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Market Coverage and Service Quality in Digital Subscriber Lines Infrastructure Planning

Tony H. Grubescic¹, Timothy C. Matisziw², and
Alan T. Murray³

Abstract

Digital subscriber lines (xDSL) belong to a family of technologies that provide the ability to transmit digital data over local telephone (copper) infrastructure. As the second most popular broadband platform in the United States, it is estimated that over twenty-five million xDSL lines are in service, capturing nearly 30 percent of the U.S. broadband market. While the service range of xDSL is somewhat limited, often extending to a maximum of 18,000 feet from a central office (CO), available bandwidth also decays as distance increases from the CO. As a result, there are often marked disparities in the quality of xDSL service within market areas. This article proposes a bi-objective location model for maximizing both service coverage and quality of coverage in siting digital subscriber line access multiplexers (DSLAMs). An application of the developed model highlights important implications for telecommunication policy.

¹ College of Information Science and Technology, Drexel University, Philadelphia, PA, USA

² Department of Geography and Department of Civil & Environmental Engineering, University of Missouri–Columbia, Columbia, MO, USA

³ GeoDa Center for Geospatial Analysis and Computation, School of Geographical Sciences & Urban Planning, Arizona State University, Tempe, AZ, USA

Corresponding Author:

Tony H. Grubescic, College of Information Science and Technology, Drexel University, Philadelphia, PA 19104, USA

Email: grubescic@drexel.edu

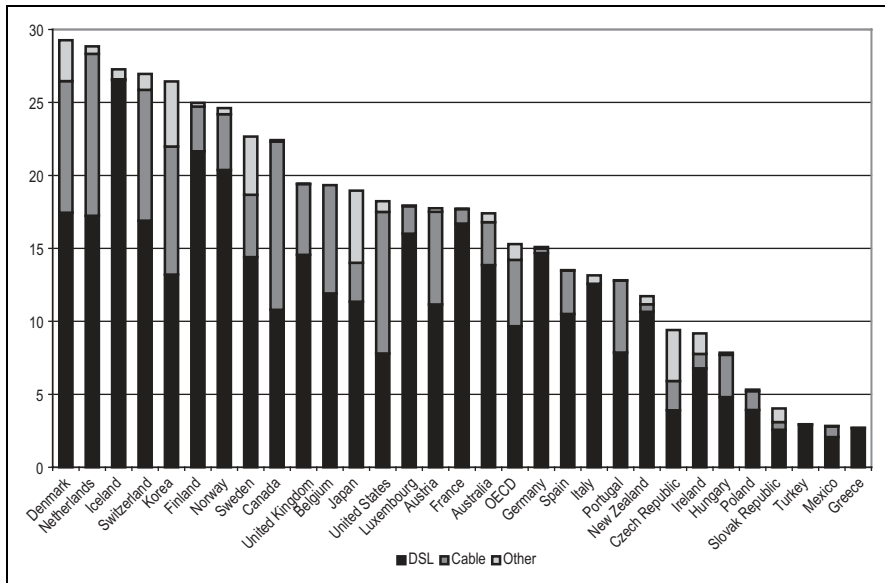


Figure 1. Broadband access by platform per 100 inhabitants (June, 2006).

Source: Organisation for Economic Co-operation and Development (OECD) 2007.

Keywords

location modeling, broadband, GIScience, digital subscriber lines, quality of service

Introduction

Residential broadband platforms are available from an array of technologies. Fijnvandraat and Bouwman (2006) classify these transmission technologies into fixed and wireless local loop options. The fixed loop generally consists of copper, coaxial, or optical fiber-based platforms. This includes digital subscriber lines (xDSL), cable, and fiber access technologies. The wireless local loop consists of wireless fidelity (Wi-Fi) and Wi-MAX, local multipoint distribution systems, free space optics, and those based on mobile telephone networks (e.g., high-speed packet access and universal mobile telecommunications systems) among several others.¹ While wireless broadband platforms continue to grow in popularity (Lehr and McKnight 2003), the vast majority of existing residential access networks in developed countries are fixed loop copper and coaxial technologies. Interestingly, while xDSL is the dominant platform in much of Europe, cable is the leading broadband technology in the United States and Canada (Figure 1).

Variations in platform dominance between Europe and North America reflect a complicated mix of national regulatory policy, supply- and demand-side

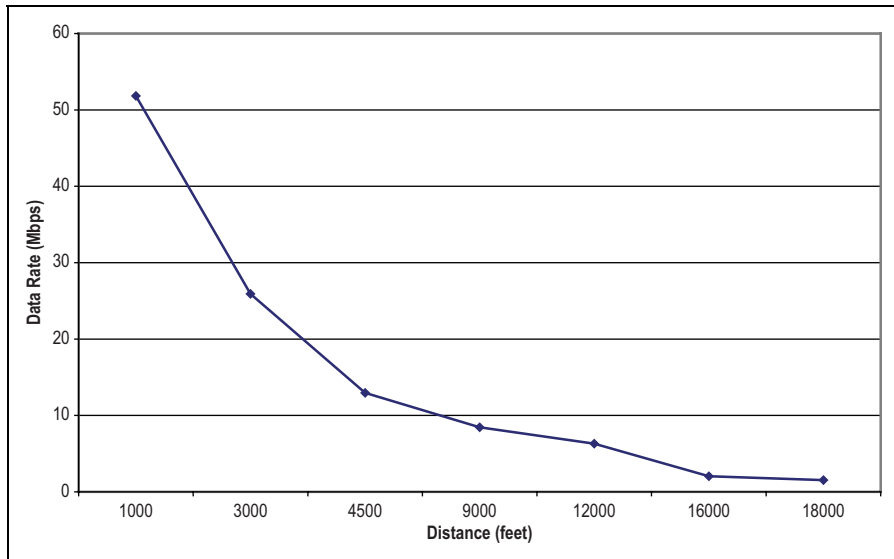


Figure 2. xDSL Capacity as a function of cable length.

Source: McAdams et al. (2000); Parker (2000); Cai (2002).

determinants, and competition. For example, cable broadband in Germany is virtually nonexistent. With a complex ownership structure, cable networks have not upgraded their systems to handle data transmission because the existing regulatory framework in Germany will not allow for an equitable split of investment costs among cooperating network operators (Stobbe 2005). In addition to regulatory barriers, there are several more subtle technological and geographical limitations associated with the provision of broadband services, particularly where xDSL is concerned. For example, one problem with digital subscriber line technology is its limited geographic range of service. xDSL is generally *unavailable* to households that are beyond 18,000 ft. of a CO (Abe 2000).^{2,3} More importantly, the quality of xDSL service and bandwidth availability varies within each local loop. Because twisted-pair copper attenuates signals proportional to wire length and frequency (Reeve 1995), the bandwidth (or data rate) associated with xDSL decays as loop length increases. Figure 2 highlights the marked disparities in bandwidth availability and associated local loop length for standard, 24-gauge twisted-pair copper wires. Because distance between customers and the CO is one determinant of quality of service (QOS), DSL service is often marketed according to various levels of minimum bandwidth availability (Verizon 2008), but this is not necessarily the case in many markets.

From a policy perspective, this variability in QOS associated with xDSL is problematic for several reasons. First, it suggests an inequitable distribution of broadband benefits. While households located closer to COs are able to obtain

higher service quality and broadband performance, those located farther away can experience poorer QOS and diminished download speeds. Although the recent literature on broadband accessibility and provision suggests that the digital divide is closing in the United States (Grubestic 2008a), the quality of one's experience "online," both in terms of speed and stability, dictates the types of activities in which the user can engage. In this context, Internet applications with higher bandwidth demands (e.g., streaming video) can be limited for xDSL subscribers located on the periphery of their wire-center service area. Second, it is likely that residential subscribers are paying identical subscription fees for xDSL service, regardless of location or performance, unless some type of differentiated service program is in place. Finally, outside of the policy context, broadband providers have a vested interest in maximizing their return on investment. The cost of upgrading a CO in order to provide xDSL can be substantial. For example, the Cisco 6160 IP DSL switch retails for approximately \$7,000 and has the capacity to serve 256 subscribers. If more capacity is needed, additional ports can be added or configurations may be subtended (Cisco 2008). Upgrading all COs in a region may therefore not be immediately possible, given budgetary limitations for network improvement. As a result, when evaluating markets for broadband provision, an important planning goal is to site available digital subscriber line access multiplexers (DSLAMs) so that potential subscriber access to xDSL service is maximized. However, because the spatial distribution of potential subscribers in most areas is heterogeneous, approaches are needed to determine which COs offer the best potential return on investment. More importantly, the ability to simultaneously maximize potential subscriber coverage and service quality (i.e., bandwidth) is a sensible strategic goal for broadband providers. Not only does this increase the likelihood of expanding subscription revenues, it also increases customer satisfaction, loyalty, and retention (Gerpott, Rams, and Schindler 2001).

The purpose of this article is to study the trade-offs between xDSL coverage and service quality in siting DSLAMs. A bi-objective location model is proposed to facilitate analysis of these trade-offs and to help in the prioritization of DSLAM siting. In addition, an application of the developed model highlights important implications for telecommunication policy. This type of analysis is important for two reasons. As mentioned previously, companies are seeking to maximize their return on investment when providing broadband services. Considering that the cost of upgrading COs for xDSL service can be significant, particularly if competitive local exchange carriers are forced to install DSLAMs and lease lines from the incumbent local exchange carriers, determining the optimal spatial configuration of markets served is essential to profitability. Second, understanding how service quality may vary within markets is not only critical for the provider during the planning process but also for local, state, or federal agencies concerned with an equitable distribution of broadband access and bandwidth availability (e.g., the Federal Communications Commission).

The remainder of this article is organized as follows. The second section provides an overview of methodologies for examining coverage and service quality in

regional planning efforts. A more focused discussion of specific modeling approaches in the telecommunications literature dealing with local network access is also provided. In order to better address digital subscriber line provision and access, a spatial optimization approach is proposed for ascertaining potential service quality and coverage within broadband market areas. An evaluation of DSL service provision in Franklin County, Ohio is detailed to illustrate the benefits of the proposed approach. Finally, discussion and conclusions are provided.

Background

Approaches for siting facilities to optimize regional coverage have a long history in the regional development and planning literature (see Plane and Hendrick 1977; Belardo et al. 1984; Daskin and Stern 1981; Owen and Daskin 1998; Murray 2005). One particular model especially relevant to the xDSL planning problem described in this article is the maximal covering location problem (MCLP). Given a set of demand areas indexed by i and a set of potential facilities indexed by j capable of providing service to area i within a specified time/distance standard S (e.g., areas j such that the distance from i to j , d_{ij} , is less than or equal to S), the MCLP identifies a siting configuration that maximizes demand coverage for p sited facilities (Church and ReVelle 1974). The MCLP is a linear-integer optimization model that can be solved using commercial optimization software as well as an array of heuristic approaches.

One of the more interesting caveats associated with standards-based modeling relates to the spatial representation of coverage. In the MCLP (Church and ReVelle 1974), all areas within the specified service time/distance standard, S , of a facility are considered covered or served. Demand locations further than S from a sited facility are considered uncovered (Figure 3a). However, in many planning applications, a binary representation of coverage is unrealistic because the actual benefits of coverage both *decay* with increasing time/distance from a facility and potentially extend beyond the specified service standard (although in diminished form; Austin 1974). To account for these realities, several types of coverage functions can be utilized and their associated benefits measured (Church and Bell 1978, 1981). For example, the associated benefit curve can be modified to adhere to a “step-like” function (Figure 3b), with benefits decreasing with increasing S . In such instances, the decay of coverage can be captured by subdividing S to represent multiple levels of service.

While Church and Roberts (1983), Berman and Krass (2002), and Eiselt and Marianov (2009) utilize discrete, “step-like” coverage decay functions, there are additional alternatives for capturing QOS levels in location models. For example, Church and Bell (1981) detail decay of service functions involving a p -median framework and continuous benefit functions. Pirkul and Schilling (1991) suggest a capacitated form of the MCLP that defines service quality as 100 percent within S but allows quality to decay linearly with increasing time/distance beyond S (Figure 3c). Araz, Selim, and Ozkarahan (2007) utilize a similar function for coverage

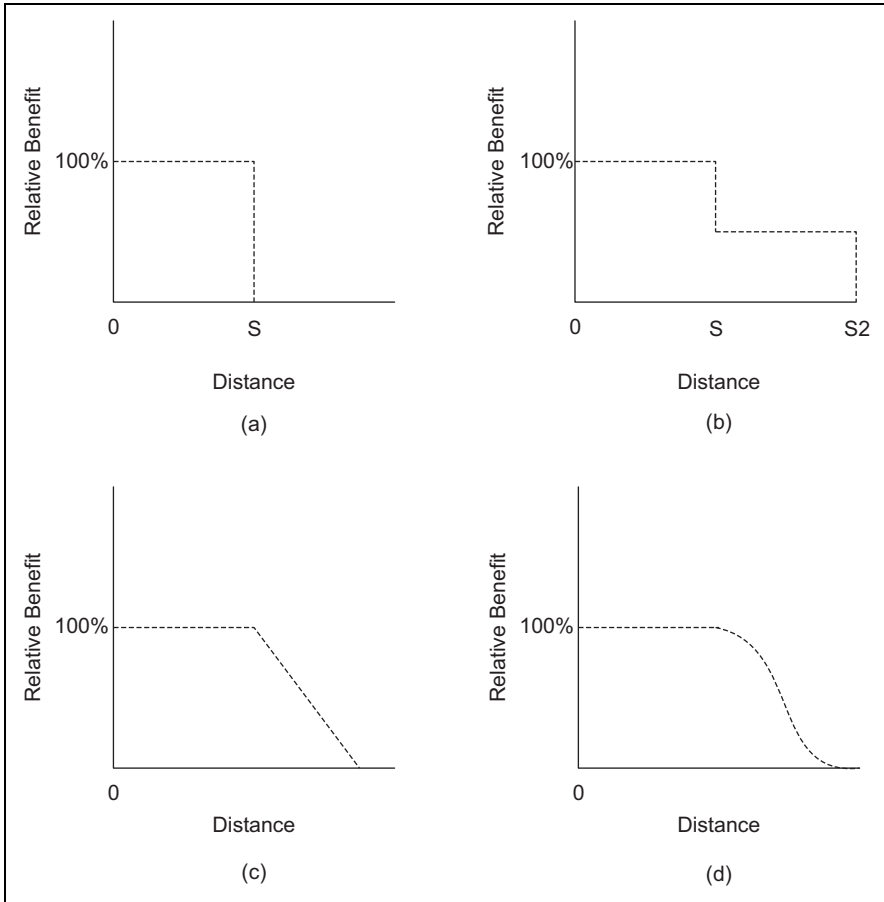


Figure 3. The spatial decay of coverage benefits.
Source: Eiselt and Marianov (2009).

decay for evaluating emergency service coverage. In another approach to the gradual covering problem, Drezner, Wesolowsky, and Drezner (2004) also dispense with the “step-like” function for coverage decay. In this instance, coverage within or beyond the service standard decays linearly, ultimately reaching a “no coverage” level. Finally, Berman et al. (2003) utilize a coverage function that is neither convex nor concave (Figure 3d).

Regardless of the coverage function utilized, one of the most important implications of these approaches for evaluating gradual coverage is the ability to measure the QOS. As discussed by Eiselt and Marianov (2009), QOS typically ranges from 0, where service is nonexistent, to 1, where service quality is 100 percent. As mentioned previously, this type of QOS measurement is conceptualized as a function

of time/distance between a facility and its demand locations in need of service. Thus, one option for measuring QOS for each demand site is as a function of the level of service available at that location (Church and Roberts 1983; Berman and Krass 2002). For example, if 1,000 households are within S of a potential fire station site and all are within a geographic range associated with a 95 percent response time, then $1,000 \times 0.95 = 950$ reflects a measure of QOS provided by that station. From a modeling perspective, Church and Roberts (1983) formulate several versions of a Weighted Benefit Maximal Covering Problem (WMBC) to account for varying QOS levels with a constraint structure that defines coverage within different ranges of distance. One of the major assumptions in the WMBC is that QOS declines with increasing distance. Further, even when more than one facility can cover a demand area, the value of coverage is associated with the closest facility, thus, demand areas are assigned accordingly.⁴

Location Modeling, Broadband, and QOS

As highlighted in the Introduction section, the quality of broadband xDSL service degrades with increasing distance. More specifically, while DSL service is available to households within 18,000 ft. of a CO, the bandwidth available from this service diminishes with distance from the CO. This confluence of geographic and technological limitations in the telecommunications industry is common to both wireline and wireless platforms. As a result, a myriad of methodological approaches and empirical analyses have been developed that incorporate these types of operational constraints. For example, Balakrishnan, Magnanti, and Wong (1995) utilize a decomposition algorithm for generating cost-effective expansion plans with performance guarantees in local access networks. Specifically, they examine the trade-offs between the costs of locating cable concentrators or simply expanding cables to accommodate demand growth. Bollapragada, Li, and Rao (2006) utilize a stochastic demand model to maximize the expected demand coverage in fixed-wireless networks from located hubs under budget constraints. In work more directly related to xDSL, Grubestic and Murray (2002) utilize a bi-objective MCLP to evaluate xDSL coverage and accessibility in Columbus, Ohio. Carpenter et al. (2001) present a dynamic programming algorithm to optimally locate broadband nodes and their related capacities. In their case, the goal is to optimally locate xDSL concentrators, where copper wire is utilized between the located node and the customer, but fiber cable is used between the located node and the CO. Elements of this problem are similar to the capacitated concentrator location problem (Klineciewicz and Luss 1986; Pirkul 1987).

In the next section, we outline a complementary, yet somewhat alternative approach to that proposed by Grubestic and Murray (2002) for xDSL network planning. Specifically, rather than deriving demand from a particular socioeconomic profile in each wire center, this approach attempts to maximize overall access to xDSL service in determining *where* to site DSLAMs. Again, because the spatial distribution of potential subscribers is relatively heterogeneous and market areas can

have scores of COs and service areas, this is a challenging task. Given that customers will experience differential levels of xDSL service based on their proximity to an upgraded CO, a second problem is to maximize service quality (corresponding to bandwidth availability) provided to customers eligible for xDSL in upgraded market areas. Since these two planning objectives can be conflicting, the challenge with this problem is in assessing the trade-offs between QOS and basic service provision when establishing xDSL upgrade priorities in a region. A spatial optimization approach is therefore proposed to model this particular planning scenario, representing an alternative to the Grubestic and Murray (2002) approach, as it explicitly accounts for QOS as a function of spatial proximity.

Spatial Modeling Approach

Given the need to prioritize the selection of COs to upgrade with xDSL, a model is structured for maximizing the provision of basic service coverage as well as QOS associated with each potential demand area. Consider the following notation:

- i = index of demand locations
 - j = index of COs
 - k = index of service quality levels (bandwidth availability)
 - a_i = demand in area i
 - q_k = bandwidth associated with QOS level k
 - b_{ik} = benefit of serving area i at QOS level k
 - d_{ij} = wire distance between demand location i and CO j
 - S = service standard for basic xDSL service
 - s_{\min}^k = minimum distance from CO at which QOS level k is the best option
 - s_{\max}^k = maximum distance from CO at which QOS level k is available
 - N_i = set of COs capable of serving area i (e.g., $j \mid d_{ij} \leq S$)
 - Φ_{ik} = set of COs capable of serving area i at QOS level k (e.g., $j \mid d_{ij} > s_{\min}^k \ \& \ d_{ij} < s_{\max}^k$)
 - p = number of COs to equip with xDSL
- $$X_j = \begin{cases} 1 & \text{if xDSL located at CO } j \\ 0 & \text{otherwise} \end{cases}$$
- $$Y_i = \begin{cases} 1 & \text{if demand } i \text{ is served} \\ 0 & \text{otherwise} \end{cases}$$
- $$Z_{ik} = \begin{cases} 1 & \text{if demand } i \text{ is served at quality level } k \\ 0 & \text{otherwise} \end{cases}$$

Using this notation, a linear-integer model for prioritizing xDSL upgrades to COs can now be formulated.

$$\text{Maximize } \sum_i a_i Y_i, \quad (1)$$

$$\text{Maximize } \sum_i \sum_k b_{ik} Z_{ik}, \quad (2)$$

Subject to

$$\sum_{j \in N_i} X_j \geq Y_i \quad \forall i \quad (3)$$

$$\sum_{j \in \Phi_{ik}} X_j \geq Z_{ik} \quad \forall i, k \quad (4)$$

$$\sum_k Z_{ik} = Y_i \quad \forall i \quad (5)$$

$$\sum_j X_j = p \quad (6)$$

$$X_j = \{0, 1\} \quad \forall j \quad (7)$$

$$Y_i = \{0, 1\} \quad \forall i$$

$$Z_{ik} = \{0, 1\} \quad \forall i, k$$

Objective (1) maximizes the total potential demand for xDSL service that can be provided suitable coverage. Objective (2) maximizes QOS provided in the selection of xDSL sites. Constraints (3) track whether a demand area, i , is served or not by a CO upgraded with a DSLAM. It is also important to note that the set N_i can have several morphological manifestations. In most instances, wire centers (these are described in the next section) are served by a single CO. Nevertheless, there are some locales, particularly central business districts, where more than one CO is present in a wire-center. Although COs cannot serve demand across wire-center boundaries (i.e., outside of their local loops; Grubestic 2008b), more than one CO can provide xDSL service within a given wire center. In such cases, however, demand areas are only assigned to a single CO, even if total demand within a wire center is split across multiple COs. Constraints (4) account for whether a demand area is served at quality level k . In this constraint, while only one CO can serve a given demand area, the quality of its service degrades with distance. Constraints (5) require that demand area i can only be served at a single QOS level. Constraints (6) stipulate that p central offices be upgraded with DSLAMs. Constraints (7) impose integer restrictions on the decision variables.

Since the specified model involves two objectives, a range of nondominated trade-off solutions can exist. The weighting method (see Cohon 1978) can be used to assist in the search for these solutions. In the weighting method, a weight (w) is used to integrate both objectives. For objectives (1) and (2), this results in the following:

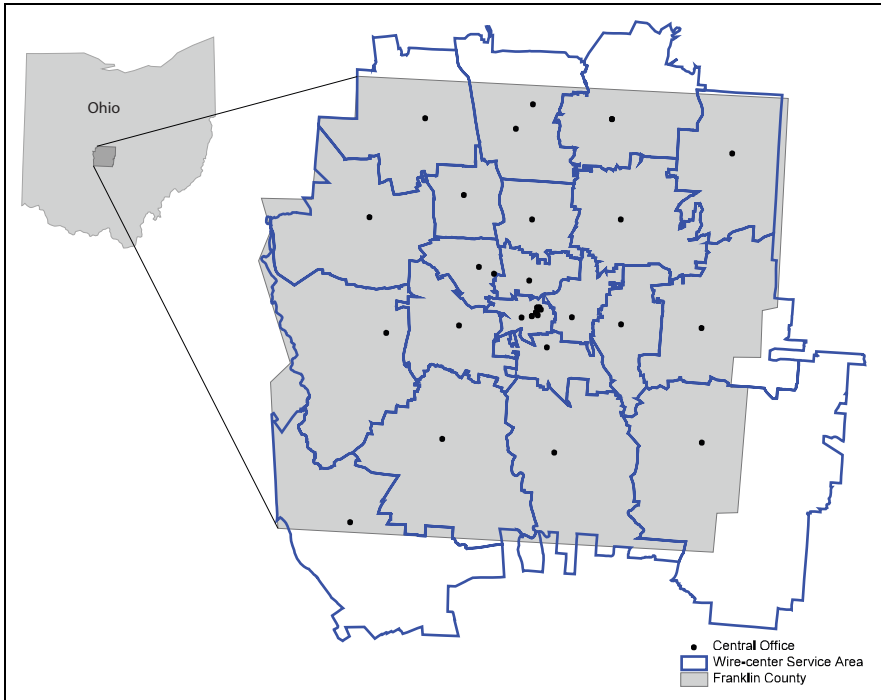


Figure 4. Franklin county Ohio and associated wire-center service areas and central offices.

$$\text{Maximize } w \left(\sum_i a_i Y_i \right) + (1 - w) \left(\sum_i \sum_k b_{ik} Z_{ik} \right), \quad (8)$$

where $w \in [0, 1]$.

By adjusting the weights associated with this bi-objective function, one can iteratively evaluate the trade-offs connected with maximizing total potential demand versus maximizing QOS.

Application

The developed model was applied to all twenty-one wire-center service areas in Franklin County, Ohio (Figure 4). As a result, the study area contains population in Franklin as well as some portions of surrounding counties. 2006 Census estimates indicate a population of 1,153,134 within the boundaries of the twenty-one wire-center service areas. The study region highlighted in Figure 4 is served by thirty COs, each of which is eligible for xDSL service.⁵ Census block centroids ($n = 13,393$ within 18,000 ft. of a CO) are utilized to represent demand areas and the

Table 1. Quality of Service Levels and Distance Constraints

QOS Level	Mbps	Min Distance (Feet)	Max Distance (Feet)
1	1.544	16,000	18,000
2	2.048	12,000	16,000
3	6.312	9,000	12,000
4	8.448	4,500	9,000
5	12.96	3,000	4,500
6	25.92	1,000	3,000
7	51.84	0	1,000

population of each block, a_i , is used as a measure of demand for xDSL service.⁶ Street network distances were derived between each CO and each demand area. This process was carried out using a commercial geographic information system. Measuring distance in this way is necessary because telephone lines are strung along public rights-of-way (e.g., streets) and the use of Euclidean distance metrics can deflate the true distances associated with line lengths from the CO to demand areas (see Prieger and Hu 2008; Grubestic 2008b). Second, as previously discussed, demand areas must be within 18,000 ft. of a CO to acquire xDSL service. Therefore, the service standard for basic xDSL coverage is set to 18,000 ft. ($S = 18,000$). Also, because QOS is based on distance, bandwidth availability based on a set of distance ranges is typically used by service providers to differentiate levels of service. Table 1 shows the bandwidth availability characterization used here (McAdams et al. 2000; Parker 2000; Cai 2002). The distance ranges for each bandwidth category k are represented as s_{\min}^k and s_{\max}^k in the model. For instance, all demand areas between 1,000 and 3,000 ft., $s_{\min}^1 = 1,000$ and $s_{\max}^1 = 3,000$, from a CO are positioned to receive service at the 25.92 Mbps level. Another modeling consideration is the derivation of b_{ik} , the benefit associated with serving demand area i at QOS level k . Here, b_{ik} is a function of demand in area i . Thus, $b_{ik} = f(a_i, q_k)$ and more specifically, $b_{ik} = a_i q_k$. The multi-objective model was solved using ILOG's CPLEX 10.01 employing the weighting method as described earlier.⁷

Results

Figure 5 displays solutions to the model in terms of percent of total population covered for a range of p values. In this instance, two curves are displayed. The first corresponds to a complete emphasis on the first objective (maximize population served by xDSL) while the second corresponds to complete emphasis on maximizing QOS. Solutions times for this particular application averaged 1.08 sec per problem instance, with maximum and minimum solution times of 1.33 sec and 0.67 sec, respectively. It is interesting to note that the level of population covered in each

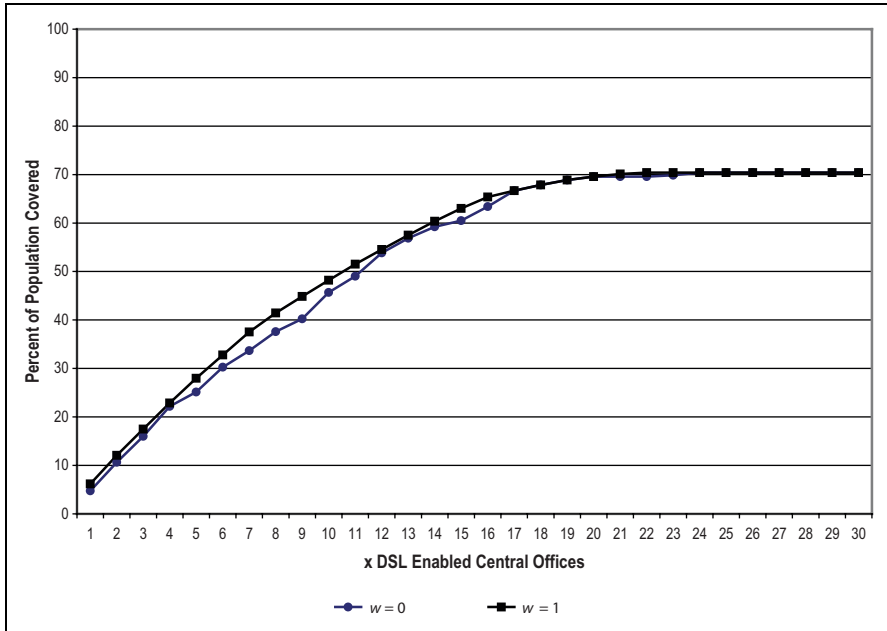


Figure 5. Cost-effectiveness curve for maximizing population coverage in DSLAM equipment location.

of these scenarios is not dramatically different, varying 4.6 percent or less in each solution. However, there is enough of a difference to suggest further exploration is necessary, particularly for detecting variations in the spatial configurations of the associated solutions.

Figure 6 displays trade-off solutions for the case where five COs are upgraded ($p = 5$) with xDSL equipment and the modeling emphasis is on maximizing QOS ($w = 0$). Solution 1 in Figure 6 represents a configuration that serves 289,884 residents with an aggregate QOS of 2,364,710. In addition to the spatial configuration of xDSL service in this case, there are several additional features worth highlighting. When the emphasis is placed on maximizing QOS, the model selects wire-center service areas that are more spatially compact and have a relatively dense population distribution near the CO. This allows for greater bandwidth to be allocated to demand areas. Solution 1 typifies this type of facility allocation, with xDSL service provided to areas immediately north of downtown (Victorian Village and Worthington), west of downtown (Franklinton), south of downtown (German Village), and in the Bexley/Whitehall area to the east (Figure 7). All of these areas have relatively compact wire-center service areas and are densely populated. A second feature worth noting is the spatial decay of the QOS levels to each block as the distance from the CO increases. While high bandwidth connections (QOS 5 and 6) are available in

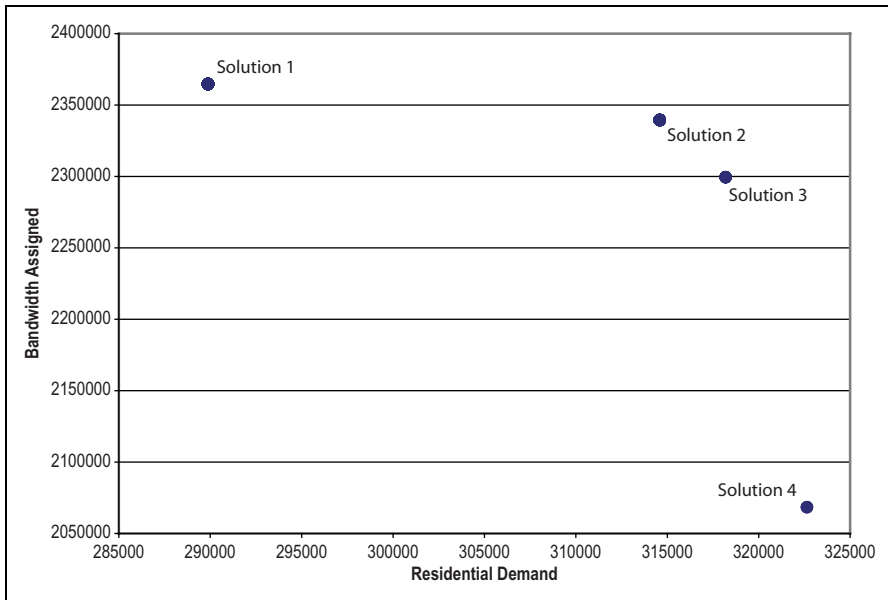


Figure 6. Nondominated trade-off curve for $p = 5$.

areas immediately surrounding each CO, bandwidth availability decays, as expected, toward the periphery of the wire-center service areas.

There are also a number of interesting aspects to the model solutions that reflect the importance of network distance. For example, there are several instances where blocks appearing to have a closer straight-line (Euclidean) distance to a CO actually have lower QOS scores (e.g., QOS level 1) than blocks appearing further away. As mentioned earlier, because telephone lines are typically strung along public rights of way such as streets, there can be major differences in wire length when compared to Euclidean distances in a market area. This often results in a cartographically, non-intuitive allocation of bandwidth and QOS for portions of a market area.

A final feature of Figure 7 worth mentioning concerns the spatial constraints on xDSL coverage to nearby demand areas and their associated implications for service allocation in Franklin County. For instance, as displayed by Figure 7, there are locations where demand areas are located closer to COs in different wire-center service areas than the CO in their own service area. From a modeling perspective, it would seem to make sense to allocate xDSL service to these areas from the nearest CO. However, as mentioned earlier, from an operational perspective, local loops never cross into adjacent wire center areas (Grubestic 2008b), therefore, xDSL service must be acquired in these demand areas from the more distant CO. In other words, COs act independently of each other. Again, even when there is more than one CO present in a wire-center service area, demand areas are allocated to a single CO.

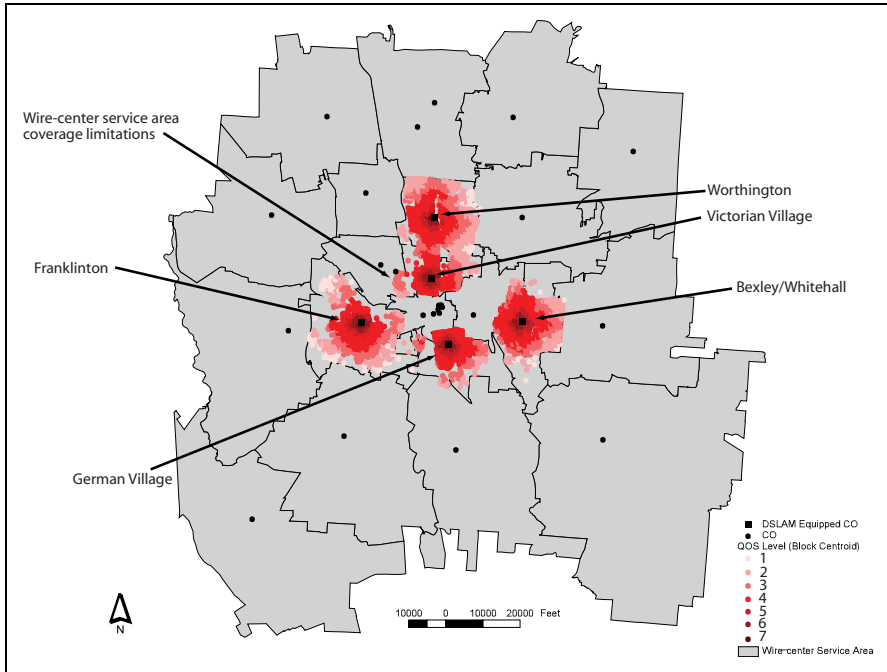


Figure 7. Nondominated trade-off solution #1 for $p = 5$.

Figure 8 illustrates an alternative, nondominated solution, where slightly more emphasis is placed on population covered ($w = 0.51$) than QOS. Solution 2 covers 314,588 people with an aggregate bandwidth of 2,339,502. This is an 8.52 percent increase in population covered and a 1.07 percent decrease in QOS. Not surprisingly, the spatial configuration of this solution also changes. Instead of providing service to the German Village CO, coverage is provided to the geographically larger and more populated service area to the east, Reynoldsburg. In this case, it is clear that xDSL service cannot be extended to all of the demand areas in Reynoldsburg (not formally highlighted on the map) because of the 18,000 ft. distance constraint on xDSL service from the CO. From a planning perspective, this wire-center service area might be a good candidate for a remote digital access multiplexer if this uncovered demand was to be met.

Figure 9 displays nondominated Solution 3, which again places more emphasis on population covered ($w = 0.92$) than QOS. In addition to a 1.14 percent increase in covered demand and a 1.74 percent loss in QOS, the spatial arrangement of xDSL coverage shifts, enabling a CO in the northwestern suburb of Westerville with xDSL service. There are several interesting features of this spatial configuration of service, most notably the major gaps in xDSL demand throughout the Westerville service area, particularly to the south and west of the CO. This lack

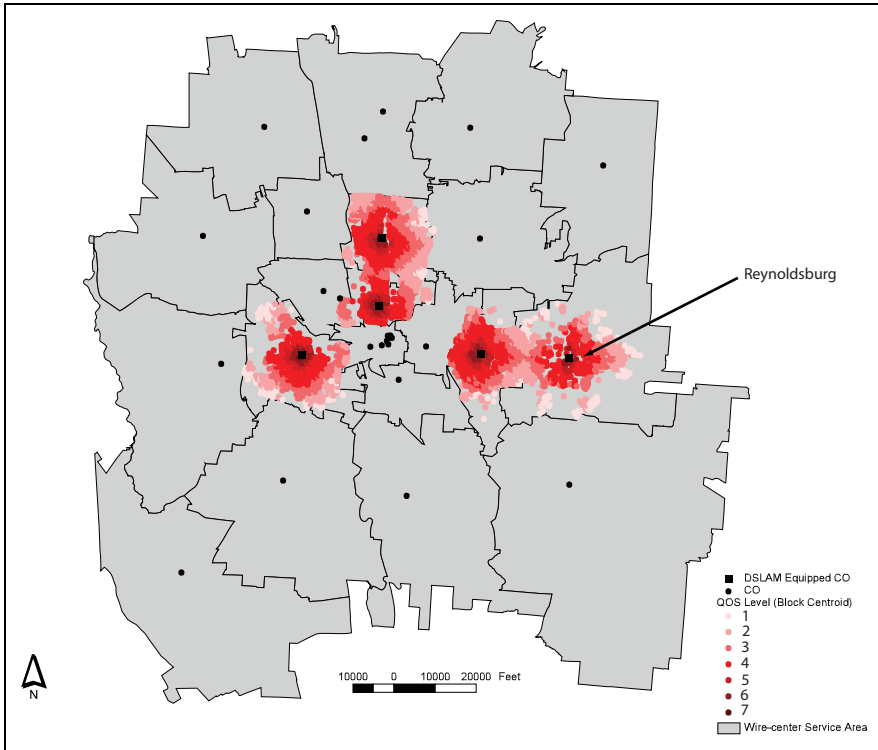


Figure 8. Nondominated trade-off solution #2 for $p = 5$.

of coverage corresponds to several large, corporate business parks, industrial areas, and resource extraction sites south of Interstate 270. In other words, there is no residential demand (i.e., population) in these areas. The other notable gap in demand to the west/northwest corresponds to the 762 acre Sharon Woods Metro Park.

The last nondominated solution is presented in Figure 10, where sole emphasis is placed on population covered ($w = 1$) instead of QOS. For this solution (#4), a population of 322,641 is covered by xDSL service and the aggregate QOS level is 2,068,398. This represents a 9.76 percent increase in population covered when compared to Solution 1 ($w = 1$ for QOS) and a 14.3 percent decrease in QOS levels. Once again, the spatial configuration of xDSL service also shifts, allocating DSLAMs to the Franklinton, Worthington, Reynoldsburg, and Westerville COs. Because QOS is less of a concern in this weighting scheme, the more highly populated suburban areas are allocated coverage while the more compact wire-center service areas such as German Village and Victorian Village are not.

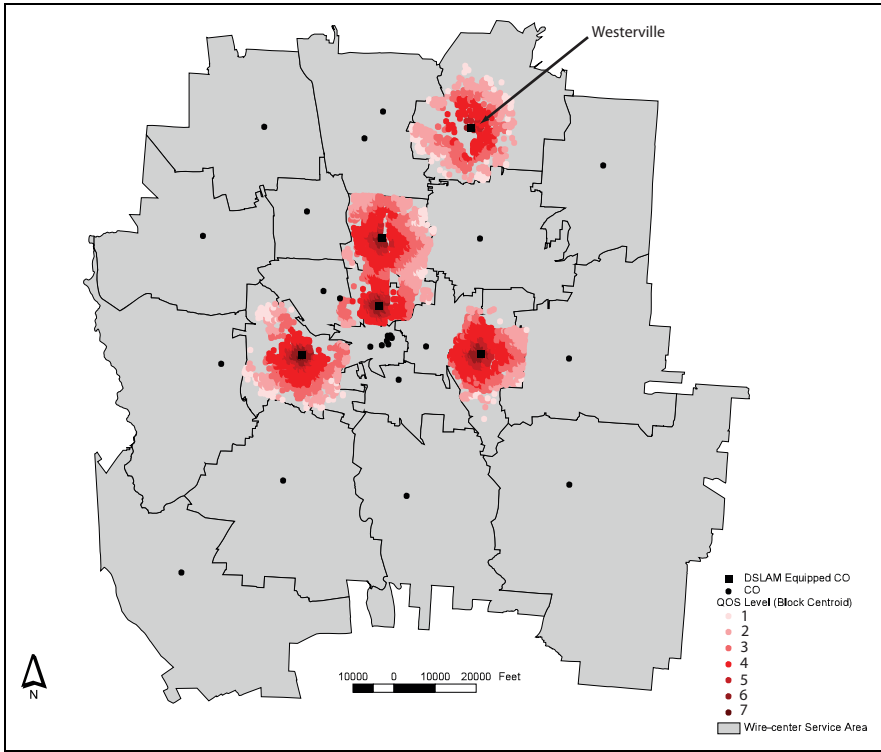


Figure 9. Nondominated trade-off solution #3 for $p = 5$.

QOS Variability

A final important aspect to this xDSL service modeling relates to how bandwidth availability and population covered varies with p . Figure 11 displays a graphical breakdown of population covered by each QOS level when $w = 1$. For example, when $p = 5$, a population of 36,647 is served by QOS level 1 (2.048 Mbps) in the study area, while 16,228 are served by QOS level 5. From an interpretive standpoint, Figure 11 suggests that QOS level 4 (12.96 Mbps) is the generally the “most available” level of service, given this objective weighting scheme (although this does vary for some values of p). This suggests that 12.96 Mbps represents the best case QOS scenario for a relatively large segment of potential subscribers in Franklin County. Obviously, this is not a guarantee of bandwidth availability, but it certainly indicates that a differentiated service program might be a viable option for broadband providers in this area. This also suggests that for all values of p , the model results are not bounded by the best and worst QOS levels. While acquiring QOS level 7 (50+ Mbps) in Franklin County is certainly the most difficult, QOS level

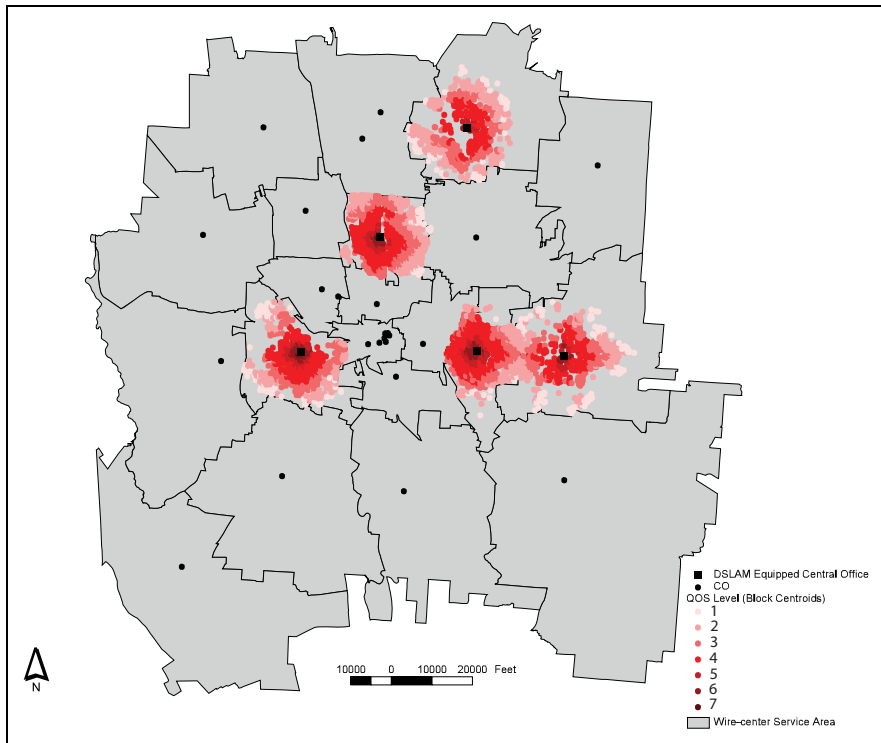


Figure 10. Nondominated trade-off solution #4 for $p = 5$.

1 is not the most prolific level in the region. To a certain extent, this can be attributed to the application of this model in a fairly large, urbanized region. An identical application in a more rural area would likely yield different results because the population distribution would be less concentrated.

Discussion and Conclusion

The nondominated solutions illustrated in the Results section clearly illustrate the trade-offs associated with covering demand and attempting to enhance QoS in xDSL service provision. Specifically, a 14.3 percent difference in QoS and a 9.76 percent difference in population covered between Solutions 1 and 4 ($p = 5$) does suggest that location plays an important role when planning for the provision of xDSL service.

In addition to the variations in coverage for a single scenario ($p = 5$), there are also issues associated with coverage for the entire region. For example, if the planning budget was expanded to include more than five locations, population covered

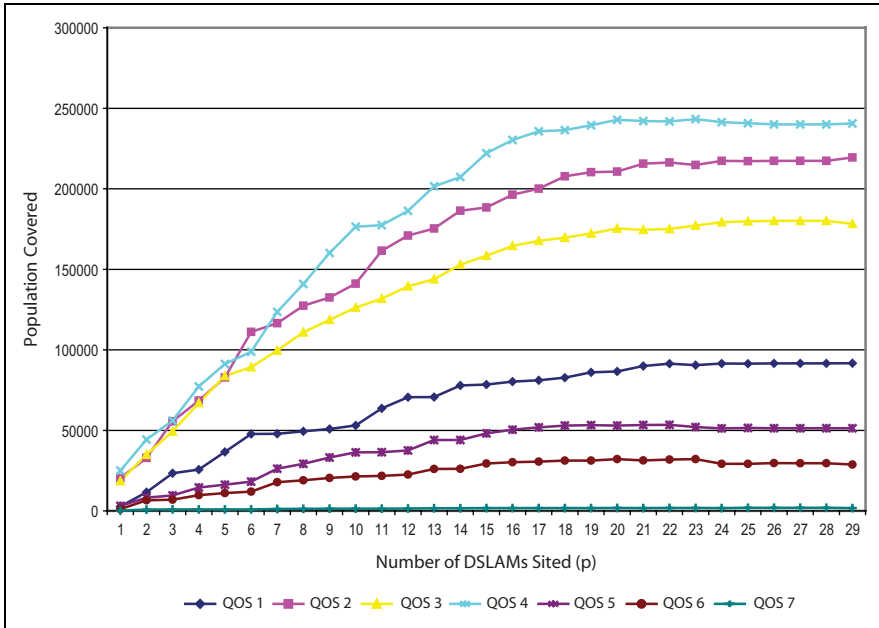


Figure 11. Quality-of-service levels and population covered.

would continue to increase, but as illustrated by Figure 5, could never exceed 70.4 percent, given the limitations of S . A careful examination of the cost-effectiveness curve also suggests that the benefits associated with population coverage are marginal beyond $p = 18$ (66.87 percent). That is, it would take an additional seven DSLAMs to cover the remaining eligible population for the study area.

It is also important to reiterate that there are technologies available for overcoming the distance constraints associated with traditional CO-based xDSL services. As noted in the introduction, remote DSLAM configurations (RDSLAM) can be employed in certain markets. For example, RDSLAMs represent an overlay solution for POTS (plain old telephone service) network that allow for the collocation of a remote DSLAM and a digital loop carrier—effectively extending xDSL service to more peripheral locations (Starr et al. 2003). A somewhat different configuration is a hybrid coaxial/fiber system that includes fiber to the curb (FTTC) DSLAM technology (Ahamed 2007). Similar to RDSLAMs, the FTTC configuration effectively decreases the distance between potential subscribers and the digital switch, thereby increasing both speed and accessibility for xDSL service. While both types of configurations represent a strategy for extending DSL service to the periphery, it is important to remember that both approaches require additional capitalized costs for broadband providers. For example, in addition to the installation of relatively expensive DSLAM equipment, configurations requiring fiber to the curb or fiber to the

neighborhood can cost thousands in rights-of-way access alone (Whitman 2007). Whitman (2007) also notes that these sunk costs pose cash-flow problems for many broadband providers and may serve as a disincentive for hybrid xDSL rollouts.

From a policy perspective, there are a few last details worth discussion. First, this type of broadband telecommunications planning approach does not take into account specific socioeconomic characteristics of the potential subscriber base within the modeling framework. As with most services, providers typically target markets that fit a certain socioeconomic and demographic profile. While Grubestic (2008a), Prieger and Hu (2008), and many others suggest that density (population and/or household) is a major demand-side determinant for broadband provision, income, education, age, and race can also influence provider market entry. This type of demand differentiation is easily accommodated by the presented model by simply adding a scalar weight to reflect socioeconomic status, median age or education, or some other sociodemographic measure to each demand area, *i*. Moreover, while we do not provide any metrics associated with the types of populations that are extended xDSL service in this article, if equity is a primary concern, these types of tabulations are easily accomplished in a geographic information system.

The notion of broadband equity also speaks to a much larger issue within the literature. Specifically, previous empirical evidence suggests that broadband providers have a tendency to cherry pick the most profitable service areas and neglect areas with higher concentrations of poverty or minority populations (Grubestic 2004). While Prieger and Hu (2008, 165) suggest that “race and ethnicity matter independently of other related factors such as income and education in the demand for DSL,” the lack of competition for many areas (e.g., from cable or wireless) can impact the pricing structure of xDSL, thereby limiting its affordability for minority groups, even when available. This finding reiterates the complex interactions of demand and supply-side factors when considering broadband provision and the existence of a broadband divide. While the results of this article neither confirm nor deny these types of socioeconomic and demographic findings, it is clear that broadband availability and QOS are highly variable in xDSL market areas.

Finally, from a modeling perspective, the model developed here compliments the WBMC of Church and Roberts (1983). As noted earlier, there are some similarities. For example, each demand node must be assigned to a facility, assignment cannot be made unless a facility is located and exactly p facilities must be located. Further, because the benefits of coverage decrease with increasing distance, we can have as many “bins” or QOS classifications as needed in the model. However, there are several distinct differences between these formulations. First, Church and Roberts (1983) only consider a single objective, one which maximizes the total weighted relative benefit of coverage. The MCLP with QOS is specified as a multi-objective problem that seeks to both maximize population with access to basic xDSL service while simultaneously maximizing the weighted QOS for a demand area.

This modification is an important one. There are planning scenarios where minimum coverage is desirable, but some type of differentiated service is offered within

the coverage area. xDSL is an excellent example of this. Broadband providers are interested in acquiring as many subscribers as possible. By locating DSLAM equipment in COs with highly populated service areas, there is a potential for higher returns on the initial investment. In this instance, it is anticipated that all demand can be met at the minimum service level. However, if broadband providers offer differentiated service packages, where additional fees provide subscribers with higher bandwidth connections, there is also a need to maximize provision exposure to these eligible demand areas. Simply put, while every demand area is guaranteed a minimal QOS, some are qualified for premium services. Again, this has the potential in dramatically increasing return on investment, because additional monies are extracted from premium subscribers, while the remainder of the service area remains covered by basic services. In an effort to accommodate this type of planning goal, the second objective involves a function of population (a_i) and QOS (q_k) to generate the benefit term (b_{ik}).

In conclusion, the results of this article suggest that the spatial distribution of broadband benefits is not always evenly distributed in xDSL-enabled service areas. While the availability of xDSL is a critical step in closing the broadband divide, the need for higher bandwidth connections is becoming more important as Internet applications continue to require greater download capacities. As a result, while households located closer to COs are able to obtain higher service quality and broadband performance, those located farther away experience diminished download speeds. The ability to model differences in QOS and population covered, therefore, is important for broadband providers during the planning process. The capability to evaluate the contingencies associated with locating DSLAMs in different market areas can help ensure a profitable rollout of broadband services and ultimately assist with customer satisfaction and retention. More importantly, the model presented in this article is also flexible enough to accommodate broadband rollout strategies where differentiated service offerings (by bandwidth) can be modeled within each service area.

Authors' Note

Any opinions, findings, and conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the National Science Foundation.

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Notes

1. For more details on FSO, see <http://www.free-space-optics.org/>.
2. There are markets where remote digital subscriber line access multiplexers (RDSLAM) are installed. In effect, this remote switch allows for additional households and businesses to be covered by xDSL technologies through the use of fiber-based relay stations.
3. The central office is a building that contains the circuit switching equipment for all telephone lines serving a geographic area. This is also the location where digital subscriber line access multiplexers (DSLAM) are installed to enable xDSL service.
4. In the second form of the WBMC model, the value of coverage is the net value of both positive and negative benefits. For more details, see Church and Roberts (1983).
5. Wire-center service areas function as the “market areas” for central offices. Simply put, each wire-center service area represents the spatial extent of the local loop associated with a central office.
6. Many blocks had no recorded population. These are usually urban parks, industrial areas or other uninhabited areas.
7. A Xeon 3.0 GHz workstation with 2GB of RAM was used to solve all problem instances.

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