A GIS APPROACH TO THE POSITIONING of Base Stations for Cellular Network Coverage of Connecticut Route 32

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ABSTRACT
The expansion of wireless communication services has been prompted in part by safety concerns with respect to automobile emergencies. The siting of cellular base stations based on the principle of serving population centers can inadvertently create coverage "holes" along highways due to topographical barriers such as mountains and hills in the coverage area. This paper presents a methodology utilizing geographic information system (GIS) technology to achieve an efficient wireless antenna network that eliminates coverage holes along a given transportation corridor. The siting methodology integrates the location set-covering problem (LSCP) with GIS functions in a closely-coupled architecture. The special structure of the LSCP is exploited to locate potential base stations for the Route 32 corridor in eastern Connecticut solely in the context of GIS operations. *Keywords: geographic information systems, cellular networks, location set-covering problem.*

Introduction

The proliferation of wireless communication service has led wireless service providers to search for the best locations to site additional antennae in order to increase their coverage areas and gain new subscribers. If the antennae are not sited in a proper geographic distribution, coverage "holes" stemming from topographical barriers such as mountains and hills in the coverage area can result (Faruque 1996; Parsons and Gardiner 1989; Dodd 2002). Coverage holes impact negatively on the issue of safety, one of the primary reasons why people subscribe to a cellular service (Couret 1999). Many people rely on their wireless phone service not just for convenience, but also to provide a sense of security in case of an automobile breakdown or highway traffic accident. If these unfortunate situations occur outside of the covered portions of the network, it is impossible to place a call that could possibly save someone's life. Although the private companies locating the base stations are not responsible for public safety, there is a public policy concern regarding the location of these facilities. Local opposition to cellular towers may be less if the towers also performed a public service.

The purpose of this paper is to develop a methodology that utilizes geographic information system (GIS) technology to achieve an efficient wireless antenna network that effectively eliminates coverage holes along a given transportation corridor. The study develops this network based on the location set-covering problem (LSCP) to determine the minimum number of antennae needed to ensure no coverage holes. Given the expense of siting antennae and often local opposition to antennae in their area, the fewer antennae that are necessary, the easier it is for service providers to expand into new geographic markets.

Background

Heinrich Hertz's experiments in the 1880s with electromagnetic waves laid the technical foundation for radio and later forms of wireless telecommunication by electronic devices (Bedell 2001). Although Hertz did not believe that telephonic communication would be possible by means of electromagnetic waves, a previous invention of a radio-conductor by Huber permitted such a possibility (Story 1904). One of the earliest uses of wireless technology for commercial purposes was Marconi's wireless ship-to-shore communication between trans-Atlantic ocean going vessels and shore stations initially for the purpose of passengers receiving news from shore (Stone 1998). The use of wireless signals during the sinking of the Titanic demonstrated the role of wireless communication as a safety tool. Wireless technology later provided the platform for ground-to-air communication with airplanes, and in the early 1930s two-way communication between police patrol cars and a central dispatcher (Murray 2001). This represented the beginning of wireless service for public affairs. Over the next decade, portable wireless technology emerged, first with the development of the "Handie-talkie" and later the "walkie-talkie" by Motorola and in 1946 the Bell System began mobile phone service for automobiles (Murray 2001). These early mobile phone systems were limited in their customer capacity. The solution to the capacity problem was the development of a cellular system in which coverage was divided into smaller areas in which calls are handed-off from one transmitter to another as the customer moves from one cell to another. In 1983, the Federal Communications Commission (FCC) finally granted the necessary bandwidth to telephone service companies for the first commercial cellular service in Chicago (Schneiderman 1994). Today's digital Personal Communications Service (PCS) wireless networks are nothing more than an advanced form of radio frequency (RF) signal technology first used to broadcast weather reports to ocean-going vessels in 1901.

In the first-generation cellular networks, also known as *analog* networks, the range of RF signal stretched between eight to ten miles across open air, also known as *free space* (Levitt 2001). With the advent of today's second-generation digital wireless networks, the effective range of signal has been shortened to between two to five miles (Levitt 2001). The reason for the decreased effective range of propagation is due to digital signals operating in the range of 1.9 gigahertz and above on the electromagnetic spectrum. The RF signals emitted by these antennae have shorter wavelengths and cannot travel as far in free space before they begin to fade (measured by *decibel loss*) and they are also much more susceptible to rain and weather conditions that introduce moisture into the surrounding air (Dodd 2002; Faruque 1996). Wireless networks therefore rely on a series of regularly spaced antennae that propagate RF signals in an omni-directional or spherical manner taking into account reflection, refraction, and absorption due to surrounding topography (Weisman 2000). This omni-directional propagation pattern can easily be used to form a covering pattern for the desired geographic area that the wireless provider wants to service. According to Bedell (2001) and Faruque (1996), a set of overlapping circles can be arranged in a hexagonal honeycomb pattern to plan new cell networks. The overlap of the circles allows for the necessary call “handoff”. This allows a call to be relayed to the next antenna seamlessly, without any disturbance in the integrity of the call.

Between 1985 and 2001, the number of cellular towers in the United States increased from almost none to over 120,000 (Wikle 2002). It is predicted that between 122,000 and 250,000 cell sites will be needed and as many as half of these sites will require new towers, especially in suburban and rural areas (Campanelli 1997). The demand for towers is fuelled by the growth of wireless customers. Between 1999 and 2000 alone, wireless subscribers increased by twenty-four million users (Dodd 2002). As wireless service providers expand their coverage areas to add more customers the two most important criteria used to indicate desirable coverage areas include population centers (potential customers) and major transportation corridors (Dayem 1997). Subsequent to the satisfying of these two criteria, remaining “holes” are covered as the demand in rural areas enables the service providers to justify the cost of additional antennae in these areas (Rinebold 2003). As mentioned above, this design is usually a hexagonal honeycomb pattern of interlocking circles. However, this type of covering pattern somewhat differs with respect to the current study as we seek to cover a single transportation corridor and not a general geographical area.

Modeling RF Propagation Using Digital Elevation Models

As soon as the base station antenna emits the RF signals, they begin to be absorbed by everything with which they come into contact, including the air itself by tiny suspended moisture droplets (Weisman 2000). Although some signals may be able to reach a handset and carry a call by way of reflection, the most effective siting of RF antennae will take into account the line-of-sight (LOS) between the location of the antenna and the desired coverage region because these signals have the greatest range when traveling unobstructed through free space (Parsons and Gardiner 1989; Feuerstein and Rappaport 1993). For this reason, terrain data must be as accurate as possible in order to predict free space around an antenna.

Digital elevation models (DEM) form the basis for computing viewsheds and three dimensional terrain modeling using GIS. These digital models consist of a grid of regularly spaced data values that correspond to elevation (above mean sea level) values of the real world terrain. These models are usually generated from USGS analog topographic maps created over the past century using a process that involves deriving height measurements from aerial photographs viewed through a stereoscope. Early in their development, Miller and LaFlamme (1958) described “clearance studies” for microwave systems as a possible application for the new DEM datasets. When conducting viewshed analysis using DEMs, it is important to consider the requirements of the application and choose a post spacing (resolution) that is most suitable. Fujimoto and James (1994) recommend that DEMs derived from USGS topographic maps to predict propagation behavior should use a higher resolution (larger scale) DEM. Lower resolution DEMs made from smaller scale topographic maps can produce incorrect answers when computing free space around a prospective antenna location.

Previous studies have used viewsheds to analyze coverage issues (Goodchild and Lee 1989;

Fisher 1994) and to examine holes in existing cellular networks and the potential insertion of new towers to fill-in these holes (Clark Labs 2004). This study examines the simultaneous location of tower placement from an efficiency perspective. It links not only the viewshed operations of GIS but also polygon overlay and other spatial join functions to solve this location problem within the technology of GIS.

Study Area and Methodology

The study area for this project is the State Route 32 corridor located in the eastern part of the state of Connecticut extending from the northern border of the state near the town of

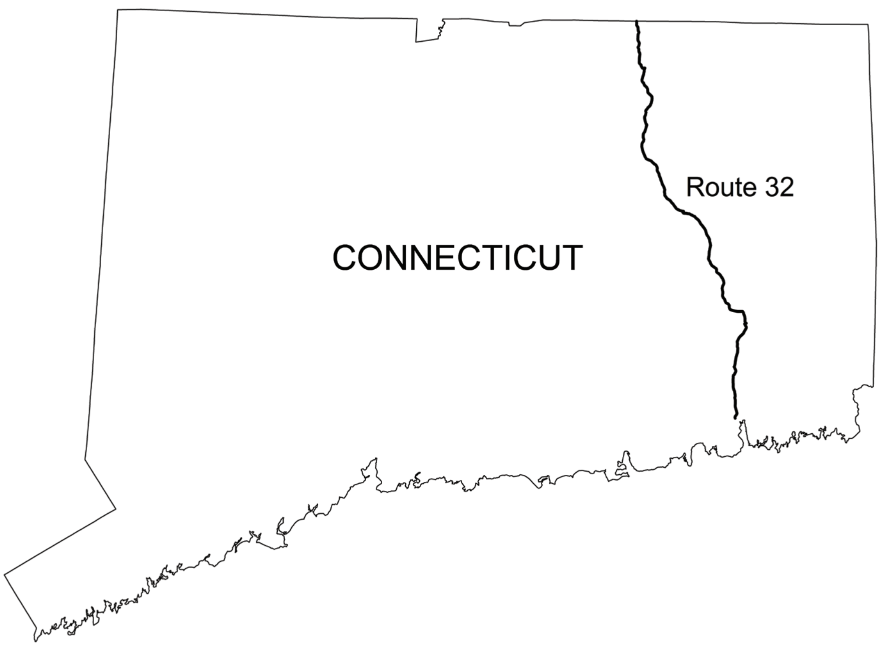

Figure 1. State Route 32 in Eastern Connecticut

Stafford Springs south to the coastal city of New London, where it terminates (Figure 1). The topography of this area can be characterized as rolling hills and low-lying river valleys and contains elevations ranging from a few feet below sea level to more than 1,000 feet above sea level. The road network totals approximately fifty-six miles in length. The spatial extent of study area was defined by buffering Route 32 to a distance of three miles on each side as this represents the

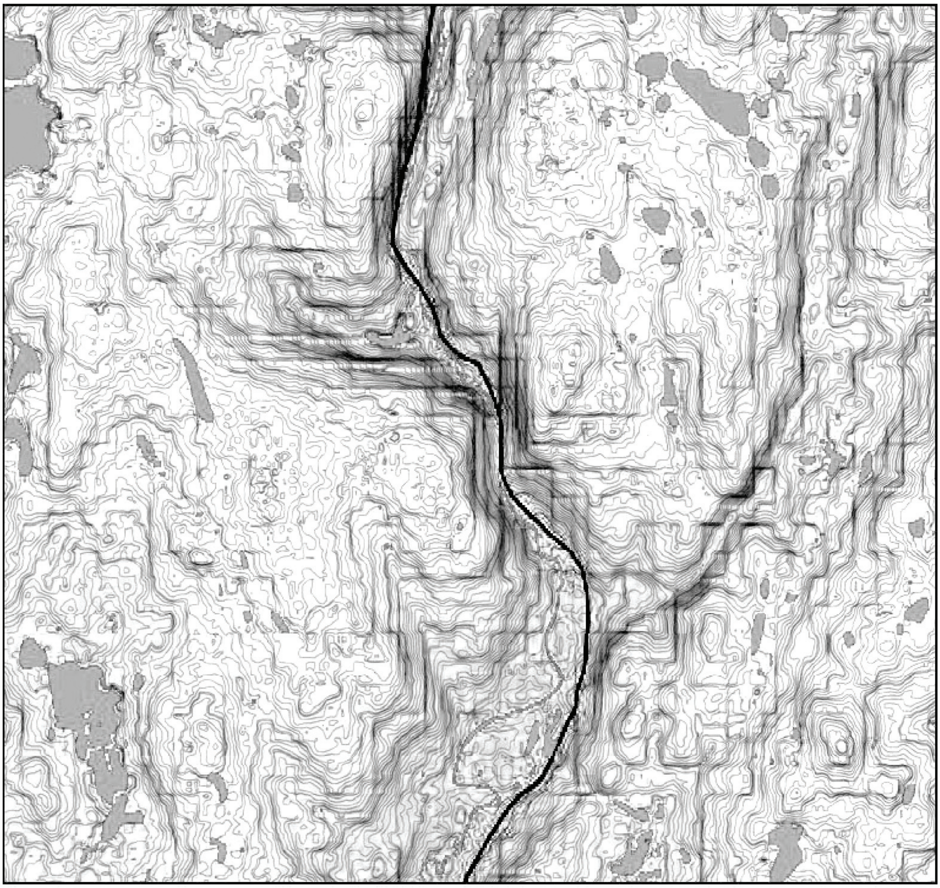

Figure 2. The Path of Route 32 Along the Willimantic River Valley in Mansfield, Connecticut.

effective limits of RF coverage. The Route 32 corridor was selected as a study area for several reasons. It is located in a series of low lying river valleys in the eastern half of the state and in many places it is not currently within the coverage viewshed of any nearby antennae. Figure 2 displays the traverse of Route 32 through the Willimantic River Valley in the town of Mansfield, Connecticut. Travel on this route is prone to holes in cellular phone coverage. Driving the length of the route with a cell phone and GPS receiver, the authors identified five significant gaps in the service area of one provider where emergencies could create safety issues (Figure 3).

The primary data set for this analysis is a DEM acquired from the United States Geological Survey's National Elevation Data (NED) website. This 30-meter resolution data layer was downloaded for the entire eastern half of Connecticut. This raster data layer was then re-projected from global geographic coordinates to the Connecticut State Plane NAD 83 projection mea-

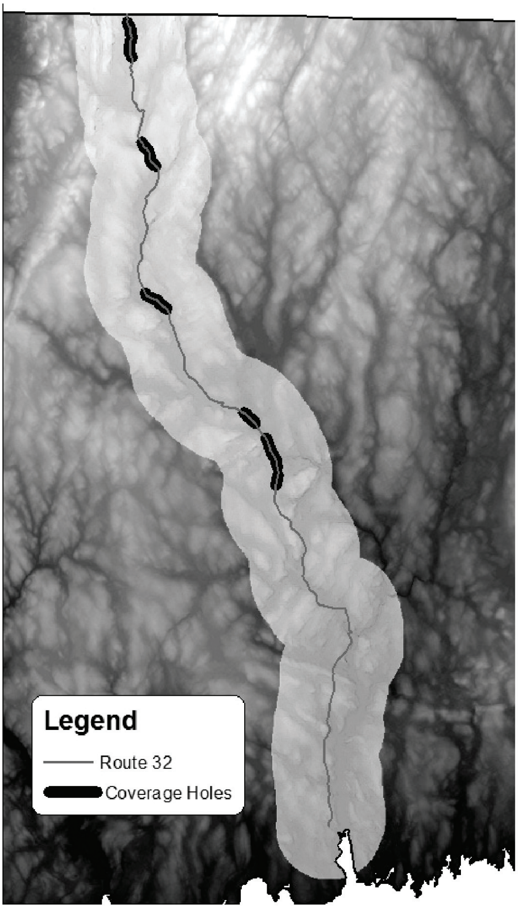

Figure 3. One Company's Existing Coverage Holes along Route 32.

sured in units of feet and all values were converted from meters to feet. This raster DEM dataset was then clipped to the study area. This data layer was then used to calculate the slope of each grid cell as well as a vector contour map of the study area using surface analysis operations within the ArcGIS 9.2 software package (ESRI, 2007). The road network and hydrography for Eastern Connecticut datasets were then downloaded from the Map and Geographic Information Center (MAGIC) at the University of Connecticut and clipped to the study area.

Candidate Site Selection

The determination of candidate sites was a two stage process. The first stage excluded regions within the study area upon which antennae could not be easily built. Due to the problems and cost associated with constructing support towers on terrain whose slope is greater than four degrees (Baker 2003), slopes greater than this steepness were removed from the acceptable region. The existing road network was next buffered to a distance of 40 feet to encompass a region that includes the road surface, surrounding sidewalks, and drainage ravines; these areas also were removed from the acceptable region. Finally, the hydrography layer was used to exclude lakes, rivers, and inland wetlands from the acceptable region.

The second stage selected a finite set of candidate sites from the acceptable region of the study area. Existing antenna locations were not necessarily included in the set of candidate sites. The purpose here is to find the minimal set necessary to provide coverage of the entire route. Existing antenna locations will be evaluated at the end of the analysis to compare against the optimal set of locations. Murray and O'Kelly (2002) have shown that the number of sites necessary to cover geographic features is a function of the number and spacing of candidate sites as well as the representation of geographic space. Because of the importance of terrain in RF coverage,

Figure 4. Locations of Potential Stations Along Route 32.

the spacing of sites will correspond to the frequency of the terrain surface. The most critical locations for identifying a terrain surface are its points of local maxima (hilltops) and minima (valley bottoms). The candidate sites are chosen from the set of local hilltops because these locations have the greatest potential for a local coverage area. The LOS associated with valleys is more likely to be obstructed by intervening slopes than those associated with hilltops and a valley viewshed is more likely to be contained within the viewshed of a neighborhoring hilltop than *vice versa*. Wentz et al. (2001) have devised an algorithm that automates the extraction of high point locations based on the difference in localized elevation values on a raster grid surface. However, given the size of the acceptable region within the study area, it was more convenient to visually identify and record these locations from a derived vector contour map because hilltops are located in the center of the most interior closed contour interval. A total of 200 candidate sites were selected (Figure 4). Although this number is arbitrary, the density of locations along the entire route was relatively uniform.

Specification of Individual RF Coverage Areas

Certain specifications on RF hardware were made in order to arrive at a standard measurement performance in range of signal over free space and to calculate the viewsheds from one standard height above ground, as denoted by the height of the antenna. It was assumed that each antenna was placed at the very top of each support tower and that all antennae were operated in an omni-directional manner. A tower height of 200 feet above ground level was chosen given that the majority of towers being constructed are near this height. The FCC requires that any manmade freestanding structure that has a height greater than 200 feet must also include and continuously operate colored flashing lights in order to alert low flying aircraft of its presence (Rinebold 2003). The 666 existing towers in Connecticut have an average height of 186 feet (Connecticut Siting Council 2003).

Location Model

It has been noted that the traditional approach to coverage planning for cellular networks is the optimal placement of equipment such that the total number of base stations is minimized while maintaining a given quality-of-service level throughout the entire coverage area

(Kamenetsky and Unbehaun 2002). The optimal positions of base stations for cellular networks have been modeled by different mathematical optimization formulations (Mathar and Niessen 2000; Mazzini, Mateus and Smith 2003). For this study, the location set-covering problem (LSCP) is used to determine the minimum number and location of base stations that ensure full highway coverage within a given quality-of-service distance. A generic LSCP is formulated mathematically as the following integer linear program (Toregas et al. 1971):

Minimize: $$\sum_{j \in J} X_j \qquad (1)$$

Subject to: $$\sum_{j \in N_i} X_j \geq 1 \quad \text{for all } i \in P \qquad (2)$$

$$X_j = (0,1) \quad \text{for all } j \in J \qquad (3)$$

Where: X_j is the decision variable to establish a facility at site j or not;

N_i is the set of all potential facility locations that cover the ith demand site;

J is the set of potential facility sites;

P is the set of demand sites.

In this model, the objective function (Equation 1) attempts to minimize the number of open facilities. Equation 2 ensures that each demand site is covered by at least one open facility. Equation 3 states that the decision variable is an integer – a facility is either open (1) or closed (0). For this study, a minimum number of base stations (facilities) must be selected to provide complete coverage to all possible road segments along a given road network (demand sites) within the specified RF signal range of 2.7 miles (critical distance). This critical distance is a conservative estimate of the effective range and could be varied somewhat. If this distance is increased, fewer sites would be located but there would be more uncertainty regarding dropped calls.

In the location-set covering problem, demand is most often represented by points or nodes (see Murray and O'Kelly 2002 for a review of representation issues). Due to the nature of this particular siting problem as it relates to ensuring coverage of a linear highway, the demand space is a line rather than a point. Revelle, Toregas and Falkson (1976) have introduced a modification of the location set-covering problem, known as the arc-covering problem, in which a minimal set of nodes in a network is found that can cover all arcs of the network. However, the approach taken by these authors is not directly applicable to highway coverage by cellular networks. For the base station problem, no facility site is a node of the transportation network and coverage is not a function of time travel but uninterrupted signal distance. The representation issue is how to define the demand elements modeled by rows in the LSCP (Equation 2). Each of these demand segments must be covered by a unique set of potential base station locations.

Defining Demand Segments

The constraint matrix of the location set-covering problem is a zero-one matrix, in which each row identifies a demand element and each column denotes a potential facility site. Each row must have at least one "1" value to ensure coverage of that demand element and each column must have at least one "1" value so that each facility could potentially cover at least one demand element. In addition, each row should have a unique combination of "0" and "1" values; otherwise the two demand elements can be covered by the same set of facility locations (more on these spatial relationships are discussed in the constraint matrix reduction technique section below).

GIS technology can aid in preparing such a constraint matrix for the base station siting problem along a highway (see Church 2002 for an overview of the integration of GIS and facility analysis). The candidate site selection process already has determined that the matrix will have 200 columns. The number of rows depends on the number of demand elements. Two approaches can be used to define the demand elements. One would be to rasterize the highway into a series of pixels. Each highway pixel then defines a row in the constraint matrix. The advantage of this approach is that viewshed analysis is a raster-based function in GIS technology and the demand elements would match the input elements of the process that ultimately determines if a demand element is covered or not. The disadvantage of this approach is that there are a very large number of highway pixels – 3,559. This would require 3,559 constraints in the location set-covering model due to the fact that each highway pixel must be covered. However, each pixel most likely would not have an associated constraint row having a unique combination of zeros and one values.

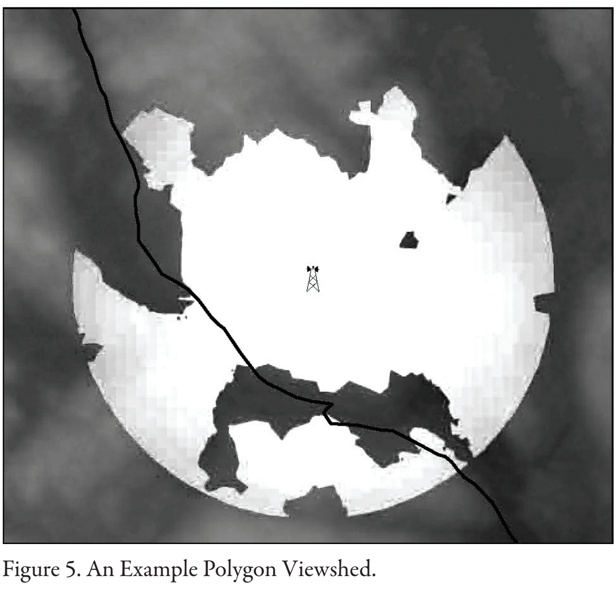

Figure 5. An Example Polygon Viewshed.

The alternative approach, then, is to define the demand highway segments as objects covered by a unique combination of potential facility sites. The constraint matrix of the location set-covering problem is identical to a spatial intersection matrix. In this case it is the intersection of the highways segments and antennae coverage areas. The constraint matrix can be defined by first defining base station coverage areas and then intersecting them with each other and the highway. The raster-based viewshed associated with each candidate was converted into a viewshed polygon (see Figure 5). The viewshed polygon of each potential antenna site is then intersected against a 2.7 mile buffer circle centered on the candidate site; 2.7 miles is given as the effective range for RF signals.

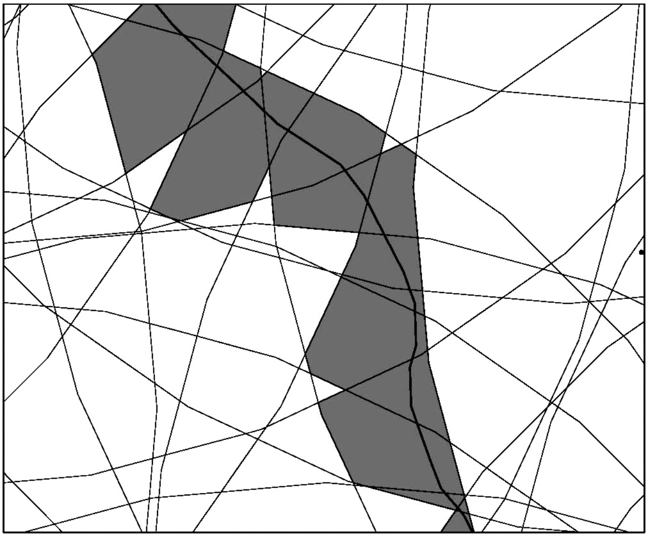

Figure 6. The Unioned Coverage Areas Containing the Highway are in Gray.

Using ArcGIS 9.2, this final coverage area for each candidate site is overlayed against all other coverage areas using the UNION command. For 200 potential base station sites, the UNION command is issued 199 times. The final UNION coverage will contain as geographic objects the geographic areas covered by a unique combination of candidate sites. This last UNION coverage is then overlayed against the highway layer using the INTERSECT command. The INTERSECT command is used because all geographic coverage areas that do not contain a highway segment will be deleted. The highway is covered only if the coverage polygons containing it are covered; covering the other polygons would be redundant (Figure 6). This intersection defines the mutually exclusive and exhaustive demand segments representing the highway.

Constraint Matrix Reduction Techniques

The final INTERSECT layer contains the constraint matrix for the location set-covering problem as part of its attribute table. This matrix however is not necessarily the smallest matrix that can be used to solve the location set-covering problem. Toregas and ReVelle (1973) have identified a series of steps that can eliminate certain columns and/or rows of the matrix. The procedure involves finding any facilities that cover all demand sites covered by another facility. Let $_{aij}$ be the (0,1) coefficient of the ith row and jth column of the matrix. Column k of the matrix is said to dominate column j of the matrix if $a_{ik} \geq a_{ij}$ for all i rows. In this situ-

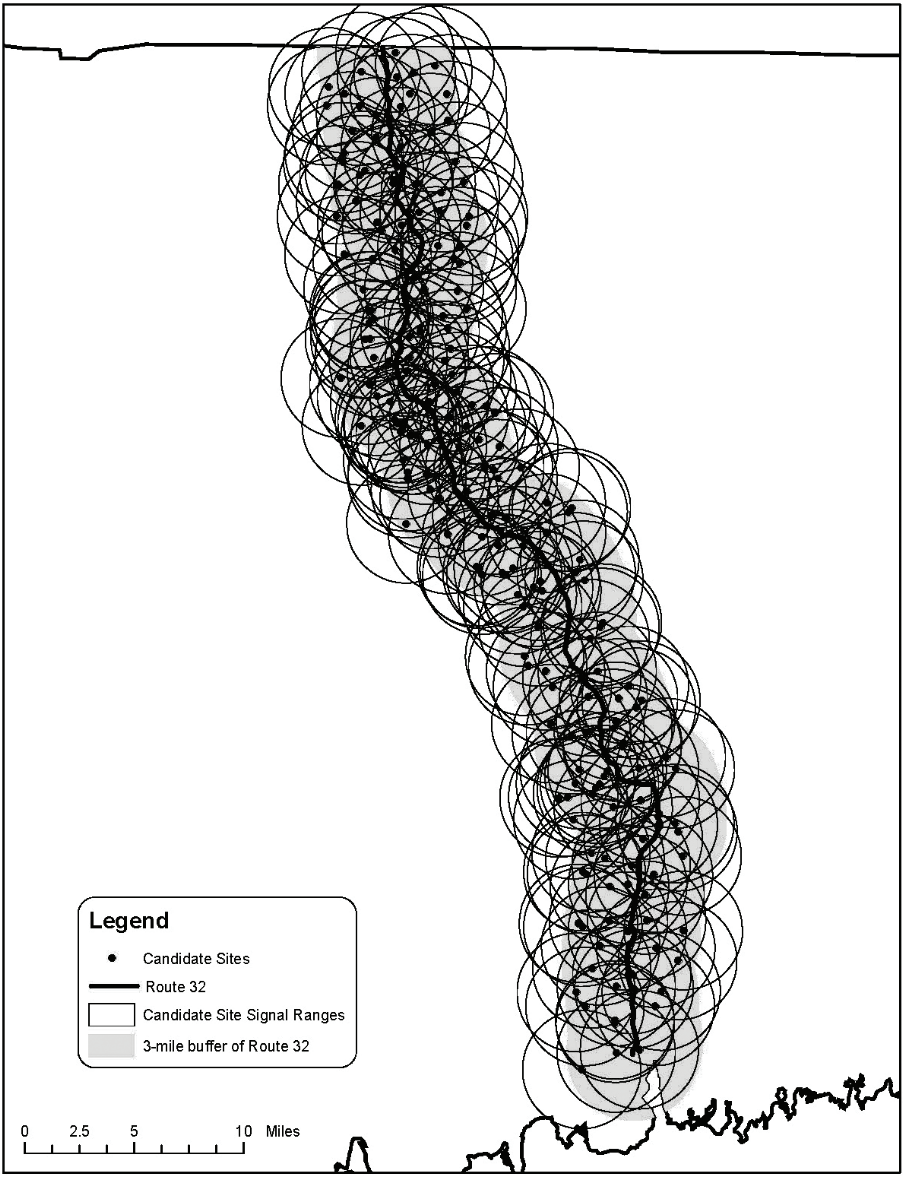

Figure 7. Distribution of Unioned Coverage Areas.

ation the kth facility site covers all of the demand sites covered by the jth facility site and more. The jth facility site can be eliminated from further consideration. This is accomplished by deleting the column of the attribute table that is dominated.

Similarly, row i of the matrix can be eliminated if $a_{ij} \geq a_{kj}$ for all j columns because once row k is covered, row i is also covered. If the raster approach had been used in defining the demand elements, many rows would be eliminated at this point. After a set of columns and row reductions have been performed any column with only zero elements can be eliminated and any column with only a single "1" value can be removed from the spatial matrix and the facility corresponding to that column would be included in the final set of open facilities. In the context of covering a highway, eliminating rows does not mean that segments of the highway are removed. Instead, shorter segments of the highway are dissolved into a longer segment. The details of this process are illustrated in the coverage analysis of State Route 32.

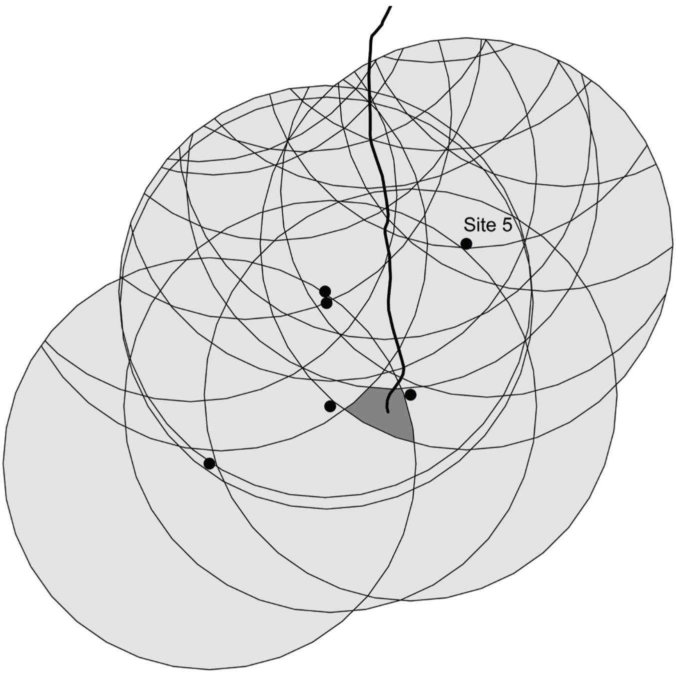

Figure 8. The Dominance of Site 5 in Covering More Coverage Polygons.

Analysis

The construction of viewsheds and their respective intersection with the 2.7 mile effective range buffers, the unioning of the resulting coverages areas, and intersection aginst the State Route 32 highway layer was implemented as an ESRI Automated Macro Language (AML) script in ArcInfo Workstation version 9.0. The GRID module was used to calculate viewsheds in raster format and then convert them to polygon coverages, and the ARC module was used for subsequent buffer, clip, union and intersect operations. The unioning of the 200 clipped viewsheds resulted in 23,262 coverage polygons having 200 coverage attributes (Figure 7). Figure 2 displays

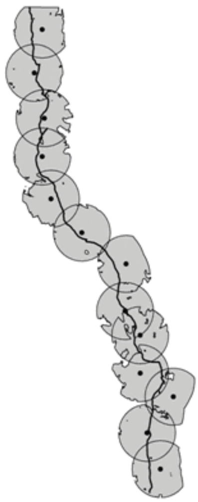

Figure 9. The Distribution of the Thirteen Stations Necessary to Cover Route 32.

the southern portion of the resulting union area. However, after the union coverage was intersected against the layer of State Route 32, the resulting layer contained 1085 demand segments and 200 coverage attributes.

Data reduction techniques were then used to compress the size of the attribute table from a 1085x200 spatial matrix to as small a size as possible. The original intent was to export the reduced attribute table and generate the final LSCP constraint matrix as a data file in SAS compatible format. This file would then have input into a PC version of SAS Operations Research software (SAS/OR, 2003; version 9.1) to determine the number and location of selected sites. However, the data reduction techniques permitted the final selection of sites to be completed entirely within ArcGIS 9.2 (ESRI, 2007). Starting with the first line segment at the lower end of State Route 32, the six towers that covered this line segment and their associated viewsheds were identified (Figure 8). Site 5 dominates the other five tower sites because it covers all of the segments they cover and more. The attribute columns for these five sites were then deactivated. The row associated with the end segment dominates all other segments covered by Site 5 and can be "eliminated". At this point, both the attribute column associated with Site 5 and the row associated with the end segment can also be removed because each has only one "1" value in its column or row. Site 5 is now added to the set of selected sites. This process is accomplished by using a query builder to first highlight all segment features for which the attribute column associated with Site 5 equals a value of zero. These are the segments not covered by Site 5. All of these segments can be converted to a new shapefile in which all segments covered by Site 5 have been eliminated.

The whole procedure is now repeated starting with the lower end segment of this new shapefile. By the end of the entire process, a total of thirteen sites have been identified and their coverage of State Route 32 is presented in Figure 9. This "string" of proposed antenna sites resembles an interlocking chain of somewhat irregular signal coverage areas. These results reveal that when viewsheds are accounted for, the chosen antenna locations are not necessarily the nearest ones to Route 32 because they tend to be located at higher elevations. These thirteen sites represent one optimal solution to the LSCP for full highway coverage. Alternative optimal solutions may exist in any LSCP. The reduction procedure could have started at the other end of the highway and a somewhat different set of sites may have been selected but only thirteen would have been found.

Conclusions

The increasing reliance on cellular networks in emergency situations arising from travel incidences requires a complete coverage of our major transportation arteries by cellular technology. The concern for safety though must always be measured against the cost of implementing such a system. This study has shown how GIS technology can be used to develop an efficient siting of cellular towers in an interlocking system of coverage. Although the focus here has been the site planning of a system in the absence of existing antennae, existing antennae could be easily accommodated in such a siting analysis by first removing lengths of a road already covered by existing base stations. The minimal number of additional new sites necessary to service the uncovered stretches of highway could be analyzed by the same GIS procedures. This study based the criteria for its set of potential locations solely on physical features of the environment without concern for zoning regulations or other social constraints to tower locations. Clearly, the set of potential locations must include these considerations as well. This could be incorporated by discussing the potential sites with community leaders and citizens to find a more refined set of locations before specifying the individual RF coverage areas associated with individual locations.

Finally, the model presented here has only permitted one standard type of equipment associated with any tower. Future research is need to develop a more realistic model that would permit a range of equipment that could have different coverage ranges; more expensive macro cells would cover larger areas than less expensive micro cells allowing for trade-offs between cost and coverage area. Efficiency would be measured in total cost of construction rather than in just the number of locations. As newer technologies are replacing older ones, GIS affords an opportunity examine the spatial implications of these technologies at both a system and local level.

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