadband strategy can help revitalize the economy.

One popular alternative strategy to "going the last mile" with copper is to provide wireless services, whereby the signal is transmitted from a tower through various alternative mechanisms to equipment at business and residential customer sites. Willebrand and Ghuman (2001) cite an example where a fiber cost of $400,000 was reduced to $60,000 with a wireless system. Advances in the technologies of wireless systems provide new opportunities for service providers. Nokia has recently announced a national initiative to bring broadband wireless connectivity to business and residential customers via their Nokia RoofTop solution (BusinessWire, 2002).

Broadband, Fixed Wireless Telecommunication Networks

Comer (3rd edition, p. 603) defines "broadband technology" as the term to describe a networking technology that uses a large part of the electromagnetic spectrum to achieve higher throughput rates. Cable TV, for example, uses broadband transmission. This is as contrasted with "baseband technology," the term used to describe a networking technology that uses a small part of the electromagnetic spectrum and sends only one signal at a time over the underlying medium (Comer, p.602). What constitutes a "large part" or a "small part" of the electromagnetic spectrum means different things to different people. For example, according to Ben Macklin, a broadband analyst at eMarketer, broadband means: a downstream connection of 256 kilobits per second (kbps) and higher to Jupiter Communications; access speeds greater than 144 kbps, and 200 kbps in at least one direction to the US Federal Communications Commission. Fundamentally, however, broadband has come to mean fast connectivity whether by a wired or wireless medium (Macklin, 2001).

Under the umbrella of broadband wireless communications, there are several different technologies. The distinguishing factor separating the technologies is frequency. Varying spectral frequencies will determine the distance of transmission, whether the transmission needs to be line of sight, and whether the FCC requires licensing. Wireless communications use frequencies ranging from radio level to optical.

Two general categories of wireless connectivity exist: fixed wireless and portable wireless. Portable wireless refers to devices such as pagers, cellular phones, and personal digital assistants (PDA), where there are fixed towers but the receivers are mobile. Fixed wireless means that both the sending and receiving components of the network are situated in fixed locations and do not move without reconfiguring the network. The focus of this research is on fixed wireless connections.

There are three different types of connection methodologies in fixed wireless communication. The first is point-to-point (PTP). This is the oldest of the three methods and is most commonly used in campus environments, where it is desirable to connect one point to another without the expense of laying cable. Of the three, PTP typically offers the greatest transmission range. The second method is point-to-multipoint (PMP). This method has a single transmitting tower and multiple receivers. Instead of sending a narrow beam to a single receiver, the transmitter has a broader beam reaching multiple receivers and, consequently a shorter distance capability from the transmitter to the receivers than PTP. With higher frequency wireless methods, every receiver must be visible to the transmitter. The third fixed wireless method is Mesh, where every receiver is also a transmitter. A mesh network will have a so-called "insertion point," which acts as a transmitter, and is connected to the network backbone. The other nodes in the mesh network act as receivers and as re-transmitters, capable of passing signal along to other nearby nodes. With a mesh, it is thus unnecessary for every node to be visible to the insertion point, so long as a path exists from a node to the backbone via other nodes.

Some current fixed wireless technologies that are one or more of the three connection methodologies are free space optics (FSO), Local Multipoint Distribution Services (LMDS), Multipoint Microwave Distribution Services (MMDS), and the IEEE 802.11 standards for wireless connectivity (See Table 1.). Free space optics (FSO), also known as "open-air photonics," "optical wireless" or "infrared broadband," transmits data using low-powered infrared lasers. FSO do not currently require FCC licensing; however, certain power restrictions must be observed. FSO is a line-of-site (LOS) technology, and to remain in the unlicensed territory, the laser must not be too highly powered. Consequently, the maximum range of FSO is a few kilometers. Furthermore, fog can corrupt the transmission as water particles act as prisms to the laser and dissipate the light beam. The data transfer rate of FSO is between 155 and 622 Megabits per second (Mbps).

Local Multipoint Distribution Services is a PMP service. It operates in the 28 GHz band and is LOS. The max range of LMDS is approximately five kilometers and can transfer data up to 2 Gigabits per second (Gbps); however, LMDS behaves more reliably when transferring data in the Mbps range.

Multipoint Microwave Distribution Services are also called Multi-channel Multipoint Distribution Systems and wireless cable. MMDS uses both unlicensed and licensed channels. This technology uses multiple channels simultaneously and, therefore, by aggregation creates large pathways between the sender and receiver. MMDS can transfer data on the unlicensed channels up to 27 Mbps and up to 1 Gbps on licensed channels. MMDS is also LOS.

In the 1990s, IEEE adopted the 802.11 standard for wireless Ethernet. In 1999, the 802.11b standard was approved. 802.11b, also known as Wi-Fi (for wireless fidelity), uses the unlicensed portion of the spectrum at 2.4GHz. Wi-Fi was originally intended for local area networks (LAN), but is now also used in metropolitan area networks (MAN). The reported range of 802.11b is approximately 100 meters, seemingly insufficient for larger scale connectivity, but it is possible to connect points over greater distances with the same technology. In fact, Wi-Fi networks are being implemented with distances of up to 15 kilometers (Carstensen and Morgan, 2002), and data transfer rates up to 11 Mbps. This Wi-Fi frequency band is part of the Industrial, Scientific, and Medical (ISM) bands. These bands are unlicensed and are usually used for household appliances such as microwaves to Wi-Fi routers. Another family of bands is the Unlicensed National Information Infrastructure (UNII) band. UNII provides 300MHz of bandwidth in the 5GHz range. 802.11a uses the UNII bands and provides 54 Mbps data transfer rate.

Planning

One common meaning of planning used in the literature is to understand the necessity of building a system (Dennis, Wixom, and Tegarden, 2002). This is not the meaning used in this research, however. Rather, this work uses a definition of planning closer to that used in artificial intelligence (AI). AI planning systems assume an initial (current) state, a goal state, and a set of allowable actions. The planning system's purpose is to specify the actions that will take the system from its initial state to its goal state, if possible (Rolston, 1988; Fikes, Hart, and Nilsson, 1972). Although planning as used here will not be utilized in a formal way to derive a sequence of actions, still the general sense of the term here will be to specify those activities that will meet a service provider's goals of maximizing profit or minimizing cost within the context of geographic, financial, and other constraints.

In general, this dissertation will not generate long-range plans (say 10 to 20 years), but rather more intermediate plans in the context of three to ten years. Plans will include the choice of wireless technology plus the time sequencing of sending and receiving antenna placement.

Spatial Decision Support Systems

Decision Support Systems (DSS), a branch of information systems, has been a topic of ongoing research for the past 30 years. They used data, models, and user interface components to help decision makers solve semi-structured or unstructured problems (Bennett, 1983). Unstructured decisions are defined as those for which no algorithm can be written, whereas algorithms can be specified for structured decisions. Semi-structured decisions fall between the other two (Keen and Scott-Morton, 1978). Keen and Scott-Morton (1978), Bennett (1983), or Turban (2001) are excellent resources for more information on DSS.

Geographic Information Systems (GIS) are a type of relational database management system used to collect, store, retrieve, and analyze spatial data. GIS link tabular data to graphical data by relating graphical layers to database tables. GIS are widely used to aid decision makers in solving spatial problems. GIS' capabilities of spatial visualization often simplify difficult problems. For example, fast food chains considering new locations can use GIS to determine where their nearest competitors are located. GIS may also be used to show demographics such as residents' income. Furthermore, the GIS can show the road network so the decision maker can determine possible traffic near their store. Any of these pieces of information may be critical in determining the financial success of the new store. The capabilities of the GIS, taken in concert with the knowledge of the decision maker, furnish a tremendous capability in solving this semi-structured spatial problem.

Marrying DSS and GIS creates Spatial Decision Support Systems (SDSS). The advantage of an SDSS is it is able to integrate the model portion of the DSS with the graphical representation of the GIS, thereby aiding decision makers with semi-structured or unstructured spatial problems. In their research, Crossland, Wynne, and Perkins (1995) determined that SDSS enabled decision makers to complete their tasks quicker, more efficiently, and with greater understanding of the problem through visualization.

SDSS is a relatively new research area, primarily because GIS software has historically needed a great amount of computing power, memory, and hard disk space. Since such equipment was very expensive, GIS software required large budgets. Because computers have become significantly cheaper and more powerful, GIS packages can now run on desktop computers, which creates more SDSS research possibilities. SDSS have been applied to siting problems (Maniezzo, Mendes, and Paruccini, 1988; Vlachopoulou, Silleos, and Manthou, 2001), land planning (Nehme and Simoen, 1999), and vehicle routing (Keenan, 1998; Tarantilis and Kiranoudis, 2002).

Statement of the Problem

Since the "last mile" of wiring has become the prohibitive factor for connectivity, wireless solutions are being aggressively pursued. However, each of the wireless technologies introduced earlier has inherent strengths and weaknesses, and it is necessary to overcome or compensate for the weakness of a specific technology in order to make it a viable method of reaching customers. Technologies that use relatively lower wireless frequencies are not as restricted by LOS problems as higher frequencies, but they are limited to short transmission distances. Furthermore, as more people use these wireless technologies, bandwidth will fill causing other problems such as interference. The situation will possibly become similar to the days when garage door openers first became popular, and it was possible to drive around town and use one remote to open other garages. Conversely, fixed wireless technologies that use relatively higher frequency bands are able to propagate data over greater distances, but are limited to LOS. That means that they are unable to transfer through walls, mountains, trees, etc. The LOS constraint requires careful planning of the wireless network. For customers to be included in a wireless network, they must maintain a clear path between themselves and a signal propagator.

One fundamental issue with high frequency, fixed wireless, PMP technologies such as LMDS is that while it may be possible to calculate the physical coverage of a tower, transmission may not be economical. Providers must still determine whether that coverage is profitable. For example, in an area of potential wireless customers under a realistic scenario that is capitally constrained, providers must determine where towers should be placed to maximize profit or alternatively to minimize cost. The solution may or may not contain locations that reach the most customers. This may be true if a minority of customers has the greatest propensity to pay for services provided, and the majority of customers are only willing to pay a minimal amount. Carstensen, Bostian, and Morgan (2001) defined the physical area that is visible from a tower as a *view shed;* part of this research determines that physical region providing profitable coverage from a tower, and labels it a *profit shed*. Since different tower placements will lead to varying levels of profitability, providers will want to determine the profit sheds yielding the greatest financial return. Factors affecting the optimal profit shed include the cost of wireless towers, the cost of receivers, the propensity to pay of the customers reached, the terrain of the region, and the range of a tower signal.

Mesh networks are able to work around the problem of a customer being too far away from a single tower, or in such a location that they cannot maintain a clear line-of-sight to the tower. By allowing each node in the network to function as a transmitter as well as a receiver, signal is passed from one node to another – theoretically allowing more customers than a PMP network. Factors that must be considered in planning a mesh network are the number of allowable hops from a node to the backbone, the capacitation of arcs between nodes, the placement of additional nodes to fill in gaps on the mesh, LOS between nodes, and the density of the neighborhood. Mesh networks do not have *profit sheds,* as do the PMP networks. Instead, there are cost incurring nodes in the network. The objective of this research is to minimize the cost of the network by using as few cost incurring nodes while maintaining a desired level of service.

This dissertation addresses the problem of generating overarching guidelines for a wide range of possible broadband, fixed wireless use. In particular, factors are delineated that differentiate the specification of present wireless technologies, and solution models are developed that determine optimal profit sheds for PMP and optimal cost for Mesh implementations.

Objective of the Study

The objective of this study is to explore the use of an SDSS for broadband fixed wireless connectivity to solve the wireless network-planning problem. The spatial component of the DSS is the locally developed (Carstensen et al, 2001) GIS tool Geographic-Engineering Tool for Wireless: Evaluation of Broadband Systems (GETWEBS). One of the functions of the GETWEBS program is the display of view sheds for specific tower locations. GETWEBS, however, has no ability to calculate the profitability of a specific region, but specifies only whether a tower signal can be received. The first SDSS proposed here incorporates cost, revenue, and performance capabilities of a wireless technology applied to a given area. It encompasses cost and range capabilities of a particular tower, the cost of receivers, the propensity to pay of customers, the market penetration of a given service offering, the topology of the area in which the wireless service is proffered, and signal obstructions due to local geography.

A major difficulty of the wireless tower location problem is the number of possible locations a tower can be placed; an exhaustive search over possible sites is prohibitive. One method explored here for solving this problem is to cast it as a *set-covering problem*, a classical mathematical programming problem formulation. The formulation requires integer solutions and is NP-hard. Moreover, the set covering formulation must be augmented to incorporate geographic constraints discovered by the GIS in order to determine profitable configurations and regions.

The second portion of this research is to develop a SDSS that incorporates a capacitated, fixed-charge network flow model to achieve a minimum cost for a Mesh network architecture. Four factors – visibility, density, hops, and bandwidth – are addressed in the planning of such networks.

The overall objective of the study is to generate understanding of the planning inherent in broadband, fixed wireless telecommunication networks and to implement that knowledge into a spatial decision support system. As steps along the way in obtaining this understanding, solutions to both fixed wireless PMP and fixed wireless mesh connectivity are developed and incorporated into the SDSS. A case study is undertaken to illustrate the general procedure and to aid in refinement of the process and use of the SDSS.

Research Methodology

This research is both quantitative and qualitative in nature. Quantitatively, the wireless network-planning problem may be formulated as integer programming problems (IP), in particular, the so-called *set covering problem* and *capacitated, fixed-charge network flow problem.* An IP formulation is developed for both the PMP and the mesh wireless network problems. The line-of-sight restriction imposed by several extant wireless technologies necessitates the incorporation of a GIS and that a spatial DSS be built to facilitate the symbiosis of the mathematics and geography.

The problem we are dealing with we will refer to as the general wireless planning problem, and is defined as providing wireless broadband services to residential and small home office customers. The qualitative aspect of this research involves the generation of planning guidelines for the general wireless planning problem. Methodologically, this requires a synthesis of the literature and insights gathered from using the SDSS above in a "what-if" mode. A limited case study is undertaken to support development and understanding of the guidelines.

Scope and Limitations

The general wireless planning problem is largely unexplored in the literature. To keep the exploration manageable, this research will focus mainly on planning to ensure profitability and economic feasibility of wireless connectivity. It will not discuss network security issues intrinsic to wireless data transfer or wireless network protocols. In general, engineering issues in the design of antennas or the propagation of radio signals at uncharted frequencies are also beyond the realm of this study. Moreover, solution strategies such as parallel computation to solve larger problems are not addressed here.

Contributions of the Research

This research makes three primary contributions.

- This dissertation provides an investigation into "going the last mile" in reaching customers with broadband fixed wireless networks.
- The research develops mathematical models embedded in an SDSS to develop *profit sheds* which are solutions to the equipment location problem for broadband, fixed PMP wireless networks maximizing profitability.
- This study also derives a model embedded in an SDSS to minimize the cost associated with equipment location for broadband, fixed mesh wireless networks.

Unification of Chapters

This dissertation, under the guidance and tutelage of Dr. Loren Paul Rees, has been written as a series of four separate journal articles all under the thematic umbrella of spatial planning of broadband wireless networks. Consequently, Chapters 3 through 5 are formatted as journal articles and are meant to stand on their own. Furthermore, each has its own title page, abstract, and references. Chapter 6 is another journal article, in preliminary form. References from each chapter have been alphabetically compiled at the end of the dissertation.

The overall theme of the dissertation is planning broadband wireless telecommunication networks, and while each chapter either describes a different methodology in application or general description, they are all thematically related. Wireless technologies may be delivered by three different network topologies, and the latter two are discussed in this dissertation. The first approach is omitted as it only allows for connecting two customers. These topologies are formulated (and solved) mathematically in Chapters 3 and 4. Chapter 5 develops managerial conclusions from the latter topology. Moreover, there are some necessary factors for planning the wireless networks that are common to all four papers. A crucial one is the utilization of a GIS that accounts for wireless technological characteristics. The method in Chapter 3 uses such a GIS, whereas Chapter 5 describes the entire process, but instead of using the GIS, it simulates the information the GIS would provide. The model presented in Chapters 4 and 5 would use the GETWEBS program for effective "real world" problem solving. Another common factor is the semi-structured nature of wireless network planning. This factor gives cause for using a decision support system. Depending upon the wireless methodology, some models are more appropriate than others in determining maximum profitability or minimum cost.

Chapter 6 would use the methods proposed in the earlier chapters, which includes the application of the GETWEBS program, to help decision makers address the larger picture of network planning, such as which methodology(s) would be most appropriate given the characteristics of the area of a desired wireless network. Therefore, while each chapter was written as a separate article and contains its own introduction, literature review, methodology, conclusions and references, they are closely related in their address of reaching the "last mile" using a spatial decision support system and wireless telecommunication networks.

Plan of Presentation

This chapter has served as an introduction to fixed wireless communications, planning, and spatial decision support systems (including geographic information systems). Additionally, it has identified a need for the application of SDSS in wireless technology – specifically in the areas of profitability, area coverage, and resolution of line-of-sight issues.

Chapter 2 is a literature review in the areas of fixed, wireless telecommunication networks, planning, and spatial decision support systems. This review establishes the need for computer support in the placement of antennas and receivers to maximize profit, minimize cost, or guarantee coverage.

Chapter 3 presents an SDSS with an embedded mathematical programming model based on the set-covering formulation in the management science literature. Two different objective functions are considered and a detailed example using a GIS in concert with a mathematical programming model is presented.

Where Chapter 3 proposes the set-covering formulation to solve PMP networks, Chapter 4 introduces a capacitated, fixed-charge network flow problem as a means of minimizing the cost of wireless mesh networks. Chapter 5 provides a major study developing managerial implications of mesh networks in rural / suburban settings a mechanism for addressing the "last-mile" problem.

Future work is outlined in chapter 6, which summarizes the research and draws conclusions by outlining an overarching planning methodology for fixed, wireless broadband telecommunications. The methodology is "delivered" to the planner in a spatial decision support system.

CHAPTER 2

LITERATURE REVIEW

The growth rate of networking, and specifically of the Internet, over the last twenty years is staggering. According to Comer (2001), only two decades ago the Internet was just a research project involving a dozen locations, but now it has grown to reach millions of people in every populated country of the world. The Internet has created a paradigm shift in the way companies do business, schools educate, consumers shop, people interact, and governmental agencies operate. The impact of the Internet has been far greater than just allowing people to send email. It has created a global community of organizations and individuals. In the United States the Internet connects companies, schools, government, and people. It has become a rare thing for a company not to have at least one network that is connected to the Internet. Individuals are also connecting either by low speed methods such as modems or high speed methods such as DSL, cable modems, satellite, or wireless. Moreover, as computers have become faster, more capable, and less expensive, owning a PC and being "on-line" is now the norm. Additionally, consumers are less satisfied with small bandwidth. They want faster connections, and to meet the demand cable and telephone companies are racing to be broadband service providers (Wagner, 2002). However, a fundamental problem exists in that cable companies or telephone companies cannot reach many areas because their infrastructure cannot handle the level of throughput required for broadband speeds. Companies such as PSINet and Quest have spent millions in laying a transcontinental fiber optic backbone (PSINet, 1988; Quest, 1998), however, connecting from homes and companies to the backbone is a much larger problem than anybody initially seemed to realize.

The need for "last mile" connectivity has never been greater. Kornbluh (2001) goes so far as to argue for governmental subsidization of connecting lower income or sparsely populated areas to revitalize the economy. She states that the underestimation of the cost of connecting end users to the backbone of the fiber-optic network has left the majority of the capacity of the network unused.

Wireless connectivity is now a rapidly growing field with many companies racing to establish a market niche for themselves. Since the wireless spectrum ranges from radio to laser, there is a myriad of possible wireless solutions to the "last mile" problem. While each alternate solution may be drastically different from another, a commonality to many, if not all, is the need for transmitters and receivers. It is in dealing with these factors that planning is essential. Decisions are costly. More specifically, hardware such as transmitting towers is costly and great prudence is required in determining their placement. Appropriate or inappropriate tower placement can mean the difference between financial success and disappointment.

This dissertation deals with the intermediate planning of broadband, fixed wireless telecommunication networks. The term *broadband* refers to the utilization of a large part of the spectrum to achieve high throughput ranges (Comer, 2001); this is in distinction to baseband networks, where a small part of the spectrum is used and signals are sent one at a time. The term *fixed wireless* means that neither transmission towers nor receiving towers are mobile. This case is as opposed to cellular telephones, for example, whereby the receivers move around with the customer. Planning, as it is used here is concerned not with implementation details, nor with the electrical engineering development of improved wireless technologies; rather, it refers to determining a proper wireless infrastructure and its deployment. Furthermore, the word *intermediate* in the phrase *intermediate planning* stipulates that the horizon is not necessarily long-range in nature, that is, of 20 to 30 years duration. Instead the focus here is upon the three to ten year horizon whereby the infrastructure to reach communities or businesses, the capability to go “the last mile,” is determined. Thus, this research deals with the intermediate-range infrastructure planning of broadband, fixed connectivity, wireless telecommunication networks.

BROADBAND TELECOMMUNICATION NETWORKS

As introduced in Chapter 1, wireless communications encompasses many different technologies differentiated by frequency. These frequencies determine the distance of transmission, whether the transmission needs to be line of sight, and whether the FCC requires licensing. They range from radio level to optical. Table 2.1 shows some of the radio frequencies and their applications.

Fixed Wireless Networks

Also mentioned in Chapter 1 are the three types of connection methodologies in fixed wireless communication: point to point (PTP), point to multipoint (PMP), and Mesh (Willis, Hasletad, Friisø, and Holm, 2001). Theoretically, one could use any of the connection methodologies at any of the frequencies to bridge the “last mile.” Practical issues, however, limit the matrix of possibilities. Factors such as the frequencies available, licensing, and transmission properties reduce the realistic combinations to a few. This research examines those frequency-connectivity choices that are being considered now or are on the horizon (Nokia, 2002; Radiant, 2001; VTCWT, 2002).

The primary focus of this research is on the Wi-Fi (802.11b) and LMDS systems. 802.11b systems operate in the 2.4 GHz range, are near line-of-sight (LOS) operation and are license free, whereas LMDS frequencies are around 28-31 GHz, require FCC licensing, and are strongly LOS. Near LOS means that signal may pass through some obstructions such as foliage, but cannot pass through mountains and such. The main advantages of LMDS over Wi-Fi are bandwidth and coverage distance. LMDS has a bandwidth that is more than twice that of AM/FM Radio, VHF/UHF Television and cellular telephones combined (VTCWT, 2002). LMDS is also able to transmit a signal over several miles versus Wi-Fi’s range of about 300 feet (Gibbs, 2001). The advantages of Wi-Fi over LMDS are that no FCC licensing is required and Wi-Fi is near-LOS, and, therefore, is not as concerned with objects blocking the tower signal. Simply stated, higher frequency means greater range, LOS, and FCC licensing. Lower frequency means shorter range, less LOS, and that FCC licensing may not be required. Although LMDS’s transmission range is so limited as to be economically prohibitive, this research examines Wi-Fi systems with a greater range, as a means of exploring possible future near-LOS systems.

The Center for Wireless Telecommunications (CWT) at Virginia Tech is an interdisciplinary research group designed to aid client companies develop new products and services using wireless technologies. Participating colleges in the CWT are Arts and Sciences, Business, and Engineering. Furthermore, CWT “has succeeded in its objective of bidding and acquiring licenses in the Federal Communications Commission's (FCC's) first LMDS auction by winning licenses to provide 1150 megahertz of wireless bandwidth for the Greater Roanoke, Danville, Martinsville and Kingsport-Johnson City market areas” (VTCWT, 2000).

Approximately 609,000 people live within the basic trading area (BTA). See Figure 2.1 for a map of CWT's BTA region.

Each CWT college brings specific capabilities to the table. The College of Engineering has technical expertise with wireless transmitters and receivers. The College of Arts and Sciences is experienced with GIS. The College of Business has financial know-how, and has created Monte Carlo simulations for various economic scenarios that determine the cost and profit of a given wireless solution. However, there does not exist a single unifying system that incorporates the capabilities and limitations of the towers, the topology of the landscape, and the economic analysis. Each component currently exists in a somewhat isolated form, and there is no integrated computer system available to do planning.

PLANNING

The American Heritage® Dictionary of the English Language (2000) defines planning as formulating "a scheme or program for the accomplishment, enactment, or attainment of," or alternatively, as "to have as a specific aim or purpose; intend." Yet, in the literature, planning is a term with many different uses. For example, a search on "planning" using ScienceDirect for the years 1999 through 2002 on titles alone (not including abstracts and keywords) results in 1863 articles. Planning in an information systems context refers to the first of four phases in the information systems development life cycle; it is crucial in understanding why an information system should be built. During this phase, the feasibility of the project is assessed, tasks are identified, and time is estimated for the software system's completion (Dennis, Wixom and Tegarden, 2002). Recent articles may also be found on network planning (Wen, Wu, and Shyur, 2002), radiation therapy planning (Hamacher and Kufer, 2002), workload planning (Lewis and Slotnick, 2002) and vehicle planning (Horng and Li, 2002). Not only are the application areas in which planning is applied varied, but the fundamental activities included may be quite different. For example, planning may be proactive such as when producing blueprints for the construction of a house, or reactive, as when preparing a retreat from a lost battle.

This work uses a definition of planning closer to that used in artificial intelligence (AI). AI planning systems assume an initial (current) state, a goal state, and a set of allowable actions. The planning system's purpose is to specify the actions that will take the system from its initial state to its goal state, if possible. A famous example of planning is STRIPS, whereby a group of wooden blocks on a table in a particular initial orientation is transformed into an alternate configuration by a computerized robot with certain well-defined actions (Rolston, 1988). Although planning as used here will not be utilized in a way to derive a sequence of automated actions, still the planning will be executed to specify those activities that meet a service provider's goals of maximizing profit or minimizing cost within the context of geographic, financial, and other constraints. For example, in Chapter 6 a general planning methodology will be outlined that maps existing infrastructure and goals into a specification of technology and equipment providing wireless capability.

SOLUTION METHODOLOGIES

As this research encompasses topics that range over different optimal specification of wireless transmitters and receivers the solution methodologies will be disparate. However, in general, each methodology will incorporate the optimization abilities of mathematical programming, the visualization facilities of GIS, and the integrating capabilities of spatial decision support systems.

Mathematical Programming

The term mathematical programming is a misnomer in the sense that the user of the approach does not program the computer by writing code in Basic, C, or another language. Rather, program is used in the sense of a set of activities or a schedule or a managerial activity for which a mathematical or quantitative solution approach will be advanced. Dantzig first used the approach to solve logistic activities during World War II (Dantzig, 1963).

Mathematical programming is used to solve constrained optimization problems, that is problems in which an objective (such to maximize profit) is pursued, but is limited by constraints (such as cash on hand). Mathematical programming problems (MP) are classified by the nature of the objective and constraints. For example, those problems in which the objectives and constraints are linear are termed *linear* programming problems (LP) (Moore, Lee, and Taylor, 1993).

Some MP can be shown to have optimal solutions that can be found algorithmically regardless of the size of the problem. For example, LP in which the constraints form a convex region can be shown to have optimal solutions that can be found by examining the so-called corner points of the region (Moore, Lee, Taylor, 1993). Conversely, many MP cannot be guaranteed to have optimal solutions that can be found quickly. In fact, many MP can be shown to require exponential solution time in n, the number of variables in the problem.

This research will show that the wireless PMP equipment location problem may be cast as a well-known MP formulation, the *set-covering problem*. For a description of the *set-covering problem,* see Taha (1975). In the simplest wireless case to be examined here, one may solve for the location of transmitters and receivers directly as integer variables in the set-covering problem. In general, however, solutions cannot be guaranteed, and heuristic solutions must be substituted. In fact, for the case of line-of-sight wireless systems, this research will embed both mathematical programming solution techniques and Geographic Information Systems into a spatial decision support system, whereby the GIS determines LOS satisfiability, and the MP solution approach generates answers to the spatially constrained optimization problem. A general wireless equipment location spatial DSS will require heuristic solution approaches as well.

Fixed-Charge Network Flow Models

Mesh networks are made up of nodes and arcs where multiple nodes at different locations all transmit signals to perhaps a single node (Willis, Hasletad, Friis∅, and Holm, 2001). A node is a point to which a signal is transmitted or received. Mesh networks may use a variety of frequencies such as 2.4GHz (Nokia, 2002), 26 GHz to 40 GHz (Fowler, 2001), and laser (Acampora and Krishnamurthy, 1999). This research uses a network flow formulation to solve the mesh network problem. The fixed-charge network flow problem (FCNFP) is one of a large class of network design problems, which have been used in many applications including telecommunications (Balakrishnan et at, 1991, Gavish, 1991), logistics and production planning (Minoux, 1989), and transportation (Magnanti and Wong, 1984). FCNFP problems are known to be NP-hard, and much research has been devoted to creating better and more efficient solutions (Kim and Pardalos, 1999, Cruz et al, 1998). In these problems, the objective is to seek the most efficient way to move flow (in our case bandwidth) on a network in order to satisfy demand between origin and destination nodes and to minimize the overall cost. A fixed cost is incurred for using arcs between nodes; therefore, it behooves the objective to use a few arcs in which costs are associated. When the network is capacitated then upper bounds exist for the amount of flow over an arc. Another consideration for some network design problems is the number of hops from a source (transmitting node) to a sink (receiving node) (Pirkul and Soni, 2002, Soni, 2001, Girish, Zhou and Hu, 2000, Gouveia and Requejo, 2000). The principal reason for constraining the number of hops in a network is to maintain a level of quality of service.

Decision Support Systems

Decision Support Systems were first developed four decades ago, primarily at MIT. The rationale for this new approach was that computers could be utilized not just to automate tasks, but also to support managers at their jobs. This new DSS era followed on the heels of Electronic Data Processing Systems in the 1950s and Management Information Systems in the 1960s.

Keen and Scott Morton (1978) noted that most managerial tasks of significance (Alter, 1980) were semi-structured or unstructured, meaning that no algorithm could be written to specify the path to task solution. This was problematic, because computer programs of that time required algorithms; hence, the computer was being asked to solve problems that it could not solve. The answer advanced was to encourage the manager and computer into a symbiotic relationship, whereby the human provided algorithmic, real-time direction at the prompting of the machine. The machine would, in turn, perform the requested operations in a representational form consistent with the preferences of the manager.

From a builder's perspective, DSS were organized into three primary, independent modules: a database, a model base, and a dialog generation component (Sprague and Carlson, 1982). The dialog module generally consisted of over half of the code and served the purpose of communication with the manager. The model base acted as a repository of models that managers might want or need in working their way through a particular problem. Supposedly, the manager could ask for any model and/or data needed for any aspect of the entire decision-making process (Simon, 1963), and the system would respond.

Early DSS failed in the sense that they were not used, in general, once developed. A variety of reasons was responsible and enhancements were made (Sprague and Carlson, 1982; Bennett, 1983). However, DSS did not reach widespread acceptance until software development introduced two fundamental capabilities: (1) the graphical user interface, whereby managers could now do dialog generation in a natural manner, and (2) the development of easily-utilized model-base competence, through such packages as Excel with its built-in functions, modules, and macros.

Today, DSS are developed routinely, with hundreds of articles in the literature, and whole conferences organized around such systems. The reader interested in further detail may consult, for example, Turban and Aronson (2001).

Geographic Information Systems

Geographic Information Systems are a type of relational database management system (RDBMS) used to collect, store, retrieve, and analyze spatial data. GIS link tabular data to graphical data by relating graphical layers to database tables. For example, a demographic layer of a town map may have sections linked to economic information such as household income or school zoning information (ESRI, 1999).

GIS are excellent tools for presenting spatial data in a format that is easy to manipulate and understand. The layering of different data makes GIS extremely powerful. However, it takes more than just layering data to extract meaningful information. For example, West and Hess (2001) point out that it often takes someone with expert knowledge in GIS to make adequate use of the system. In fact, they suggest using software agents to format the information in a manner most helpful to the user. GIS often require the user not only to be facile in manipulating the GIS, but also to possess expert domain knowledge.

Spatial Decision Support Systems

Spatial Decision Support Systems (SDSS) combine DSS and GIS. The advantage of an SDSS is the seamless integration of the model portion of the DSS with the graphical representation of the GIS, thereby aiding decision makers with semi-structured or unstructured spatial problems. Crossland, Wynne and Perkins (1995) determined that SDSS, through visualization, enabled decision makers to complete their tasks quicker, more efficiently, and with greater understanding of the problem.

SDSS is a relatively new research area, primarily because GIS software has historically needed a great amount of computing power, memory, and hard disk space. Since such hardware was expensive, GIS software required large budgets. As computers have become cheaper and more powerful, GIS packages can now run on desktop computers, and the SDSS research stream is beginning to flow. SDSS have been applied to siting problems (Maniezzo, Mendes, and Paruccini, 1988; Vlachopoulou, Silleos, and Manthou, 2001), land planning (Nehme and Simoen, 1999), and vehicle routing (Keenan, 1998; Tarantilis and Kiranoudis, 2002). GIS have been combined with LP models to solve cropland allocation and land-use modeling (Campbell, Radke, Gless, & Wirtshaffer, 1992; Chuvieco, 1993), and to perform multicriteria analysis (Laaribi, Chevallier, & Martel, 1997; van der Merwe, Lohrentz, 2001)

This research will develop an SDSS to solve the line-of-sight tower location problem for a PMP network. Objective functions considered include maximization of profit, minimization of cost, and the maximization of area coverage. The dissertation will also utilize the SDSS to solve mesh-connectivity wireless problems utilizing its mathematical programming and GIS components.

In conclusion, a review of the literature indicates a plethora of knowledge on mathematical programming/set covering and GIS, but a dearth of work utilizing the techniques in concert. By building an SDSS to combine these symbiotically, this research develops a tool to address important variations of the wireless equipment location problem (in Chapters 3 and 4). However, once the new tool is assembled, an additional host of problems becomes amenable to solution, including issues such as infrastructure development and recovery, for example with developing countries, Native American lands, and both urban and rural disaster recovery. This future research subject is introduced in Chapter 6.

Table 2.1. Some wireless communications examples.

Frequency Band	Applications
170 - 190 kHz	VLF band radios Beacons
550 - 1600 kHz	AM broadcast communications Low power voice and data
27 MHz	CB radios Low power voice and data
49 MHz	Remote control Cordless telephones Low power voice and data
88 - 108 MHz	FM radios Low power voice and data
150 - 170 MHz	Commercial two-way voice Pager services
260 - 470 MHz	303 MHz garage door openers Keyless entry systems Security alarms
824 - 849 MHz and 869 - 894 MHz	Cellular phones
902 - 928 MHz	ISM band Wireless LAN's Part 15 devices (spread spectrum cordless phones, etc.) Military radiolocation systems Federal mobile communications
930 MHz	Pager services with high transmitter power
2.4 - 2.4385 GHz	Amateur satellite Part 15 devices Microwave ovens and systems Army packet radio development **802.11b**
5.15-5.25GHz **5.25-5.35GHz**	U-NII 802.11a
5.727 - 5.875 GHz	Amateur satellite Part 15 devices Naval radar systems Test range instrumentation radars 802.11a **802.16 – (Tsunami equipment)**
24 - 24.25 GHz	Radio navigation
28 – 31 GHz	**Local multipoint distribution service (LMDS)**

Source: The Virginia Tech Center for Wireless Communications. (http://www.cwt.vt.edu/wireless_faq/default.htm).

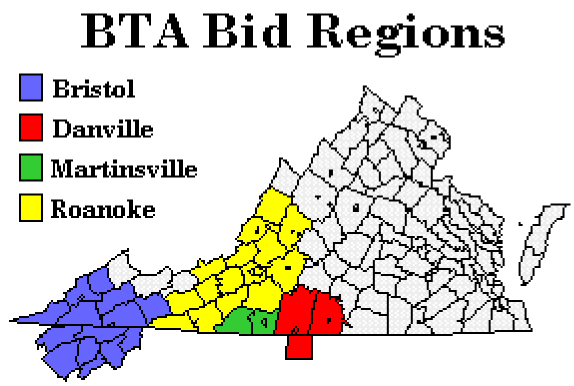

Figure 2.1. Virginia Tech Center for Wireless Telecommunications BTA Regions shown shaded on a map of Virginia (United States)

CHAPTER 3

A MATHEMATICAL-PROGRAMMING AND GEOGRAPHIC-INFORMATION-SYSTEM FRAMEWORK FOR WIRELESS BROADBAND DEPLOYMENT IN RURAL AREAS

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A MATHEMATICAL-PROGRAMMING AND GEOGRAPHIC-INFORMATION-SYSTEM FRAMEWORK FOR WIRELESS BROADBAND DEPLOYMENT IN RURAL AREAS

ABSTRACT

Organizations and individuals are calling for the universal availability of broadband as a national imperative by 2010. Although the United States has the requisite cross-continental fiber-optic backbone infrastructure in place, only 2% to 5% of that nationwide network is used today. This is because of the prohibitive cost necessary to extend the backbone to many small businesses and homes, even for a relatively short distance. For example, nine out of ten American small businesses are less than one mile from the backbone, but still do not have service – the "last mile" problem.

This research integrates a mathematical programming model and a specially developed geographic information system to examine the potential of "going the last mile" using current wireless telecommunication costs in a rural county in the Mid-Atlantic United States. The appropriateness of current wireless technologies in both for-profit and government subsidized scenarios is discovered. Implications for the national scene are discussed.

Keywords: Wireless telecommunications, Broadband, Geographic information systems, Decision support systems, Set covering problem, Mathematical programming optimization

A MATHEMATICAL-PROGRAMMING AND GEOGRAPHIC-INFORMATION-SYSTEM FRAMEWORK FOR WIRELESS BROADBAND DEPLOYMENT IN RURAL AREAS

MOTIVATION

TechNet, a bipartisan group comprising more than 300 chief executive officers and senior partners of the major companies in the fields of information technology, biotechnology, venture capital, investment banking and law, claims that (1) "widespread adoption of true broadband will increase the efficiency and productivity of Americans at work and at home – with a potential $500 billion impact on the United States economy. The benefits to quality of life are immeasurable," and that (2) true broadband is the key to the next generation of communications and Internet services (TechNet, 2002, p. 1). However, Kornbluh (2001, p.21) points out that this potential will remain unrealized without government action. She states in an op-ed piece in the *New York Times,* that although investors have plowed $90 billion into a cross-continental fiber-optic broadband network, today merely 3% of that backbone is in use – it is the "digital equivalent of fallow farmland." The problem, she states, is that entrepreneurs failed to foresee the enormous cost of upgrading the "last mile – copper telephone wires that connect individual homes and small businesses to the broadband backbone" (Kornbluh, 2001, p. 21). In an article in *Scientific American*, Acampora (2002) elaborates by noting that for nine out of 10 American businesses with more than 100 workers, the backbone is less than a mile away.

TechNet has called on the President and policymakers to make broadband a national priority and to set a goal of making an affordable 100-megabits per second (Mbps) broadband connection available to 100 million American homes and small businesses by 2010 (TechNet, 2002). They note that to achieve the 100 million homes goal will require network providers to invest hundreds of billions of dollars to upgrade infrastructures and increase bandwidth capacity in the last mile, primarily by providing new fiber connections to homes and offices. Today, virtually no homes have connections with such bandwidth (TechNet, 2002). An intermediate goal is the "availability of affordable broadband at speeds of at least 6 Mbps from 2 or more providers to at least 50% of U.S. households and small businesses by 2004" (TechNet, 2002, p. 6). TechNet developed 6 principles to address roadblocks and provide a guide to a national broadband policy. Principle 5 reads as follows (pages 2-3):

> Investment incentives, potentially including targeted tax incentives, should encourage broadband deployment to underserved communities and businesses. … In a market-oriented environment that encourages the deployment of broadband networks, there may still be a segment of the U.S. population that does not have broadband availability. Public policies should seek to narrow the current and future disparity in the level of high-speed access to the Internet, to ensure that all Americans can enjoy the benefits of broadband.

Similarly, Kornbluh encourages both Congress and the president to subsidize sparsely populated regions of the country, or low-income users or both, suggesting that an ambitious broadband strategy can help revitalize the economy. (Kornbluh, 2001, p.21)

The focus of this research is on the sparsely populated segment of this problem. For reasons that will be explained in the next section, this paper examines the wireless provision of broadband service to rural homes and small businesses using current costs and technologies. Because the wireless technologies require "line of sight" or "near line of sight" operation, it will be necessary to develop a special-purpose geographic information system (GIS) and then integrate it with the mathematical programming formulation we derive. Solutions will be generated for both "for profit" and government subsidized scenarios. The procedure will be demonstrated for a rural county in the mid-Atlantic region of the United States, and several implications will be drawn for the rural "last mile" problem as a whole.

BACKGROUND

TechNet defines *broadband* as the capacity to deliver Internet access with a continuous 'always on' connection and the ability to both receive and transmit digital content or services at high speeds (TechNet, 2002). Although other definitions of the term abound, most agree with this one – except as to what precisely is meant by "fast." Today, approximately only 4.4% of American households have speeds approaching 400 Kbps (TechNet, 2002). In order to facilitate telecommuting, it is estimated that speeds of 10 Mbps will be required. Many experts have defined 100 Mbps as the speed at which the web's true potential can be achieved. (TechNet, 2002)

Copper wires and coaxial cables connecting buildings do not possess the gigabit per second capacity necessary to carry advanced bandwidth-intensive services and applications, whereas optical fiber bridges needed to connect millions of users to the optical-fiber backbone would cost too much to install (between $100,000 and $500,000 a mile). As these costs are prohibitive, service providers are looking to other transmission media, and in particular to wireless telecommunications. Willebrand and Ghuman (2001) cite an example whereby a fiber potential cost of $400,000 was reduced to $60,000 with a wireless system. Nokia has recently announced a national initiative to bring broadband wireless connectivity to business and residential customers via their Nokia RoofTop solution. (Nokia, 2002)

Wireless Telecommunication

For years, many consumer devices such as AM/FM radio, cordless and cellular phones, satellite television, CB radios, pagers, car alarm signalers, garage door openers, and television channel changers have applied wireless technology. More recently, wireless computer networking has seen increasing employment, including applications meeting the IEEE 802.11 standard for local area networks (LAN), the IEEE 802.16 standard, and local multipoint distribution service (LMDS). These standards are described below. Table 3.1 indicates radio frequencies allocated for several different applications.

Different Wireless Systems

Operationally, wireless radio systems may be classified along several dimensions. The systems we explore in this chapter are *fixed, point-to-multipoint* systems. "Fixed" wireless networks are those where the transmitter and receiver locations are *fixed*, as opposed to *mobile* networks, such as utilized with cellular telephones. *Point-to-multipoint* (PMP) networks are those where a single source (in our case an antenna or antennas on top of a tower) connected to a backbone network propagates signal to multiple customers (in our case, receiving antennas located at customer premises). *Multipoint-to-multipoint* networks (MPM), such as *mesh networks* (Fowler, 2001; Willis, Hasletad, Friis∅, and Holm, 2001), whereby multiple sources at different locations all transmit signals to perhaps the same customers, will be discussed in Chapters 4 and 5.

The three wireless technologies mentioned above (IEEE 802.11, 802.16, and LMDS) share similarities in characteristics and properties and are the leading contenders for fixed PMP service. They are all either line-of-sight, or near line-of-sight, broadband wireless communications, but vary in the degree of throughput. LMDS offers very high-speed connectivity, but is the most costly of the three. The 802.16 technology (also known as WirelessMAN) is less expensive than LMDS, but the customer premise equipment (CPE) costs are still high. Finally, 802.11b (Wi-Fi) service is gaining acceptance and market share, thus allowing for a greater number of choices in equipment and, consequently, lower prices. Tower costs may be similar to 802.16, but in some cases customer premise equipment is one-fourth that of the WirelessMAN.

Costs

As this paper considers only fixed PMP systems, there is a tower cost at the hub (the "point") as well as customer premise equipment costs (the "multipoints"). Tower costs can vary widely, depending on location and terrain, and include components such as cost of land/right of way, structure, connecting the tower to the backbone, power, bringing power to the tower, antennas, and annual maintenance. At each CPE site there are receiving antenna costs and installation costs (so called "truck rolls", Schrick and Riezenman, 2002), which include antenna alignment and positioning expenses.

Differences Among Wireless Systems

It might be supposed that one could apply directly a solution methodology for cell phone networks to the wireless network determination problem. Such is not the case, however, because of three primary differences between the two wireless technologies. First, the receivers in the cell phone scenario are mobile, allowing users to switch from one tower to the next as they travel; utilizing the same frequencies at adjacent towers is not a problem. Such is not the case with broadband. Second, the expectations in terms of service level are much higher for broadband (the so-called "five nines" – 99.999% reliability), as opposed to cell phone users accustomed to breakup, callbacks, and frequent fading and/or loss of signal. Third, the transmission range from towers for cell phones is much greater than for broadband because cell phone frequencies are much lower. Consequently, to determine a broadband distribution network requires the ability to position towers in locations that guarantee reliable line-of-sight transmission. To make this determination, we turn to geographic information systems and decision support systems.

Geographic Information Systems and Decision Support Systems

Decision Support Systems (DSS), a branch of information systems, has been a topic of ongoing research for the past 30 years. Using data, model and user interface components, DSS aid decision makers to solve semi-structured or unstructured problems (Bennett, 1983) and cover all phases of Simon's (1960) decision-making process. According to Keen and Scott-Morton (1978), unstructured decisions are defined as those for which no algorithm can be written, whereas algorithms can be specified for structured decisions. Semi-structured decisions fall between the other two. The reader interested in further detail may consult, for example, Keen and Scott-Morton (1978), Bennett (1983), or Turban and Aronson (2001).

Geographic Information Systems (GIS) are used to collect, store, retrieve, and analyze spatial data and can provide decision support. GIS link tabular data to graphical data by relating graphical layers to database tables. For example, a demographic layer of a town map may have sections linked to economic information such as household income or school zoning information (ESRI, 1999).

Marrying DSS and GIS creates Spatial Decision Support Systems (SDSS). The advantage of an SDSS is its ability to integrate the model portion of the DSS with the graphical representation of the GIS, thereby aiding decision makers with semi-structured or unstructured spatial problems. In their research, Crossland, Wynne and Perkins (1995) determined that SDSS enabled decision makers to complete their tasks quicker, more efficiently, and with greater understanding of the problem through visualization.

SDSS is a relatively new research area, primarily because GIS software has historically needed a great amount of computing power, memory, and hard disk space. Since such equipment was very expensive, GIS software required large budgets. As computers have become cheaper and more powerful, GIS packages can run on desktop computers, which creates more SDSS research possibilities. SDSS have been applied to (among others) siting problems (Maniezzo, Mendes, and Paruccini, 1988; Vlachopoulou, Silleos, and Manthou, 2001), land planning (Nehme and Simoen, 1999), and vehicle routing (Keenan, 1998; Tarantilis and Kiranoudis, 2002).

As part of the National Mapping Program, the United States Geological Survey (USGS) produces Digital Elevation Models (DEMs). A DEM is a digital file containing terrain elevation information that has been sampled at regularly spaced intervals, and stored in raster (matrix of rows and columns) format. There are five DEM products for sale by the USGS, 7.5-minute, 7.5-minute Alaska, 15-minute, 2-arc-second, and 1-degree. These five products fall into one of three different scale categories, large, medium, and small. Larger scale means greater map detail. The large-scale category includes 7.5-minute and 15-minute maps with ratios of 1:24,000 and 1:63,360 respectively; the medium-scale category includes 2-arc-second maps with a ratio of 1:100,000; and the small-scale category includes the 1-degree case with a ratio of 1:250,000.

The 7.5-minute DEM provides the greatest level of detail from the USGS with 30x30 meter data spacing. These maps are produced either by digitizing cartographic map contour overlays or by scanning photographs from the National Aerial Photography Program (USGS, 2002).

ESRI, now based in Redlands, CA, was founded as Environmental Systems Research Institute in 1969 as a privately held consulting firm that specialized in land use analysis projects. ArcView GIS is a desktop geographic information system from ESRI, now the leading global provider of GIS software (ESRI, 1999). In this research we use ArcView version 3.2 to develop our own special-purpose GIS software.

(NEAR) LINE-OF-SIGHT OPTIMIZATION MODELS

As a simplified introduction to the problem, consider wireless service that does not require line of sight. Assume for pedagogical purposes that service is to be provided to a rectangular-shaped geographic area, and divide the rectangle into a grid of n equi-sized smaller rectangles, called cells.

Notation

Define the following four n x 1 vectors:

- Let **x** represent a decision variable indicating tower placement in cells; in particular,

$$\text{let } x_i = \begin{cases} 1, & \textit{if a tower is placed at (the center of) cell i of the grid;} \\ 0, & \textit{if no tower is placed anywhere in cell i of the grid.} \end{cases}$$

- Let **c** represent a vector of costs incurred by placing towers in the grid, namely c_i equals the cost of placing a tower in cell i. Note that this allows costs to vary from cell to cell.

- Let **r** be a vector of revenues, where r_i indicates revenue generated in cell i by a tower placed somewhere in the grid (not necessarily in cell i) that provides signal to cell i.

- Let $\boldsymbol{e}$ be an n by 1 vector of ones such that $\boldsymbol{e}^t = (1\ 1\ \ldots\ 1)$, where $\boldsymbol{e}^t$ represents the transpose of $\boldsymbol{e}$.

In order to express mathematically a tower's ability to transmit signals successfully to cells in the grid (i.e., "cover" the cell), we define an n x n binary matrix E, which we call the *exposure* matrix. In particular,

$$E_{ij} = \begin{cases} 1, & \text{if a tower placed at the center of cell j provides a signal to cell i} \\ 0, & \text{if a tower placed at the center of cell j does not furnish a signal to cell i.} \end{cases}$$

In general, note that E_{ij} might equal zero for either of two basic reasons: A tower placed at j cannot transmit a strong enough signal to a distant cell i, and/or a signal between i and j might not have line-of-sight (due to terrain). But since in the simplified non-line-of-sight case being considered at the moment it does not matter whether the receiving antenna can see the tower, the second reason is of no concern, an assumption we will relax shortly.

With these definitions the following should be observed:

- The number of towers placed equals the vector dot product $\boldsymbol{e}^t \cdot \boldsymbol{x} = \sum x_i$.
- The cost of placing towers is $\boldsymbol{c}^t \cdot \boldsymbol{x} = \sum c_i x_i$.
- If we denote the ith row of the E matrix as the 1 x n vector $E_{\boldsymbol{i}\bullet}$, then the dot product $E_{\boldsymbol{i}\bullet} \cdot \boldsymbol{x}$ equals the number of signals cell i will receive from all towers actually placed.

This latter observation leads to the formulation of several important potential constraints:

- The specification $E_{\boldsymbol{i}\bullet} \cdot \boldsymbol{x} \geq 1$ specifies that cell i must receive at least one signal.

- The matrix stipulation $E \cdot \boldsymbol{x} \geq \mathbf{e}$ mandates that each cell in the grid must receive at least one signal.

Finally, note that $E_{i\bullet} \cdot \boldsymbol{x}$ takes on the value zero if cell i receives no signal and equals a positive integer value if a signal or signals are received. Consequently, we may write total revenue generated in the entire grid as

$$\text{revenue in cell } i = \begin{cases} r_i, & \text{if } E_{i\bullet} \cdot x > 0 \\ 0, & \text{otherwise.} \end{cases} \tag{1}$$

View Sheds

Introducing the line-of-sight requirement necessitates a fundamentally different analysis because terrain, buildings, and (sometimes) even trees must be considered. "Near" line-of-sight is less restrictive. Signals still cannot go through large obstructions such as mountains; trees and smaller hindrances are not a problem. This means that DEM maps contain the topographic detail necessary to ascertain near line-of-sight capability.

To exploit these maps, Bill Carstensen wrote a special-purpose geographic information system (Carstensen, Bostian, and Morgan, 2001) and introduced the view shed concept. The modified GIS, the Geographic-Engineering Tool for Wireless: Evaluation of Broadband Systems (GETWEBS), can determine the visibility over an area of any tower signal, given the height and tower location on a DEM, and the transmission signal strength. Figure 3.1 shows (superimposed on a DEM) the view shed, i.e., area that can see a tower's transmission given the tower's location and height (40 feet) in a rural county in the mid-Atlantic United States. One thing we are interested in is determining the *profit shed*, i.e., the region that can both see a tower's signal and generate a profit for a service provider. To determine this, we integrate the GETWEBS view shed with a mathematical programming formulation, as will now be explained.

Enhance the notion of E, the exposure matrix, by defining an n x n binary matrix V, which we term the *view shed* matrix. Whereas the exposure matrix assumes that an antenna within the tower's range can receive any signal sent from a tower, we define V_{ij} such that

$$V_{ij} = \begin{cases} 1, & \text{if, given the terrain, a tower placed at the center of cell j provides a signal to cell i} \\ 0, & \text{if, given the terrain, a tower at the center of cell j does not furnish a signal to cell i.} \end{cases}$$

That is, values of one for elements V_{ij} in the matrix V indicate which cells j actually receive signal from a tower placed at the center of cell i. GETWEBS must make this determination. This is done in practice by making a point-to-multipoint determination within the GIS of what can be seen. A simple example illustrates the concept.

Pedagogical Mini-Example

Consider a fictitious town (shown in Figure 3.2a) whose elevation profile is indicated in Figure 3.2b. This town is chosen so we may calculate both exposure and view shed matrices without relying on GETWEBS. If the town is divided into a grid of rectangular cells 1 kilometer on a side, and planners consider tower placements using line-of-sight LMDS technology with an omni directional antenna array reaching $2.5\sqrt{2}$ kilometers (see Figure 3.2c for the pedagogic rationale for this "unusual" choice), then the exposure matrix E ignoring line-of-sight issues and the view shed matrix including those considerations may be written as indicated in Figure 3.3. (We have assumed a tower height of zero for pedagogic reasons.) Note that since the east part of town is flat (no hills or valleys), the portion of the view shed matrix corresponding to that part of town is identical to the exposure matrix E. The same is not true on the other side of the tracks, as can be seen in Figure 3.3, because the hill prevents signals from a tower on one side of it from reaching the other side.

Profit Model

A wireless Internet, etc., provider will most likely want to maximize profit subject to financial capabilities. This suggests an integer mathematical programming formulation similar to the set-covering problem (Taha, 1975). We develop the wireless formulation by way of a simple example.

Consider another fictitious small, flat town in which we want to consider providing wireless service. Since the town is completely flat, we note that the V matrix is equivalent to the E matrix. For pedagogical purposes we divide the town into only 6 cells (see Figure 3.4) and assume that a tower placed at the center of any cell will cover that cell and any cell it touches horizontally and vertically, but not in a diagonal direction. For example, a tower in cell 2 will cover cells 1, 2, 3, and 5. This may be seen in the second row of the V matrix:

$$V = \begin{pmatrix} 1 & 1 & 0 & 1 & 0 & 0 \\ 1 & 1 & 1 & 0 & 1 & 0 \\ 0 & 1 & 1 & 0 & 0 & 1 \\ 1 & 0 & 0 & 1 & 1 & 0 \\ 0 & 1 & 0 & 1 & 1 & 1 \\ 0 & 0 & 1 & 0 & 1 & 1 \end{pmatrix}.$$

Recall that $V_{1\bullet}$ indicates the first row of the V matrix; it specifies which towers, if placed, will reach cell 1. That is, cell 1 will get coverage if towers are placed in cells 1, 2, or 4.

Although the expression $V \cdot \boldsymbol{x} \geq \mathbf{e}$ guarantees coverage of all cells, maximized revenue cannot be determined without defining a new binary variable that indicates whether a cell is covered:

Let $z_i = \begin{cases} 1, & \textit{if cell } i \textit{ receives (at least) one signal;} \\ 0, & \textit{if cell } i \textit{ does not receive a signal at all.} \end{cases}$

Furthermore, stipulate that $z_1 \leq x_1 + x_2 + x_4$ (or, equivalently, $z_1 \leq V_{1\bullet} \cdot \boldsymbol{x}$).

Now if $x_1 = x_2 = x_4 = 0$, then $z_1 = 0$. This says (as desired) that if there is no tower in cells 1, 2, or 4, then cell 1 receives no signal. But if one or more of x_1, x_2, and $x_4 \neq 0$, then z_1 may equal either 0 or 1, whereas we want z_1=1. To fix this, we say

max z_1
subject to $z_1 \leq x_1 + x_2 + x_4$;

then if $x_1 = x_2 = x_4 = 0$, then z_1 still equals 0, and if one or more of x_1, x_2, and $x_4 \neq 0$, then $z_1 = 1$, as desired. The objective max $\boldsymbol{r}^{\mathbf{t}} \cdot \boldsymbol{z}$ subject to $\boldsymbol{z} \leq V\ \boldsymbol{x}$ allows us to write the vector version including all cells.

If we let $\rho_i = r_i - c_{cpe}$ (where c_{cpe} is the customer-premise-equipment cost), then in general, with a budget of M, we may write:

$$\max \rho^{t} \cdot z - c^{t} \cdot x \tag{2a}$$

$$\text{st/} \quad V\ \boldsymbol{x} \geq \boldsymbol{z} \tag{2b}$$

$$\boldsymbol{c}^{\mathbf{t}} \cdot \boldsymbol{x} + \boldsymbol{c}^{\mathbf{t}}_{\text{cpe}} \cdot \boldsymbol{z} \leq M \tag{2c}$$

$$\boldsymbol{x_i}, \boldsymbol{z_i} \in \{0,1\} \quad \forall i. \tag{2d}$$

If *everyone* must receive a signal, then constraint (2e) below is added to the system:

$$V\ \boldsymbol{x} \geq \mathbf{e} \tag{2e}$$

If there is no budgetary restriction, then M is allowed to approach infinity, and constraint (2c) is removed from the model.

Pedagogical Example

To illustrate the model for our six-celled, fictitious town, we further specify the following: Assume M = \$500K, c_i = \$200K ($\forall i$), $c_{cpe} = 0$, there is a 5-year economic horizon, and all cells have the same number of households, penetration, and propensity to pay, namely:

N_i = 70 households;

propensity to pay = \$50/month or \$3000/horizon, and

penetration = 1/3.

Then, revenue = r_i = 70 * (1/3) * \$3000 = \$70,000 for each cell ***if*** a signal is received in that cell.

Equations (2) are written as (dollars are in thousands):

$$
\begin{array}{ll}
\text{Max} & 70(z_1 + z_2 + z_3 + z_4 + z_5 + z_6) - 200(x_1 + x_2 + x_3 + x_4 + x_5 + x_6) \\
\text{st/} & 200(x_1 + x_2 + x_3 + x_4 + x_5 + x_6) \leq 500 \\
& \quad x_1 + x_2 \qquad + x_4 \qquad\qquad \geq z_1 \\
& \quad x_1 + x_2 + x_3 \qquad + x_5 \qquad \geq z_2 \\
& \quad \qquad x_2 + x_3 \qquad\qquad + x_6 \geq z_3 \\
& \quad x_1 \qquad\qquad + x_4 + x_5 \qquad \geq z_4 \\
& \quad \qquad x_2 \qquad + x_4 + x_5 + x_6 \geq z_5 \\
& \quad x_3 \qquad + x_5 + x_6 \qquad\qquad \geq z_6 \\
& \quad x_i, z_i \ \varepsilon\ [0,1] \text{ for all } i.
\end{array}
$$

The solution is $x_2 = x_5 = 1$; $x_1 = x_3 = x_4 = x_6 = 0$, which says to place towers in cells 2 and 5 only. Moreover, $z_1 = z_2 = z_3 = z_4 = z_5 = z_6 = 1$, which states that all cells are covered. The total revenue generated is $420,000; the cost of placing towers is $400,000; and the profit is $20,000. Of the $500,000 budget, $100,000 remains unspent.

Maximizing Exposure Model

In addition to the profit maximization model formulated above, an important model maximizes exposure within a prescribed budget. This model is interesting in examining regions where profit cannot be made, but government subsidy is considered at a specified level. If h_i is the number of households in cell i, then the exposure model is

$$\max h^{t} \cdot z \tag{3a}$$

$$\text{st/ } V\,\boldsymbol{x} \geq \boldsymbol{z} \tag{3b}$$

$$\boldsymbol{c}^{\mathbf{t}} \cdot \boldsymbol{x} + \boldsymbol{c}^{\mathbf{t}}_{\text{cpe}} \cdot \boldsymbol{z} \leq M \tag{3c}$$

$$\boldsymbol{x_i}, \boldsymbol{z_i} \in \{0,1\} \;\; \forall i. \tag{3d}$$

Additional Constraints

There are other constraints not indicated above that may be written when appropriate. These include: budget constraints for any given time period, the exclusion of a particular cell from tower placement, the insistence that a tower be placed in a given cell, the specification of an existing tower in a cell, the requirement that a specified fraction of total households be serviced, the demand that k out of r cells (where k and r are specified constants) be given service, etc. The reader interested in incorporating such constraints should consult a basic mathematical programming text, such as Taha (1975).

A Spatial Decision Support System

We have built an SDSS that implements the mathematical modeling features described above with the GETWEBS geographic information system. The point noted here with this SDSS is that general modules have been/can be written that allow various equipment, forecasting, and financial modeling to be intertwined in the appropriate mix. A graphic description of the SDSS architecture we employed is shown in Figure 3.5.

Figure 3.5 shows three paths to the (output) profit-shed module: the visibility module, the revenue module, and the evaluation module. The visibility module consists of the equipment definition sub module, and the view shed sub module. In addition to descriptive information on each type of equipment, the equipment sub module contains technical capabilities, including the range, angle of transmission, and shape of the region covered by each antenna (e.g., circular, elliptical, etc.). An example of a tower specification screen is shown in Figure 3.6. The view shed sub module calculates exposure (i.e., the view shed matrix V) given the antenna specified and the GETWEBS program. The revenue module includes the census data access and various marketing revenue sub modules, and the evaluation module contains both the max profit and max exposure mathematical programming models as well as requisite financial sub modules.

REACHING THE LAST MILE

Having developed a mathematical programming model with an embedded geographic information system, we now return to the issue posed at the beginning of this paper, namely the lack of broadband infrastructure going "the last mile." Recall that Kornbluh (2001) noted that 97% of the broadband backbone is *not* in use, with only 10% of households and small businesses connected to it.

To demonstrate proof of concept, we develop profit and exposure models for various near line-of-sight technologies for a region approximately 40 km (25 miles) on a side. We use USGS census maps in the GETWEBS program. We base our wireless cost data on actual systems with which we are familiar, although some cost specifications are difficult and approximate, as will be noted.

GETWEBS Data

Montgomery County is a medium-sized county in the mid-Atlantic United States. It has a population of 77,500 (about 29,000 households), consists of 393 square kilometers in a rural setting, and has an active interest in low-cost, high–speed Internet service, partly due to the presence of a large land-grant university. Figure 3.1, seen earlier, shows a screenshot of this county displayed in the GETWEBS program.

The county is approximately a 40 km by 40 km rectangle, which we subdivide into 394 cells (arranged roughly as 20 rows with 20 columns), each cell being a square of side 2 kilometers. As mentioned, census data down to squares 30 meters on a side is available, and the process described below would be unchanged if analysis in greater detail were desired, although computational complexity would be significantly multiplied. For simplicity, we assume transmission towers may be placed only in the middle of any 2-kilometer cell.

GETWEBS considers a transmission tower centrally placed in a cell, and then determines whether line-of-sight exists to each of the other ("receiving") cells. Three notes should be made with respect to this calculation: (1) this is a point-to-multipoint GIS calculation, from the tower to each locale in the receiving cell; (2) the software reports the percentage of the receiving cell able to get a signal; and (3) the search over the receiving cells can be significantly limited by the range of the signal. For example, in one scenario considered here, the signal is such that any one transmitting cell can reach at most only 28 other cells, and transmitting cells on edges of the region have an even further reduced set of possible receiving cells.

The output from our view shed software is a 394 by 394 matrix filled with percentages. We arbitrarily specify that a cell with greater than 50% coverage from a tower is covered, and enter a "1" in the corresponding cell for the view shed matrix. Obviously the 50% threshold may be adjusted to meet particular circumstances.

Wireless Parameters and Costs

We examine the three fixed, point to multipoint technological options currently under most consideration: local multipoint distribution systems (LMDS), the 802.16 standard, and the 802.11b option. The parameters we used are based on published data.

Range

We use a range (i.e., transmission signal from the tower) of $5\sqrt{2} \approx 7.1$ kilometers. This value is within the scope of all three systems and is chosen because a tower placed at the center of a cell can reach diagonally to all households two cells away.

Tower Costs

We assume four 90º sectored antennas at each tower, providing omni-directional coverage. Costs for each tower, beyond the antennas and the structure, include the cost of land purchase and/or right-of-way, getting electricity to the site, and connecting (or transmitting) to the backbone. As the non-antenna costs dominate, it is a fair approximation to say the tower costs of all three technologies are approximately the same. The tower costs, even for Montgomery County, will vary considerably depending on the location and accessibility to other infrastructure. Talks with "experts" suggested that we model tower costs probabilistically; we chose a triangular distribution with a minimum value of \$100,000; a maximum of \$500,000; and a most likely value of \$150,000.

Customer Premise Equipment Cost

The receiver antenna costs do vary widely by technology, and depend primarily on the electronics costs of each system. The costs we used were \$7,900 for LMDS; \$1295 for the WirelessMAN (IEEE 802.16); and, \$230 for the Wi-Fi system.

Revenue Model

Actual year 2000 number of households and per household annual income are available or can be calculated from United States census data for each cell in Montgomery County. We assume the following functional form to calculate revenue: $\%P = f(I \mid p_m)$, where %P is the percent participation, I is the average annual household income for a cell, and p_m is the price per month for the wireless broadband offering. That is, the percentage of households in a cell purchasing ("participating") in the broadband offering is a function of the average household income in that cell given the monthly price of that service. These functional relationships were estimated from information on "related" services in the local area, namely, the price charged for DSL and for Adelphia Internet service. At a similar price, one would expect the wireless broadband service to do at least as well as the two alternatives mentioned, as the wireless bandwidth would be an order of magnitude or so better, depending on the wireless technology employed. The particular functional relationships employed in the study are shown in Table 3.2. Note that in that table, I is the average per-household annual income (in 000s of dollars), p_m is expressed in dollars, and %P is a number between 0 and 100.

Results

The profit model developed above is run for each of the three technologies. First, the view shed matrix V is determined by GETWEBS and substituted into equation (2b). Then the system given by equations (2a), (2b), and (2d) is solved.

LMDS at $50 per month

This technology, though touted for several years until the fairly recent past, is substantially too expensive for deployment in a county similar to Montgomery County. The system solution declares that no profit can be made and that, hence, no towers should be placed.

802.16 (WirelessMAN) at $50 and $100 per month

The WirelessMAN reduces the customer premise equipment to $1295. Nonetheless, at a price of $50/month, once again wireless service is not profitable. At a price of $100/month, the optimal solution suggests that one tower be placed reaching approximately 700 households (less than three percent of the county total). Moreover, only (approximately) $25,000 in profit is generated. The one tower placed is positioned in the northern portion of the county (see Figure 3.1). Regions in the profit shed (i.e., in a view shed that generates profit) are shaded.

Wi-Fi at $50 per month

With CPEs down to $230, the 802.11b Wi-Fi alternative generates a significant profit. Almost 80% of the county is projected to participate, requiring 6 towers (see Figure 3.7), generating a profit of $5M on a cost of $6.2M.

DISCUSSION

The previous section examined three wireless technologies in a "for profit" context. Even with the Wi-Fi scenario, universal service was not nearly achieved. We now examine Kornbluh's (2001) and Technet's (2002) calls for government subsidization to see at what cost Montgomery County can reach more households with broadband availability. We consider only the Wi-Fi (802.11b) alternative.

We first consider the case where a for-profit service provider has found a limited level of service profitable, but the government wishes to increase the number of households reached. For example, in the Wi-Fi example given above, the maximum-profit solution provides service to 80% of the households in Montgomery County. If the government decides it wishes service to be provided to (say) 90% of the households in the county, then the for-profit provider will not want to service the extra households because less profit will be obtained. If the government agrees to a subsidy to the provider for reaching the extra homes, the amount of the subsidy could be studied using the spatial decision support system – one merely adds a constraint to the profit maximization model requiring service to the desired percentage of homes. (See Figure 3.8 for some results at different levels of coverage.) For example, if the government agrees to make up for the provider's loss in profit, the subsidy would be $500K. Alternatively, if the government agreed to make up for the difference in total costs (not shown), the subsidy would be $1.7M. Moreover, further analysis with the tool can be performed to determine the incremental benefit of reaching additional homes. For example, data indicate that the profit begins to drop quite sharply beyond 90% coverage, where tower costs increase dramatically. What is happening is that, with the easiest-to-reach people having been served, towers must be placed that cover relatively few individuals. So, for Montgomery County, a government subsidy to provide service beyond 90% would give relatively little marginal benefit for the marginal expenditure.

A second subsidization alternative beyond the cooperative venture between the government and a for-profit firm is one in which *no* for-profit wishes to provide broadband service to a region. In such a case the government may believe it is necessary to subsidize the project. In this situation the maximum exposure model of equations (3) could be utilized, specifying the subsidization amount in equation (3c). For example, for a small subsidy of $500K in Montgomery County, 1670 households can be reached, with one tower being placed.

CONCLUSIONS

This paper has shown how mathematical programming can be integrated with an enhanced geographic information system to build a spatial decision support system for analyzing options in the deployment of wireless broadband alternatives in rural areas. Both profit-maximization and subsidization scenarios were presented in addressing the “last-mile” problem in a particular county in the mid-Atlantic United States region.

It is not possible to generalize from one county to draw conclusions about broadband in the United States as a whole. Nonetheless, it is safe to draw several general conclusions. It is seen that at current technology levels and costs, providing widespread broadband service to many rural regions will require significant government subsidization. The cost of customer premise equipment is the largest problem, and is still prohibitive for sparsely populated, hilly terrain. Tower costs also need addressing, although little can be done to lower several components of these costs, including the cost of land access, provision of power, and connecting from the tower to the backbone. However, the spatial decision support system developed in this paper can be used to determine the magnitude of the last-mile problem and analysis of different policy options, although significant effort may be required to generate reliable estimates. In particular, census data maps are available with household data, and DEMs can be analyzed to develop view sheds. But what is hard to specify are tower costs and revenue projections. To the extent that appropriate probabilistic models can be formulated to specify local tower costs and revenue receipts, one could generate answers for the entire United States, given sufficient effort.

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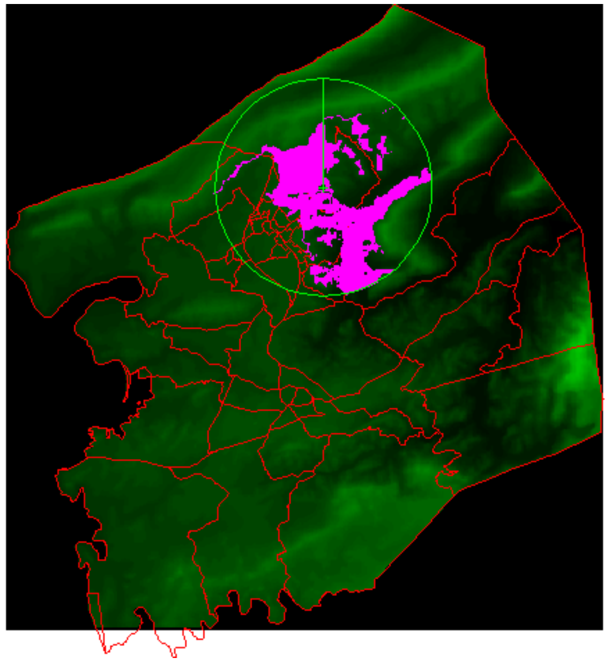


Figure 3.1. A GETWEBS screen shot indicating the view shed of a tower placed at the dot near the center of the top of the screen and with range indicated by the circle.

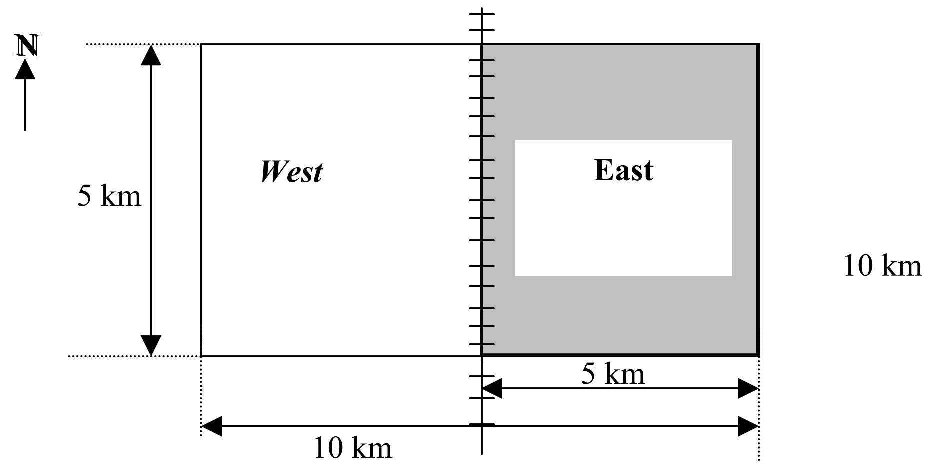


Figure 3.2a. A fictitious town, divided into an east and west region by a railroad track that runs north/south through the center of town.

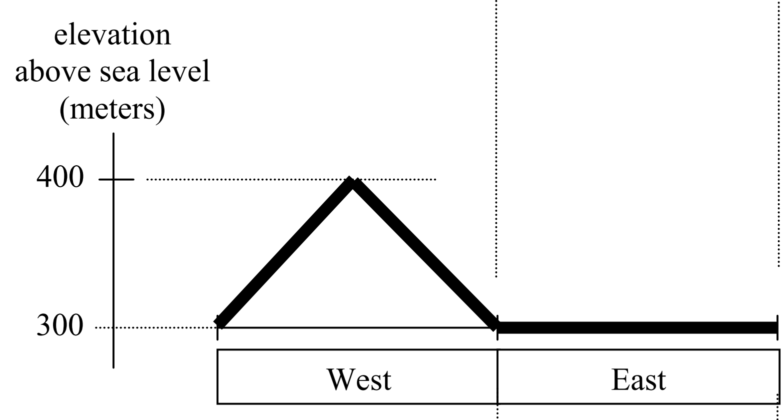


Figure 3.2b. An elevation map of the fictitious town.

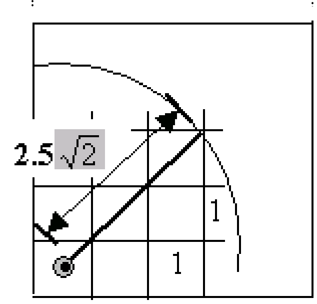
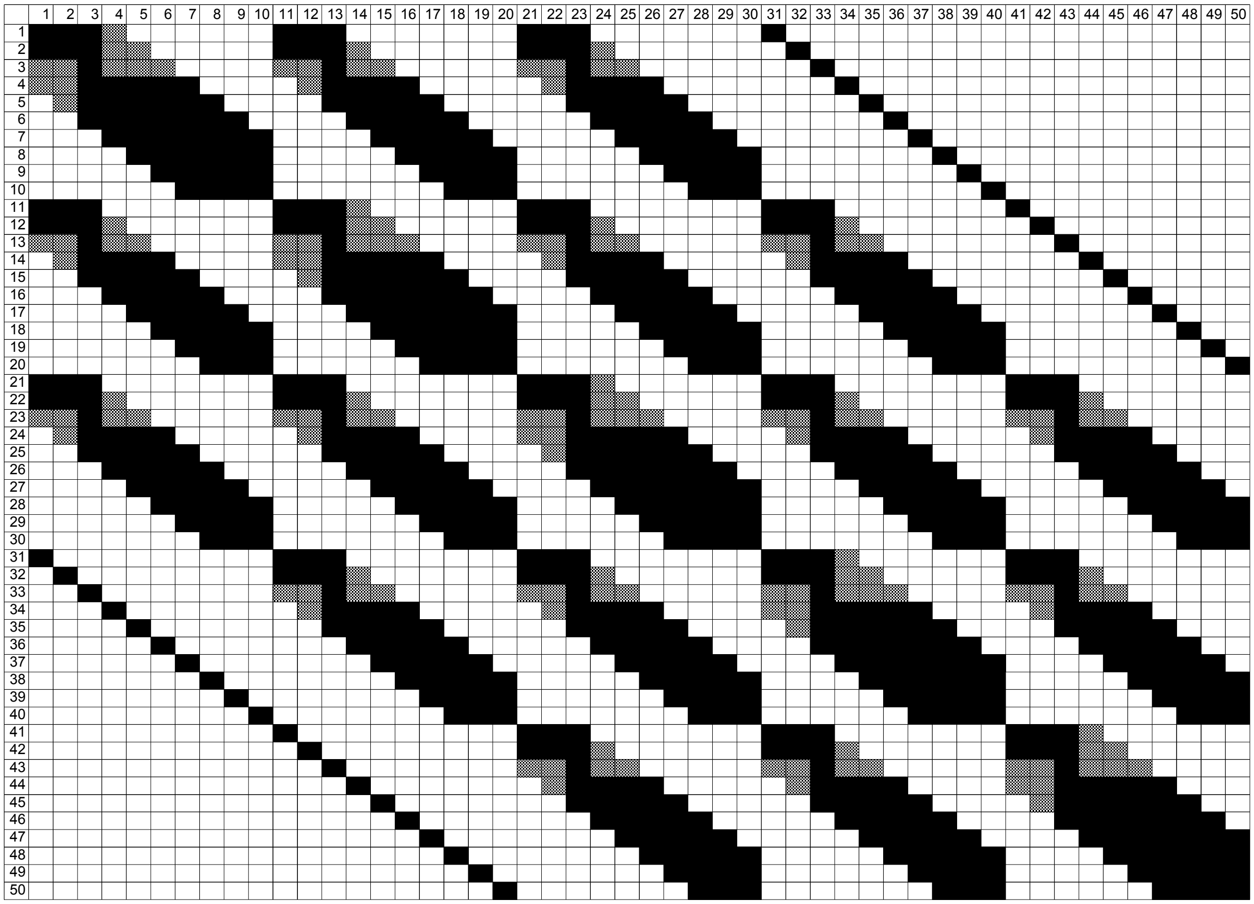


Figure 3.2c. A transmission tower's signal can reach diagonally to all households two cells away.



Notes:

1. With regard to Figure 3.2, cell 1 is in the upper left corner of the town, and cell 50 the bottom right corner.
2. Black cells indicate a 1 in cell (*i, j*), wheras white cells indicte a 0.
3. Checkered cells indicate a 1 in the exposure matrix *E* and a 0 in the view shed matrix *V.*

Figure 3.3. The exposure matrix *E* and the view shed matrix *V* for the fictitious town depicted in Figure 3.2.

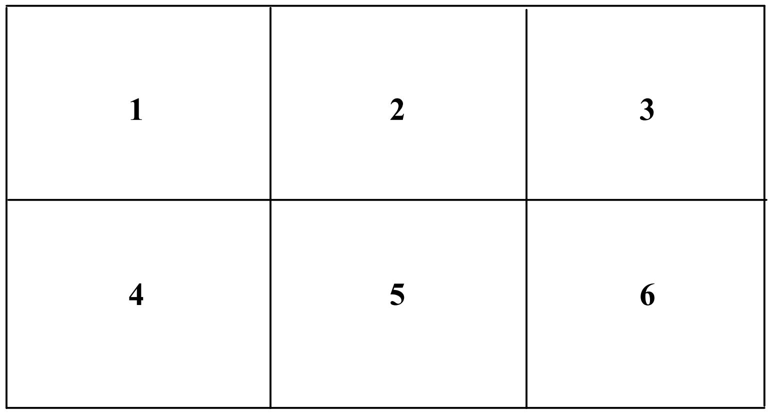


Figure 3.4. A fictitious mini-town, divided into six cells.

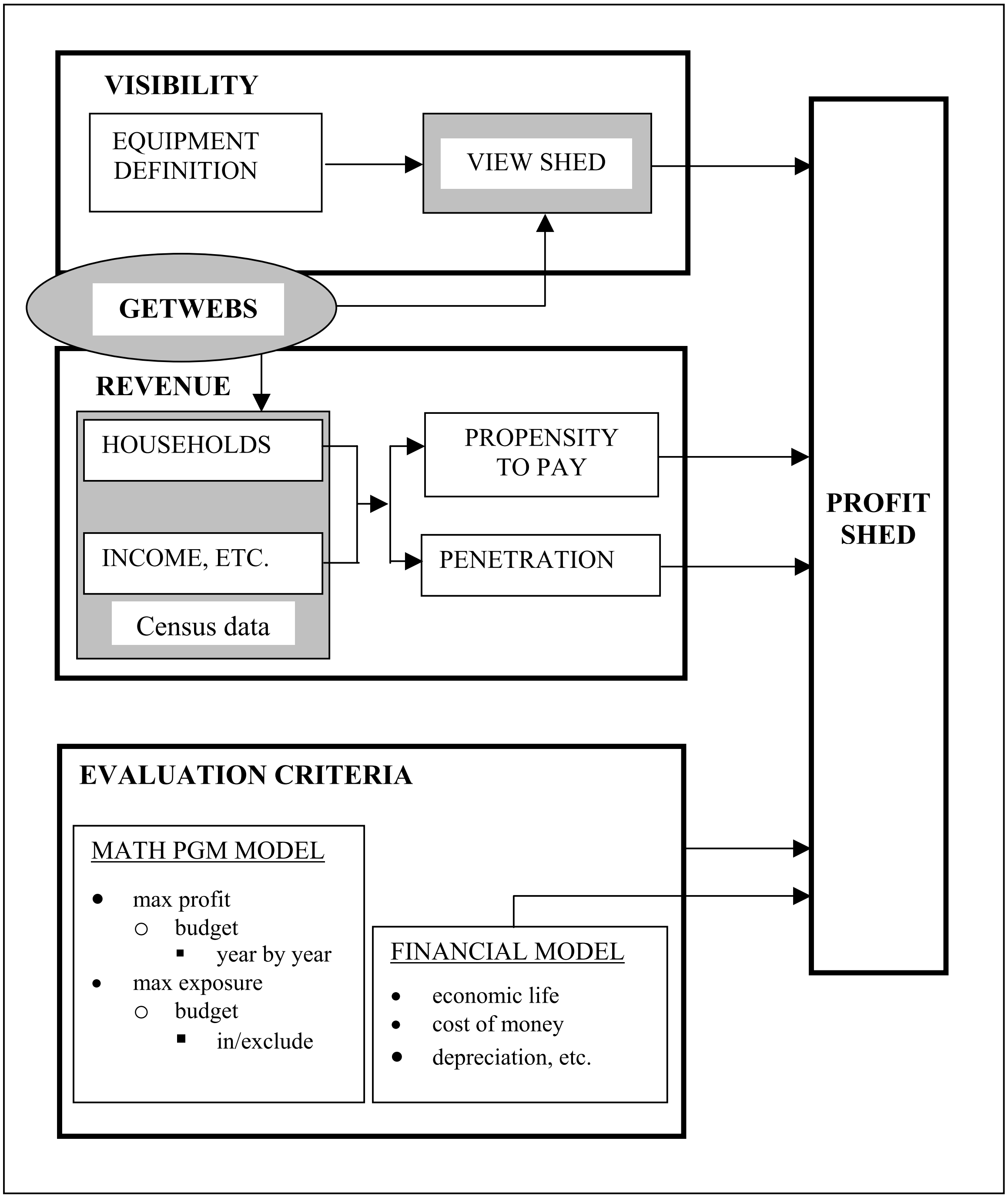


Figure 3.5. The wireless spatial DSS architecture

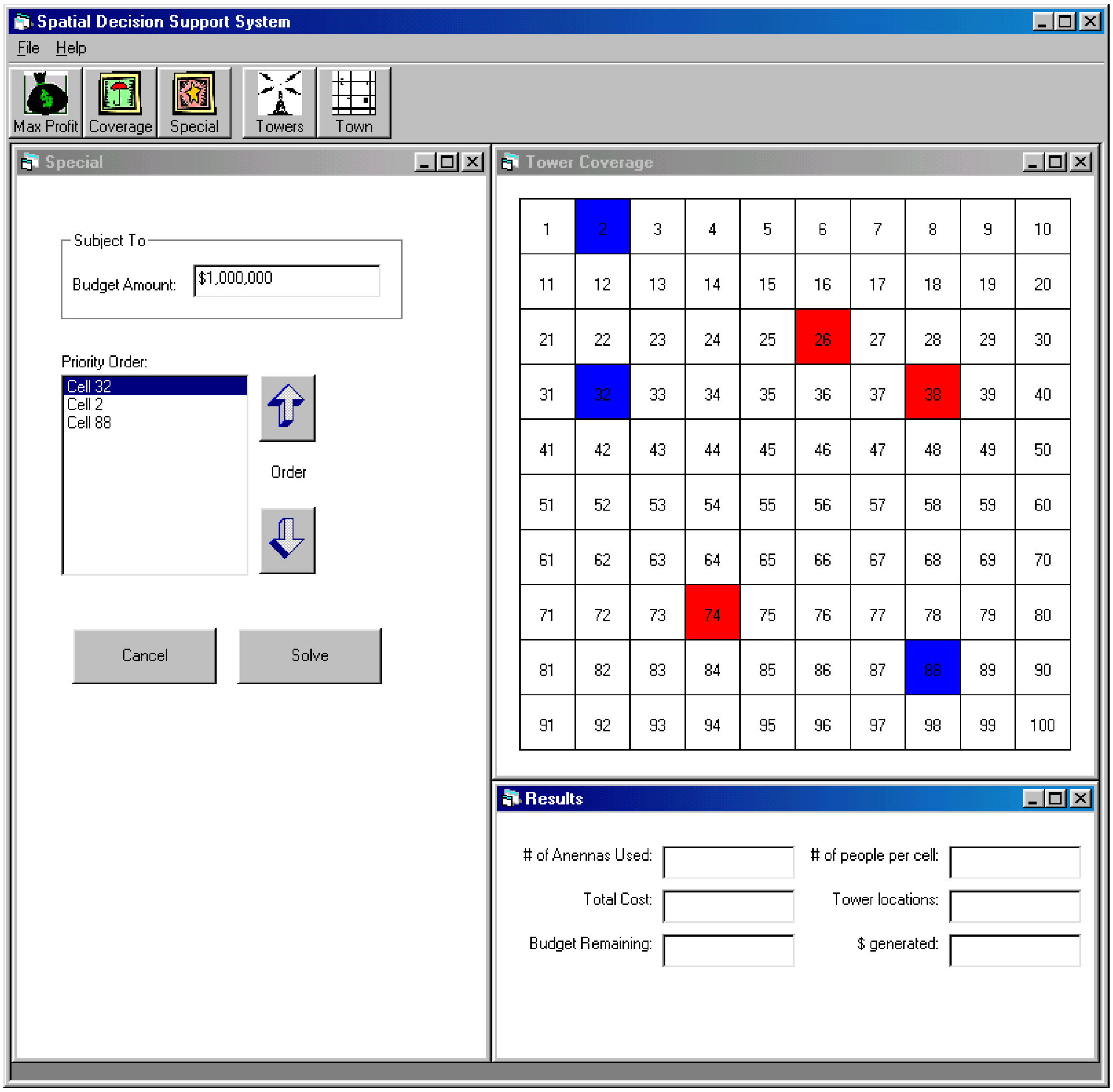


Figure 3.6. Cells may be individually excluded from (e.g. 26, 38, and 74) or included (e.g. 2, 32, and 88) for tower placement as desired.

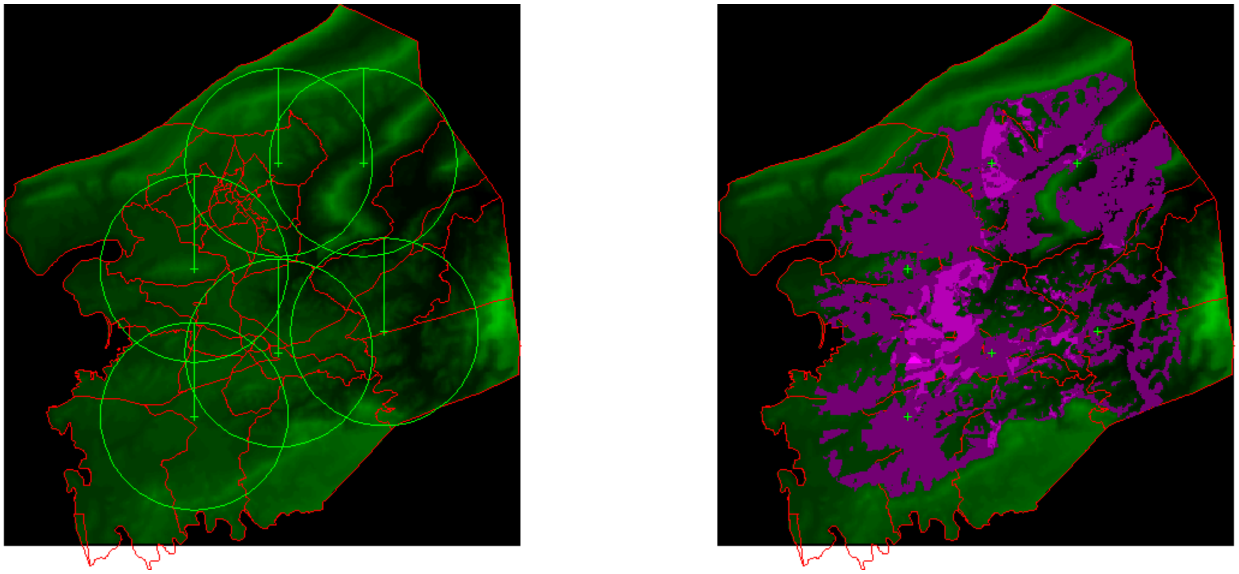


Figure 3.7. Tower placement and profit sheds (magenta) for Wi-Fi (802.11b) service offered at $50/month.

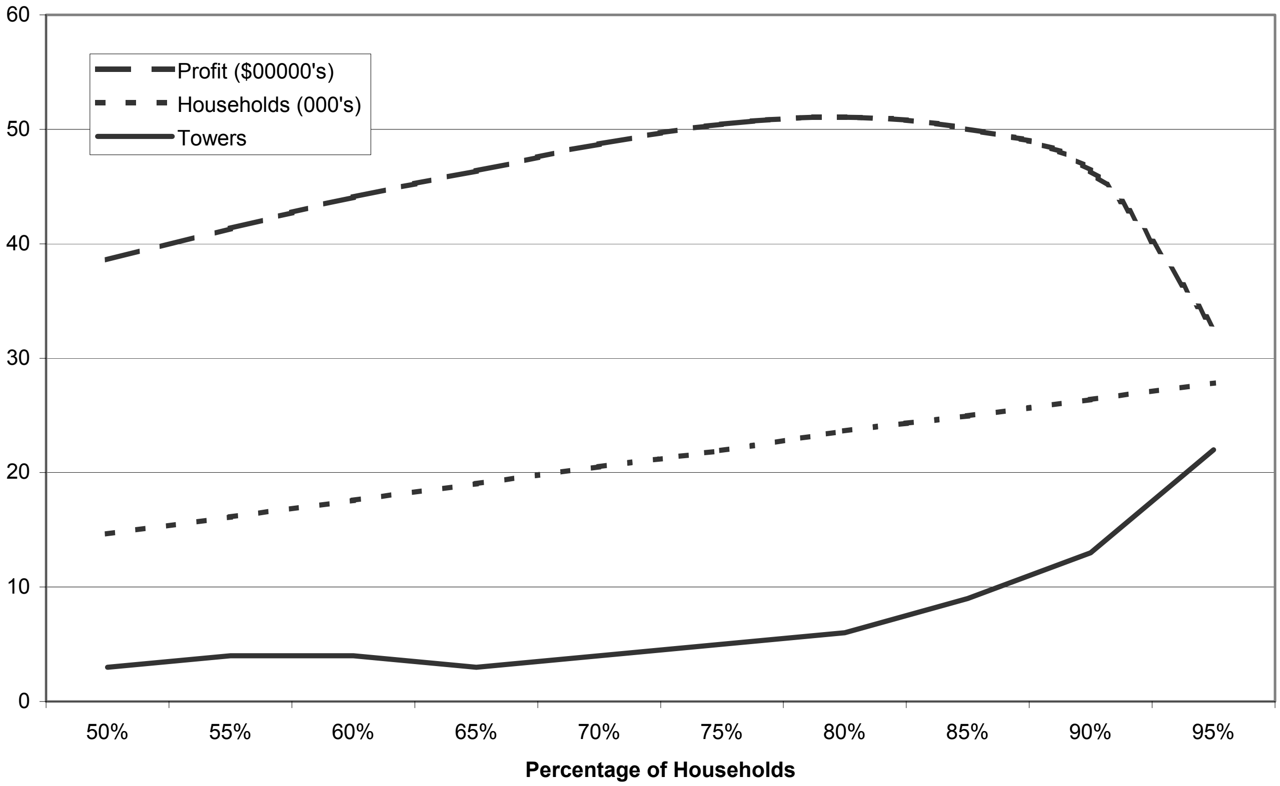


Figure 3.8. Profit, households, and towers in Montgomery County as a function of percent coverage with Wi-Fi broadband.

Table 3.1. Some wireless applications and their allocated frequencies.

Frequency Band	**Applications**
170 - 190 kHz	VLF band radios Beacons
550 - 1600 kHz	AM broadcast communications Low power voice and data
27 MHz	CB radios Low power voice and data
49 MHz	Remote control Cordless telephones Low power voice and data
88 - 108 MHz	FM radios Low power voice and data
150 - 170 MHz	Commercial two-way voice Pager services
260 - 470 MHz	303 MHz garage door openers Keyless entry systems Security alarms
824 - 849 MHz and 869 - 894 MHz	Cellular phones
902 - 928 MHz	ISM band Wireless LAN's Part 15 devices (spread spectrum cordless phones, etc.) Military radiolocation systems Federal mobile communications
930 MHz	Pager services with high transmitter power
2.4 - 2.4385 GHz	Amateur satellite Part 15 devices Microwave ovens and systems Army packet radio development **802.11b**
5.15-5.25GHz **5.25-5.35GHz**	U-NII 802.11a
5.727 - 5.875 GHz	Amateur satellite Part 15 devices Naval radar systems Test range instrumentation radars 802.11a **802.16 – (Tsunami equipment)**
24 - 24.25 GHz	Radio navigation
28 – 31 GHz	**Local multipoint distribution service (LMDS)**

Source: The Virginia Tech Center for Wireless Communications. (http://www.cwt.vt.edu/wireless_faq/default.htm).

Table 3.2. The percentage participation (in Montgomery County) as a function of average household annual income, given the price per month for wireless service.

Average Annual Household Income, in 000s (I)	**Percent Participation (%P)**		
	\$50/mo price	**\$75/mo price**	**\$100/mo price**
\$0 to \$75	%P = 0.2 I	%P = 0.1 I	%P = 0.05 I
\$75 to \$100	%P = 0.4 I – 15	%P = 0.1 I	%P = 0.05 I
>\$100	%P = 25	%P = 10	%P = 5

CHAPTER 4

A CAPACITATED, FIXED-CHARGE, NETWORK-FLOW MODEL FOR SOLVING HOP CONSTRAINED, WIRELESS MESH NETWORKS

A CAPACITATED, FIXED-CHARGE, NETWORK-FLOW MODEL FOR SOLVING HOP CONSTRAINED, WIRELESS MESH NETWORKS

ABSTRACT

Wireless mesh networks are proposed as a possible solution to the "last-mile" problem in broadband communications. A solution procedure is developed here that generates all feasible customer paths to the backhaul in a preprocessing step, then solves the resulting problem as a fixed-charge, capacitated, network flow problem, whose solution is well known. In particular, mesh networks with hop constraints that ensure transmission quality are examined. The model is capable of handling differing bandwidth requirements for each customer.

Keywords: Network Flow Models, Math Programming, Broadband Wireless Telecommunications

A CAPACITATED, FIXED-CHARGE, NETWORK-FLOW MODEL FOR SOLVING HOP CONSTRAINED, WIRELESS MESH NETWORKS

INTRODUCTION

The popularity and rate of growth of the Internet over the last decade has been prodigious; what was once a medium for government and academics to exchange ideas has now become an almost ubiquitous entity that assumes many shapes – from personal communications, to on-line shopping, to global information collection. As more people and companies today do business on line, the need for greater bandwidth increases; it is not longer sufficient to connect to the Internet with low speed modems. Broadband telecommunications have become a necessity, whereby broadband is meant the capacity to deliver high speed, always "on" service. (TechNet, 2002)

In the 1990s, companies poured billions of dollars into building a transcontinental fiber optic backbone (Kornbluh, 2001, p. 21). However, as Kornbluh states in her *NY Times* op-ed article, only three percent of that backbone is currently in use. This is due, primarily, to underestimation of the cost of delivering broadband service the "last-mile," where the "last-mile" is that part of the telecommunication network that connects the homes and businesses to the high speed backbone. While most American homes and businesses exist relatively near the backbone, they are not connected to it. In fact, Acampora (2002) states that for nine out of ten American businesses with more than 100 workers, the backbone is less than a mile away.

This last-mile link to the customer has traditionally consisted of copper wiring, and has been sufficient for voice communications for half a century. But it will not be adequate, particularly financially, to meet for the broadband requirements of the new millennium. One approach to solving this problem is wireless telecommunications (Willebrand and Ghuman, 2001). Several varieties of this approach exist (see, e.g., Scheibe, Carstensen, Rakes, and Rees, 2003, for a discussion of the *point-to-multipoint* (PMP) line of attack), including mesh, which we will define shortly.

The purpose of this paper is to ascertain the minimum-cost, mesh network configuration of a neighborhood. We will utilize Geographic Information Systems (GIS) in a preprocessing analysis step to determine which neighbors can see each other electronically, as obstructions such as buildings and terrain prohibit transmission. This discovery of viable communication links is combined with an enforcement of number of hops from each source (customer) to sink (backhaul), thereby ensuring a quality of service (QoS) level. We then enumerate every viable, feasible path from customers to the backhaul, and formulate a mixed integer programming problem, namely the capacitated, fixed-charge, network flow problem (FCNFP), to determine the optimal network with minimal cost. After background material on meshes as well as on the general capacitated FCNFP, the solution methodology (including the mixed integer formulation) is presented. This is followed by an example, and then by implications and limitations. Finally, the paper concludes with a summary of contributions and requisite future work.

BACKGROUND

Mesh Networks

As mentioned, the fundamental issue with the last mile problem is that capacity exists in broadband network, but it is not economic to connect residential neighborhoods and/or businesses by wire to that backbone. To facilitate discussion of our approach to providing such capability in a wireless manner, we define some terms as they are used in practice or in the literature.

In Figure 4.1 an existing backbone and neighborhood without broadband service are shown. The *backhaul point* (*BH* in Figure 4.1) is that location along the backbone network where the mesh network will connect. The backhaul is then generally "wired" (say with fiber optics) to *trunk connection points*, shown as T_1 and T_2 in Figure 4.1; the transmission medium changes to wireless at these trunk connection points. The wireless signal is not, in general, transmitted from the trunk connections directly to customers, however. The signal is sent to *mesh insertion points* (*MIPs*, labeled M_1, M_2, and M_3 in the figure) that are closer to customers. These mesh insertion points do transmit and receive directly to/from customers. Generally, once signal is received at a MIP back from a customer, it is only forwarded to a trunk connection point and then to the backhaul. That is, signals are not transmitted from customers to MIPs, and then back out to customers.

One of the key features of mesh networks is that customers are used to forward signals on to other customers, up to the capacity limits of the receiver and transmitters. This can reduce network costs as well as provide network survivability, that is, redundant paths. However, sometimes it is necessary to insert repeater nodes into the network when there are not enough customers nearby to get messages to every customer. Repeater nodes are generally identical to customer equipment – there is just not a customer at the repeater location. Thus a repeater may be thought of as a non-revenue generating customer. Mesh networks may use a variety of frequencies, such as 2.4 GHz (Nokia, 2002), 26 GHz to 40 GHz (Fowler, 2001), and laser (Acampora and Krishnamurthy, 1999).

Because mesh frequencies are in the gigahertz range, transmission between each transmitter and receiver must be *line of sight*. That is, not only must equipment be proximate and within range, there must be no obstruction between transmitter and receiver.

In a mesh network signals from a customer seeking the backhaul may be forwarded from customer to customer (possibly including repeaters), until finally a mesh insertion point is reached. The MIP then sends the signal to a trunk connection point, and finally to the backhaul. Each link in the chain back to the backhaul is called a *hop.* Too many hops in a chain of connectivity can cause inordinate delay, or *latency*. Latency is the time it takes for a packet to travel from source to destination (Webopedia, 2003). To ensure quality of service, the probability of a network meeting a given traffic contract (Wikipedia, 2003), it is sometimes necessary to restrict the number of hops in each transmission path. A traffic contract may be viewed as an agreed upon throughput rate during peak usage times. Although hop constraints are not new to network design (Balakrishnan and Altinkemer, 1992), there has been little discussion in the literature as to what should be the optimal number of links for a wireless mesh network. Whitehead suggests that six to ten hops offer an acceptable level of service (Whitehead, 2000).

Wireless networks have traditionally been point-to-multipoint (PMP) networks (Whitehead, 2000). Mesh networks overcome several limitations of point-to-multipoint (PMP) networks. The former work with strategically placed towers, connected to the backhaul, and within range of the maximal number of potential customers. That approach necessitates purchase of/permission to use land, permitting, bringing electric power to the tower, etc. Mesh networks obviate most of these concerns. Note also that with a mesh, a connection point does not need to be optimally placed to reach every customer directly. This allows for greater flexibility in choosing connection node locations, and should lower the initial investment cost (Whitehead 2000). With mesh networks, it is not crucial to locate the single tower location that will best serve the entire area; it is only necessary to determine a connection point location that will bring signal into one section of the mesh. From that point, the other nodes will pass the signal along. Moreover, the incremental addition of customers to the network is inexpensive; often, the only cost is the customer premise equipment. In fact, by adding more customers, the cost of the mesh network can decrease. This occurs when, as more customers join the network, the need for repeater nodes decreases because paths to the backbone may be found through revenue-paying customers (Fowler, 2001).

Fixed-Charged Network Flow Models

The fixed-charge network flow problem (FCNFP) is one of a large class of network design problems, which has been used in many applications including telecommunications (Balakrishnan, Magnanti, Shulman, and Wong, 1991; Gavish, 1991), logistics and production planning (Minoux, 1989), and transportation (Magnanti and Wong, 1984). FCNFP problems are known to be NP-hard, and much research has been devoted to creating better and more efficient solution procedures (Kim and Pardalos, 1999; Cruz, Smith, and Mateus, 1998). In these problems, the objective is to seek the most efficient way to move flow (in our case bandwidth) on a network in order to satisfy demand between origin and destination nodes and to minimize the overall cost. A fixed cost is incurred for using arcs between nodes; therefore, it behooves the objective to use as few arcs as possible for which costs are associated. When the network is capacitated, upper bounds exist for the amount of flow over an arc. Another consideration for some network design problems is the number of hops from a source to a sink (Pirkul and Soni, 2002; Soni, 2001; Girish, Zhou, and Hu, 2000; Gouveia and Requejo, 2001). The principal reason for constraining the number of hops in a network is to maintain a level of quality of service. Simply stated, the greater the number of hops between nodes, the greater the amount of time it takes for data to be transferred between them; the longer it takes, the lower quality of service.

The mesh network can be cast as a FCNFP with the customers acting as sources, the backhaul as the sink, and TCN, MIP, and repeaters as transshipment nodes. There is a fixed cost associated with arcs that are connected to and from the transshipment nodes, and arcs are constrained with an upper bound or bandwidth capacity.

The capacitated, fixed-charge, network-flow problem can be formulated mathematically as follows: Given a directed graph $G = (N, A)$ where N is a set of n nodes and A is a set of m arcs, let (i,j) denote a directed arc from node i to node j. Every node is classified into one of three categories: *Source* nodes, which produce flow; *sink* nodes; which consume flow; and *transshipment* nodes, which pass flow through. We assume a balanced network where total supply equals total demand (or that we have balanced the network by introducing either slack or surplus variables to consume excess capacity or demand). For each node k, the design cost is denoted f_k, which is assumed to be nonnegative. The objective is to minimize the design costs that occur when arcs are used. Let d_j denote the supply or demand at node j, and $u_i > 0$ be the capacity of each node i.

In this formulation, we also define x_{ij} to be the flow on arc (i,j), and y_i to be a binary variable equal to one when node i is in use and zero otherwise. The resulting formulation is

$$\min \sum_{k \in N} f_k y_k, \tag{1}$$

$$\sum_{k \ni (k,j) \in A} x_{kj} - \sum_{k \ni (j,k) \in A} x_{jk} = d_j, \quad \forall j \in N \tag{2}$$

$$\sum_{i,j} x_{ij} \le u_i y_i, \quad \forall i \in N; (i,j) \in A \tag{3}$$

$$x_{ij} \ge 0, \quad \forall (i,j) \in A, \tag{4}$$

$$y_{ij} \in \{0,1\} \tag{5}$$

Constraint (2) is the *flow conservation constraint* and ensures that demand/supply is satisfied at each node j, and that inflows equal outflows for transshipment nodes. If $d_j > 0$, then j is a sink node. If $d_j < 0$, then j is a source node, and if $d_j = 0$, then j is a transshipment node. Constraint (3) is the *flow capacity constraint*, and it ensures that flow on all arcs leaving a node will not exceed the capacity of the node at the start of that arc, and will be zero if the node is not made operative in the design.

METHODOLOGY

The approach taken in this chapter is to introduce a preprocessing step whose main purpose is to determine, given a hop constraint, all viable paths from each customer back to the backhaul. It is possible to enumerate these paths, as the number of customers for any mesh insertion point is bounded by the technology and since the number of hops on each possible path is also constrained by quality of service considerations. Once all possible paths are enumerated, a minimum cost solution may be found using integer programming solution packages.

Preprocessing

Step 1 –Potential Equipment Placement and Line-of-Sight Determination

Preprocessing begins with the specification of the backhaul point, trunk connection points, and all possible mesh insertion points. These equipment locations are primarily a matter of physical characteristics of a neighborhood, that is, where right-of-way/permissions are available, terrain is not obstructive, etc. Again, with the methodology developed here, the location of the single backhaul point and two trunk connection points are assumed. It is unknown how many MIPs will be economic, but all potential locations are to be specified; which locations are chosen is an economic decision to be determined by the model.

Next, all known customer locations are specified. The situation to this point is indicated in Figure 4.2, where each circle (node) indicates the (geographic) location of the equipment/customer indicated. Line-of-sight must be determined next; either a geographic information system (GIS) or field visit is required. Figure 4.3 can then be generated, where a dotted line between any two circles indicates no obstruction between the two nodes. (Lack of a dotted line indicates no feasible transmission; e.g., customer C3 cannot transmit or receive to/from customer C4 in Figure 4.3.) At this point it may occur that a customer desirous of service cannot obtain a signal, either because transmission range limits are exceeded or because obstructions block all possible paths to the customer. In such an eventuality, potential repeater nodes (Figure 4.3) are defined at non-customer locations that will ensure an unobstructed path to the backhaul for each customer. Finally in Figure 4.3, arrows are shown on the links from each MIP to its closest trunk connection point, and from each trunk connection point to the backhaul. Recall that signals received at MIPs from customers do not go back out to other customers; they move on to trunk connection points. Information equivalent to Figure 4.3 may be stored in tabular form (see Table 4.1). Once this information is in hand, all possible paths from each customer to the backhaul may be enumerated, given a limit on number of hops. The possible paths for customer C1 are shown in Figure 4.4.

Step 2 – Artificial Directional Node Determination

We use Excel to process feasible, hop-constrained paths. Excel has proven to be an excellent tool for many problems of this sort (Ragsdale, 2001). With this approach the simplest way to generate these paths is to define what we term artificial directional nodes (ADNs). A simple example is presented in Table 4.2 that is based on Figure 4.4 and Table 4.1 and a (temporary) hop limit of six that illustrates the process for customer C1.

The method for creating and naming the ADNs is as follows. Begin with the source node (in this case, C1), count the number of hops from the source to the BH, and append that number after a period. For example, the first row of Table 4.2 has node C1 reaching the backhaul in three hops, so C1 becomes C1.3 in Table 4.3. Next, move from the source to the subsequent hop in line to the BH; if the next node is not a MIP, a TCN, or the backhaul, then append the number of hops to the BH from that point. On line two of our example, the next node from C1.4 is C2, which becomes C2.3. Every number with a period represents an ADN. Following this procedure creates a new (artificial) node for every possible number of links from the node back to the backhaul. ADNs are generated in this fashion for *every* customer and repeater node; they are not needed for MIPS, TCNs, or the backhaul, as the number of nodes from each is constant. Shown in Table 4.3 and Figure 4.5 is the example with artificial directional nodes. Table 4.4 lists each node as a source and indicates the one-step-away nodes, one per row. With this list the construction of any feasible path may be automated, as the connectivity and hop constraint information is all included.

Figure 4.6 shows the re-integration of the nodes into the mesh by connecting them to their artificial directional nodes. Since ADNs are not actual physical nodes in the network, their addition does not violate any hop constraints. Even though it appears that node C1 must now also pass through C1.3 – C1.6, they are all actually node C1 themselves. Therefore, there is no hop constraint violation.

Table 4.5 presents the new mesh network with all the artificial directional nodes along with the re-integrated nodes themselves. This is the last step before transforming the data into a form that may be solved directly with the network flow model.

Network Flow Model

Once the artificial directional nodes and the actual nodes have been integrated into the new mesh network, the network flow model may be formulated. The nodes may be viewed as a series of sources and sinks, as shown in Table 4.6. Each row in the table represents an allowable hop within the mesh network.

We modify the general FCNFP model of equations (1) – (5) as follows. Let N be the set of all nodes and N^a be the set of artificial nodes. Further designate T, M, R, and C as the sets of trunk connection nodes, mesh insertion points, repeater nodes, and customer nodes respectively. Finally, define the set of all arcs in the network by the letter A.

For each node k, let the cost of activating that node be f_k, which is assumed to be nonnegative; any artificial nodes have a cost of 0. The objective is to minimize total cost. Let d_j denote the supply or demand at node j, all artificial nodes should be considered transshipment nodes (with a supply of 0). Let $u_i > 0$ represent the capacity on the arcs emanating from node i. x_{ij} is the flow on arc (i,j), and y_i is a binary variable equal to one when node i is in use and zero otherwise.

The model may be written as

$$\min \sum_{k \in N} f_k y_k, \tag{6}$$

$$\sum_{k \ni (k,j) \in A} x_{kj} - \sum_{k \ni (j,k) \in A} x_{jk} = d_j, \quad \forall j \in N \tag{7}$$

$$\sum_{j \ni (i,j) \in A} x_{ij} \le u_i y_i, \quad \forall i \in (T \cup M) \tag{8}$$

$$\sum_{j \ni (i^*,j)} x_{ij} \le u_i y_i \qquad \forall i \ni \{[i \in (C \cup R) \cap (i \notin N^a)] \cap [(i,i^*) \in A] \cap [i^* \in N^a]\} \tag{9}$$

$$x_{ij} \ge 0, \quad \forall (i,j) \in A, \tag{10}$$

$$y_i \in \{0,1\}, \quad \forall i \in N \tag{11}$$

Constraint (7) ensures flow conservation, whereas constraints (8) and (9) are *flow capacity constraints*. Constraint (8) restricts flow from trunk nodes and mesh insertion points, whereas (9) restricts flow emanating from customer or repeater nodes, as follows. Flow leaving either a customer or a repeater node (i.e., the sum of flow over all arcs leaving such a node) cannot exceed the capacity of the transmitter at that node; moreover, if the transmitter is inoperative, no flow may traverse any arc departing that node.

EXAMPLE

To demonstrate the model a small example was constructed. The example consists of three neighborhoods with a total of 25 houses requiring wireless broadband service. There are two potential TCNs connected to the backhaul, eight potential MIPs, and fourteen potential repeaters. The actual location of the aforementioned nodes is set; their potentiality exists in whether or not they will be used. The example assumes a visibility of 60%, meaning that nodes that are located near enough to each other for a signal to pass between may still have a 40% chance that something obstructs line of sight. The lots are assumed to be one acre each, and the houses are placed on the center of each lot. We consider two independent variables, the number of hops and bandwidth. These factors have three levels each – low, medium, and high. The levels of the hops are five, seven, and nine, and the levels for the bandwidth will be 2 Mbits/s, 5Mbits/s, and 10 Mbits/s. The arcs between nodes are capacitated at 30 Mbits/s between customer nodes and repeaters, 80 Mbits/s between MIPS and any other nodes, and 200 Mbits/s between TCNs and MIPS. The cost for using repeaters is $2,500 each; the cost for MIPs is $5,000 a piece; and the cost for TCNs is $25,000 each. Shown in Tables 4.7 and 4.8 are some results of the example.

Table 4.7 shows pertinent data from the example's preprocessing step, in particular, the number of source and sink nodes and viable paths created for each of the hop levels. Note from this example that while the number of viable paths increased dramatically with each level of hops, the number of source and sink nodes did not. This is due to high level of redundancy of paths from a node to the backhaul. While the number of viable paths may be high, many of the paths will pass through the same pairs of nodes. Table 4.8 shows some of the results of running the mixed integer problem code, namely the total cost for each network. Since the network is capacitated, as the number of Mbits increases, the bandwidth is split up over multiple paths, thus increasing the cost as more repeaters and MIP nodes are required. Another noteworthy point is that the cost does not necessarily decrease as the number of hops increases. While it may seem intuitive that the cost would decrease by increasing the number of hops, and consequently, the number of viable paths from a customer node to the backhaul, if the nodes are not located such that they may avoid repeater nodes, the overall cost may actually increase.

Although this is a minimum cost solution procedure, results may be manipulated to examine sundry revenue schemes. For instance, in the example given above and its assumed cost structure, revenue of $127 per month for the basic 2 megabit service with a hop constraint of seven proves profitable within a five-year window – a not very lucrative opportunity.

IMPLICATIONS

The solution procedure successfully generates answers to the wireless mesh broadband service problem. Small problems may be run using Excel combined with Frontline's Premium Solver (Frontline, 2002). Larger problems may need a more sophisticated integer-programming engine. The procedure works reasonably well at nine or fewer hops, but, as mentioned, generates a very large number of viable paths in the preprocessing step. With each additional hop added to the allowable number, the problem size grows dramatically, and consequently, proves expensive to solve. This issue must be addressed in future work. Although mesh networks should not indiscriminately route customer signals over too many hops, nine hops is probably not excessive. However, it is approaching an upper bound on the number of hops. Several simple heuristics can be attempted (such as limiting the search to a fixed number of randomly chosen paths as the algorithm steps out from each node in search of additional hops to the backhaul) to limit the number of paths and thus the execution time of the integer programming part of the problem.

CONCLUSIONS AND FUTURE WORK

A methodology has been presented to determine minimum cost wireless mesh network configurations. The methodology preprocesses data by first using a GIS and then manipulating customer requests and equipment locales to form a list of feasible paths from which the optimal set of paths may be found by solving a well-known network-flow problem. The network generated is constrained by a given number of hops, or links, to ensure quality of service, and allows differing bandwidths for each customer, as desired. An example was shown demonstrating how an Internet service provider (ISP) would approach service provision constrained at seven hops in a new neighborhood. Bandwidth requested was ten megabit per second for all customers. Results were also shown when quality of service was loosened to nine hops and tightened to five hops with three different bandwidth levels.

Future work examines managerial implications of wireless mesh technology. Implications of customer density, cost of technology, and the effects of quality of service and bandwidth are possible. This research is important in estimating the extent to which wireless mesh broadband solutions may be expected to mitigate the "last-mile" problem. The tool developed here may not only be used by ISPs, but by policy bodies to examine the wisdom of subsidies, and by equipment manufacturers to examine the likely adoption of new transmitters with improved ranges and lower costs.

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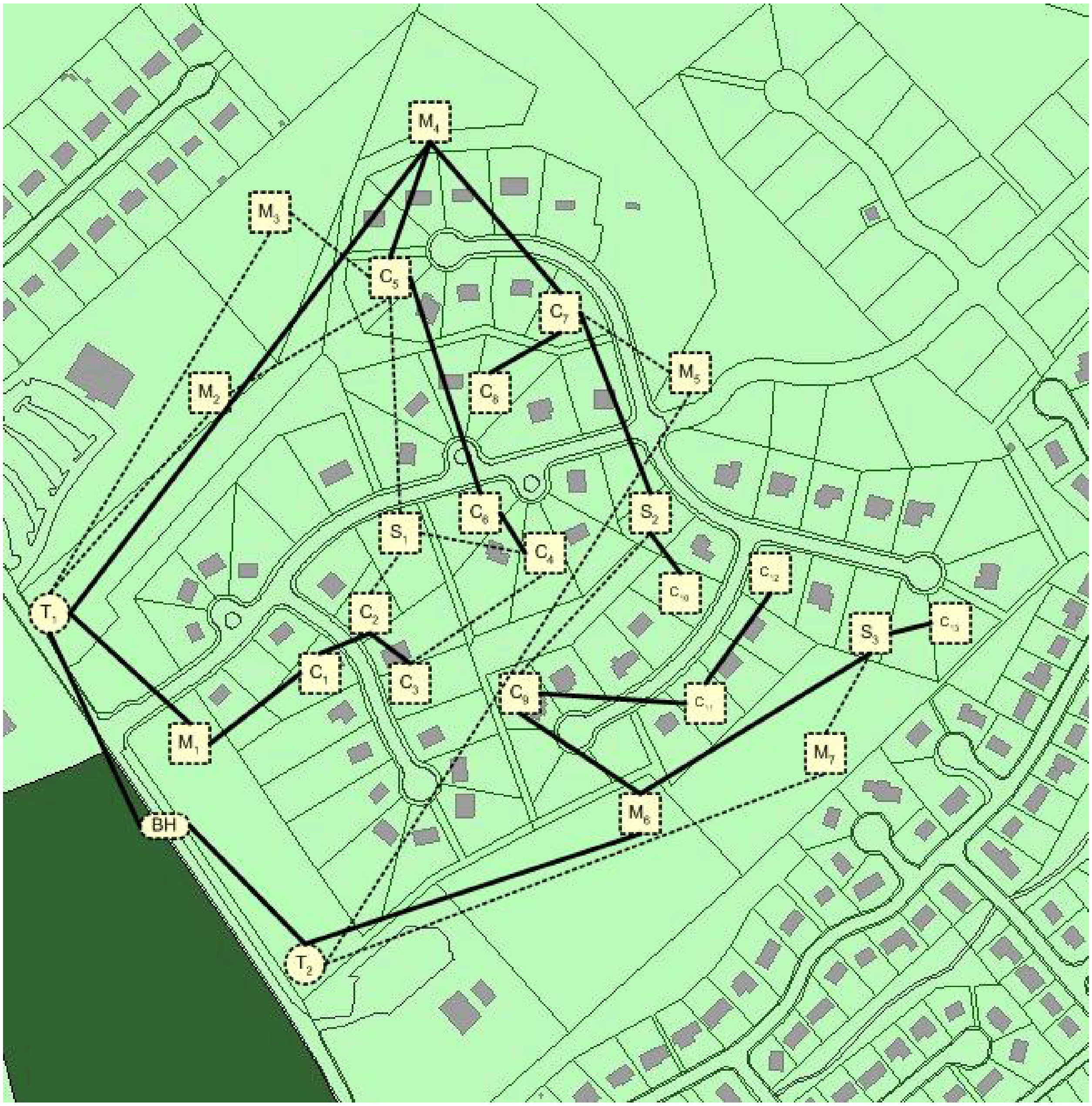
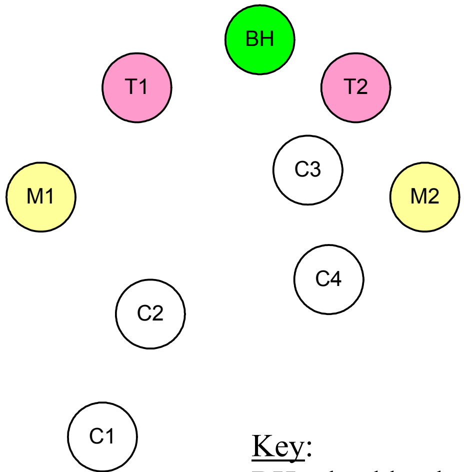


Figure 4.1. Providing broadband service to a neighborhood with a wireless mesh network.



Key:
BH – backhaul
Ti – trunk i
Mj – mesh insertion point j
Rk – repeater k (not shown)
Cℓ – customer ℓ

Figure 4.2. Nodes represent potential wireless mesh equipment locations.

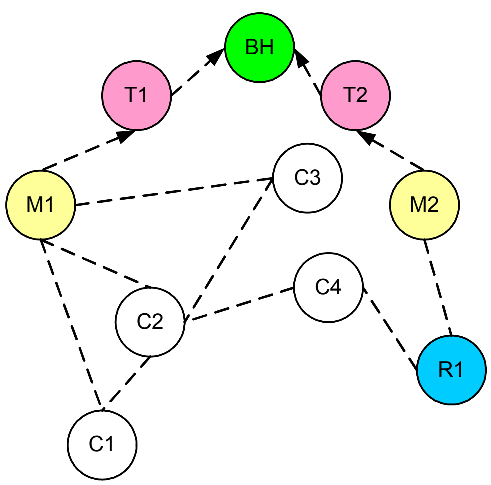


Figure 4.3. Nodes shown linked together with line-of-sight capabilities.

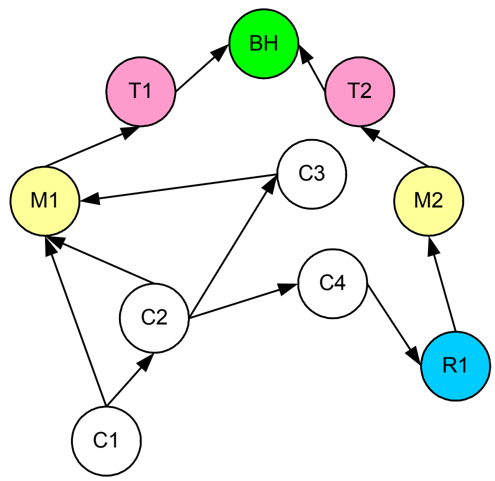


Figure 4.4. Viable paths for customer C1 to communicate with the backhaul, given the line-of-sight configuration of Figure 4.3.

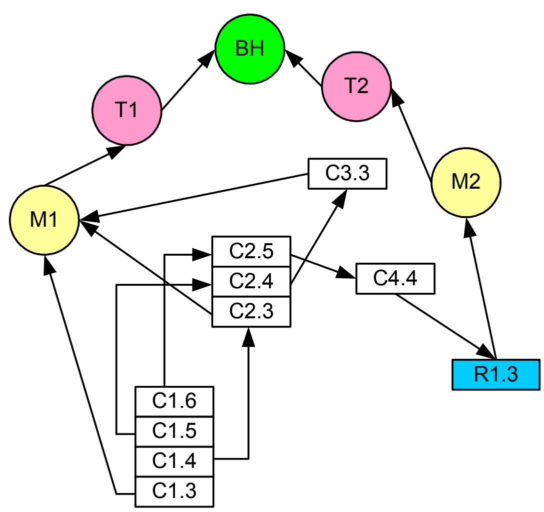


Figure 4.5. Customer C1 viable paths expressed in terms of artificial directional nodes.

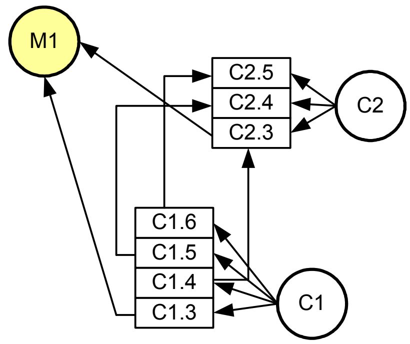


Figure 4.6. Re-linking nodes to their artificial directional nodes.

Table 4.1. Source and neighbor nodes

Source	"Reachable" Neighbors			
C1	M1	C2		
C2	M1	C1	C3	C4
C3	M1	C2		
C4	R1	C2		
R1	M2	C4		
M1	T1			
M2	T2			
T1	BH			
T2	BH			

Table 4.2. Viable paths for customer C1 to communicate with the backhaul

Source	Viable paths					
C1	M1	T1	BH			
C1	C2	M1	T1	BH		
C1	C2	C3	M1	T1	BH	
C1	C2	C4	R1	M2	T2	BH

Table 4.3. Viable paths for node C1 with artificial directional nodes

Source	Viable paths					
C1.3	M1	T1	BH			
C1.4	C2.3	M1	T1	BH		
C1.5	C2.4	C3.3	M1	T1	BH	
C1.6	C2.5	C4.4	R1.3	M2	T2	BH

Table 4.4. Source and immediate destination nodes with artificial directional nodes included

Source	Immediate Destinations
C1.3	M1
C1.4	C2.3
C1.5	C2.4
C1.6	C2.5
C2.3	M1
C2.4	C3.3
C2.5	C4.4
C3.3	M1
C4.4	R1.3
R1.3	M2
M1	T1
M2	T2
T1	BH
T2	BH

Table 4.5. Re-linking nodes to their artificial directional nodes

Source	Possible Immediate Destinations			
C1.3	M1			
C1.4	C2.3			
C1.5	C2.4			
C1.6	C2.5			
C2.3	M1			
C2.4	C3.3			
C2.5	C4.4			
C3.3	M1			
C4.4	R1.3			
R1.3	M2			
M1	T1			
M2	T2			
T1	BH			
T2	BH			
C1	C1.3	C1.4	C1.5	C1.6
C2	C2.3	C2.4	C2.5	
C3	C3.3			
C4	C4.4			

Table 4.6. List of sources and sinks for direct inclusion into the network flow model

Source	Sink
T1	BH
T2	BH
M1	T1
M2	T2
C1	C1.3
C1	C1.4
C1	C1.5
C1	C1.6
C1.3	M1
C1.4	C2.3
C1.5	C2.4
C1.6	C2.5
C2	C2.3
C2	C2.4
C2	C2.5
C2.3	M1
C2.4	C3.3
C2.5	C4.4
C3	C3.3
C3.3	M1
C4	C4.4
C4.4	R1.3
R1.3	M2

Table 4.7. Some Results from the Example's Preprocessing Step

	Source and Sinks	Viable Paths
Five Hops	337	2,131
Seven Hops	832	18,928
Nine Hops	760	1,202,048

Table 4.8. Results from the Example's Capacitated, Fixed-Charge, Network-Flow Problem

	2 Mbits/s	5 Mbits/s	10 Mbits/s
Five hops	$255,000	$255,000	$300,000
Seven hops	$190,000	$205,000	$285,000
Nine hops	$190,000	$210,000	$295,000

CHAPTER 5

ADDRESSING UNIVERSAL-BROADBAND-SERVICE IMPLICATIONS WITH WIRELESS MESH NETWORKS

ADDRESSING UNIVERSAL-BROADBAND-SERVICE IMPLICATIONS WITH WIRELESS MESH NETWORKS

ABSTRACT

Demand is increasing for broadband telecommunications, but most areas lack adequate means of delivering the desired services to residential customers and businesses – at least for the last mile of connectivity. A new approach to providing broadband technology is wireless communications, and this technology has been touted as a possible savior for broadband.

This paper proposes a methodology for supplying broadband services using a wireless mesh network structure. In order to examine the potential of such networks to mitigate the "last-mile" problem in rural/suburban areas, 270 "neighborhoods" are randomly generated, and then each neighborhood is evaluated for fiscal promise under nine different cases of bandwidth offerings and quality of service. Results are discouraging for almost all cases. In fact, costs would have to decrease (through either technological advances or government subsidy/tax breaks) by 45% just to break even. Stated differently, customer monthly charges would have to be reduced by \$62/month per customer over five years for wireless broadband to achieve profitable status. A study exploring government options is suggested as future work.

Keywords: Mesh networks, Wireless telecommunications, Geographic information systems,

Spatial decision support systems, Planning, Broadband service

ISRL Categories:

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INTRODUCTION

Broadband is the capacity to deliver Internet access with a continuous connection and the ability to both send and receive digital content or services at high speeds (TechNet, 2002). Organizations such as TechNet, a bipartisan group comprising more than 300 chief executive officers and senior partners of the major companies in the fields of information technology, biotechnology, venture capital, investment banking and law, claim that the productivity of Americans in their homes and at work will increase with widespread adoption of broadband. This, in turn, will have a potential affect on the United States (US) economy by $500 billion, and positively benefit quality of living. Secondly, TechNet says true broadband is the key to the next generations of communications and Internet services. (TechNet, 2002, p. 1)

However, Kornbluh (2001, p.21) points out that this potential will remain unrealized without government action. She states in an op-ed piece in the *New York Times* that although investors have plowed $90 billion into a cross-continental fiber-optic broadband network, today merely 3% of that backbone is in use. She says it is the "digital equivalent of fallow farmland," and the problem is entrepreneurs failed to foresee the enormous cost of upgrading the "last mile – copper telephone wires that connect individual homes and small businesses to the broadband backbone" (Kornbluh, 2001, p. 21). In an article in *Scientific American*, Acampora (2002) elaborates by noting that for nine out of ten American businesses with more than 100 workers, the backbone is less than a mile away.

The issue of broadband connectivity has attracted the attention of the highest levels of the US government. The current (2003) presidential administration has made statements concerning the importance of broadband connectivity, although they have not been as strong as some in congress would like. Senator Tom Daschle (D - SD) has made a call to bring broadband to every American by the end of the decade, and a joint letter to President Bush from Senator Daschle and Senator Gephardt (D - MO) states that deploying the technology should be a "national imperative" (Dreazen, 2002). Moreover, TechNet has called on the president and policymakers to make broadband a national priority and to set a goal of making an affordable 100-megabits per second (Mbps) broadband connection available to 100 million American homes and small businesses by 2010 (TechNet, 2002). To reach this goal, network providers will need to invest hundreds of billions of dollars to upgrade infrastructures and increase bandwidth capacity in the last mile, primarily by providing new wired connections to homes and offices. Today, virtually no homes have connections with such bandwidth (TechNet, 2002). An intermediate goal is the "availability of affordable broadband at speeds of at least 6 Mbps from 2 or more providers to at least 50% of U.S. households and small businesses by 2004" (TechNet, 2002, p. 6). TechNet developed 6 principles to address roadblocks and provide a guide to a national broadband policy. Principle 5 reads as follows (pages 2-3):

> Investment incentives, potentially including targeted tax incentives, should encourage broadband deployment to underserved communities and businesses. … In a market-oriented environment that encourages the deployment of broadband networks, there may still be a segment of the U.S. population that

> does not have broadband availability. Public policies should seek to narrow the current and future disparity in the level of high-speed access to the Internet, to ensure that all Americans can enjoy the benefits of broadband.

Similarly, Kornbluh encourages both Congress and the president to subsidize sparsely populated regions of the country, low-income users, or both, suggesting that an ambitious broadband strategy can help revitalize the economy. (Kornbluh, 2001, p.21)

While broadband connectivity is becoming a technological necessity, and while the United States has a fiber-optic backbone that is severely underutilized with members of both the government and industry calling for greater broadband coverage, America continues to fall behind other developed countries in deployment of broadband services. Five years after the phone and cable companies began offering broadband services, a mere fifteen percent of US households use them (Woolley, 2002). This is primarily due to prohibitive cost of services. Countries in which products and services have generally been more expensive, such as Japan, are offering broadband services at almost half of what American citizens pay. As a result, while Japan previously lagged behind the US by a factor of twenty in broadband usage, they have not only caught up but are surpassing them (Woolley, 2002).

One popular alternative, which has emerged for providing this "last mile" connectivity, is wireless networks (Willebrand and Ghuman 2001). Prompted by the high cost of fixed-media connections and the problems with obtaining permission to run cable trenches within urban areas, wireless technologies have received renewed attention. As an example, one case encountered by LightPointe Communications involving the tradeoff between fiber cable and laser-based wireless for connecting three urban buildings to a backhaul hub clearly illustrates the cost differential (Willebrand and Ghuman 2001). Fiber cost was calculated on the basis of 1220 meters required to interconnect the buildings to the hub. At $325 per meter for trenching, cable, and installation, the cost came to $396,500. In comparison, the cost to interconnect wirelessly was a mere $59,000 for the transmitting and receiving equipment across the four locations. While relative costs obviously depend on the number of locations, distance involved, local labor rates, and numerous other factors, it is clear that wireless connectivity provides an alternative worth exploring in many network settings.

This paper proposes a mesh network planning methodology and examines mesh networks as a possible solution to the last-mile problem. In particular, after discussion of some background material, details of the planning methodology are explained, and then results of applying the approach to approximately 2500 randomly generated neighborhoods are presented. The effects of density, quality of service, equipment costs, and transmission ranges are examined. The paper concludes with overarching thoughts on the practicality and likely success of the wireless mesh approach to solving the last-mile problem.

BACKGROUND

Technology Options

Some current fixed wireless technologies are Local Multipoint Distribution Services (LMDS), Multipoint Microwave Distribution Services (MMDS), the IEEE 802.11 standards for wireless connectivity, and free space optics (FSO). Although other options exist, these four provide a significant starting point for this research.

LMDS

Local Multipoint Distribution Services operates in the 28 GHz band and cannot be transmitted through obstructions (such as buildings and mountains). The maximum range of LMDS is approximately five kilometers, and though it can transfer data up to 2 gigabits per second (Gbps), LMDS behaves more reliably when transferring data in the Mbps range.

MMDS

Multipoint Microwave Distribution Services are also called Multi-channel Multipoint Distribution Systems and wireless cable. MMDS uses both unlicensed and licensed channels. This technology's key feature is that it uses multiple channels simultaneously and, therefore, by aggregation creates large pathways between the sender and receiver. MMDS can transfer data on the unlicensed channels up to 27 Mbps and up to 1 Gbps on licensed channels. It also cannot transmit though obstructions.

Wi-Fi

The variations of the Institute of Electrical and Electronics Engineers (IEEE) wireless standards and their usage are rapidly increasing, as, for example, the 802.11b standard shows. This is more commonly known as Wi-Fi (short for wireless fidelity). The Wi-Fi was originally intended for local area networks (LAN), but is now also used in metropolitan area networks (MAN). The reported range of 802.11b is approximately 100 meters, seemingly insufficient for larger scale connectivity, but it is possible to connect points over greater distances with the same technology. In fact, Wi-Fi networks are being implemented with distances of up to 15 kilometers (Carstensen and Morgan, 2002). Other IEEE 802 wireless standards are also available, such as 802.16 (Wireless MAN), 802.11a, 802.11g, and others.

Wi-Fi technology is becoming popular in an application related to, but distinct from, that considered in this research. According to *USA Today* (Kessler, 2003, p.1), "big companies are starting to pour big bucks into Wi-Fi technology – marking a turning point for the young technology." Companies such as Starbucks and McDonald's are putting so-called "public access points" in their stores – Starbucks in 1200 stores across the country, and McDonald's in 10 stores on a trial basis in Manhattan. There are currently 5,900 public access points in the United States; this figure is projected to grow to 103,800 in 2006. Cell phone maker Ericsson is building 5,000 wireless hot spots in the United Kingdom (UK), Toshiba plans to install 10,000 more across the United States by the end of 2003, and Cometa Networks (financed by IBM and AT&T, among others) plans to have wireless networks installed in 50 US cities by year's end. Intel is also squarely behind the push; it plans to build the Wi-Fi capability right into its chips. Intel will spend over $300 million touting this advance, its biggest marketing blitz ever. (Kessler, 2003)

The use of Wi-Fi in coffee shops and McDonald's does not solve the last-mile problem. But the availability of Wi-Fi on chips and across the US and UK will only help promote usage of the technology and drive down prices and improve the electronics as time goes on.

Free Space Optics (FSO)

Free space optics (FSO), also known as "open-air photonics," "optical wireless" or "infrared broadband," transmits data using low-powered infrared lasers. FSO do not currently require FCC licensing; however, certain power restrictions must be observed. FSO is a line-of-site (LOS) technology, and to remain in the unlicensed territory, the laser must not be too highly powered. Consequently, the maximum range of FSO is a few kilometers. Furthermore, fog can corrupt the transmission as water particles act as prisms to the laser and dissipate the light beam. The data transfer rate of FSO is between 155 and 622 Megabits per second (Mbps).

Network Configuration Options

Wireless technologies have been deployed in three basic network configurations, point to point, point to multipoint, and mesh (also known as multipoint to multipoint) – the subject matter of this paper.

Point to Point (PtP)

Point-to-point is the oldest of the three configurations and consists of transmission from one location to a second point. This is in distinction from technologies that broadcast from a single point to multiple homes or businesses, or that broadcast from multiple points to multiple homes and businesses.

This methodology is typically implemented when there are two buildings that need to be connected as part of a LAN. Instead of laying wire or fiber optics between the edifices, it is often more straightforward to place two small directed antennas on the tops of the buildings. The advantage of this methodology is its simplicity for connecting two locations, and the cost of the wireless equipment is often substantially less than that of a traditional wired network. The disadvantages are potential security issues and possible weather disruptions. A very common application area is campus (school) environments. Some applications of PtP connections use the Free Space Optics technology. Such connections are often found in metropolitan areas when two offices for the same company are in separate buildings, and it is desirable to have them part of the same network. Since the technology of FSO is a fairly narrow laser beam, this introduces another complication, namely the sway of the buildings involved. Several solutions have been introduced to address this particular problem. It is also worth noting that since FSO's laser beam is very high frequency and is very directed, security becomes a relative non-issue. It is not possible to “eavesdrop” on a FSO signal without blocking the beam and thereby notifying the sender and receiver.

Point to Multipoint (PMP)

PMP networks have a single source connected to a backbone network that propagates signal to multiple receivers. This type of network may be envisioned with a single tower blanketing an area with a signal, and everything falling under that blanket part of the network. PMP often must deal with either line-of-sight (LOS) issues, where obstructions cause loss of signal, or near-line of-sight complications, where some obstructions (buildings, e.g.) cause failure, but lesser obstructions (e.g., trees) do not.

PMP networks operate somewhat similarly to those of cellular telephones in the sense that when one is within a “cell,” coverage is provided by one tower. However, there are two major differences between cell telephone provision and wireless PMP broadband coverage. The first deals with line of sight. Broadband wireless typically operates in higher frequencies and thus requires its receivers to be line-of-sight with the transmitter, whereas mobile wireless (cellular) does not need this imposition. Second, to maintain expected quality of service (QoS) for broadband, there must not be any interference with other signals. Cellular telephone does not have this stipulation either. This is primarily because audio communication occurs at such low data rates; moreover, people are very forgiving of interference (including minor static, lost syllables or words) that mobile networks can operate satisfactorily where broadband networks could not. Therefore, planning for PMP networks is significantly different from that of cell phone towers and networks. The reader interested in additional information about the planning of PMP networks is directed to Scheibe, Carstensen, Rakes, and Rees (2003).

Mesh

Since mesh (or multipoint to multipoint) networks do not have a tower or towers that must reach all customers, several drawbacks of PtP and PMP are immediately overcome. The tower-based networks require permission, purchase/lease of land, bringing electric power out to a (perhaps) remote site, etc. With these non-mesh systems, it is also important to have already generated a critical mass of customers that will pay for the service, because of the high cost of the tower.

Mesh networks, the most recent of the network configurations and also the focus of this research, obviate many of these issues by using smaller, cheaper, multiple transmitters. For example, with mesh networks, as long as a customer is within range and view of another customer that is within range and view of yet another customer or piece of equipment that is eventually connected to the backbone, then the signal may be received. The incremental addition of customers to the network is often inexpensive, with the only additional cost being that of the customer premise equipment. In fact, increasing the number of customers can decrease the cost of the mesh network, as will be seen later.

Radiant Networks, a Cambridge, England, based company announced plans to implement a mesh wireless network in the South Wales region, planning to offer services equivalent to asymmetric digital subscriber line (ADSL) networks (Willis et al., 2001). In February 2002, Nokia announced that more than 50 customer were using their Nokia RoofTop™ Wireless Routing mesh network solution. Nokia claimed this was the first commercially successful deployment of a wireless mesh system (Nokia, 2002). Vista Broadband Networks has adopted Nokia's technology and has deployed equipment providing residential customers up to 512 Kbps speeds. They also provide businesses with up to 3 Mbps access speeds (Wery, Kar, and Woodrum, 2002). A small municipality in western England has taken upon itself to provide broadband wireless access to its citizens by purchasing MeshBoxes and strategically placing them throughout the area. Citizens need only to have Wi-Fi cards for their PCs to be part of the mesh (Batista, 2003). As to future plans, companies such as Mesh Networks "envision blanketing cities and highways with a peer network to provide continuous 802.11 presence" (Gillmor, 2002). VoiceStream, a company offering broadband services over public access Wi-Fi networks, cites figures from Gartner Inc. in Stamford, Connecticut, and predicts that by 2006, more than 19 million mobile and remote workers will regularly use public access Wi-Fi networks (Brewin, 2002). Finally, the need for and interest in wireless connectivity is increasing in the global market. Former Soviet President Mikhail Gorbachev appealed to American companies and investors to bring information technology outsourcing to Russia to strengthen their wireless infrastructure. (Hamblen, 2002)

Mesh Network Terminology

In order to define terminology common to mesh implementations, Figure 5.1 shows a neighborhood for which a mesh network has been provided. The *backhaul point* (*BH* in Figure 5.1) is that location along the backbone network where the mesh network will connect. The backhaul is generally "wired" (say with fiber optics) to *trunk connection points*, shown as T_1 and T_2 in Figure 5.1; the transmission medium changes to wireless at these trunk connection points. The wireless signal is not, in general, transmitted from the trunk connections directly to customers, however. The signal is sent to *mesh insertion points* (*MIPs*, labeled $M_1, M_2, \ldots M_7$ in the figure) that are closer to customers. These mesh insertion points do transmit and receive directly to/from customers. Generally, once signal is received at a MIP back from a customer, it is only forwarded to a trunk connection point and then to the backhaul. That is, signals are not transmitted from customers to MIPS, and then back out to customers.

As mentioned, one of the key features of mesh networks is that customers are used to forward signals on to other customers, up to the capacity limits of the receiver and transmitters. However, sometimes it is necessary to insert repeater nodes into the network when there are not enough customers nearby to get messages to every customer. Repeater nodes are generally identical to customer equipment – there is just not a customer at the repeater location. Thus a repeater may be thought of as a non-revenue generating customer.

In a mesh network signals from a customer seeking the backhaul may be forwarded from customer to customer (possibly including repeaters), until finally a mesh insertion point is reached. The MIP then sends the signal to a trunk connection point, and finally to the backhaul. Each link in the chain back to the backhaul is called a *hop.* Too many hops in a chain of connectivity can cause inordinate delay, or *latency*. Latency is the time it takes for a packet to travel from source to destination (Webopedia, 2003). To ensure quality of service, that is, the probability of a network meeting a given traffic contract (Wikipedia, 2003), it is sometimes necessary to restrict the number of hops in each transmission path. Although hop constraints are not new to network design (Balakrishnan and Altinkemer, 1992), there has been little discussion in the literature as to what the optimal number of links should be for a wireless mesh network. Whitehead suggests that somewhere from six to ten hops still offers an acceptable level of service (Whitehead, 2000).

Since slightly different equipment and terminology are in use with different mesh providers, and since cost data are confidential, Table 5.1 only gives a rough profile of current mesh equipment costs. These numbers are an amalgamation of numbers we have heard informally or seen in various internal publications/white papers, etc.

WIRELESS MESH PLANNING METHODOLOGY

The methodology proposed in this research to plan wireless mesh networks is a four-step procedure. The first three steps are used to prepare (i.e., preprocess) the neighborhood or region being analyzed for solution.

Step 1 – Potential Equipment Placement and Line-of-Sight Determination

Preprocessing begins with the specification of the backhaul point, trunk connection points, and all possible mesh insertion points for a specified geographic region. (We will call these *neighborhoods*, whether residential or commercial.) These equipment locations are primarily a matter of physical characteristics of a neighborhood, that is, where right-of-way/permissions are available, terrain is not obstructive, etc. With the methodology developed here, the locations of the single backhaul point and two trunk connection points are assumed. It is unknown how many MIPs will be economic, but all potential locations are to be specified; which locations are chosen is an economic decision to be determined by the model.

Next, all known customer locations are specified. The situation to this point is indicated in Figure 5.2, where each circle (node) indicates the (geographic) location of the equipment/customer indicated. Line-of-sight must be determined next; either a geographic information system (GIS) or field visit is required. Figure 5.3 can then be generated, where a dotted line between any two circles indicates no obstruction between the two nodes. (Lack of a dotted line indicates no feasible transmission; e.g., customer C_3 does not have line of sight with customer C_4.) At this point it may occur that a customer desirous of service cannot obtain a signal, either because transmission range limits are exceeded or because obstructions block all possible paths to the customer. In such an eventuality, potential repeater nodes (e.g., R_1 in Figure 5.3) are defined at non-customer locations that will ensure an unobstructed path to the backhaul for each customer. Finally in Figure 5.3, arrows are shown on the links from each MIP to its closest trunk connection point, and from each trunk connection point to the backhaul. Recall that signals received at MIPs from customers do not go back out to other customers; they move on to trunk connection points.

Step 2 – Feasible Path Enumeration

Once the information from step 1 is in hand, all possible paths from each customer to the backhaul may be enumerated, given a limit on number of hops. To generate these paths efficiently, it is helpful to define artificial directional nodes; discussion of these is beyond the scope of this paper. Interested readers may consult Scheibe, et al. (2003). Four possible paths to the backhaul for customer C_1 may be traced in Figure 5.4.

Step 3 – Network-Flow Model Formulation

Once the feasible paths have been generated, they may be cast into the form of a mathematical programming problem, namely the capacitated, fixed-charge, network-flow model, (see Appendix I). The fixed-charge network flow problem has been used in many applications including telecommunications (Balakrishnan, Magnanti, Shulman, and Wong, 1991; Gavish, 1991), logistics and production planning (Minoux, 1989), and transportation (Magnanti and Wong, 1984). We have written an Excel (preprocessing) program that does this.

Step 4 – Solution Generation

The results from our Excel preprocessing program leads to data entered in Excel cells that can be run directly in an integer programming package within Excel. We used Frontline's Premium Solver as this package (Frontline, 2002), and use the capacitated, fixed-charge network flow formulation described in Chapter 4.

EXPLORATORY STUDY

To examine the potential of wireless mesh technology to reach previously unreached (and perhaps unreachable) customers in relatively low-density areas – the case of most economic uncertainty, we randomly generated 270 such neighborhoods, and invoked the procedure above for nine different cases on each. The point was to study suburban and more rural areas as candidates for profitable wireless mesh operation. The method of neighborhood generation is outlined below.

Random Problem Generation

We randomly placed customer homes in a square grid to achieve differently configured neighborhoods with three different rural/suburban densities; two hundred seventy such neighborhoods were produced, ninety at each density. Low-density neighborhoods (L) were constructed on 1.6-acre plots; medium-density areas were spawned with 1-acre lots; and high-density regions (H) were created on ¼-acre lots. Three levels of visibility were specified in order to introduce the effect of obstructions (i.e., terrain, buildings, etc.) and thereby portray realistically line-of-sight issues among customers. A level of 40% visibility (low) infers that only two-fifths of the possible connections among homes within the broadcast range of the transmitter are viable, whereas a (medium) visibility level suggests that three fifths of homes have such line of sight. The high level of visibility was set at 80%. Connections were randomly assigned to the visible or obstructed categories according to their likelihoods. Table 5.2 shows each factor and its corresponding level.

Each of the 270 neighborhoods was then evaluated on two different factors at three levels, resulting in nine different cases. Each factor reflected different aspects of quality of service (QoS); in particular, bandwidth and number of hops were each evaluated at low, medium, and high levels. Bandwidth was studied at 2, 5, and 10 Mbps rates. The levels examined of number of hops were five, seven, and nine. This means that, for example, at the medium hop level, no path from a customer proceeding to the backhaul is allowed to exceed seven hops; this keeps latency in check, thereby helping ensure a level of quality.

The particular cost and other assumptions made in the study are listed in Table 5.1.

MANAGERIAL IMPLICATIONS

The results from the 2,430 computer runs are economically disappointing. That is to say, the use of Wi-Fi technology at current costs is economically infeasible.

The details from the study are shown below for each factor. We then show data indicating the decline in costs necessary to “prove in” this technology for rural/suburban areas at the densities examined in the study. Such drops in costs could be achieved either through technological advances or government incentives/subsidies. Development of these scenarios is beyond the scope of the present paper.

Each section below discusses in a similar manner one of the factors explored. Plots are generated showing the monthly revenue required per customer to achieve breakeven under the conditions given.

The data below are hindered in several cases by an inability to generate feasible neighborhoods or solutions. When this occurred it sometimes became difficult to make comparisons across factors. This suggests that for the journal article to be generated from these results, factor levels be changed to include only feasible alternatives. Appendix II discusses several of these anomalies.

Effect of Customer Density

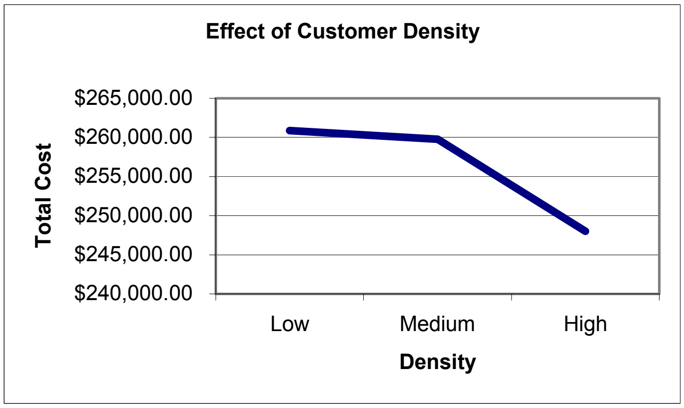

Figure 5.5. Effect of Customer Density

It can be seen from Figure 5.5 that as the density of an area increases the cost of bringing a broadband wireless mesh network decreases. Although the drop visually appears significant, none of the three cases is financially feasible. If a five-year payback period is specified, breakeven revenue is $174/month at a low density and $165/month at a high density. Both are beyond the ordinary reach of residential customers.

Effect of Obstructions

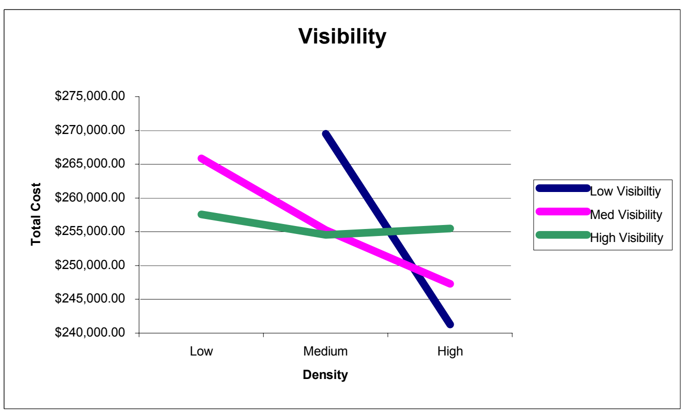

Figure 5.6. Visibility

(The low visibility / low density point was excluded from this graph because no feasible solution was found at those factor levels.)

Not surprisingly, the lower the visibility, the steeper the descent from high cost across the density levels. This is because with many buildings and/or terrain to obstruct signal paths (i.e., low visibility), the harder it is at even medium customer densities to get from the customer's home to the backhaul; this necessitates more hops and often more repeaters. Managers will be interested to note the magnitude of this change: for the low visibility case, the cost is increased by 25% in going from a high customer density to a medium one.

Effect of Quality of Service: Hops

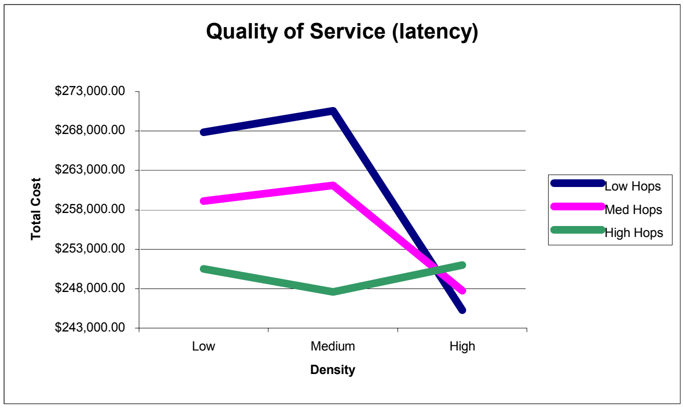

Figure 5.7. Quality of Service (latency)

The message of Figure 5.7 is that, at low densities, there is a large price to pay in reducing latency. For example, when a five-hop maximum is enforced (thereby maintaining fairly low transmission delay), the cost is increased by $18,000 (14%) over a more lax nine-hop maximum number of hops. This is a significant cost to pay for quality; it is not clear that managers will enforce such restrictions once they become aware of these cost penalties.

Effect of Quality of Service: Bandwidth

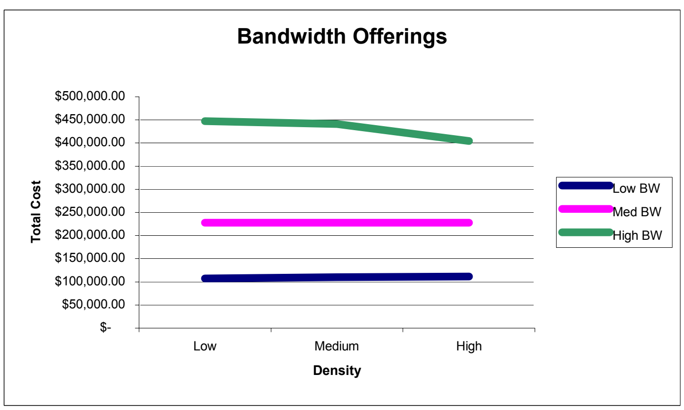

Figure 5.8. Bandwidth Offerings

Figure 5.8 illustrates the changes in cost over the three density levels for each level of bandwidth. With a five-year payback, monthly revenue charges for breakeven are $287/month for the 10 Mbps case; $152/month for the 5 Mbps scenario; and, $73/month for the 2 Mbps setting. This indicates a hefty charge for the fastest rate of service – one that is prohibitive for almost all residential customers. The 5-Mbps rates are perhaps affordable for business customers, but not for residential, and the 2-Mbps is only slightly more than what many residential customers are currently paying for about 1/3 the throughput. Finally, note that there is very little effect as customer density changes for any bandwidth.

Effect of Cost: Bandwidth

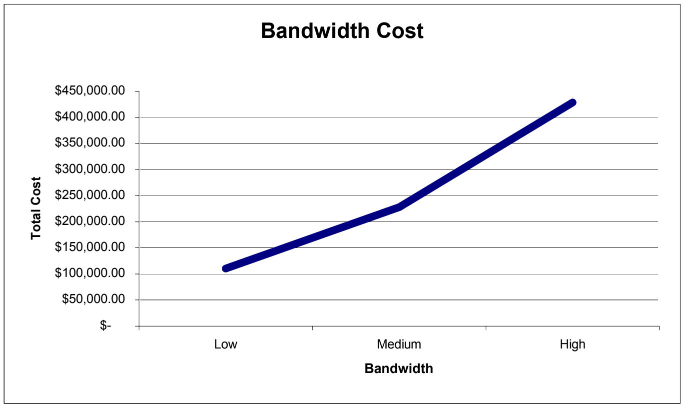

Figure 5.9. Bandwidth Cost

It can be seen from Figure 5.9 that averaged over all other factors, as the bandwidth increases, the cost of bringing a broadband wireless mesh network also increases. The cost increase is almost a factor of five – the difference between a profitable service offering and an unaffordable one.

Cost Reductions Necessary to Achieve Profitability

To illustrate the need for cost reduction, consider a case of medium-level factors. That is to say, each of the four factors in this study takes on a medium level: visibility is 60%, density is one-acre lot sizes, QoS (latency) is restricted to seven hops, and bandwidth is 5 Mbps. The total cost for providing mesh service to the average 25-customer neighborhood is $205,000. If the desired time to recoup the investment were specified to be five years, then each customer would be required to pay a monthly fee of approximately $137 for his or her service. While under current conditions this rate may be very reasonable, we believe that very few end users would be willing to pay that much. If we assume customers are willing to pay $75/month for such service, then the total cost of equipment would need to be reduced to $112,500 to break even – a 45% cost reduction. One way of viewing this result is to say that, on average and under average/medium conditions, Wi-Fi costs need to drop by 45% to achieve breakeven.

CONCLUSIONS

A planning methodology has been developed that configures wireless mesh networks in an optimal manner. This methodology was employed in a large computer study to assess wireless technology as a mechanism for solving the last-mile problem of broadband provision in rural/suburban areas.

The study finds that Wi-Fi service is not economically viable at current costs. The analysis also concludes that, under average conditions, costs would have to drop by 45% (or revenues be supplanted by $62/month per customer for five years) to become profitable. There are those in government and industry who have called for the federal government to intervene through subsidy and/or tax breaks to make broadband service “universally” available. Now that a methodology is available for analysis of wireless mesh implementation, we view the next area of future work to be an inquiry into various governmental options. Costs and penetration could be assumed for the promising scenarios to see whether such expenditures are socially possible or desirable.

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APPENDIX I: THE WIRELESS MESH PROBLEM MODEL

The fixed-charge, network-flow problem (FCNFP) model as applied to the wireless mesh problem is formulated as follows. Let N be the set of all nodes and N^a be the set of artificial nodes in the network. Further designate T, M, R, and C as the sets of trunk connection nodes, mesh insertion points, repeater nodes, and customer nodes respectively. Finally, define the set of all arcs in the network by the letter A.

For each node k, let the cost of activating that node be f_k, which is assumed to be nonnegative; any artificial nodes have a cost of 0. The objective is to minimize total cost. Let d_j denote the supply or demand at node j; all artificial nodes should be considered transshipment nodes (with a supply of 0). Let $u_i > 0$ represent the capacity on the arcs emanating from node i. x_{ij} is the flow on arc (i,j), and y_i is a binary variable equal to one when node i is in use and zero otherwise.

The model may be written as

$$\min \sum_{k \in N} f_k y_k, \tag{A-1}$$

$$\sum_{k \ni (k,j) \in A} x_{kj} - \sum_{k \ni (j,k) \in A} x_{jk} = d_j, \quad \forall j \in N \tag{A-2}$$

$$\sum_{j \ni (i,j) \in A} x_{ij} \le u_i y_i, \quad \forall i \in (T \cup M) \tag{A-3}$$

$$\sum_{j \ni (i^*,j)} x_{ij} \le u_i y_i \qquad \forall i \ni \{[i \in (C \cup R) \cap (i \notin N^a)] \cap [(i,i^*) \in A] \cap [i^* \in N^a]\} \tag{A-4}$$

$$x_{ij} \ge 0, \quad \forall (i,j) \in A, \tag{A-5}$$

$$y_i \in \{0,1\}, \quad \forall i \in N \tag{A-6}$$

Constraint (A-2) ensures flow conservation, whereas constraints (A-3) and (A-4) are *flow capacity constraints*. Constraint (A-3) restricts flow from trunk nodes and mesh insertion points, whereas (A-4) restricts flow emanating from customer or repeater nodes, as follows. Flow leaving either a customer or a repeater node (i.e., the sum of flow over all arcs leaving such a node) cannot exceed the capacity of the transmitter at that node; moreover, if the transmitter is inoperative, no flow may traverse any arc departing that node. Further details may be found in Scheibe, Ragsdale, Rakes, and Rees (2003).

APPENDIX II: PROBLEMATIC CORNERS

In the study described in this chapter, one constant is the range of the wireless transmission. The technology used is IEEE 802.11b or Wi-Fi. The range of Wi-Fi antennae can very from 300 feet to 23,000 feet. For this design, the range is conservatively held constant at 900 feet. As initial tests were performed with these factors, certain "corners" of the design proved to be problematic for analysis – specifically, low visibility / low density and high visibility / high density / high hops.

When the density of the area in which a wireless mesh network may be desired is low, it makes sense that some nodes in the network may be too far from others to be a part of the network. When this is the case, then it may be necessary to add a repeater node to bridge the gap and bring the customer node into the mesh. If an area's density is very low, then it just may not be feasible to create a mesh. Similarly, when the visibility is low, while nodes may be close enough for the signal to reach, there is something blocking the visibility. If the visibility is too low, then, again it may not be feasible for a mesh network. When the two factors are brought together, low visibility and low density, then it becomes virtually impossible to create a mesh network. During the pre-testing of these factors, the computer would randomly generate neighborhoods based upon factor parameters. When the parameters were low visibility and low density the computer could not generate a neighborhood that met the necessary criteria of each customer node being able to see at least one other node. The visibility was set at 20% and the density was set at 5-acre lots. The computer created over 100,000 neighborhoods, and not one neighborhood met the necessary criteria. Therefore, it became necessary to increase the density and visibility to a level where tests could be run. It is worth noting, however, that some neighborhood configurations are very rare. For example, for the computer to generate twenty-three neighborhoods with medium visibility and low density, it took approximately 214,000 generations. When the hop level was set at 5, it took another 225,000 generations just to create the twenty-three. The implications are that neighborhoods that have medium visibility, low density and require a high QoS are very rare and prove difficult to serve.

Neighborhoods with high density and high visibility created an entirely different, but equally interesting condition. This is especially true when the number of hops is set at the maximum level. It is very easy to generate a neighborhood where all the necessary criterion are met, however, it was discovered, that the redundancy of paths from a node to the backhaul made computation exceedingly difficult. To illustrate this issue consider a neighborhood with a visibility of 50%, a density of one-acre lots, and a hop level of seven. The number of viable paths for every node to the backhaul may range from 500 to more than 12,000. In its present state, the algorithm used to generate every viable path may take a half of a minute to several minutes. Now consider when the visibility is 80%, the density is ¼ acres, and the hops are nine. The total number of viable paths may be in the 100 thousands to millions, and the time to compute them exponentially increases. This is exclusively due to the high level of redundancy within the mesh paths.

There are a few practical conclusions that may be drawn from the two corners just discussed. The first is when an area has a density and/or visibility that are very low it may be practically impossible to bring in a mesh network. There are many such neighborhoods in the United States, and wireless service providers should be wary before attempting to penetrate such areas. If the visibility is sufficient, but the area is not dense, then it may be possible to change the wireless technology to one that is capable of transmitting over greater distances. Of course, the costs change with different technologies.

Another practical conclusion is when the density is high, the visibility is high, and the hops are high. While the mesh network will certainly work in neighborhoods with such characteristics, there is a level of “overkill.” It may be worth considering using a wireless technology that has a shorter signal distance, and, thereby, potentially reducing network costs. Another means of addressing the overkill issue is to reduce the number of hops from a node to the backhaul. This may or may not be desirable as the number of viable paths decreases so does the network’s ability to simultaneously transmit multiple packets over different routes.

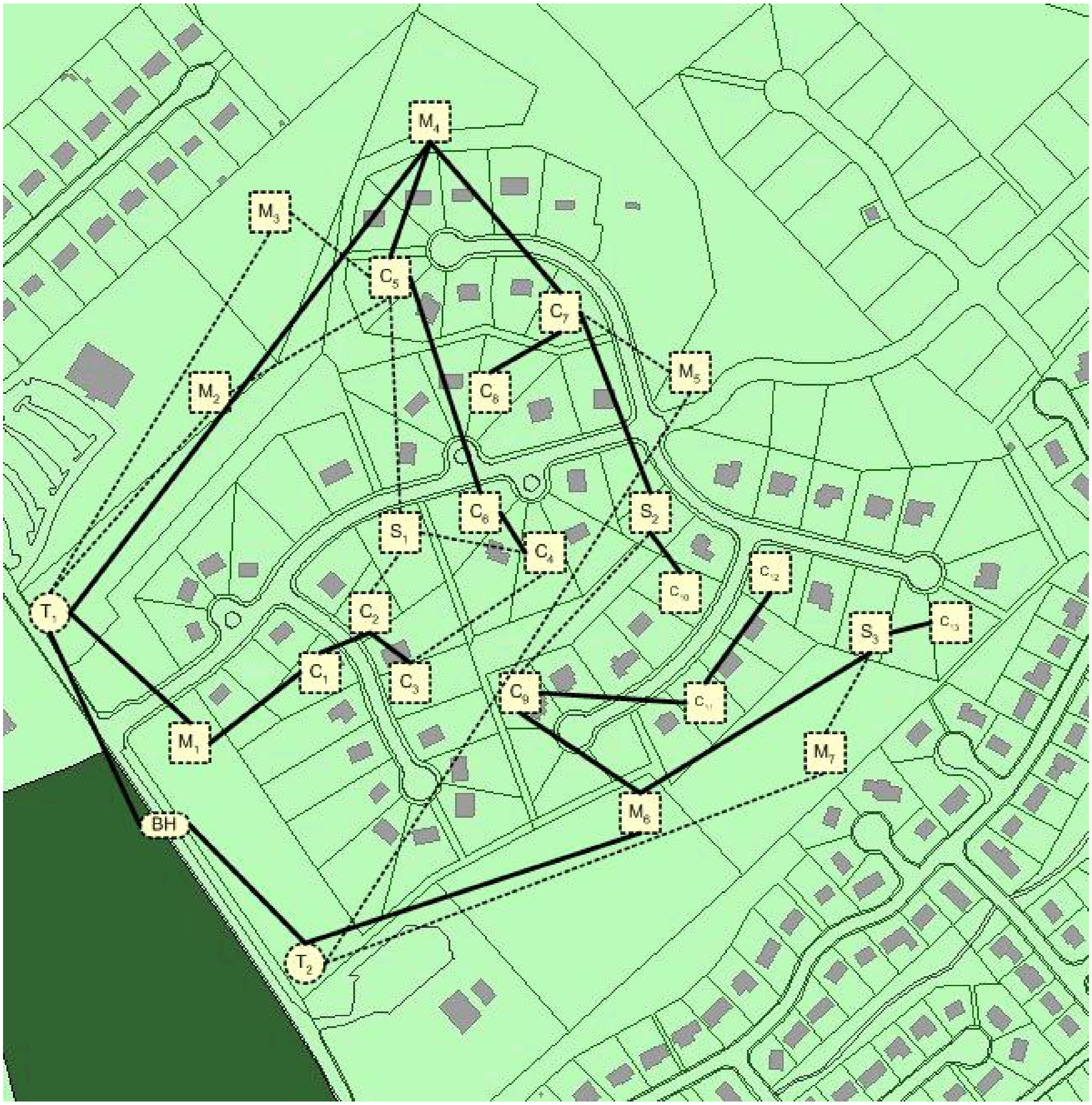

Figure 5.1. Providing broadband service to a neighborhood with a wireless mesh network.

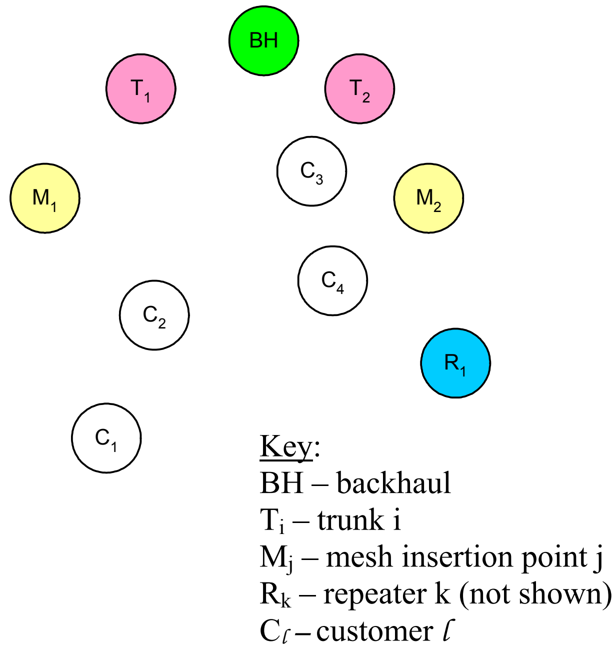

Figure 5.2. Nodes represent potential wireless mesh equipment locations.

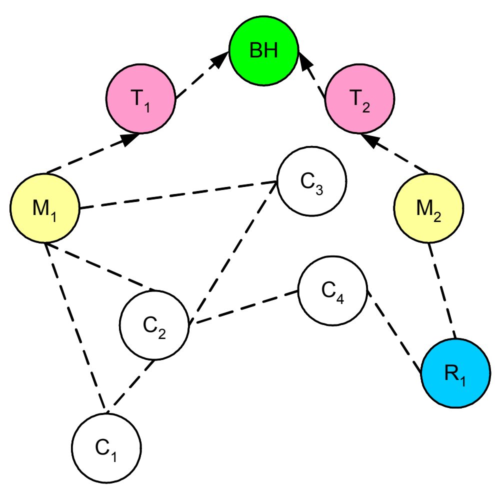

Figure 5.3. Nodes shown linked together with line-of-sight capabilities.

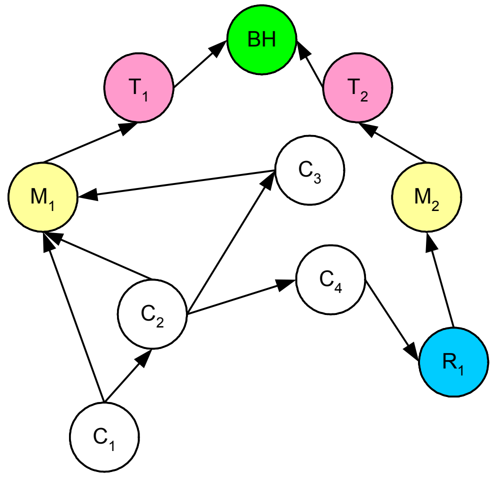

Figure 5.4. Viable paths for customer C_1 to communicate with the backhaul, given the line-of-sight configuration of Figure 5.3.

Table 5.1. “Typical” Wireless Assumptions

	Equipment Cost Assumptions	**Capacity Assumptions**
Trunk Connection Nodes	$50,000	200 Megabits/second
Mesh Insertion Points	$10,000	80Megabits/second
Repeater Nodes	$5,000	30 Megabits/second
Customer Premise Equipment	$5,000	30 Megabits/second
Antenna Range		900 Feet

Table 5.2. Factor Levels

	Visibility	Hops	Density	Bandwidth
Low	40%	5	1.6 Acre Lots	2 Mbps
Medium	60%	7	1 Acre Lots	5 Mbps
High	80%	9	.25 Acre Lots	10 Mbps

Note: We performed 30 replications in each cell.

CHAPTER 6

A GENERAL FRAMEWORK FOR PLANNING BROADBAND, FIXED WIRELESS TELECOMMUNICATION NETWORKS

Under the recommendation of my dissertation chair and committee, this dissertation chapter merely outlines and sketches future work to be done in developing a planning methodology for fixed, wireless broadband networks. As such, this future journal submission is more developed in some sections than others; it is research in progress and a document in progress.

A GENERAL FRAMEWORK FOR PLANNING BROADBAND, FIXED WIRELESS TELECOMMUNICATION NETWORKS

ABSTRACT

Wireless broadband telecommunication networks have been touted as being the solution to the "last-mile" problem. With this problem, 97% of the United States' broadband network is laying fallow because it is too expensive to go the remaining distance from the broadband backbone to American residences and businesses. In two previous papers, the authors demonstrate how to apply different wireless technologies in suburban and rural settings in a minimum-cost manner. This paper presents a planning methodology that shows how and when to apply which technologies, given parameters such as customer density, terrain, and infrastructure. The methodology varies in scope from metropolitan areas to developing countries. A spatial decision support system is proposed as a delivery mechanism for the planning methodology.

Keywords: Broadband Wireless Telecommunications, Geographic Information Systems, Decision Support Systems, Network Planning

A GENERAL FRAMEWORK FOR PLANNING BROADBAND, FIXED WIRELESS TELECOMMUNICATION NETWORKS

INTRODUCTION

Broadband communication refers to high speed, always "on" connections, (TechNet, 2002) and fixed, wireless telecommunications refers to those network delivery mechanisms that depend on electromagnetic propagation to non-mobile customers, as opposed to copper, coaxial, and fiber-optic connectivity. In previous work, the authors demonstrated two methodologies for planning broadband, fixed wireless telecommunication networks (Scheibe, et al., 2003; Scheibe, et al., 2003). These two methods of point to multipoint and mesh were presented as means of bringing broadband communication to homes and small office / home offices (SOHO). Each method shared a particular physical requirement due to the nature of the transmission and the physical medium for broadband wireless telecommunications, namely a line-of-sight (LOS) stipulation. LOS means that the path between transmitting and receiving antennas cannot be obstructed; the antennas must be visible to each other for a signal to pass successfully. The physical reason for the LOS requirement is the high frequency level of the signal; in fact, it is generally correct to say that as frequency increases, so does the necessity of LOS. Lasers provide a good example of this phenomenon; even fog and mist can disrupt a laser signal, whereas they have very little effect on FM radio, which is lower in the frequency spectrum than laser. Note that, by definition, a second shared characteristic of the two fixed wireless methodologies is that each antenna is fixed in a specific location; that is to say, antennas do not move as do mobile telephones.

Physically speaking, therefore, it is incumbent on a fixed wireless planning methodology to consider directly the terrain over which the technology is to be applied. Geographic information systems (GIS) lend themselves well to this class of problems. In each of the methodologies mentioned above, we use a GIS to aid in the determination of optimal tower placement in one case, and equipment visibility in the other. A particular GIS tool developed locally (GETWEBS) takes topography into consideration as well as radio frequency characteristics (Carstensen, Morgan, and Bostian, 2002) and is recommended in this planning methodology. The power of this GIS is that it allows the decision maker to evaluate alternatives in a straightforward, quick manner

A second necessary component for a fixed wireless broadband planning methodology is a mechanism to deal with the fairly sophisticated mathematics (mixed integer programming solution) necessary for minimum-cost solution of the problem. In this research we propose a spatial decision support system (SDSS) to encapsulate the methodology. SDSS contain three major components: a spatial database (which can be manipulated by GETWEBS in our case); a model base, i.e., collection of requisite mathematical models (the mixed integer programming models in our system); and a GUI dialog system. SDSS seem to fit naturally with the planning methodology we are developing as the purpose of this research.

In this paper we advance an SDSS for planning fixed wireless broadband networks. The next section provides background knowledge, particularly with respect to assumptions made in our two previous papers dealing with broadband service via two different network topologies: point-to-multipoint networks (PMP), and mesh networks. The subsequent section presents the actual methodology. Two (large-scale) examples are presented next, and the implications then discussed. Finally, conclusions are drawn and future work discussed.

BACKGROUND

SDSS

(This section will provide a very brief overview of spatial decision support systems, their design, and limitations.)

Network Topologies

(Current major topologies – such as PMP and mesh – will be outlined. Emphasis will be placed on limitations and conditions of their applicability, as is understood from our previous work.)

Technology Issues

(This section will discuss issues such as the major technologies, the equipment they demand, and limitations such as transmission ranges and capacities.)

METHODOLOGY

Database/GIS

Factors and items stored in the spatial (and non-spatial, as well) database will include:

For the geographic area under consideration:

- Developed/undeveloped
- Infrastructure
- Terrain visibility
- Customer density
- Customer clustering
- Disaster recovery an issue?

For each viable technology:

- Transmission range (for various technologies)
- Transmission capacities

The above issues will be incorporated into the methodology as root nodes in decision trees, independent variables in charts, etc.

Model Base

This portion of the SDSS will contain three major model sections: a marketing component, whereby customer demand is developed; a decision model section, in which minimum-cost solutions are computed for a given technology/topology combination; and helper models.

Marketing models

- Propensity to pay
- Demand models

Decision models

These models provide the mathematical wherewithal to solve a particular topology/technology implementation at minimum cost, once those issues have been determined by the system.

- Set covering problem. (The PMP solution requires this – see Scheibe, Carstensen, Rakes, and Rees, 2003.)
- Capacitated, fixed-charge, network-flow problem. (The mesh solution requires this – see Scheibe, Ragsdale, Rakes, and Rees, 2003.)

Helper models

This class of models, in general, provides support to the other SDSS components. For example, some of these models would manipulate data and graphs from one format to another. Also providing support are

- Forecasting models
- Tax data/models, etc.

GUI Base

The GUI base will contain presentation formats for the different aspects of the methodology. Formats most appropriate to the task at hand are

- Decision trees
- Rules
- Charts
- Tables

Possible Synthesis/Flow of Above Factors in the Planning Methodology

To adequately address holistic planning of wireless broadband networks, it is crucial to view the big picture. The foremost question should be, what is the desired service. Broadband communications encompass a variety of services, including telephone, Internet, and cable. Therefore, it is important to know not only the level of demand for a service, but also which service is demanded. For example, individuals in a developing area/country that has no network infrastructure whatsoever may demand basic services such as telephone before requesting high speed Internet. However, when planning a network, future demand as well as current demand should be considered. While voice may be the only current requirement, it would be inappropriate to fail to plan for cable or Internet connectivity as well.

The next factor which should be considered in this planning phase is the characteristics of the area for the desired service. There are several sub-factors, including topography, weather characteristics, location and condition of nearest existing infrastructure, location of available power, population and/or household density of the area, socio-political conditions of the area, is it a new network or augmentation of an existing network, and is the area a new development or a disaster recovery?

After the characteristics of the area under investigation have been determined, the next set of facts to be examined is the wireless frequencies and their inherent capabilities and weaknesses. This should be done in conjunction with the potential wireless topology such as point-to-point, point-to-multipoint, or mesh. The characteristics of the area will play a large role in determining which methodology should be used. Moreover, they will also determine which frequency may best suit the area. For example, if the area were often very foggy, then higher frequencies such as those used with free space optics would not be appropriate, or if the area had much rain, then microwave frequencies would not be appropriate, etc.

Given the multitude of factors that affect the planning of a wireless network and how the planning process, in general, lacks structure, a decision support system would certainly be advantageous, and perhaps a necessary tool for a planner. Once the facts have been collected, the next step is to recommend a technology/topology pair, and then to analyze them within the SDSS. This research suggests using three decision aids to narrow the possible choices for a broadband wireless network – charts/graphs, rules, and decision trees.

Possible Products/Outcomes/Outputs of the Methodology

Charts/Graphs

As an example of this potential SDSS output, consider which topology to utilize in planning wireless networks. Based upon customer density and clustering, regions of topology applicability can probably be derived. These regions may be appropriately displayed in charts or graphs plotted against the key factors, say customer density on one axis and degree/type of clustering on another. A graph could be generated for any cost profile assumed for the given technology.

Rules

Another approach to reducing the number of planning choices to only the necessary few is to employ rules in a top-down fashion. Three examples of rules are shown below.

Rule 1:	if	the area is undeveloped, and
		there is no existing infrastructure close by,
	then	high bandwidth PtP is necessary from the backhaul
Rule 2:	if	the area is developed, and
		a disaster has occurred
	then	high bandwidth PtP should be used to bridge network gaps
Rule 3:	if	the weather for area is foggy
	then	use lower frequency communications

This scenario suggests that it may be propitious to embed intelligence in the SDSS in the form of an expert system (i.e., develop a knowledge base that integrates with the rest of the system).

Decision Trees

A third possible beneficial SDSS output is a decision tree. Decision trees are visually informative; as one prunes off branches one can see, for instance, how the search space has been reduced. Decision trees also help enforce organization and complete consideration of all factors to be considered in planning.

EXAMPLES

(Two detailed examples will be developed and analyzed. The current plan is for these examples to possess widely different characteristics.)

MANAGERIAL IMPLICATIONS

(Implications will be drawn from the examples as to the utility and limitations of the fixed wireless broadband planning methodology.)

CONCLUSIONS AND FUTURE WORK

While the research in this paper is yet untested, it is believed that a way of thinking methodically about broadband such as has been suggested here would greatly benefit decision makers at higher levels.

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