A Techno-Economic Approach for Broadband Deployment in Underserved Areas

Ramakrishnan Durairajan
University of Wisconsin-Madison
rkrish@cs.wisc.edu

Paul Barford
University of Wisconsin-Madison & comScore, Inc.
pb@cs.wisc.edu

ABSTRACT

A large body of economic research has shown the strong correlation between broadband connectivity and economic productivity (*e.g.*, [1–3]). These findings motivate government agencies such as the FCC in the US to provide incentives to services providers to deploy broadband infrastructure in unserved or underserved areas. In this paper, we describe a framework for identifying target areas for network infrastructure deployment. Our approach considers *(i)* infrastructure availability, *(ii)* user demographics, and *(iii)* deployment costs. We use multi-objective optimization to identify geographic areas that have the highest concentrations of un/underserved users and that can be upgraded at the lowest cost. To demonstrate the efficacy of our framework, we consider physical infrastructure and demographic data from the US and two different deployment cost models. Our results identify a list of counties that would be attractive targets for broadband deployment from both cost and impact perspectives. We conclude with discussion on the implications and broader applications of our framework.

CCS Concepts

•Networks → Network management;

Keywords: Broadband deployment targets; Multi-criteria optimization; Underserved areas

1. INTRODUCTION

The importance of broadband connectivity in the US is highlighted by the following quote from the FCC's National Broadband Plan, "Like electricity a century ago, broadband is a foundation for economic growth, job creation, global competitiveness and a better way of life" [4]. Despite the compelling case for broadband access and significant efforts by the FCC over the past six years, 6% of the Americans still lack access to broadband service (threshold defined to be 25 Mbps download/3 Mbps upload for fixed services) and the percentages are much higher in rural and tribal areas [5].

Expansion of broadband access in the US, as it is in other states, is a complex matter. First, the FCC does not build, own or operate Internet infrastructure. Instead it works with municipalities, private service providers and other sponsors by providing guidance and economic incentives to deploy broadband infrastructure in un/underserved areas (*e.g.*, via the Connect America Fund [6]). Second, there are legal and policy concerns such as laws that limit or prohibit non-telecom companies from deploying communication infrastructure [7]. Third, defining and identifying underserved areas that are the *best targets* for new or upgraded infrastructure deployment requires consideration of a variety of geographic, economic and demographic factors—the main focus of this work.

In this paper, we describe a techno-economic framework and system for identifying targets for future broadband expansion. The objective of our work is to provide flexible decision support on opportunities for broadband deployment that enables economic and technical issues to be considered simultaneously. Specifically, our framework considers *(i)* infrastructure proximity, *(ii)* demographics, and *(iii)* deployment costs. We employ geographically-based, multi-objective optimization to identify the *highest* concentrations of un/underserved users and that can be upgraded to the broadband threshold at the *lowest* cost. Our work takes advantage of new maps of long-haul infrastructure in the US [8, 9] that are critical for accurate cost modeling.

We demonstrate the efficacy of our approach by considering US demographic data and two different deployment models: upgrading existing infrastructure and deploying new infrastructure. Our results highlight the tradeoffs of the different deployment models and identify a list of US counties that would be attractive targets for broadband deployment from both cost and impact perspectives and that correspond closely with areas identified by Connect America map [10]. While our analysis focuses on the US, our method is generic and can be applied in other regions where similar data is available.

2. CONNECTIVITY ANALYSIS

In this section, we assess connectivity and need in US counties (and county equivalents) using *provider data* [11] from broadbandmap.gov, *census data* [12] from census.gov and *infrastructure data* from Internet Atlas [8, 9]. Our analysis considers the presence of Internet Service Providers (ISP) and the characteristics of user populations in counties. We spatially integrate the infrastructure datasets from Internet Atlas and census.gov to highlight the presence of "digitally divided" regions across US.

2.1 Service Provider Prevalence

Similar to [4], our analysis of connectivity begins by counting the number of providers with presence in US counties. First, we extract population information and FIPS codes of

3,142 US counties using census data. Next, we look up FIPS code in provider data and count the unique number of service providers present in each county in the form of a broadband/fiber provider or a reseller.

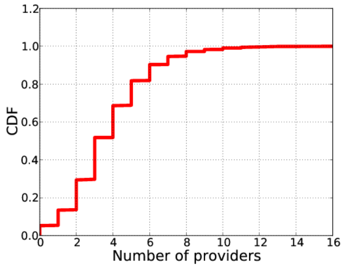

Figure 1. CDF of number of providers with presence in 3,142 US counties (and county equivalents).

Figure 1 shows the distribution of service providers in US counties. For 50% of the counties, the number of service providers present is less than or equal to 3. Surprisingly, 170 counties do not have *any* provider presence. These counties are spread across 30 states leaving 38,464,508 users—or 12% of the US population[1]—disconnected from the Internet, which is consistent with observation from others [14]. Finally we observe that less than 1% of the counties (across 17 states) have provider presence greater than 10. Manual comparison with physical infrastructure repository and fiber assets [8, 9] showed that the increased presence of providers in these locations corresponds with the presence of either *(1)* a co-location facility, an Internet Exchange Point (IXP) and/or a submarine cable landing station, or *(2)* high availability of fiber resources to meet large user demand (*e.g.*, a major metropolitan area).

2.2 Infrastructure vs. Population

We compare the availability of infrastructure versus population to assess the prevalence of underserved communities. Similar to [4], we use the unique number of service providers with a presence in a county as a proxy for the infrastructure availability. Our intuition for this analysis is that the trend in population should be proportional to number of unique providers to completely connect *all* communities in a region.

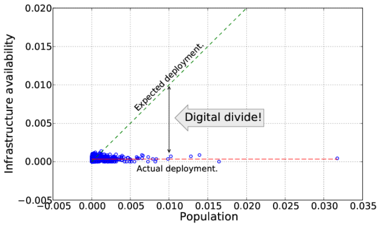

Figure 2. Availability of infrastructure vs. population.

Figure 2 depicts the normalized population versus the normalized infrastructure availability in US counties. The expected and the actual deployments are also shown. The plot highlights the fact that there are a sizable number of population centers in the US that have infrastructure provided by a small number of ISPs.

A natural question is can a region with only one service provider effectively serve and provide broadband access to every community in that region? Even though such a scenario is possible, we argue that the geographical diversity of infrastructure deployments will suffer as a consequence of one-provider-services-all model since business imperatives may lead to delays in broadband deployments to all communities. It may also lead to choke points and single points of failure in the Internet [9] that may otherwise be obviated in more competitive areas.

2.3 Availability of Infrastructure

Finally, we consider the issue of level of service in an area by using a Geographic Information System (GIS) to spatially integrate areas of counties from census.gov and physical infrastructure assets from *(1)* the Internet Atlas project [8] and *(2)* the long-haul infrastructure information from the InterTubes project [9]. Our objective is to analyze the proximity of population centers to infrastructure for network connectivity. To facilitate this analysis, we use the *spatial query* and *overlap* capabilities in ESRI ArcGIS [15].

We start by layering the infrastructure shape files from Internet Atlas and InterTubes atop the counties. We invoke *spatial overlap* and *select by location* queries on these spatially integrated datasets. Figures 3-(left) and -(right) distinguish the digitally disconnected regions (in red) from those that are well connected (in green) to physical long-haul fiber data from InterTubes (dataset D1) and 100 US-based networks from Internet Atlas repository (dataset D2) respectively. We call these the *infrastructure availability map*. These maps form the basis of our targeting assessments described below.

3. DEPLOYMENT OBJECTIVES

In this section, we state the broad objectives for an ISP's operational success, which are important in understanding how to create incentives for broadband deployment in un/underserved areas.

Maximize value. The primary objective of any company is to maximize shareholder value. The question is how ISPs go about doing this? While large ISPs have complex business models that are beyond the scope of this paper, several key factors including revenue growth, cost management, customer satisfaction, and maintaining technological and operational capabilities.

Growing the user base. Revenue growth can be directly tied to expansion of an ISPs user base. This can be done in a variety of ways including expanding infrastructure into previously unserved or underserved areas or by upgrading capabilities that allow for higher service charges. Expanding the user based is one of the primary motivations for expanding to un/underserved areas.

Minimize CAPEX. Expanding or upgrading infrastructure is capital expense (*i.e.,* an investment that depreciates over time) for ISPs. Many factors must be considered before making capital expenditures including *(1)* proximity/type of current infrastructure, *(2)* geographical feasibility (mountains vs. existing right of ways) and *(3)* market economics and competition. CAPEX is one of the primary deterrents to expanding to un/underserved areas.

---

[1] Based on projected US population of 320,090,857 on Jan. 01, 2015 [13].

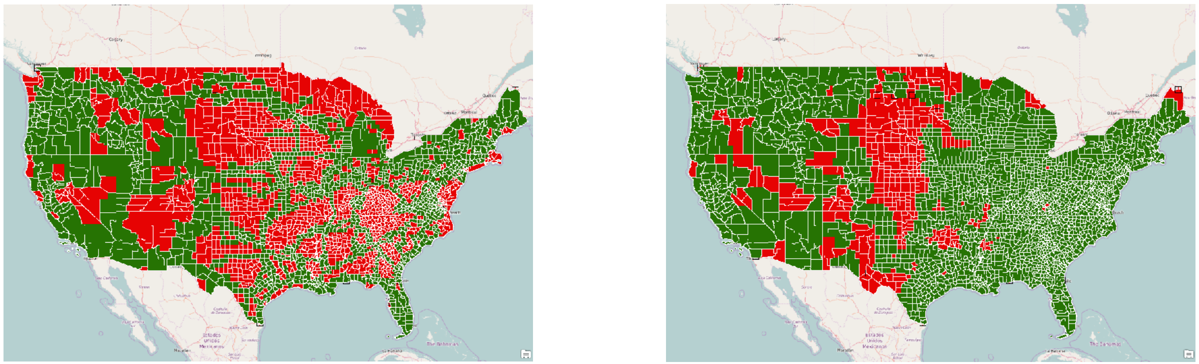

Figure 3. Spatial selection of counties using long-haul dataset [9] (left) and 100 US-based networks in Internet Atlas [8] (right). Counties with and without infrastructure are shown in green and red respectively.

Minimize OPEX. Operational expense (OPEX) refer to costs associated with operating and maintaining an infrastructure. A variety of factors contribute to OPEX including environmental factors (*e.g.,* power, cooling, etc.), miscellaneous factors (*e.g.*, taxes, repairs, etc.) and personnel costs. Economies of scale for OPEX argue for expanding to un/underserved areas.

Minimize risk. Any infrastructure or service expansion implies CAPEX and OPEX commitment. Any analysis of the opportunities for increased revenue through new user service adoption must be complemented by an analysis of the risks associated with deployment and operating costs. The more accurate these analyses, the more likely service providers are to commit to expansion. This is one of the goals of our work.

4. TECHNO-ECONOMIC FRAMEWORK

In this section, we describe our geo-based optimization framework that guides infrastructure deployment in new geographic locations. We identify two deployment scenarios that are affordable for the end users and that are practical and cost-effective for the ISPs. We conclude this section with an evaluation of the identified scenarios using our framework.

4.1 Techno-Economic Model

We consider the problem of assigning a list of *nodes* to a list of *locations*, where our objective is to assign each node (*i.e.,* network infrastructure) to a location such that the total cost is *minimized* and the number of users [2] is *maximized*. This is an extension of Koopmans-Beckmann version of the Quadratic Assignment Problem (QAP) [16] where, apart from the objective of minimizing costs associated with a node assignment to a location, we also consider maximizing number of end users who could benefit from the *new* deployments.

Note that the objective of maximizing the number of users is in conflict with the objective of minimizing total costs. For example, more users implies a larger infrastructure and thus higher the total costs for CAPEX and OPEX (unless one further assumes a per user revenue model, which we argue is not of intrinsic importance to this step in the analysis—revenue modeling including incentives can be done post-facto). Because of the conflicting nature of these two objectives, we model the assignment problem as a multi-objective optimization problem, subject to various technical, economical and ISP-centric constraints. Specifically, given a list N of k nodes, where N is defined as,

$$N = \{n_1, n_2, n_3, \ldots, n_k\}$$

the multi-objective problem can be formulated as,

$$\textbf{max.} \sum_{i=n_1}^{i=n_k} B_{i\gamma(i)} + \textbf{min.} \sum_{i=n_1}^{i=n_k} C_{i\gamma(i)} \qquad (1)$$

subject to the following constraints,

$$Budget_{min} \leq C_{i\gamma(i)} \leq Budget_{\max}, \quad \forall i = n_1, \ldots, n_k \qquad (2)$$

$$k \leq K \qquad (3)$$

where, $B_{i\gamma(i)}$ is the benefit factor to users at location $\gamma(i)$ for deploying a node i, $C_{i\gamma(i)}$ is the total cost of deploying node i at location $\gamma(i)$, $Budget_{min}$ and $Budget_{max}$ are the minimum and maximum budgets allocated for deployments, and K is the maximum number of deployments planned by the ISP.

Implementation. The optimization model described above is implemented in approximately 450 lines of python code using the DEAP evolutionary computation framework [17]. DEAP enables rapid prototyping of *any* evolutionary algorithm with minimal developer efforts.

Advantages. Our optimization framework has the following advantages: (1) *flexibility*, where equation 1 can be extended to accommodate other objectives such as considering only a subset of user population (*e.g.*, based on economics) and the ones described in §3 instead of maximizing the number of users; (2) *simplicity*, where the cost and benefit factors can be varied as per service provider's requirement; and (3) *modularity*, where different evolutionary algorithms can be plugged in to perform a wide spectrum of analyses.[3]

4.2 The Solutions

To facilitate our deployment analysis, we studied solutions proposed by researchers and consider both the practicality and cost-effectiveness of each. First, we study solutions including *(a)* WiMax [19]; *(b)* radio wave mesh-based networking [20]; *(c)* li-fi technology [21]; and *(d)* satellite-, balloon- and aircraft-based networking [22,23]. Our conclusion is that

---

[2] For simplicity, we simply consider the total population in a target area.

[3] In our evaluation, we use NGSA-II evolutionary algorithm [18] with Ant heuristics.

these technologies are quite costly for deployments that cover broad geographic areas, which are common in underserved areas. For example, a typical satellite deployment costs about $500M and includes high equipment costs ($150-200M), high maintenance and operational costs ($120M for launch, $20M for launch insurance, $20M for in-orbit insurance, $15M for operations, and special manpower at about $10M a year per specialist) [24]. It is somewhat surprising that industrial projects [22, 23] continue to push at these solutions despite the challenges and practicality issues.

Next, we investigated a set of technologies that are more cost-effective and practical. To that end, we consider the following two options: (1) connect existing transmission infrastructure (*e.g.*, public switched telephone network (PSTN) or cable television network) to IP infrastructure using Multiservice Access Node (MSAN) at strategic locations and use cable or DSL modems at the user end; or (2) leverage power line infrastructure to enable connectivity. Even at locations where PSTN is not installed, there are almost always power lines installed, which enables broadband over power line (BPL) or distribution line carrier (DLC). Since the latter is proven successful and is already the goal of many companies [25], in our evaluation we only explore the former (scenario 1 below). Finally, to add perspective, we also consider the scenario where a service provider is willing to invest on building new fiber infrastructure to connect a region.

4.3 Evaluation

Scenario1: Upgrading existing infrastructure. We first examine the possibility of leveraging existing infrastructure (*e.g.*, PSTN and cable network) to connect un/underserved counties. We augment the GIS-based approach described in §2.3 with other analysis capabilities in ArcGIS and QGIS to identify new deployment locations. Specifically, for this scenario, we leverage the *hub distance* tool in MMQGIS [26] to identify a number of locations that do not have any connectivity and that could be cost-effectively connected to other areas with connectivity in Figures 3. By using the infrastructure availability map as input to the hub distance tool, we create hubs in green polygons which serve as the deployment location for MSANs. These MSAN locations are connected to the nearest red polygon, which indicates the absence of connectivity.

Since all the identified hub-locations cannot be connected, as it is impractical in terms of cost, we apply our techno-economic framework to maximize connectivity with minimum deployment costs for a given deployment budget. For this scenario, we assume that the cost[4] of an MSAN is $100K and that the telephone and cable networks are available in all the un/underserved areas. We also assume that the cost to connect a household with a modem is $25 and that the cost to connect network access points in underserved regions to the households in every region is negligible. So, the cost to connect a region using this scenario is simply the sum of MSAN costs at hubs divided by the number of counties sharing that hub plus the cost to install modems in every household in a region. We set the maximum deployment budget per location to be $100K.

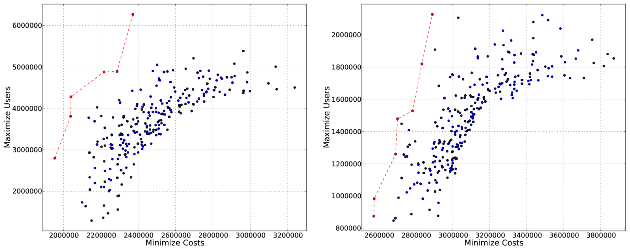

Figure 4. Deployment solutions produced by our framework for D1 (left) and D2 (right). The evolution (blue) and pareto front (red) of the solutions are also shown.

Figure 4 shows both the Pareto-optimal or non-dominated solutions (in red) and the evolution of these solutions (in blue) for this scenario. For example, based on our cost model for hub-based deployment, a little over than 4.2M users in all (red) counties in D1 can be connected at a cost of $2.2M. Note that all the Pareto-optimal solutions are also globally optimal solutions. By analyzing the tradeoff between the multiple objectives and depending on the deployment budget, the network operator can choose a particular solution to make an appropriate deployment decision.

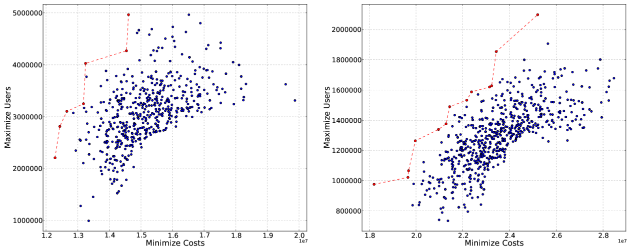

Figure 5. Deployment solutions produced by our framework for D1 (left) and D2 (right). The evolution (blue) and pareto front (red) of the solutions are also shown.

Scenario2: Deploying new infrastructure. In this scenario, we assume that the service provider is considering building their own infrastructure in un/underserved areas by deploying fiber assets along the existing ROWs (*e.g.*, road and rail). We begin by layering the ROW shapefiles [8] on top of the infrastructure availability map and use spatial overlap capability to select only those ROW features that intersect with the regions that do not have any connectivity. Next, we use the *cost distance* capability in ArcGIS and create a low-cost minimum spanning tree of the ROW features to identify the new fiber ROW deployments. Figures 6-(left) and -(right) shows the ROW-based fiber deployments for datasets D1 and D2 respectively. As one might expect based on results in [8], the resulting infrastructure bears a striking resemblance to current fiber deployments.

Next, we apply our techno-economic framework to create a more optimized deployment scenario. For this scenario, we assume CAPEX cost of fiber per mile is $1500 and OPEX per mile per year is $300. So, the cost to connect a region is the sum of fiber miles multiplied by these costs. Our objective for this scenario is to minimize these costs. Figures 5 plots both the Pareto-optimal solutions (in red) and the evolution of these solutions (in blue) for the ROW-based fiber deployment

---

[4] All costs in our study are based on personal communication with network operators [27].

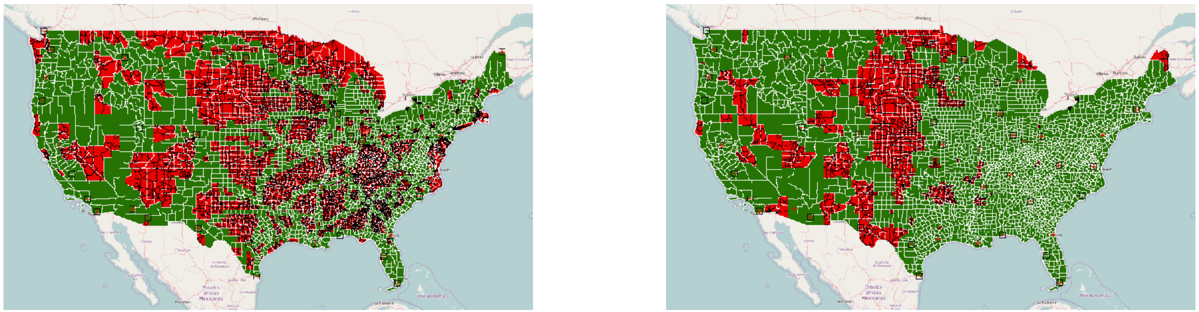

Figure 6. Spatial selection of counties using D1 (left) and D2 (right). New fiber-based ROW deployments are shown in black.

scenario. Based on our cost model for this scenario, a little less than 5M users in all (red) counties in D1 can be connected at a cost of about $14.5M.

Top 20 deployment targets. Based on the above two scenarios, we identified the following 20 counties based on its occurrence across both the scenarios. The counties include Niobrara, Lamar, Weston, Hot Springs, Foard, Crook, Coahoma, Washakie, Val Verde, Slope, Schleicher, San Juan, Roosevelt, Panola, Newton, Mono, Mercer, McDonough, Los Alamos, and La Paz. Unsurprisingly, these counties are rural areas that are predominantly located in states like Texas, Wyoming, North- and South-Dakotas—an observation consistent with prior work [28].

Validation with Connect America map. To validate our methodology for selecting deployment targets, we compare the regions identified by the FCC's Connect America Fund for phase II funding [10] and the ones identified by our framework. Specifically, we calculate the percentage of agreement between the FCC's accepted areas dataset and the counties identified by our analysis above. For D2 dataset, our framework has 86.62% agreement with that of the accepted areas (395 out of 456 counties). Similarly, for D1 dataset, 1405 out of 1521 counties (*i.e.*, 92.38%) identified by Connect America agrees with our analysis.

In short, these results, apart from validating our framework, shows that the funding attempt by Connect America is progressing in a way that is balancing deployment in areas with a large number of users with costs. Note that we see a higher percentage of agreement for D1 because counties listed by Connect America are based on long-haul providers, which is the main focus of D1 dataset. More broadly, we believe that this comparison highlights the utility of our framework and the potential for its application in other areas and under a wide variety of cost/impact assumptions.

5. RELATED WORK

Understanding the Internet penetration rate and its economic impact has been a subject of inquiry for the last two decades [1–3]. These studies consistently conclude that Internet connectivity at broadband speeds is essential for growth and economic prosperity. Since the dot-com bubble, several efforts studied the Internet adoption rate in un/underserved areas, both empirically [29] and qualitatively [28], and found several interesting rate determining factors, including gender [30, 31], age [32] and race [33]. Even though these factors influence Internet penetration to some extent, key determinants like availability of telecom infrastructure, federal regulations and economic affordability play a significant role in closing the digital divide in un/underserved areas [34, 35]. Finally, several research projects have proposed paradigms [36], technologies (both traditional [37] and alternative [38]) and approaches [39] for improving Internet penetration in un/unserved communities.

Determining target areas for infrastructure deployment and optimizing deployment costs are two key components of our framework. While we take a GIS-based approach similar to prior efforts [40, 41] for the former, we use insights from Ranaweera *et al.* [42] for various cost optimizations (*e.g.* upgrading existing infrastructure) to address the latter. We argue that our framework offers the ability to assess technological and economic tradeoffs in deploying or upgrading infrastructure in a way that has not been considered in these prior studies.

6. SUMMARY AND FUTURE WORK

In this paper, we consider the problem of identifying target areas for network infrastructure deployment in un/underserved areas. Our techno-economic approach applies geo-based multi-objective optimization to find the areas with the highest concentration of un/underserved users at the the lowest cost to service providers. We demonstrate the efficacy of our methodology by considering physical infrastructure and demographic data for US counties along with deployment cost models that include upgrading existing infrastructure and deploying new infrastructure. While we do not argue that the quantitative aspects of our cost models are representative of any specific service provider, our results identify a list of counties that would be attractive targets for broadband deployment and that correspond closely with those already identified for future deployments in the US.

In on-going work, we are considering how to enrich our model to provide details that can catalyze infrastructure deployments on multiple geographic levels. This would accommodate underserved users in areas that may not otherwise be overlooked. More broadly, we believe that our framework can be applied in areas beyond the US that have limited or different types of data that could provide insights on deployment opportunities. We also argue that while our framework is currently focused on un/underserved areas, it could also be used to consider other business needs of service providers including identifying new market opportunities.

Acknowledgements

We thank Rodney Heil and Anton Kapela for their feedback and helpful discussions. This material is based upon work supported by the DHS grant BAA 11-01 and AFRL grant FA8750-12-2-0328. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the author and do not reflect the views of the DHS or AFRL.

References

[1] R. W. Crandall, W. Lehr, and R. E. Litan, *The Effects of Broadband Deployment on Output and Employment: A Cross-sectional Analysis of US Data*. Brookings Institution, 2007.
[2] R. Katz, "The Impact of Broadband on the Economy: Research to Date and Policy Issues," *Broadband Series*, 2012.
[3] N. Czernich, O. Falck, T. Kretschmer, and L. Woessmann, "Broadband Infrastructure and Economic Growth," *The Economic Journal*, 2011.
[4] "FCC BroadBand Plan." https://www.fcc.gov/general/national-broadband-plan.
[5] "FCC BroadBand Progress." https://www.fcc.gov/reports-research/reports/broadband-progress-reports/eighth-broadband-progress-report.
[6] "Connect America." https://www.fcc.gov/general/connect-america-fund-caf.
[7] "GAO Report." http://www.gao.gov/assets/670/662711.pdf.
[8] R. Durairajan, S. Ghosh, X. Tang, P. Barford, and B. Eriksson, "Internet Atlas: A Geographic Database of the Internet," in *ACM HotPlanet*, 2013.
[9] R. Durairajan, P. Barford, J. Sommers, and W. Willinger, "InterTubes: A Study of the US Long-haul Fiber-optic Infrastructure," in *ACM SIGCOMM*, 2015.
[10] "Connect America Accepted Areas." https://www.fcc.gov/reports-research/maps/caf-2-accepted-map.
[11] "2014 Provider Dataset from `broadbandmap.gov`," http://www.broadbandmap.gov/data-download.
[12] "2014 Population Dataset from `census.gov`," http://www.census.gov/popest/data/counties/totals/2014/CO-EST2014-alldata.html.
[13] "Population Estimates from `census.gov`," http://www.census.gov/newsroom/press-releases/2014/cb14-tps90.html.
[14] "2016 Broadband Progress Report by FCC." https://www.fcc.gov/reports-research/reports/broadband-progress-reports/2016-broadband-progress-report.
[15] "ESRI ArcGIS." https://www.arcgis.com/features/.
[16] T. Koopmans and M. Beckmann, "Assignment Problems and the Location of Economic Activities," *Econometrica*, 1957.
[17] F.-A. Fortin, D. Rainville, M.-A. G. Gardner, M. Parizeau, C. Gagné *et al.*, "DEAP: Evolutionary Algorithms Made Easy," *JMLR*, 2012.
[18] K. Deb, A. Pratap, S. Agarwal, and T. Meyarivan, "A Fast and Elitist Multiobjective Genetic Algorithm: NSGA-II," *IEEE TEC*, 2002.
[19] "IEEE 802.16 standard." https://standards.ieee.org/about/get/802/802.16.html.
[20] "Facebook Developing Radio Wave Mesh to Connect Offline Areas," https://thestack.com/cloud/2016/02/10/facebook-developing-radio-wave-mesh-to-connect-offline-areas/.
[21] "The Li-fi technology," http://www.ted.com/talks/harald_haas_a_breakthrough_new_kind_of_wireless_internet.
[22] "Google's Project Loon," https://www.google.com/loon/where/.
[23] "Facebook's Connectivity Lab," https://info.internet.org/en/story/connectivity-lab/.
[24] "Satellite Deployment Costs." http://www.globalcomsatphone.com/hughesnet/satellite/costs.html.
[25] "List of PLC manufacturers." https://en.wikipedia.org/wiki/List_of_PLC_manufacturers.
[26] "MMQGIS. Hub-distance capability." http://michaelminn.com/linux/mmqgis/.
[27] "Network Operators." Personal Communication, 2016.
[28] "Mapping the Digital Divide." https://www.whitehouse.gov/sites/default/files/wh_digital_divide_issue_brief.pdf.
[29] D. J. Aron and D. E. Burnstein, "Broadband Adoption in the United States: An empirical analysis," *Down to the Wire: Studies in the Diffusion and Regulation of Telecommunications Technologies, Allan L. Shampine, ed*, 2003.
[30] A. Rickert, A. Sacharow *et al.*, "It's a Woman's World Wide Web," *Media Metrix and Jupiter Communications*, 2000.
[31] L. Rainie, S. Fox, J. Horrigan, A. Lenhart, and T. Spooner, "Tracking Online Life: How Women Use the Internet to Cultivate Relationships with Family and Friends," *Washington, DC: The Pew Internet and American Life Project*, 2000.
[32] I. Austen, "Studies Reveal a Rush of Older Women to the Web." *The New York Times.*, 2000.
[33] G. L. Rohde, R. Shapiro *et al.*, "Falling Through the Net: Toward Digital Inclusion," *US Department of Commerce*, 2000.
[34] M. D. Chinn and R. W. Fairlie, "The Determinants of the Global Digital Divide: A Cross-country Analysis of Computer and Internet Penetration," *Oxford Economic Papers*, 2007.
[35] D. M. West, "Digital Divide: Improving Internet Access in the Developing World through Affordable Services and Diverse Content," *Brookings Institution*, 2015.
[36] A. Sathiaseelan and J. Crowcroft, "LCD-Net: Lowest Cost Denominator Networking," *ACM SIGCOMM CCR*, 2013.
[37] C. O. Rodriguez, "Affordable Wireless Connectivity Linking Poor Latin American Communities Binding Their Schools by Sharing ICT Training for "Maestros" of Primary Schools," in *Internationalization, Design and Global Development*, 2009.
[38] J. Saldana, A. Arcia-Moret, B. Braem, E. Pietrosemoli, A. Sathiaseelan, and M. Zennaro, "Alternative Network Deployments. Taxonomy, Characterization, Technologies and Architectures," IETF Internet Draft, Tech. Rep., 2015.
[39] L. Townsend, A. Sathiaseelan, G. Fairhurst, and C. Wallace, "Enhanced Broadband Access as a Solution to the Social and Economic Problems of the Rural Digital Divide," *LE*, 2013.
[40] G. Cai, "A GIS Approach to the Spatial Assessment of Telecommunications Infrastructure," *NSE*, 2002.
[41] M. Sawada, D. Cossette, B. Wellar, and T. Kurt, "Analysis of the Urban/Rural Broadband Divide in Canada: Using GIS in Planning Terrestrial Wireless Deployment," *GIQ*, 2006.
[42] C. Ranaweera, P. Iannone, K. Oikonomou, K. C. Reichmann, and R. Sinha, "Cost Optimization of Fiber Deployment for Small Cell Backhaul," in *NFOEC*, 2013.