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Evaluating Service System Coverage of Wireless Internet Access

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Evaluating Service System Coverage of Wireless Internet Access

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by

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ABSTRACT

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by

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Spatial optimization and facility location models have been structured for a wide variety of applications in order to mimic real world service systems as closely as possible, often with an eye towards maximizing efficiency while reducing costs. Telecommunications is an important aspect of most people's daily lives and figures prominently in access to the Internet through wireless technologies. From a location modeling perspective, wireless access points are a type of facility with several unique characteristics. First, access points provide service coverage that is often three-dimensional in nature, rather than planar. Without obstructions, the service area of an individual access point would be spherical, but obstacles in the form of building materials, furnishings, and vegetation all affect the propagation of signal coverage. Beyond service performance characteristics, there is a range of legacy and technical conditions that must be considered in the design, reconfiguration, and upgrade of wireless services. This paper examines wireless service provision on a university campus. Location coverage models are used to support analysis and planning efforts. Service system evaluation investigates context and technological considerations. The findings suggest that there are varying levels of wireless access facilities across the campus, driven in part by system history and evaluation as well as fragmented decision making processes. Rearrangement provides opportunity for strategically enhancing the system's quality of service.

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INTRODUCTION

A service network, consisting of several facilities interacting with demand (or users), is initially planned and deployed but continues to evolve over time, often with the incremental addition(s) of a new facility. A variety of system types develop in this way, including municipal utilities, social services, transportation infrastructure, production and distribution systems, and telecommunication access. While the locations of facilities in a system are generally selected with an explicit or implicit objective in mind, such as minimizing costs or maximizing response, most systems do not remain static over the long-term. Change occurs through growth in demand for service, regional expansion and contraction, facility deterioration/degradation, technology improvement, etc. During periods of growth or decline, it is rare for an entire system configuration to be reassessed or for existing facilities to be moved or decommissioned.

System efficiency is important in many ways. Often operational costs are among the critical considerations. In times of shrinking budgets and increasing concern for fiscal responsibility in the private and public sectors, operational costs are a primary emphasis because of the potential for oversight and control. One method of reducing the overall cost of a system is through strategic removal of facilities, or facility delocation. The objective for a facility delocation problem might be to close outlets or shrink service while limiting the overall degradation of service (ReVelle et al., 2007). Efforts along these lines have focused on public school utilization and excess capacity (Church & Murray, 1993; Teixeira et al., 2007), closing redundant bank branches after corporate merger/acquisition (Ruiz-Hernández et al., 2015), transit system stop placement (Delmelle, Li, & Murray, 2012; Murray, 2001), minimization of fire station service area overlap (Murray, 2015; Church & Li, 2016), evaluation of Essential Air Service airports (Grubesic et al., 2012) and other important issues. Many of these planning and policy contexts are multiobjective, in which several different considerations are simultaneously taken into account.

Of course, costs are not the only concern – many services are provided in order to address issues of need, equity, access, and accessibility. Nevertheless, system efficiency and fiduciary responsibilities dictate that care be given to issues involving financial commitments, particularly costs and associated benefits. For most service systems, the primary types of costs associated with a facility are fixed and annual. Specifically, land must be purchased or leased, construction or remodeling of one or more facilities undertaken, personnel employed, and equipment and supplies bought and maintained. Thus, the configuration of facilities is important because an inefficient arrangement not only increases both fixed and annual costs but also decreases the quality of service provided. Reconfiguring and rearranging facilities to be more efficient offers a range of benefits, including the flexibility to offer more (or different) services as well as the potential to expand services to a larger area or increase access to services for a greater amount of demand. An efficient configuration could shrink costs by identifying unnecessary facilities and reducing the total number of facilities placed, built, or maintained. This was the case for Essential Air Service airports considered in Grubesic et al. (2012) and fire stations evaluated in Murray (2015). Unplanned or incremental system growth is problematic because it can result in inefficient facility placement when issues of access and accessibility are vital. A challenge therefore is measuring and assessing inefficiency and developing strategic plans to address it.

Wireless telecommunication, and especially Wi-Fi (Wireless Fidelity) connection to the Internet, is a service for which access is critical for most people. Political discussions surrounding net neutrality, the idea that Internet service providers must not discriminate between users, and debates regarding whether the Internet constitutes a basic utility underscore the importance of the provision of this service. Considerations of access to and accessibility of a wireless connection to the Internet have been previously studied with special attention paid to the digital divide. The term digital divide refers to inequities in Internet availability among different segments of the population. Studies have demonstrated the presence of this divide between urban and rural communities and shown that rural and suburban areas may have inadequate service (Grubesic & Murray, 2002, 2004a). Last mile infrastructure refers to the technology by which end users are connected to the Internet. Historically, this connection has been provided by terrestrial, wired forms of connection such as dial-up or DSL service provided through a telephone connection or cable modem in which access is limited by geographic range (Grubesic & Murray, 2004b). Increasingly, the last mile is served by wireless access to the Internet, which eliminates the geographic restriction of usage. Irrespective of the technologies relied upon, wireless access to the Internet is crucial and communities are taking steps to provide and ensure access for all.

This paper discusses the use of spatial analytics, including geographic information systems (GIS), spatial optimization, and location modeling to evaluate an existing service system with respect to service efficiency. This can be achieved by first identifying an efficient and/or ideal service system configuration and then comparing it to the current, existing system. The next section gives a review of related literature. This is followed by the introduction of methods to support this analysis. In particular, location analytics that can be used for modeling wireless oriented service systems are highlighted, but there are also important technical considerations that must be taken into account. The case study setting of wireless access on a university campus is then detailed. Application results are derived and presented, characterizing the current system and offering insights about structure and service. The paper ends with discussion and conclusions.

BACKGROUND

There has been considerable research focused on telecommunication infrastructure in which spatial analytics have been critical for evaluation, management, planning, and decision making. Central to these analyses has been spatial optimization, which includes a range of methods and approaches (Tong & Murray, 2012). Figuring prominently in this research is location analysis and modeling, which is fairly broad and encompassing in scope. An overview of location science can be found in Church and Murray (2009) and Laporte, Nickel, & da Gama (2015), with a range of application studies detailed in Eiselt & Marianov (2015). Of particular interest and importance to wireless access and accessibility is the class of location covering models. The Location Set Covering Problem (LSCP) introduced in Toregas & ReVelle (1972) is foundational, seeking to site the minimum number of facilities necessary to provide coverage to a set of users/demands based upon a service standard. The LSCP has previously been applied in the context of wireless network coverage (Huang & Tseng, 2003; Lee & Murray, 2010). This work has shown that the range of a wireless sensor can be considered a unit-disk or a sphere and can be used to determine the number of wireless sensors needed to cover an area (Huang & Tseng, 2003; Lee, 2015). A wireless network can be designed to connect routers in a way that would maintain network reliability if some facilities are lost (Lee & Murray, 2010). The focus of existing work in this area has generally been on broad regional coverage and has ignored the nuances of Wi-Fi technology encountered across a campus environment.

Another seminal location modeling approach is the Maximal Covering Location Problem (MCLP) detailed in Church & ReVelle (1974). The MCLP recognizes investment constraints which limit the number of facilities that can be sited and seeks to configure a system that covers the most demand possible under such conditions. Grubesic and Murray (2002) explored DSL coverage using the MCLP. Extension of the MCLP to include quality of service issues along with demand coverage was considered in Grubesic et al. (2011). While the above work utilizes coverage models to analyze Internet access through DSL technology, this is landline based and does not address wireless access.

Much research has considered issues of efficiency in existing service systems. Spatial optimization and location modeling have been used to identify redundancy in a variety of contexts, where a facility corresponds to an airport, fire station, and bank branch, among others. The LSCP was used to evaluate total government subsidy provided to regional airports while maintaining service to all tracts, finding that some government subsidized locations could be eliminated without impacting service (Grubesic et al., 2012). The LSCP was also applied to fire station siting in Los Angeles to estimate spatial efficiency (Church & Li, 2016). Multiple instances of service response overlap were identified, often where a city fire station and county fire station operated in close proximity due to political boundaries. A covering model was also applied to bank branches after merger/acquisition to identify unnecessary facilities for an integrated system (Ruiz-Hernández et al., 2015).

Although location models have been applied to support evaluation of efficiency and redundancy in a variety of applications, there have been limited studies of wireless service efficiency. The MCLP was applied to a single university building to determine optimal configuration of access points and identify redundancies in the current configuration (Lee, 2015). However, wireless efficiency studies have not considered a larger study area where mandatory closeness between facilities and demands is expected and is combined with service quality decay based on proximity.

Discussion of wireless access issues has been undertaken by many researchers, primarily focused on geographic implications. Gorman and McIntee (2003) considered the impact of wireless Internet on communities and its ability to connect disparate areas. Torrens (2008) argues that any consideration of Wi-Fi networks must consider geography, outlining a number of concerns, including infrastructure mapping, analysis of coverage, and usage of Wi-Fi. Increasingly, this is tied to the Internet of Things – the concept that connected ‘smart’ devices will reshape the Internet as we conceive of it now (Mehta et al., 2018). The growth of the Internet of Things depends upon the presence of efficient wireless connections to the Internet for transfer of information between non-hardwired devices. Communities are embracing the Internet of Things as they move towards becoming “smart cities” and use sensed data to make efficient regional decisions. On an urban scale, the importance of connected devices means wireless service is more significant than ever and becoming increasingly so.

Because of these region-wide efforts, concerns about differential access to wireless are important. It has been demonstrated that there are differences in Internet coverage between urban and rural areas and that not all areas have sufficient access (see Grubesic & Murray, 2002, 2004a). Additionally, there is a difference in coverage between terrestrial and wireless Internet access (e.g., Gorman & McIntee, 2003). If wireless Internet access is an essential service yet coverage is incomplete, it is important that existing facilities be placed as efficiently as possible. Wireless access points (APs) are unique in that quality of coverage decreases with distance. The further a user is from an access point, the weaker the signal acquired by that user and the slower their data transmission rates. At some maximum service distance, quality of service decreases to a negligible amount. Previous studies have recognized this distance decay impact on service quality (Torrens, 2008; Grubesic et al., 2011). It has also been noted that imperfect spatial information, including inaccurate distance measurements, can result in evaluations of service that are in error (Grubesic & Murray, 2005). Challenges therefore remain in modeling to support evaluation, analysis and planning associated with wireless access and accessibility, particularly in an environment like a university campus.

METHODS

A variety of methods fall under the umbrella of spatial analytics and quantitative geography. Of particular significance to this research are those methods included in the analytical framework summarized in Figure 1. Important categories are geographic information systems (GIS) and spatial optimization. Use of these categories, and others, can be combined for a comprehensive analysis of a problem, enabling various explorations and inquiries. Thus, the overarching theme of the framework is exploratory spatial data analysis (ESDA), which refers to the process of using a range of methods to generate insights into the characteristics of and relationships between spatial data without prior assumptions (Guo, 2017). Systematic evaluation often involves some combination of geographic query, spatial statistics, clustering, and visualization. GIS is the combination of hardware, software, and processes to support creation, management, manipulation, analysis, and display of spatial data (Longley, Goodchild, Maguire, & Rhind, 2015). Although widely used in a variety of fields, it is the implicit attributes of GIS that are often most important in quantitative geography (Murray, 2017). Spatial optimization is the formalization and solution of a problem involving geographic decisions which are subject to some constraining factors (Tong & Murray, 2012). ESDA, GIS, and spatial optimization are often used in combination – GIS to integrate data, ESDA to understand the nature of spatial relationships within the data, and spatial optimization to formalize and evaluate planning problem issues. This integration, therefore, represents a framework for synthesis and systematic study.

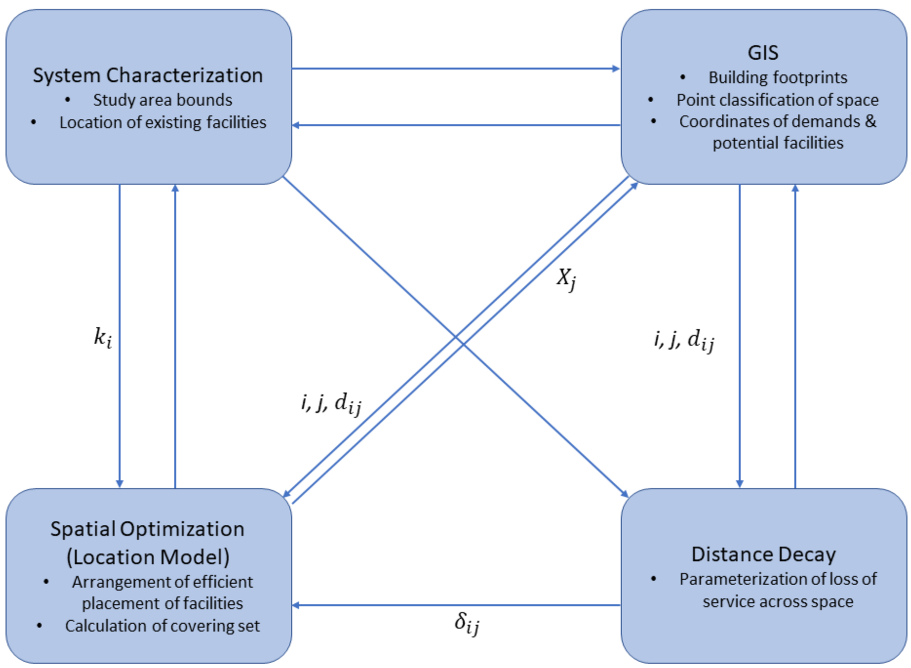

Figure 1: Methodological Framework

System characterization must function as the starting point for understanding the components of the system being studied. Here, system characterization included geographic boundaries of the area and the nature of the facilities in use. The study area is a university campus in which some buildings require service, and some do not; those buildings being served become the spatial extent of the study. Facilities, in this case wireless access points, have specific attributes – how many users they can serve at a time and at what distance. Additionally, there is a set number of facilities currently in the system at specific locations in space. These system components can be displayed and quantified in a GIS. Beyond this, spatial representation issues can be managed, and layers derived, using GIS functions. In this research, point representations of space were created. Demand and potential facilities were points.

Important aspects of wireless access are the range and degradation of service quality. Based on these aspects, service standards could be assessed, derived and evaluated using GIS proximity functionality. In addition, it is possible to approximate performance degradation using a gravity model that incorporates distance decay characteristics. Distance decay, the idea that as the distance between two things increases the interaction between them decreases, is an important component of spatial interactions. Formally, spatial interaction can be stated mathematically following the gravity model (Church & Murray, 2009):

$$\delta_{ij} = \kappa \frac{a_i^{\alpha} a_j^{\beta}}{d_{ij}^{\lambda}} \tag{1}$$

where i and j are two locations and δ_{ij} is the amount or measure of interaction between these locations. This interaction is predicated on a function of distance between the locations. Equation (1) indicates that the gravity approach accounts for this using the inverse distance, with d_{ij} representing the distance between i and j that is parameterized using the exponent λ.

Other elements include inertia weights for each location, a_i and a_j, parameterized using the exponents α and β, respectively. Finally, the interaction amount can be standardized using the parameter κ. Using equation (1), the gravity model, it is possible to account for distance decay behavior contributing to the interaction between two locations. The parameters in the decay function between two locations depend on the specific system and observed performance.

Components from systems characterization, GIS capabilities, and distance decay parameterization all supply inputs to spatial optimization, in this case location models. The coverage requirements per building were derived from the existing system. Demands, potential facilities, and the distances between them were obtained from GIS. Quality of service, based on distance decay, was derived from the parameterization of loss of service across space.

Three location cover models are utilized in this research to evaluate system configuration. Important considerations included the ability to account for facility service range, minimize system costs, and maximize coverage of demand areas. Models discussed below are the LSCP, the Multi-Service Location Set Covering Problem (MS-LSCP), and an extension of the MCLP to impose mandatory closeness. A review and technical details of these and other coverage models can be found in Church and Murray (2018), including original formulation and developed solution approaches. Consider the following notation:

i = demand locations (total number n)

j = potential facilities (total number m)

N_i = set of potential facilities which can provide service to demand i

k_i = number of facilities required to serve demand i

$X_j = \begin{cases} 1 \text{ if facility j is sited} \\ 0 \text{ otherwise} \end{cases}$

The formulation of the MS-LSCP is as follows:

$$Minimize \sum_{j=1}^{m} X_j \tag{2}$$

$$Subject\ to \sum_{j \in N_i} X_j \geq k_i \ \ \forall\, i \tag{3}$$

$$X_j = \{0,1\} \tag{4}$$

The MS-LSCP objective (2) seeks to minimize the total number of facilities required. Constraints (3) require that each demand location must be covered by at least the number of facilities indicated, k_i. This is unique for each demand area i. Constraints (4) force the decision variables to be binary.

The MS-LSCP is a generalization of the LSCP. While the k_i may take on any positive value in the MS-LSCP, the LSCP is defined expressly for the situation where $k_i = 1$ for each demand i. Given this, the structure and formulation of the MS-LSCP means that it can be used to reflect different covering modeling orientations. Irrespective of orientation, the unique characteristic of these two models is that they require each demand in a region to be covered or served at the stipulated level/number of facilities.

While the LSCP and MS-LSCP require all demand to be covered within the standard, the MCLP recognizes that investment may be limited and serving the entire region may be infeasible. Therefore, the MCLP seeks to cover the most demand possible given a constraint on the number of facilities that can be sited. Given that facility service quality begins to decay beyond some distance, particularly for wireless service, we seek to reflect this in the coverage model. In particular, it is important to not only asses suitable access to wireless but also proximity-based service quality. Thus, a coverage model that combines aspects of the LSCP with that of the MCLP along with distance decay considerations is structured. For lack of a better or a more succinct labeling, this model is termed the Multi-Service Maximal Covering Location Problem with Mandatory Closeness and Distance Decay (MS-MCLP-MCDD) in order to account for the various extensions incorporated. Consider the following additional notation:

δ_{ij} = quality of service provided to demand i by facility j

$Z_{ij} = \begin{cases} 1 \text{ if demand } i \text{ is covered by facility j} \\ 0 \text{ otherwise} \end{cases}$

p = number of facilities to site

With this notation, the MS-MCLP-MCDD is as follows:

$$Maximize \sum_{i=1}^{n} \sum_{j=1}^{m} \delta_{ij} Z_{ij} \tag{5}$$

$$Subject\ to \sum_{j=1}^{m} X_j = p \tag{6}$$

$$\sum_{j \in N_i} X_j \geq k_i \;\; \forall\, i \tag{7}$$

$$\sum_{j \in N_i} Z_{ij} \leq 1 \;\; \forall\, i \tag{8}$$

$$Z_{ij} \leq X_j \; \forall i, j \in N_i \tag{9}$$

$$X_j = \{0,1\} \tag{10}$$

$$Z_{ij} = \{0,1\} \tag{11}$$

The objective (5) seeks to maximize the total amount of demand covered. The quality of service that each demand receives by a particular facility is reflected in δ_{ij}, which in this case can range from 0 to 1. Constraint (6) requires that p facilities are sited. Constraints (7) require each demand to be covered by at least k_i facilities. Interestingly, if p is lower than an optimal solution to the corresponding LSCP or MS-LSCP then there will be no feasible solution. Constraints (8) impose that each demand can be assigned to at most one facility. Constraints (9) ensure that demand can only be assigned to a facility which has been sited. Finally, constraints (10) and (11) force the decision variables to be binary.

How these parameters and variables fit into the methodological framework is outlined in Figure 1. The interaction and integration of different methods enables these location models to be structured. Solutions to these models can then be derived using different heuristic or exact approaches. Exact solutions are reported here using a commercial optimization software package. The solutions identified are then used to evaluate an existing system configuration.

CASE STUDY

A university campus is a unique mix of different departments, with individual funding sources, sharing physical space and resources. Most campuses have a cohesive campus wireless Internet system. In Summer 2018, the University of California, Santa Barbara (UCSB) wireless system was overhauled by replacing 982 existing wireless access points with upgraded units. This study was undertaken to assess the efficiency of the configuration of these APs.

UCSB upgraded all APs to units that conform to 802.11ac Wave 2 performance. These APs cost between $500-$700 per unit and unobstructed are expected to provide service of 150 feet in all directions. The age of and materials within a building affect propagation of signal inside buildings, with a worst case of 60 feet propagation distance. These are dualband units and 50 users can generally be hosted on each band. In a classroom setting, where concurrent usage Wi-Fi needs are less extensive, more users can be hosted. Although wireless Internet is a 3-dimensional service, for this study it was assumed that each floor requires its own wireless APs for service because of concrete floors and other materials limiting signal propagation.

Not all buildings on campus are covered by the current system and residence halls are on a separate system. Only those buildings covered by the 982 units being replaced were considered in this study. The footprints of the buildings covered by Wi-Fi at UCSB were extracted from a campus building database. A point abstraction of the building footprints was extracted, resulting in essentially 20 feet between points. The process of selecting distances which serve as a reasonable representation is addressed in the Discussion. This resulted in 7,566 points which were utilized as both the potential facility sites and as the demands to be covered (Figure 2).

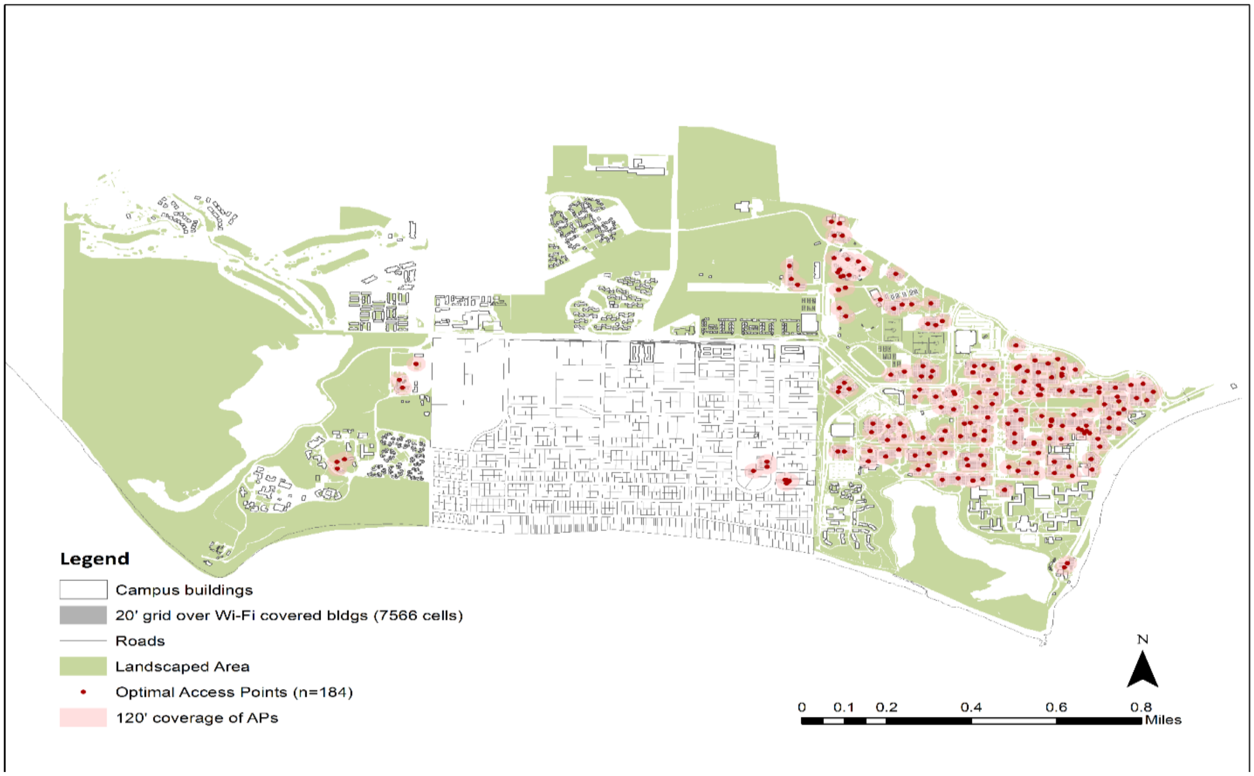

Figure 2: Optimal Wi-Fi configuration on UCSB campus (120 feet service distance)

In addition to the campus-wide analysis, a single building, Ellison Hall, was studied in greater detail. This building represents the general complexity of a university building. Ellison Hall has six floors, the top three with a smaller footprint than the bottom three (Figures 3 & 4). A point representation was extracted for potential facility sites and demand points. A spacing of 2 feet was used, resulting in 7,093 points for the larger floors and 4,107 points for the smaller floors.

The LSCP was solved with the maximum coverage distance standard for facilities of 60, 100, 120, and 150 feet to represent the range of service distances an AP could be expected to provide. The LSCP uses the formulation of the MS-LSCP above with k_i = 1 for all demands. The MS-LSCP was solved to consider classroom seating capacities. This serves as a proxy for a capacity constraint. Rather than limiting the number of demands that can be assigned to an AP, the seating capacity of classrooms was considered to represent an upper limit on the number of demands in that building. Each AP was assumed to serve a maximum of 150 devices in a classroom setting, and the required number of APs was determined based on actual seating capacities. Values of k_i across the campus ranged from 1 to 6. For 83.2% of buildings (n = 84), k_i = 1; for 15.8% (n = 16), k_i = 2; for 14.9% (n = 15), k_i = 3; for <1% (n = 1), k_i = 4; for 2.0% (n = 2), k_i = 5; and for <1% (n = 1), k_i = 6. Ellison Hall has no large capacity classrooms, so the LSCP and MS-LSCP were equivalent in this case. The LSCP identified how many and where in each building APs should be sited under ideal conditions.

The MS-MCLP-MCDD was run to account for the distance decay attribute of wireless service. The rate at which service decays over distance was determined based on published results for 802.11ac Wave 2 units (CISCO, 2014). The approximation of this decay used in the models is given in Figure 5. Quality of service is 1 (100% of possible) if a user is within 30 feet of an AP. Between 30-150 feet, service quality decreases exponentially from 1 to 0.01. At distances greater than 150 feet, service quality is considered negligible. Following the notation of Equation (1), the decay function between 30-150 feet takes the form $\delta_{ij} = 1.7682e^{-d_{ij}/52.63158}$. Models were run for *p* varying from the LSCP minimum (the minimum required for all demand points to have a non-zero level of coverage) until complete coverage of all demand was reached.

For Ellison Hall, the actual placement of the 60 existing APs was determined (to the room number level) and evaluated using a GIS representation of the building (Figure 4). Based on their locations and the maximum service distances considered, the percent of each floor of Ellison Hall covered by the existing APs was derived. The quality of coverage, based on distance decay, was also determined.

RESULTS

The wireless network serving academic buildings at UCSB consists of 982 APs providing service to 105 buildings and areas. The number of floors per building ranges from 1 to 8. The LSCP and MS-LSCP were solved to identify the number of APs required to provide coverage to all of the buildings served by the current configuration. Demand and potential facility points were 20 feet apart, so a building was considered covered if all of the demand points within it were served by a sited facility. Models were solved for service distances of 60, 100, 120, and 150 feet (Table 1). The number of required facilities to cover the ground floor of all buildings currently served by Wi-Fi ranged from 105 (LSCP with 150 feet service distance) to 409 (MS-LSCP with 60 feet service distance). A shorter service distance standard and multiple service requirements result in more facilities needing to be sited. When number of floors per building is considered, MS-LSCP results range from 378 required APs (150 feet service distance) to 1,199 (60 feet service distance). At all service distances, over 99% of the building footprints are covered.

MS-LSCP results were also determined for a single campus building, Ellison Hall (Table 2). Rather than demand points sited every 20 feet, points were spaced 2 feet apart. The number of required facilities per floor ranged from 2-6, which matched the number of sited facilities in this building in the coarser resolution, campus analysis. The total number of selected facilities for the building ranged from a total of 12 (2 per floor at 120 feet service distance) to 26 (6 per floors 1-3, 4 per floors 4-6 at 60 feet service distance). In each of these results over 99.9% of the building footprint is covered.

The actual AP configuration of Ellison Hall consists of 60 units. These 60 APs are not evenly distributed. The 1st floor has 9 APs (Figure 4a), the 2nd floor 29 (Figure 4b), the 3rd and 5th floors 11 (Figure 4c, 4d), and the 4th and 6th floors none. Although the lower three floors have a larger footprint than the upper three, the layout of all floors is very similar – they are dominated by offices with some classrooms and computer labs on the 2nd and 3rd floors. Based on the arrangement of existing APs in Ellison Hall, coverage was calculated for maximum service distances of 60, 100, and 120 feet (Table 3). The percent of uncovered area varies greatly among the different floors and different service distances. The floors with no APs sited have no service from the perspective of each floor as an independent entity. In reality, there is likely service in some areas provided from APs on the floor above or below, but this is beyond the scope of this study. The floors that do have APs range from 79.6-100% covered when a 60 feet service distance is considered and 98.45-100% covered when a 120 feet service distance is used.

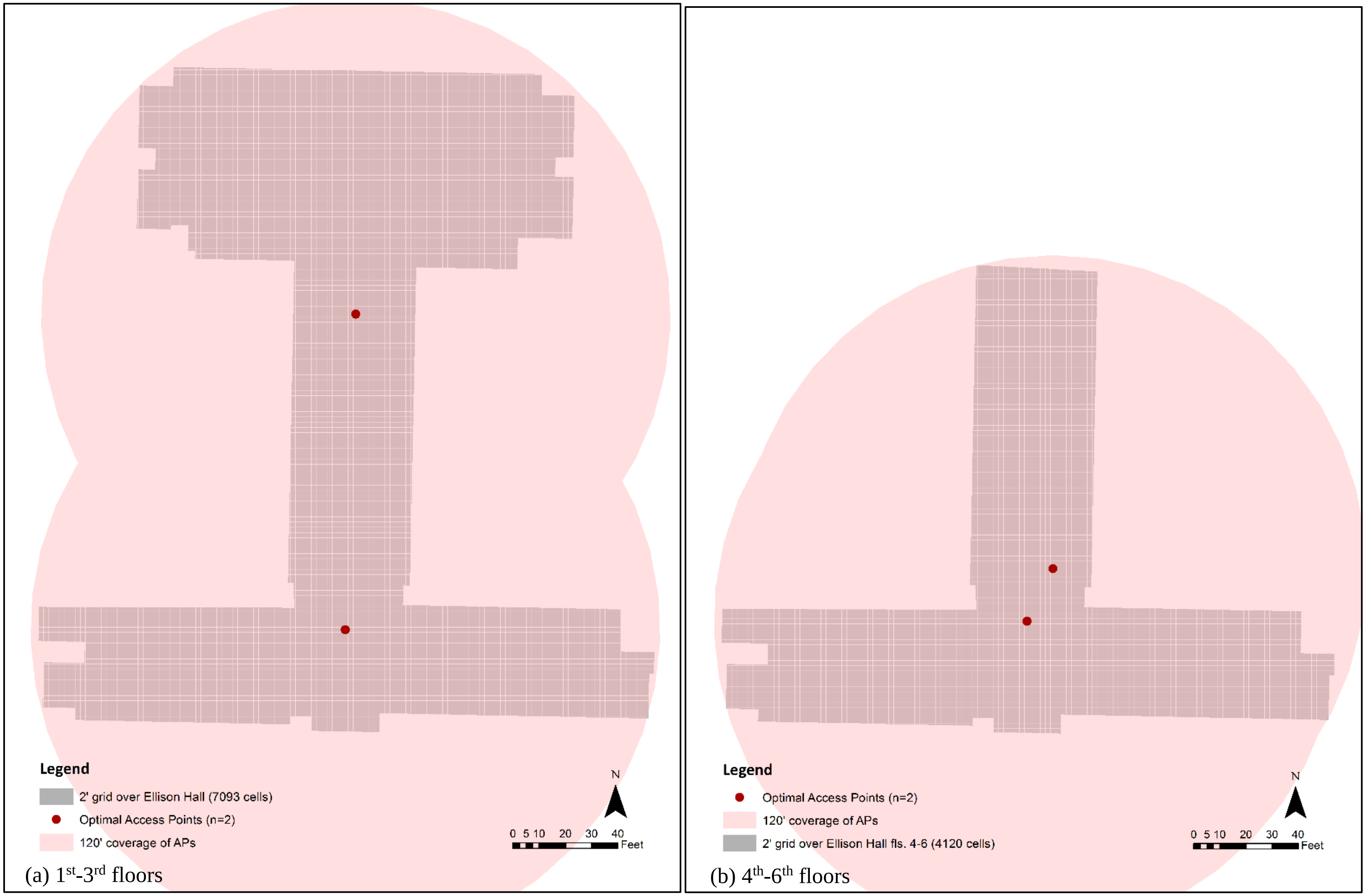

Figure 3: Optimal Wi-Fi configuration in Ellison Hall (120 feet service distance)

Table 1: Application results for coverage of campus (20 feet spacing)

Type of Coverage	# of potential facility points	maximum service distance (feet)	# of selected facilities (to cover ground floor)	# of facilities x # of floors per building	% of building footprints covered
LSCP	7,566	60	396		
LSCP	7,566	100	189		
LSCP	7,566	120	147		
LSCP	7,566	150	105		
MS-LSCP	7,566	60	409	1,199	99.090
MS-LSCP	7,566	100	219	589	99.733
MS-LSCP	7,566	120	184	476	99.794
MS-LSCP	7,566	150	153	378	100.000

Table 2: Application results for coverage of Ellison Hall (2 feet spacing)

Coverage area	# of potential facility points	maximum service distance (feet)	# of selected facilities	# of facilities selected by campus LSCP	% of building footprints covered
Floors 1-3	7,093	60	6	6	99.989
Floors 1-3	7,093	100	3	2	100.000
Floors 1-3	7,093	120	2	2	99.997
Floors 4-6	4,107	60	4	N/A	99.977
Floors 4-6	4,107	100	3	N/A	100.000
Floors 4-6	4,107	120	2	N/A	99.995

Table 3: Coverage of actual AP placement in Ellison Hall

Floor	# of facilities	maximum service distance (feet)	uncovered area (square feet)	% of floor covered (without distance decay)
1st	9	60	5,484.229	79.757
		100	1,587.852	94.139
		120	418.998	98.453
2nd	29	60	0.000	100.000
		100	0.000	100.000
		120	0.000	100.000
3rd	11	60	2,829.124	89.560
		100	82.744	99.695
		120	0.000	100.000
4th	0	60	15,641.079	0.000
		100	15,641.079	0.000
		120	15,641.079	0.000
5th	11	60	0.000	100.000
		100	0.000	100.000
		120	0.000	100.000
6th	0	60	15,641.079	0.000
		100	15,641.079	0.000
		120	15,641.079	0.000

Table 4: MS-MCLP-MCDD results for Ellison Hall coverage

Number of facilities sited (p)	% of demand covered
2	67.900
3	75.530
4	82.755
5	90.134
6	94.518
7	96.701
8	98.046
9	98.834
10	99.351
11	99.678
12	99.828
13	99.958
14	99.985
15	100.000

Table 5: Distance decay coverage of actual AP placement in Ellison Hall

Floor	# of facilities	maximum service distance (feet)	% of floor covered (with distance decay)
1st	9	150	82.424
2nd	29	150	99.478
3rd	11	150	90.127
4th	0	150	0.000
5th	11	150	99.759
6th	0	150	0.000

Figure 4: Actual Wi-Fi configurations in Ellison Hall

The MS-MCLP-MCDD model, with the objective of maximizing demand covered while integrating distance decay was solved for the larger area, lower floors of Ellison Hall. For this model, the maximum service distance was set at 150 feet and demand points were at 5 feet intervals (1,092 points per floor). The number of facilities to be sited, *p*, ranged from 2, the minimum required for all demand to be covered at some level of service, to 15, the minimum required for all demand to be covered at 100% service (Table 4, Figure 6). 5 APs are required for >90% demand covered, and 10 APs are required for >99% demand covered.

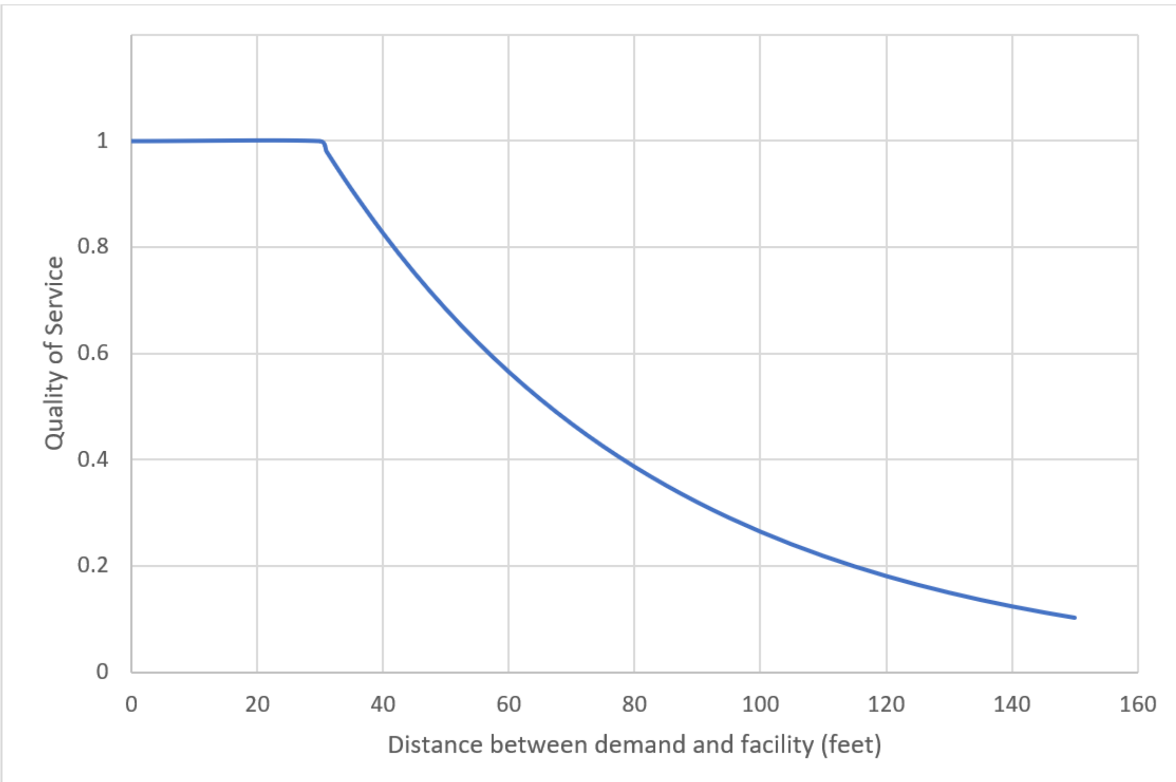

Figure 5: Distance decay function for Wi-Fi APs

The service coverage based on existing APs was derived (Table 5). The 1st floor has 9 APs sited. In an optimal configuration these could be arranged to cover 98.8% of demand points. The actual configuration results in 82.4% of demand covered, which is 16.6% below optimal. The 3^{rd} floor has 11 APs configured to cover 90.1% of demand, when 11 APs could be arranged to cover 99.7% of demand. This is a gap of 9.6% below optimal. The 2^{nd} floor has 29 APs sited which cover 99.5% of demand. These could be arranged to easily cover 100% of demand.

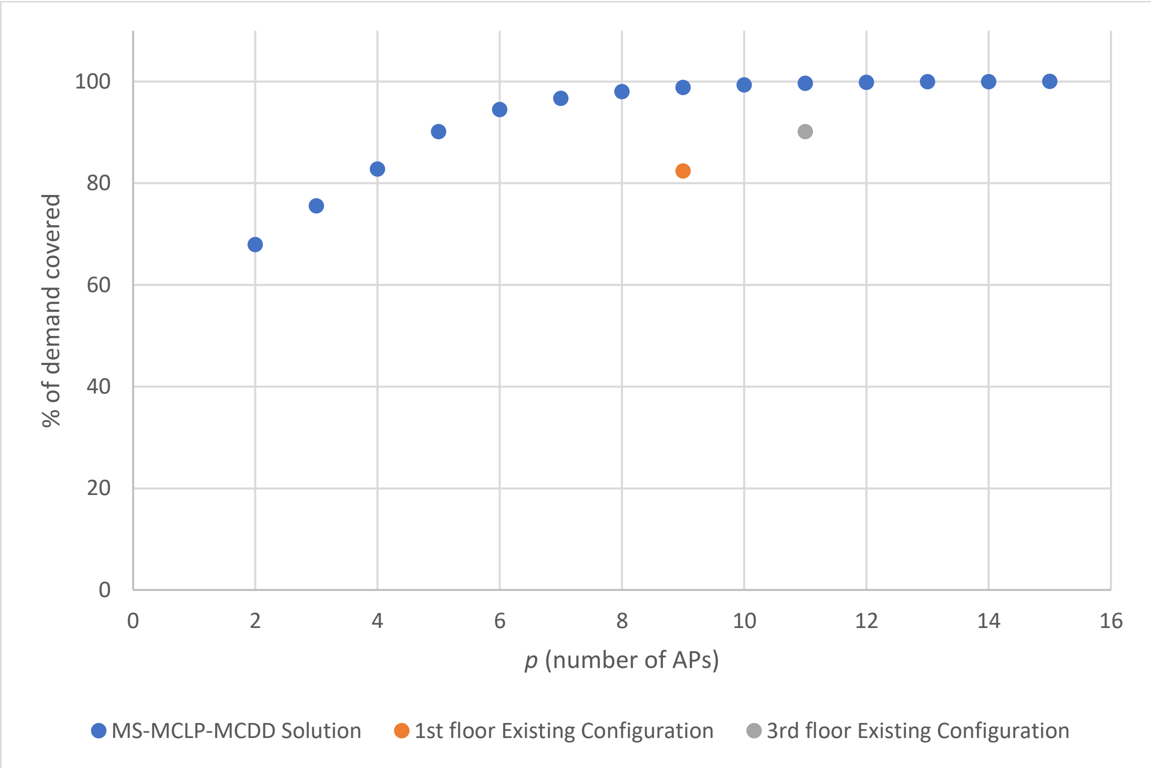

Figure 6: MS-MCLP-MCDD and existing configuration coverage solutions

DISCUSSION

Spatial Representation

In this study a point representation was used to approximate what is actually a continuous space problem. In reality, demand for wireless coverage exists across space and facilities could be placed anywhere. The representation of demand and facilities as discrete points is an approximation adopted due to the complexity of solving a continuous space problem.

An MS-LSCP equivalent model specification based on continuous space can be derived. This is denoted here as the Multi-Service Continuous Space Set Coverage Problem (MS-CSSCP), extending the formulations of Murray & Wei (2013), Wei & Murray (2016), Church & Murray (2018), and Murray (2018). Consider the following additional/modified notation:

Φ = demand region

i = index of demand sub-areas in region

Δ = set of sited facilities

j = index of sited facilities

$f_i(\Delta)$ = demand coverage function for area i based on sited facilities Δ

k_i = coverage required to serve demand i

γ_i = area of demand i

The formulation of the MS-CSSCP is as follows:

$$Minimize\ |\Delta| \tag{13}$$

$$Subject\ to\ \iint f_i(\Delta)d\Phi = k_i\,\gamma_i \quad \forall\, i \tag{14}$$

$$(\varphi_j, \gamma_j) \in\ \Phi \quad \forall\, i \tag{15}$$

The MS-CSSCP objective (13) seeks to minimize the total number of facilities required. Constraints (14) indicate that each demand sub-area must be covered by the system of service facilities at the level required, k_i. Demand coverage is measured by function $f_i(\quad)$ for each sub-area, where the set of facilities Δ and their locations dictates what coverage is possible. Constraints (15) require that the sited facilities be within the demand region.

The MS-CSSCP is provided as an example of a continuous space model for the problem under consideration. A continuous space model could also be formulated for the MS-MCLP-MCDD. In considering continuous space, demand may exist everywhere and facilities can be sited anywhere, so there are infinite locations to consider. Thus, continuous space models along these lines are highly non-linear and may be impossible to solve exactly (Wei & Murray, 2015). For these reasons, a point representation of space was used in this study.

Computational Capabilities

The computational complexity of associated spatial optimization problems encountered in this research has limited the extent of what is possible for some aspects of this analysis. As discussed above, a point representation was used due to the complexity of continuous space siting (and coverage). An additional, and related, concern is the spacing of demand points. Such representational issues have been of particular interest in research (see Murray, 2005; Murray & O'Kelly, 2002; Murray, O'Kelly, & Church, 2008), with implications for the so called modifiable areal unit problem (Murray, 2018). Placing point representations of demand nearer one another more closely approximates continuous coverage but results in a greater number of points. This increases problem size, and generally makes it more complex to solve. For example, with points spaced approximately 20 feet apart, one floor of Ellison Hall is represented by 105 points. If spacing is reduced to 10 feet, 343 points represent one floor. At 5 feet spacing, 1,092 points, and at 2 feet spacing, 7,093 points. At 5 feet spacing, the MS-MCLP-MCDD took between 333.297 ($p = 3$) and 1,228.26 ($p = 14$) seconds to solve. The MS-MCLP-MCDD was attempted for the 2 feet spacing representation; after more than a week no solution was produced, and model solution was halted.

The consistency of results, in terms of number of facilities sited using the MS-LSCP, for the range of representation spanning 20 feet and 2 feet spacing suggests that both resolutions are appropriate. The MS-MCLP-MCDD is more computationally complex to solve than the LSCP, so, as noted above, it was necessary to use 5 feet point representation rather than 2 feet to solve the MS-MCLP-MCDD for evaluating Ellison Hall. This reduction in the number of demands and potential facilities, from 7,093 for 2 feet to 1,092 for 5 feet, enabled the MS-MCLP-MCDD to be solved.

Service Considerations

There are additional considerations in providing wireless access that have not been considered in this study. First, wireless access is indeed a 3-dimensional service, as noted in Lee (2015). There will be some bleed-through of service from an AP to the floors above and below. Additionally, building materials make a big difference in propagation of service. Each building could be considered separately, and the best service distance could be selected for each. Lastly, demand to be covered was represented as points in this study and thus represents a lower bound on the number of APs needed to fully cover a continuous space (see Murray and Wei, 2013). The actual coverage was examined using GIS, with results greater than 99% of actual area covered for each configuration, but there are still some gaps for which an alternative efficient solution might be appealing and useful.

System Legacy & Evolution

Examining the service provided by the actual distribution of APs across UCSB, and for Ellison Hall in specific detail, demonstrates that a system which evolves can result in significant inefficiency. The 60 APs in Ellison Hall could be rearranged to provide service quality above 99% to the entire building, but the current suboptimal arrangement has resulted in significant gaps in service.

Considering the MS-LSCP with a maximum service distance of 60 feet, 36 APs would be required to serve the building's 6 floors. With this model, each floor would need either 4 or 6 APs, so the existing units could easily be rearranged to provide this higher service standard. The results of the distance decay MS-MCLP-MCDD suggest similar efficiency gains. Even the floor with the fewest number of APs (9) has enough facilities to provide service to 98.8% of the footprint if the APs were rearranged into a more efficient configuration.

Such inefficient configurations are likely a byproduct of previous policies regarding placement of APs and of replacement of outdated technologies. The building currently houses three departments; most floors are now solely occupied by one department, but several are shared. The departments housed in this building and the rooms they occupy have changed over the years. Previously, there were many departments on each floor and departments had to pay the university to have wireless Internet infrastructure added for departmental usage. Although this financial requirement is no longer in place, the current policy replaces already established APs. Such a policy has resulted in patchy Wi-Fi coverage across campus and within certain buildings. This also helps explain why some floors in the building have no APs while some have 29, as an example.

UCSB's policy to replace APs where they are has also extended across technological advances. As Wi-Fi technology has improved, APs have been able to serve more users in a larger area. For previous generations of APs, 29 units on the 2nd floor of the building may have been appropriate for either service distance or amount of use reasons. As technology has improved, the location of facilities has not been reevaluated and altered, which has resulted in the observed redundancy and inefficiency reflected in the current service system.

CONCLUSIONS

The wireless Internet example is just one in a suite of systems which take form in a similar way. Although there is upfront planning, after a system is initialized there is often little reanalysis and existing facilities are left as they are. Wi-Fi access points are a type of facility that is easy to move to a different location, making it potentially amenable to systematic reevaluation. Of course, infrastructure and security needs may limit this to some degree, but the point is that incremental change without considering broader system performance is problematic.

As demonstrated by this study, computation challenges exist in applied work and models must be formulated to address these issues. The methods in this study can be applied to a variety of services to assess the efficiency of an existing system and design strategies for improvement.

Once efficiency has been measured, the next step would be to plan to improve the system. The modeled solution can be used as a performance bound and costs can be considered to determine how to move the existing system in the direction of the modeled solution. An important consideration will be balancing the cost of improving the system with benefits gained.

REFERENCES

Church, R. L., & Li, W. (2016). Estimating spatial efficiency using cyber search, GIS, and spatial optimization: a case study of fire service deployment in Los Angeles County. *International Journal of Geographical Information Science*, *30*(3), 535–553.

Church, R. L., & Murray, A. (2018). *Location Covering Models*. Berlin: Springer.

Church, R. L., & Murray, A. T. (1993). *Modeling School Utilization and Consolidation*. *119*(1), 23–38.

Church, R. L., & Murray, A. T. (2009). *Business Site Selection, Location Analysis and GIS*. New York: Wiley.

Church, R., & ReVelle, C. (1974). The maximal covering location problem. *Papers of the Regional Science Association*.

CISCO. (2014). 802.11ac: The Fifth Generation of Wi-Fi. *Cisco Public Information*, 1–25.

Delmelle, E. M., Li, S., & Murray, A. T. (2012). Identifying bus stop redundancy: A gis-based spatial optimization approach. *Computers, Environment and Urban Systems*, *36*(5), 445–455.

Eiselt, H. A., & Marianov, V (Eds.). (2015). *Applications of Location Analysis.* Berlin: Springer.

Gorman, S. P., & McIntee, A. (2003). Tethered connectivity? The spatial distribution of wireless infrastructure. *Environment and Planning A*, *35*(7), 1157–1171.

Grubesic, T. H., Matisziw, T. C., & Murray, A. T. (2011). Market coverage and service quality in digital subscriber lines infrastructure planning. *International Regional Science Review*, *34*(3), 368–390.

Grubesic, T. H., Matisziw, T. C., & Murray, A. T. (2012). Assessing geographic coverage of the essential air service program. *Socio-Economic Planning Sciences*, *46*(2), 124–135.

Grubesic, T. H., & Murray, A. T. (2002). Constructing the divide: Spatial disparities in broadband access. *Papers in Regional Science*, *81*(2), 197–221.

Grubesic, T. H., & Murray, A. T. (2004a). Waiting for Broadband : Local Competition and the Spatial Distribution of Advanced. *Growth and Change*, *35*(2), 139–165.

Grubesic, T. H., & Murray, A. T. (2004b). "Where" matters: Location and Wi-Fi access. *Journal of Urban Technology*, *11*(1), 1–28.

Grubesic, T. H., & Murray, A. T. (2005). Geographies of imperfection in telecommunication analysis. *Telecommunications Policy*, *29*(1), 69–94.

Guo, D. (2017). Exploratory Spatial Data Analysis. In D. Richardson, N. Castree, M. F. Goodchild, A. Kobayashi, W. Liu & R. A. Marston (Eds.). *International Encyclopedia of Geography: People, the Earth, Environment and Technology*, New York:Wiley.

Huang, C.-F., & Tseng, Y.-C. (2003). The coverage problem in a wireless sensor network. *Proceedings of the 2nd ACM International Conference on Wireless Sensor Networks and Applications - WSNA '03*.

Laporte, G., Nickel, S., & da Gama, F. S. (Eds.). (2015). *Location Science*. Berlin: Springer.

Lee, G. (2015). 3D coverage location modeling of Wi-Fi access point placement in indoor environment. *Computers, Environment and Urban Systems*, *54*, 326–335.

Lee, G., & Murray, A. T. (2010). Maximal covering with network survivability requirements in wireless mesh networks. *Computers, Environment and Urban Systems*.

Longley, P., Goodchild, M., Maguire, D., & Rhind, D. (2015). *Geographic Information Science and Systems*. New York: Wiley.

Mehta, R., Sahni, J., & Khanna, K. (2018). Internet of Things: Vision, Applications and Challenges. *Procedia Computer Science*, *132*, 1263–1269.

Murray, A. T. (2001). Strategic analysis of public transport coverage. *Socio-Economic Planning Sciences*, *35*(3), 175–188.

Murray, A. T. (2005). Geography in coverage modeling: Exploiting spatial structure to address complementary partial service of areas. *Annals of the Association of American Geographers*.

Murray, A. T. (2015). Fire Station Siting. In H. A. Eiselt & V. Marianov (Eds.). *Applications of Location Analysis* (pp. 293-306), Switerland:Springer.

Murray, A. T. (2017). Regional analytics. *Annals of Regional Science*, *59*(1), 1–13.

Murray, A. T. (2018). Evolving Location Analytics for Service Coverage Modeling. *Geographical Analysis*.

Murray, A. T., & O'Kelly, M. E. (2002). Assessing representation error in point-based coverage modeling. *Journal of Geographical Systems*.

Murray, A. T., O'Kelly, M. E., & Church, R. L. (2008). Regional service coverage modeling. *Computers and Operations Research*.

Murray, A. T., & Wei, R. (2013). A computational approach for eliminating error in the solution of the location set covering problem. *European Journal of Operational Research*.

ReVelle, C., Murray, A. T., & Serra, D. (2007). Location models for ceding market share and shrinking services. *Omega*, *35*(5), 533–540.

Ruiz-Hernández, D., Delgado-Gómez, D., & López-Pascual, J. (2015). Restructuring bank networks after mergers and acquisitions: A capacitated delocation model for closing and resizing branches. *Computers and Operations Research*, *62*, 316–324.

Teixeira, J., Antunes, A., & Peeters, D. (2007). An optimization-based study on the redeployment of a secondary school network. *Environment and Planning B: Planning and Design*, *34*(2), 296–315.

Tong, D., & Murray, A. T. (2012). Spatial Optimization in Geography. *Annals of the Association of American Geographers*.

Toregas, C., & ReVelle, C. (1972). Optimal location under time or distance constraints. *Papers in Regional Science*.

Torrens, P. M. (2008). Wi-Fi geographies. *Annals of the Association of American*

Geographers, *98*(1), 59–84.

Wei, R., & Murray, A. T. (2015). Continuous space maximal coverage: Insights, advances and challenges. *Computers and Operations Research*, *62*, 325–336.

Wei, R., & Murray, A.T. (2016). A parallel algorithm for coverage optimization on multi-core architectures. *International Journal of Geographical Information Science, 30:*3, 432-450.