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An Analysis of Broadband Accessibility at the County Level in the United States: a Spatial Analytical Approach Using GIS

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미국 카운티의 초고속 인터넷 서비스에 대한 접근성 분석: GIS를 이용한 공간 분석적 접근

이건학*

Abstract : As demand for high speed Internet service has explosively increased in the United States for the past decade, the construction or upgrades of telecommunication infrastructure has also been rapidly followed. Though currently many people in urbanized areas can be provided advanced broadband services, there are still challengeable areas to be served, such as remote or low populated areas because those areas are potentially non-profitable to commercial broadband service providers. This paper addresses the spatial disparity or in a broader term, the 'digital divide' of the broadband access by the county level in the United States. We propose the quantified measure of the county level broadband accessibility for identifying such digital divide. The developed measure is a hybrid form of the classical gravity based potential model and network topological accessibility, encouraged from the lack of prior efforts trying to explicitly incorporate the understanding of the whole process of the Internet access. The computational tasks are performed in a GIS platform, which includes several programmed functions.

Key Words : broadband accessibility, digital divide, gravity based potential model, network topological measure, GIS

요약 : 지난 10여년간, 미국의 초고속 인터넷 서비스에 대한 수요가 폭발적으로 증가함에 따라, 정보통신 인프라의 신축 및 업그레이드 또한 빠르게 진행되었다. 비록 현재 도시화된 지역들의 많은 사람들이 고급 인터넷 서비스를 이용할 수 있지만, 원거리 또는 소규모 인구 지역과 같은 곳은 상업적 인터넷 서비스 공급자들에게 잠재적으로 이윤을 창출해 주지 못하기 때문에, 여전히 서비스에 대한 접근이 제한되고 있다. 이 연구는 미국 카운티에 따른 초고속 인터넷 서비스에 대한 접근의 공간적 불균형, 보다 광범위한 개념으로, '정보 격차' 에 대해서 다루고 있으며, 이러한 공간적 현상을 규명하기 위해 카운티에 따른 인터넷 접근성의 계량적 측정 모델을 제안하고 있다. 개발된 측정 모델은 전통적인 중력 모형 기반의 잠재력 모델과 네트워 위상적 측정을 혼합함으로써 인터넷 서비스의 전반적 프로세스에 대한 이해를 명시적으로 포괄하고 있다. 접근성 측정을 위한 일련의 계산들은 GIS플랫폼에서 여러가지의 프로그램된 기능들을 통해 이루어졌다.

주요어 : 인터넷 접근성, 정보 격차, 중력 모형 기반의 잠재력 모델, 네트워 위상적 측정, GIS

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1. Introduction

For the past decade, the rapid growth of demand for high speed Internet access, often called a broadband access[1], has accelerated the establishment and upgrade of the telecommunication infrastructure in the United States. Despite enormous expansion of telecommunication infrastructure, uneven access to broadband service has been observed at different demographic and socioeconomic levels (Gabel and Kwan, 2001; Prieger, 2003; Strover, 2003a). More recently, many studies have focused on the spatial aspect of such inequality of broadband access and provided empirical evidences at various geographic levels such as local, regional, and national geography. A common conclusion from analyses is that spatially unequal access to broadband service indeed exists due to the uneven spatial distribution of existing infrastructure and physical limits of broadband technologies currently available[2].

However, there is little work found to examine broadband service access by incorporating the topological structure of telecommunication network. In general, the access to broadband service begins from residential and business locations to broadband facilities locally identified via a ground wires or wirelessly and then data transmitted is routed to national backbone structure, and finally reaches targeted destinations. Geographically, this whole process of digital flow is essentially related to a broader spectrum from local to national geography. Previous studies, however, have focused on only one specific level of network structure and its related geographic level. For example, O'Kelly and Grubesic (2002) examined the spatial distribution of backbone infrastructure in the United States and discussed the access at a city level.

Evaluating the level of access to broadband service of a given location can be effectively benefited from developing a comparative indicator, referred to as an accessibility index. The concept of accessibility has been widely used in both private and public sectors such as retail facility or service, industrial headquarter, emergency services, and other urban opportunities. Measuring accessibility is useful to examine and evaluate the potential of access to opportunities available. Typically accessibility depends on the magnitude of opportunities and their qualities (O'Kelly and Horner, 2003). However, opportunity's quality might be differently defined from an application to another. For instance, the characterizing factors of a shopping center would differ from factors of critical telecommunication infrastructure in nature.

This paper addresses broadband accessibility regarding a two-tier hierarchical structure of telecommunication network at a county/MSA (Metropolitan Statistical Area) level in the Unites States. For measuring accessibility of each county, we develop a hybrid form of potential accessibility model and network topological measures. The remaining of the paper is organized as follows. Section 2 discusses some theoretical background. In Section 3, the broadband accessibility measure is developed. In Section 4, by using the developed measure, we compute the county level accessibility to broadband service using GIS (Geographic Information Systems). Finally, we conclude the paper by summarizing results and discussing implications.

2. Background

1) Spatial construction of the digital divide

Recently, the term 'digital divide' has been broadly used to describe the gaps in information technology access or digital communication (NTIA, 1999). The digital divide has been found from a variety of socioeconomic and demographic perspectives (Servon, 2002; Strover, 2003b; van Dijk and Hacker, 2003; Warschauer, 2003). The inequality of access to telecommunication service, particularly, broadband service, has been also considerably observed in geography as well. Since most of the commercial Internet service providers are privatized and profit seeking (O'Kelly and Grubesic, 2002), they are not willing to invest on upgrading or establishing their infrastructure in unprofitable areas such as low density and remote rural areas. This economic behavior is quite obvious for facility based and capital intensive broadband service (Strouse, 2004). Also, technological limitation of broadband service such as geographic limit of service coverage (e.g., the provision of guaranteed 1.5Mbps (megabit per second) bandwidth within 18,000 feet from the central office for DSL service[3]) makes telecommunication infrastructure more concentrated at highly populated urban centers. This uneven distribution of telecommunication infrastructure yields spatially unavailable areas for broadband service. Gorman and Malecki (2000) and Wheeler and O'Kelly (1999) identified the digital divide at the regional/national level. Moss and Townsend (1998) also presented the uneven distribution and complex hierarchy of backbone infrastructure in the Unites States utilizing spatial distribution of Internet domain registration. Malecki and Boush (2003) showed rural and urban variation using the central office switch capability at the regional level. From a local geographic perspective, Grubesic and Murray (2002) showed the empirical evidence of spatial disparity of residential DSL broadband access and provided an insight to the spatial construction of digital divide.

2) Accessibility measures

For examining and evaluating urban transportation systems, land use patterns, and access to other facilities or opportunities in both public and private domains, traditionally comparative measurement, often called a accessibility, has been widely used (Church and Marston, 2003; Dalvi and Martin, 1976; Davidson, 1977; Hanson and Schwab, 1987; Kwan, 1998; Murray and Wu, 2003; O'Sullivan et al., 2000). However, the concept of accessibility is hardly defined and is often defined as an operationalized form according to different perspectives and contexts of applications (Dalvi and Martin, 1976; Kwan, 1998). Though there is rarely shared consensus on the definition of accessibility, the following measures are frequently used to calculate accessibility: cumulative opportunity measure, potential accessibility, utility based accessibility, network topological measure, and space-time constrained accessibility. A cumulative opportunity measure quantifies the number of opportunities within a certain distance (Hanson and Schwab, 1987; Ingram, 1971; Wachs and Kumagai, 1973). A potential accessibility, which is based on the spatial interaction model (or gravity model), is measured by summing all possible interactions between a particular area and opportunities (Hansen, 1959; Harris, 1954). A utility based accessibility assumes that people make their choices in a manner of maximizing net benefit or utility. Miller (1999) shows a framework for measuring utility based accessibility within transportation networks. Under the consideration

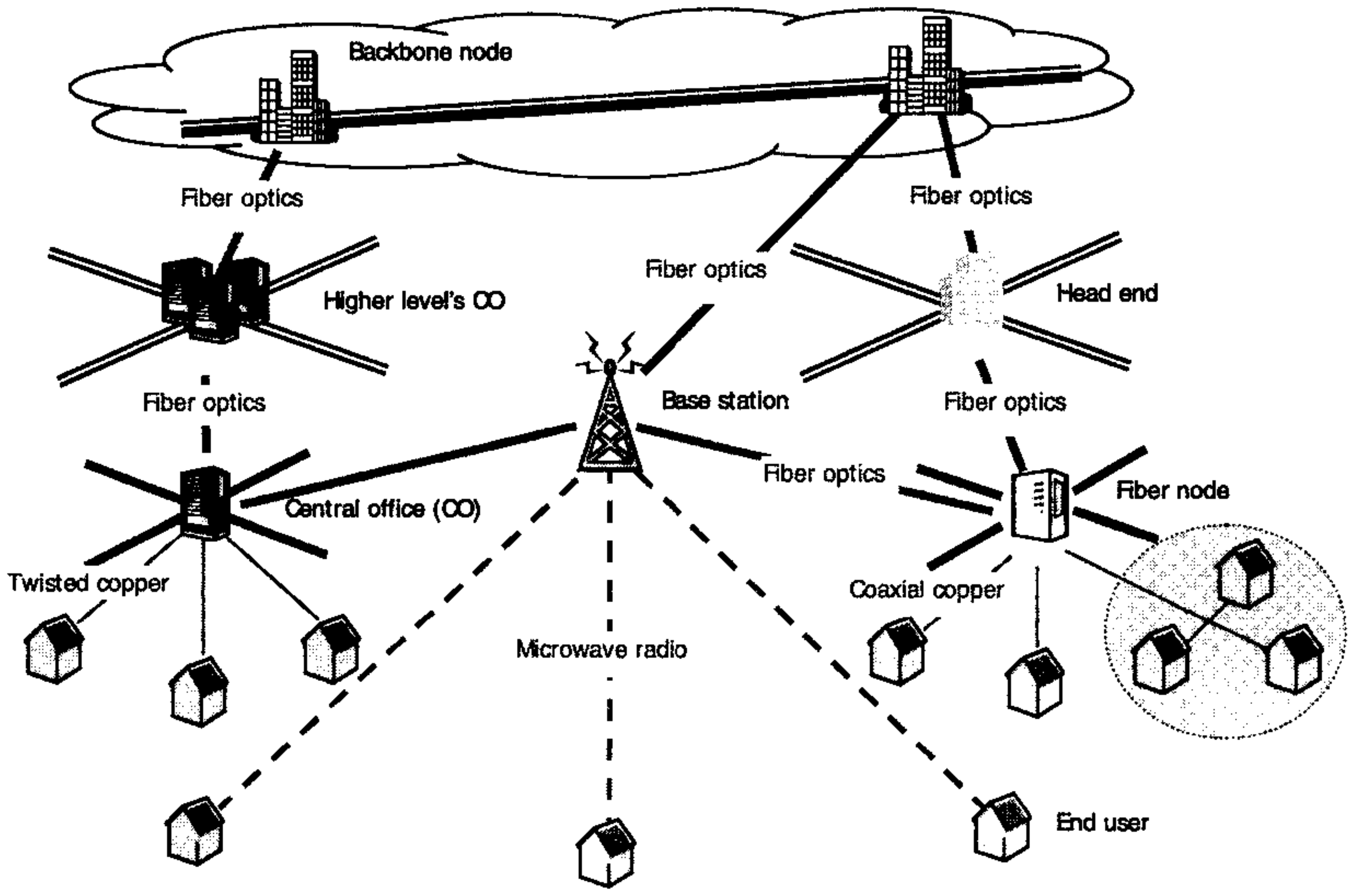


Figure 1. Topological structure of broadband access

(From left, DSL, fixed wireless, and cable broadband services, referenced by Bhagavath (1999) , Bisdikian (1996), O'Donnell (2001), and Webb (2001))

of network representation, a topological measure can be benefited from graph theory. Wheeler and O'Kelly (1999) and O'Kelly and Grubesic (2002) investigate a city and regional level accessibility on the basis of commercial Internet backbone infrastructure in the United States utilizing several network topological measures. A space-time constrained measure, which is more recently introduced by several authors (Kwan, 1998; Miller, 1991), utilizes a space-time framework (H?gerstrand, 1970).

3) Topological structure of broadband service

The structural feature of telecommunication network is very complex because the Internet consists of 'clouds' with a variety of networks. Thus the Internet is often referred to as a 'network of networks.' Though the Internet is described as an amorphous clouds, it has a distinctive physical structure and hierarchy (Gorman and Malecki, 2000). Telecommunication network topology can be classified in different ways. The most commonly used way is to separate telecommunication network into two hierarchical structures. One is the structure between end users or terminals and concentrators (e.g. telephone central office or cable company head end). The other is the structure between concentrators and central units or a part of the backbone infrastructure. Particularly, the former is often called a 'last mile' or 'local access' which indicates the first connection from user premise to broadband service provider. The latter is referred to as a 'backbone structure.' (Cai, 2002; Klincewicz, 1998). Each structure in telecommunication network consists of the different types of network topology such as a centralized star, a tree, path, or loop. Thus the whole network topology can be classified by various combinations according to topological relationship for each part. Figure 1 demonstrates simplified Internet access topology under several local access technologies (e.g., DSL, cable broadband, and fixed wireless).

3. A county level accessibility measure for broadband service

Based on discussion above, we develop a county level broadband accessibility index incorporating broadband network topological structure locally and nationally indicated from a geographical standpoint.

The suggested measure takes a hybrid form of spatial interaction based potential accessibility and network topological measures. Generally, the potential accessibility is a useful indicator when it comes to the potential of a demand area to access to opportunities available by evaluating the access to each individual opportunity and summing all. Moreover, the access of a demand area to an individual opportunity is alternatively measured using the spatial interaction between them. The noticeable benefit from the use of interaction form is that a number of characterized attributes for attracting and impeding factors influencing accessibility can be summarized as a single measurement. The conventional potential accessibility measure of a demand area i is defined as follows:

$$A_i=\sum_j I_{ij} \qquad (1)$$

where I_{ij} is the spatial interaction between a demand area i and an opportunity j.

The spatial interaction, I_{ij} is typically expressed as a function of the attracting and impeding factors as follows:

$$I_{ij}=O_iM_jf(d_{ij}) \qquad (2)$$

where O_i is a pushing attribute of a demand area i; M_j is a pulling attribute of an opportunity j; $f(d_{ij})$ is the function of the distance between demand node and opportunity.

In general, the interaction is proportional to attracting factors such as O_i and M_j, and inversely proportional to impeding factors such as spatial separation between a particular area and an opportunity, represented as $f(d_{ij})$. As indicated in the equation (2), attracting factors are positively influencing the interaction, but the distance has a negative effect on the interaction. Although a variety of functional forms have been used to represent the distance effect on the interaction, negative power ($f(d_{ij})=d_{ij}^{-\beta}$) or exponential ($f(d_{ij})=\exp(-\beta d_{ij})$) functions are most commonly used (Kwan, 1998). The parameter β indicating the sensitivity of distance decay on the interaction is often empirically estimated (O'Kelly, 1987; O'Kelly and Horner, 2003). By simply putting the equation (2) into the equation (1), the accessibility measure of a demand area i is rewritten as follows:

$$A_i=\sum_j O_iM_jf(d_{ij}) \qquad (3)$$

In the context of broadband service application, the broadband accessibility can be regarded as the relative potential of locally located spatial units (i.e., county) for the access to the Internet backbone infrastructure which is present at a regional level. Since the spatial unit in this paper is a county in the United States; thereby population is aggregated in a county, the local access structure of broadband service in the local geography, indicating the first connection from user and transmitter, is hard to be represented and resolved for measuring accessibility. Alternatively, the level of access of individual users to locally positioned broadband facilities as opportunities must be aggregated in a county level with an appropriate proxy. The spatial interaction model provides a formal way to incorporate this local access structure in the formulation. The pushing factor with positive influence on accessibility O_i can contain the aggregated measurement of a county. By focusing on the local geographies of the Internet activity, Grubesic (2002) pointed out from multiple regression analysis that household density, median income, urbanized area, and the presence of college or university are statistically significant components on the Internet activity represented as the number of domain registrations for each zip code, particularly in the state of Ohio. By utilizing such proxies of a pushing factor for each county, we define a pushing factor of a county *i* as a linear combination of such contextual variables as follows:

$$O_i = aHD_i + bMI_i + cUB_i + dUV_i \tag{4}$$

where *HD*, *MI*, *UB*, and *UV* indicate household density (total households per square kilometer), median household income (dollars), urbanized area (zero-one dummy variable), and the presence of college or university (zero-one dummy variable), respectively; Parameters, *a*, *b*, *c*, and *d* denote their corresponding weights.

Since the first connection from end-users to the Internet requires an immediate connection to the national backbone infrastructure through the POPs (Points Of Presence[4]) for a long-haul transmission, the backbone infrastructure is also substantially important for the entire access to broadband service. Particularly, a backbone POP, usually interconnected via fiber optics, will be regarded as the opportunity of broadband infrastructure. The measure of accessibility incorporates the access from each county to locations of POPs in networks as another tier of topological structure at a regional level. The pulling factor in the spatial interaction model will represent attractiveness or quality of each backbone POP. In fact, attractiveness of a backbone node is essentially associated with network performance. Network performance can be indirectly evaluated using several topological properties largely benefited from graph theory. In this paper, we utilize the following topological measures of individual node: the degree of node, total accessibility, the shortest path step, and clustering coefficient.

Suppose a network made up of a set of nodes (e.g., backbone POP) and links (e.g., fiber optics). The degree of node depicts a simpler nodal accessibility indicating the number of 1-step connections of a particular node. This measure can be easily computed by summing direct connections from a node in the adjacency matrix[5], **C**. The degree of a node *j*, Q_j can be stated as follows:

$$Q_j = \sum_l c_{jl} \tag{5}$$

where c_{jl} is the cell entry of *j* row and *l* column in the adjacency matrix, **C**.

Total accessibility, namely **T**-matrix, indicates total number of ways of moving from a node to every node via direct or multiple step paths. By considering indirect connection and multiple step paths, it will be a useful proxy of network redundancy ensuring alternative routings. This is particularly important when backbone network becomes congested (O'Kelly and Grubesic, 2002). Higher degree of total accessibility is desirable for measuring an opportunity's attractiveness. Total accessibility, can be expressed in a matrix form as follows:

$$T_j = \sum_k \mathbf{C}^k = \sum_k \sum_l c_{jl}^k \tag{6}$$

where *k* is the power of matrix multiplication.

According to the equation (6), $\mathbf{C}^2$ is derived from $\mathbf{C}^1 \times \mathbf{C}^1$, where $\mathbf{C}^1$ is identical to the adjacent matrix, **C**. Basically matrix multiplication is the element by element multiplication of rows in one matrix by columns of another (Taaffe et al., 1996).

The shortest path step is a measure of the minimum number of steps (or hops) for a node to reach all other nodes. This measure is often called a Shimbel distance or **D**-matrix (Shimbel, 1953). **D**-matrix can be computed by powering the adjacency matrix, **C** to network's diameter[6]. From the **D**-matrix, the shortest steps of a node j, D_j can be easily calculated by simply summing all the shortest path steps to every other node. The equation (7) defines this measure.

$$D_j=\sum_{l} s_{jl} \tag{7}$$

where s_{jl} is the shortest path hops between nodes j and i.

The clustering coefficient indicates local interconnectivity by involving interconnection between neighboring nodes (Pastor-Satorras and Vespignani, 2004). Mathematically, the clustering coefficient for a node j, E_j is defined as follows:

$$E_j=\frac{2e_j}{n_j(n_j-1)} \tag{8}$$

where e_j is the number of edges among its immediately connected neighbors; n_j is the number of neighboring nodes of a node j; $n_j(n_j-1)$ is the maximum possible connections between neighboring nodes.

Based upon above topological measures, the pulling factor, M_j is written simply as a linear combination of topological measures as follows:

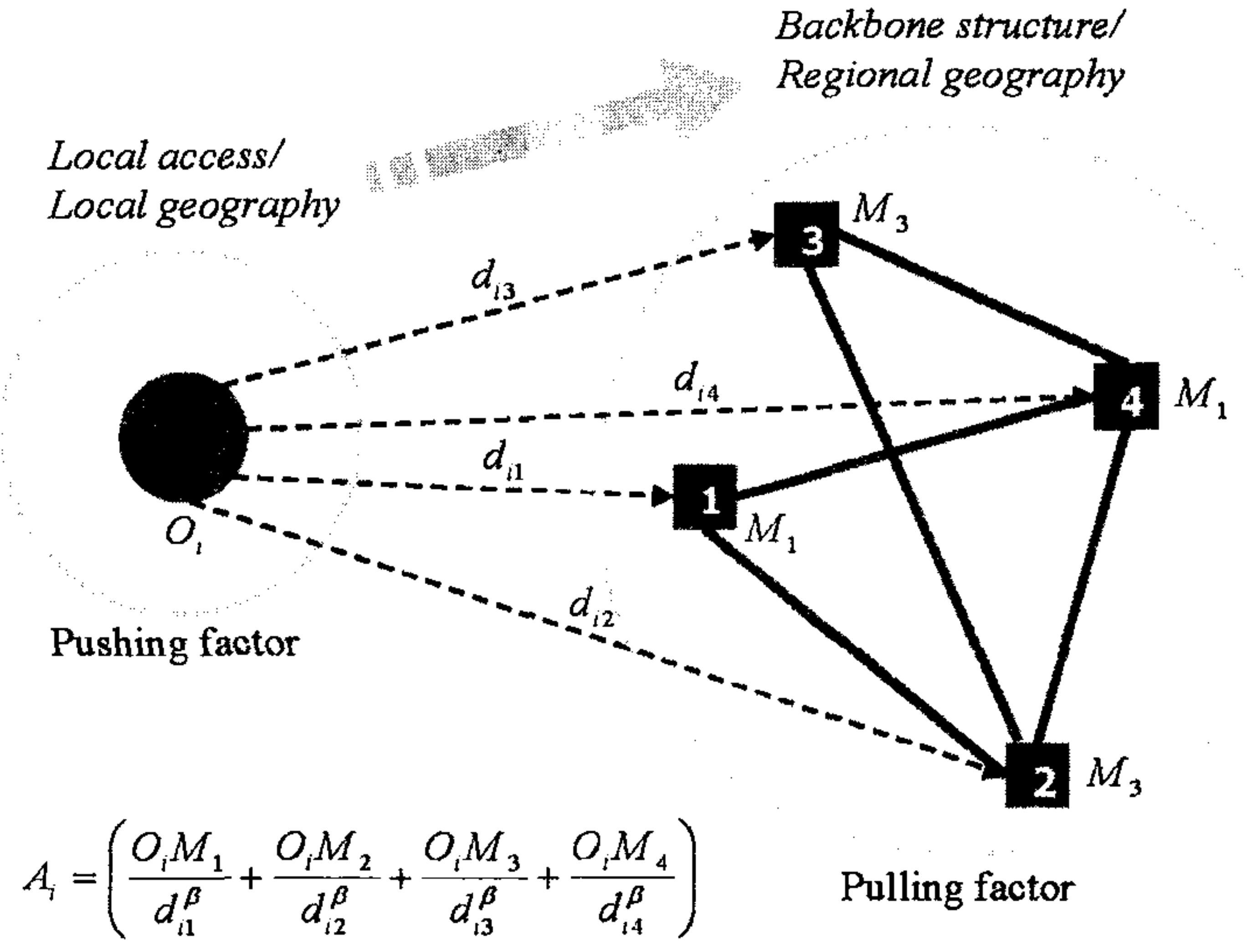
$$M_j=eQ_j+fT_j-gD_j+hE_j \tag{9}$$

where parameters, e, f, g, and h denote corresponding weights for network measures.

For broadband accessibility, the equation (3) is now re-expressed using a combined pushing factor of a county (Eq. 4) and a combined pulling factor of backbone POPs (Eq. 9) as below:

$$A_i=\sum_{j}[(aHD_i+bMI_i+cUB_i+dUV_i)(eQ_j+fT_j+g(\omega-D_j)+hE_j)(d_{ij}^{-\beta})] \tag{10}$$

The weights for attributes of a county are predefined as $a = 0.00417$, $b = 0.0814$, $c = 0.611$, and $d = 1.139$ following Grubesic's (2002) results. Not surprisingly, all involved variables effect positively on the Internet activity. This is what we can expect. Regarding coefficients in Eq. (9) showing the effect of each network measure on the pulling factor, e, f, g, and h are set to 1 in practice. Since the actual impact of the individual measures as well as any functional form of combined effects of network measures on attractiveness of infrastructure or overall network performance have not been found in previous literature, a linear combination of equally weighted variables might be an alternative way to easily capture unique contribution of each network measure. Note that smaller value of D_j means better network capability of a node, implying negative contribution to the pulling factor. Thus, a constant ω, which is large enough, is added to ensure consistency of positive contribution to M_j (Eq. 10). We define the distance decay function as a hypothesized negative power function ($d_{ij}^{-\beta}$) and the parameter of distance decay, β as 0.1 for simplicity of analysis. It is noted that digital signal transmission over fiber optics is relatively less influenced by physical distance than conventional copper wires. For example, while the copper wire based telecom services require repeaters or regenerators[7] spaced much closely (i.e., every 2-4 miles for voice signal), fiber optic is capable of



$$A_i = \left(\frac{O_i M_1}{d_{i1}^{\beta}} + \frac{O_i M_2}{d_{i2}^{\beta}} + \frac{O_i M_3}{d_{i3}^{\beta}} + \frac{O_i M_4}{d_{i4}^{\beta}} \right)$$

Figure 2. Illustration of measuring broadband accessibility

transmitting signals over distance 600 miles without a repeater or regenerator (Horak, 2002). That is, the digital signal will decrease along distance but is relatively less sensitive to distance for backbone infrastructure. Nevertheless, for estimating distance decay effect more realistically, it is required to examine digital signal attenuation through a physical medium, typically fiber optics using empirical digital flow data. Figure 2 illustrates a way of computing broadband accessibility measure graphically.

4. Empirical analysis

For analysis, the contextual variables for each county can be effectively available at the Census dataset[8] publicly released from the U.S. Census Bureau. For the acquisition of backbone network infrastructure data, it is noted that the backbone networks are mutually interconnected in general by means of a peering agreement[9] among Internet backbone providers (IBPs). This peering occurs typically at some city nodes, referred to Internet hubs, represented as IXs (Internet eXchange points)[10] including public NAP (Network Access Points), and private MAE (Metropolitan Area Exchanges). Though there are a large number of IBPs currently operating, it is difficult to obtain information of all network configurations and their peering (e.g., locations of nodes and topological linkages) because they are commercially sensitive and are change so frequently over time (O'Kelly et al., 2006). Alternatively, we examine backbone networks of the selected five IBPs (i.e., FNS, ICG, IDT, SAVVIS, and SERVINT) utilized in O'Kelly et al. (2006). From a practical standpoint, five backbone networks are merged depending on locations of IXs (certain cities) and peering for measuring network topological properties. Then the city nodes on merged network are regarded as the opportunities of broadband service for each county (backbone POP). All datasets described above are transformed into individual GIS layers. A number of standard GIS functionalities (e.g., distance calculation, overlay, buffer, and other spatial relationships) built in most commercial GIS software can help store, manipulate, and visualize spatial data in an efficient manner. However, standard GIS functions are not directly applied to the computation of several network measures and the developed accessibility model. Thus we incorporate the programmed modules for calculating network measures and accessibility scores using ArcObjects with VBA (Visual Basic for Application) embedded in ArcGIS 9.2 (ESRI).

Figure 3 demonstrates the merged backbone network and individual autonomous networks of selectively involved IBPs. Each of selected IBPs seems to have geographically national level of coverage spread across the entire United States. Overall configuration of merged network shows a great number of interconnections among backbone POPs, thereby making network topology more complicated. The backbone POPs are mainly located at major cities of MSA, to some extent having different levels of topological connectivity. This concentration of critical telecommunication infrastructure mostly at urbanized areas provides a brief snapshot of spatial uneven access to broadband service.

For measuring the accessibility for each county, it is important for the first step to take a look closely at the Internet activity of each county. Figure 4 shows the pattern of the Internet activity for each county using a standardized pushing factor combining household density, median household income, urban area, and the presence of higher education institutions. The spatial pattern of the Internet activity varies across counties. This is an evidence of the unequal access or the digital divide in a broader and more general term, according to different socioeconomic and demographic status. By briefly looking, the locations of backbone POPs seem to follow the distribution of the Internet activity. In other words, highly active counties are containing Internet hub cities or vicinity. This makes sense because commercial service providers will establish their infrastructure at highly service demanded areas from the

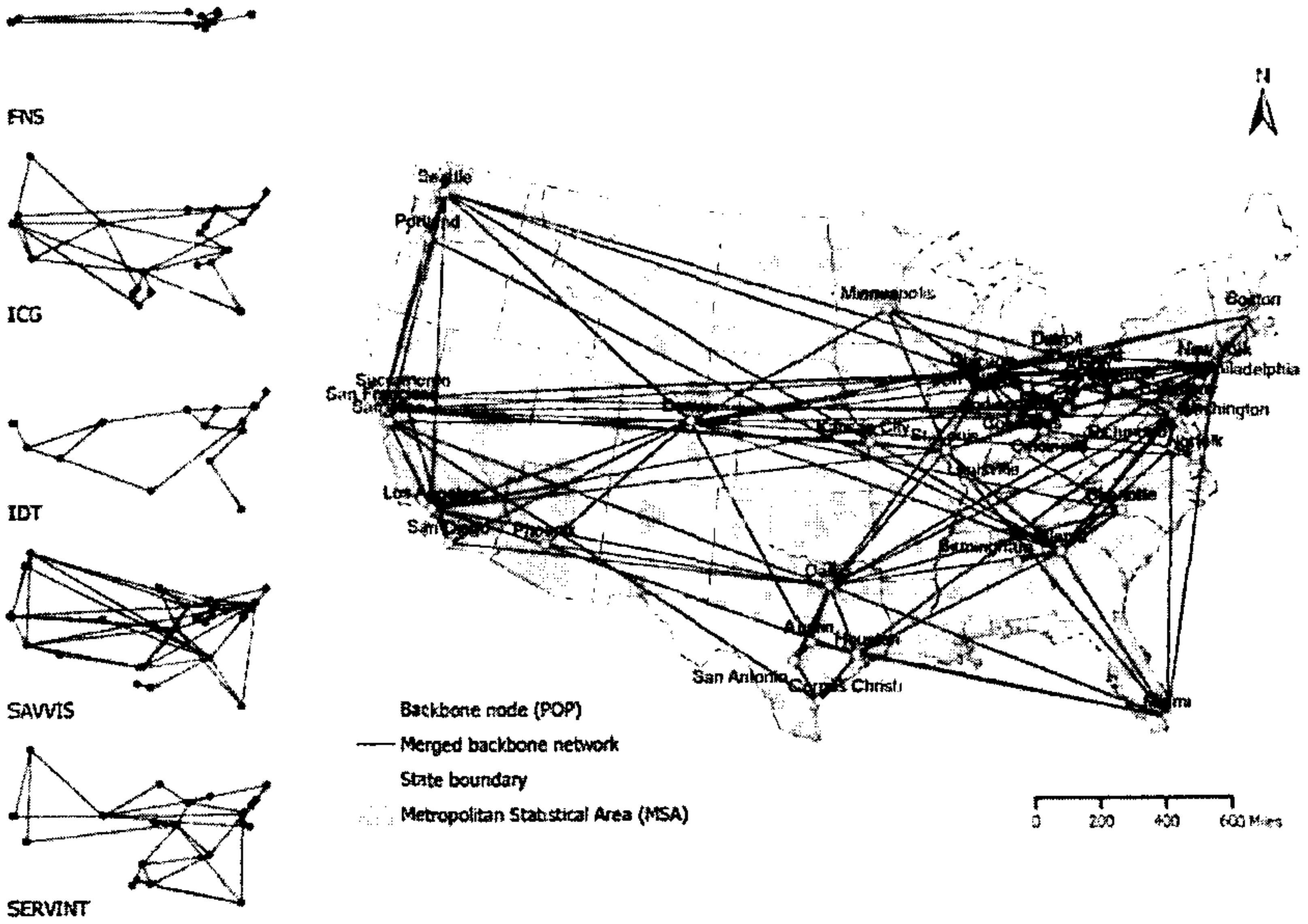


Figure 3. Transit backbone network and individual networks of the selected IBPs

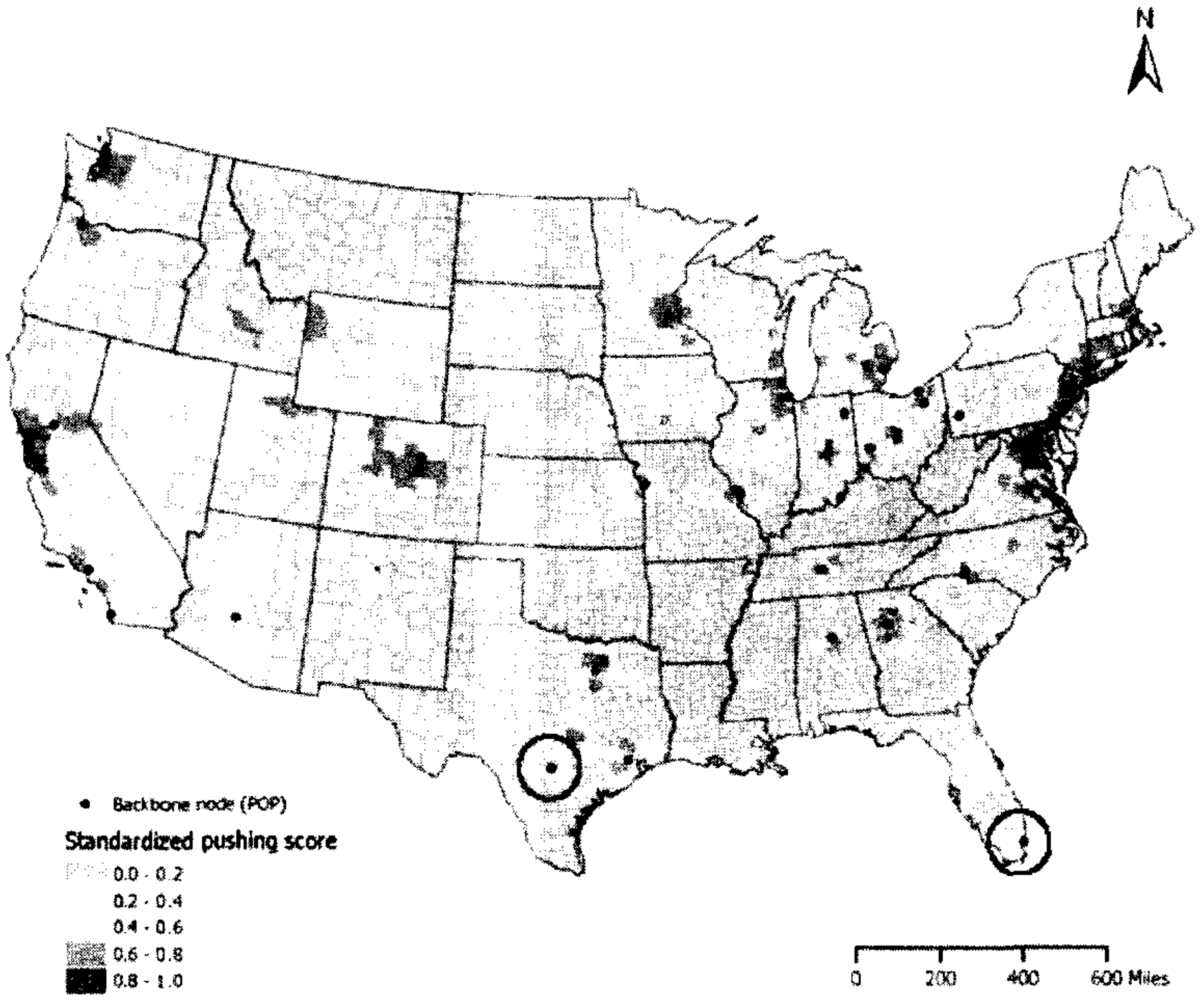


Figure 4. Spatial distribution of the Internet activity by county

economic sense. Interestingly, some Internet hub cities (circled ones) at the Southern U.S. are located at somewhat less attractive counties. However, those cities might be critical locations for IBPs as intermediate nodes to expand their cross-sectional service coverage from the East to West. Also, they are likely to provide services to the Southern U.S. This becomes more obvious when looking at network connections in Figure 3.

Table 1 presents the top 30 counties in terms of the Internet activity. As expected, all counties listed in Table 1 are placed within MSA. Regarding the distribution of MSA, MSAs containing two more highly active counties are San Francisco CA, Atlanta GA, Chicago IL, Minneapolis-St. Paul MN-WI, Middlesex-Somerset-Hunterdon NJ, New York NY, and Washington DC-MD-VA-WV. Geographically, it looks broadly dispersed pattern over the entire U.S. but even more concentrating at the Northeast. Noticeably, Washington DC-MD-VA-WV contains 23% of the top 30 counties, implying the largest potential demand to broadband opportunities. Interestingly, the highest ranked county is Douglas (Denver CO MSA) in the West. This makes sense when looking closely at demographic characteristics. According to the Census 2000, Douglas has relatively higher household density (28.3 households per square kilometer) and remarkably the highest median household income ($82,929) in the United States as well.

Considering network topological characteristics, Figure 5 and Table 2 present the city/regional level accessibility using a combined pulling score for the opportunity. From the visual inspection, most accessible cities such as Dallas (TX), Chicago (IL), Atlanta (GA), New York (NY), and Denver (CO) seem to be representative infrastructure for each regional division given network configuration. Surprisingly, traditional centrality of cities in the Northeast is not apparent. Only New York (NY) in the Northeast is positioned at high ranking. Rather the cities in

Table 1. Internet activity ranking for the top 30 counties

Rank	County	State	MSA	Pushing score
1	Douglas	Colorado	Denver CO	1.000
2	Fairfax	Virginia	Washington DC-MD-VA-WV	0.978
3	Loudoun	Virginia	Washington DC-MD-VA-WV	0.973
4	Hunterdon	New Jersey	Middlesex-Somerset-Hunterdon NJ	0.963
5	Los Alamos	New Mexico	Santa Fe NM	0.953
6	Morris	New Jersey	Newark NJ	0.933
7	Somerset	New Jersey	Middlesex-Somerset-Hunterdon NJ	0.928
8	Falls Church	Virginia	Washington DC-MD-VA-WV	0.904
9	Santa Clara	California	San Jose CA	0.897
10	Howard	Maryland	Baltimore MD	0.895
11	Putnam	New York	New York NY	0.872
12	Nassau	New York	Nassau-Suffolk NY	0.869
13	Montgomery	Maryland	Washington DC-MD-VA-WV	0.863
14	Marin	California	San Francisco CA	0.860
15	Fayette	Georgia	Atlanta GA	0.859
16	Hamilton	Indiana	Indianapolis IN	0.857
17	San Mateo	California	San Francisco CA	0.854
18	Collin	Texas	Dallas TX	0.854
19	Williamson	Tennessee	Nashville TN	0.833
20	Forsyth	Georgia	Atlanta GA	0.831
21	Rockland	New York	New York NY	0.820
22	DuPage	Illinois	Chicago IL	0.819
23	Fairfax City	Virginia	Washington DC-MD-VA-WV	0.816
24	Livingston	Michigan	Ann Arbor MI	0.813
25	Delaware	Ohio	Columbus OH	0.811
26	Lake	Illinois	Chicago IL	0.808
27	Stafford	Virginia	Washington DC-MD-VA-WV	0.806
28	Scott	Minnesota	Minneapolis-St. Paul MN-WI	0.803
29	Washington	Minnesota	Minneapolis-St. Paul MN-WI	0.800
30	Prince William	Virginia	Washington DC-MD-VA-WV	0.799

the Midwest, West, and South have more competitive advantages. More specifically, the cities in the West like Los Angeles and Seattle are less accessible than cities in the Midwest and South. As shown in Table 2, Dallas (TX) is the most accessible city top-ranked in all network measures except **D**-matrix. Dallas has total 14 direct connections to other cities and contains 7,984 either direct or indirect routing paths, indicating the provision of more redundant network routing. Chicago (IL) has the first ranking in both degree and **D**-matrix. As indicated in the **D**-value, the minimum number of hops for Chicago (IL) to reach all other cities is 64. Interestingly, Denver (CO) seems to be benefited from the intermediate location. Its degree is 13 (3rd rank) and **D**-matrix value is 67 (2nd rank tied with Dallas and New York). From overall looking, the top 5 cities in a combined accessibility are retained in all involved network measures but Denver (CO) has relatively lower **T**-matrix ranking and clustering coefficient.

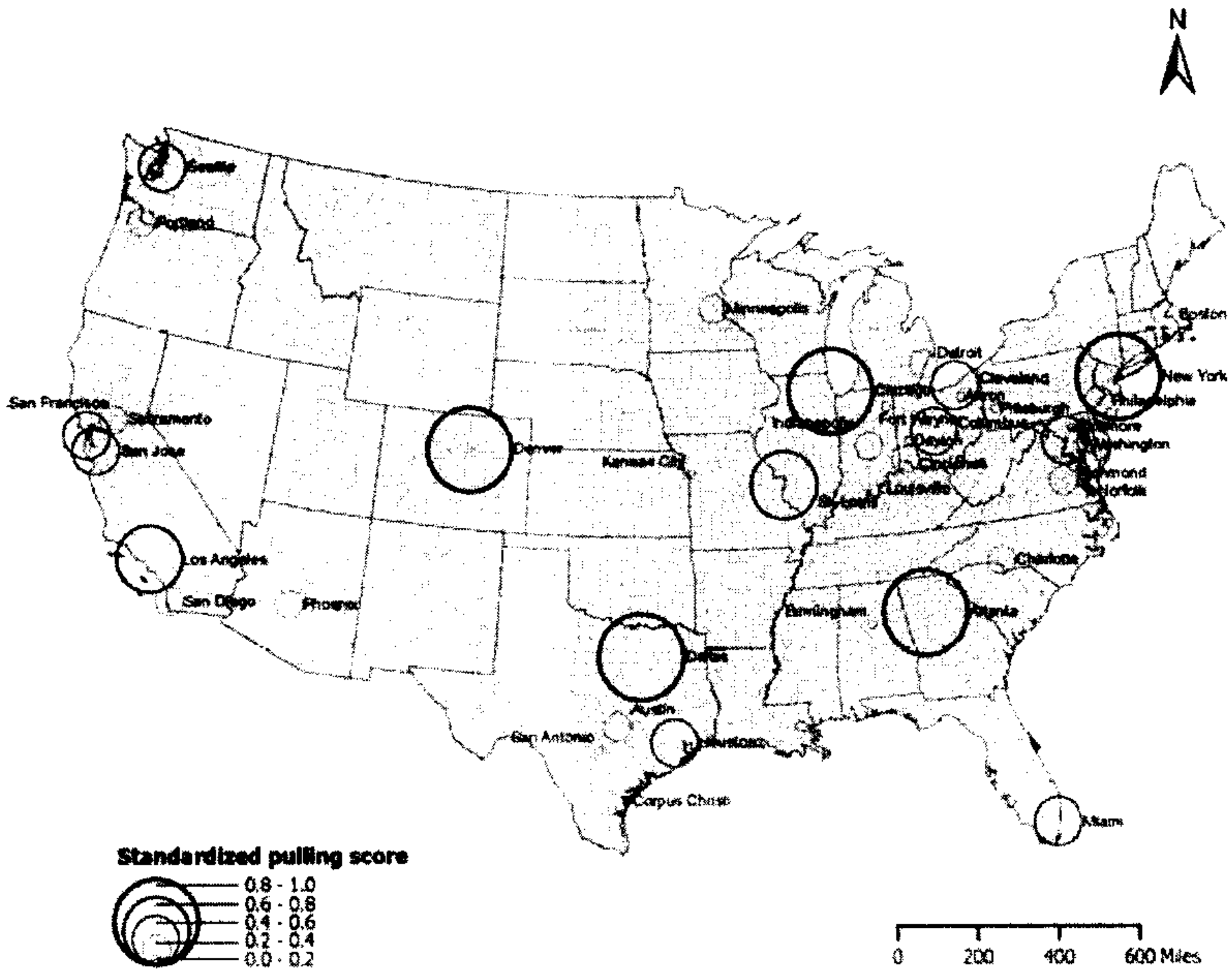


Figure 5. Network topological accessibility for each backbone POP

Table 2. Network accessibility ranking for the top 10 cities

Rank	City	Pulling Score	*Degree of node*		*T-matrix*		*D-matrix*		*Clustering coefficient*	
			Value	Rank	Value	Rank	Value	Rank	Value	Rank
1	Dallas	1.000	14	1	7984	1	67	2	40.857	1
2	Chicago	0.973	14	1	7772	2	64	1	37.143	2
3	New York	0.887	12	4	7583	3	67	2	33.000	3
4	Atlanta	0.830	12	4	6832	4	68	5	29.333	4
5	Denver	0.805	13	3	6568	6	67	2	24.000	6
6	St. Louis	0.777	10	6	6781	5	70	6	28.800	5
7	Los Angeles	0.631	8	9	5669	7	77	11	22.750	7
8	Columbus	0.588	10	6	4346	11	78	12	18.000	9
9	Cleveland	0.558	9	8	4145	12	78	12	17.778	10
10	Seattle	0.556	8	9	4771	10	74	7	15.750	12

* each network measure is standardized for comparative analysis simply by dividing each measure by its maximum value.

Although Columbus (OH) has a higher direct connection, relatively lower **T**-matrix and **D**-matrix values make its overall accessibility lower. The benefits of both Columbus (OH) and Cleveland (OH) in the Midwest seem to be hindered from nearby highly accessible cities such as Chicago (IL) and New York (NY).

Based upon computed pushing and pulling factors from the socioeconomic and demographic characteristics, and the network accessibility for regional backbone structure, Figure 6 shows the broadband accessibility score for each county. The spatial pattern of broadband accessibility shows regional variation over counties, to some extent indicating spatially clustering of high accessible counties in areas following the regional division and major backbone hub cities. This gives another evidence of spatial disparity of the access to broadband services in terms of physical distribution of telecommunication infrastructure. Table 3 provides the detailed information of accessibility pattern. The 10 most accessible counties are substantially concentrated in the Northeast, particularly, Washington MSA and New Jersey MSAs. Only two counties are included in other regions (e.g., Douglas in the West and Los Alamos in the South). More geographically, top 10 accessible counties seem to be benefited from a large number of closely existing high accessible backbone POPs, as well as their large potentials of the Internet access shown in Figure 4 and Table 1. The most accessible county is Fairfax (VA) in Washington MSA. Though Douglas (CO) in Denver MSA is considered as the most potentially demanded county for the Internet access (see Table 2), the accessibility score becomes slightly reduced by 2 positions after incorporating the access to backbone infrastructure. Considering the counties in the Western coast from a ranking list, the first highest ranked county is Santa Clara (CA) but its ranking is relatively lower (15th rank) than other regionally highest counties (e.g., Los Alamos in the South (7th)). This is somewhat unexpected finding when it comes to large concentration of high-tech industries in the Western coast. However, regarding a combined network measures of backbone structure, surrounding backbone hub cities in the Western coast, such as San Francisco, San Jose, Sacramento, and Los Angeles, are not much prevailing, as indicated by the size of circle. Although a county has a large potential of the Internet access, the disadvantage of the access to backbone network will significantly reduce the potential of the broadband access. This is the case when Santa Clara (CA) is considered (9th ranking for the Internet activity but 15th ranked position for accessibility).

Compared to the Internet activity, some interesting findings are observed. Broadly speaking, most of top 30 active counties are also

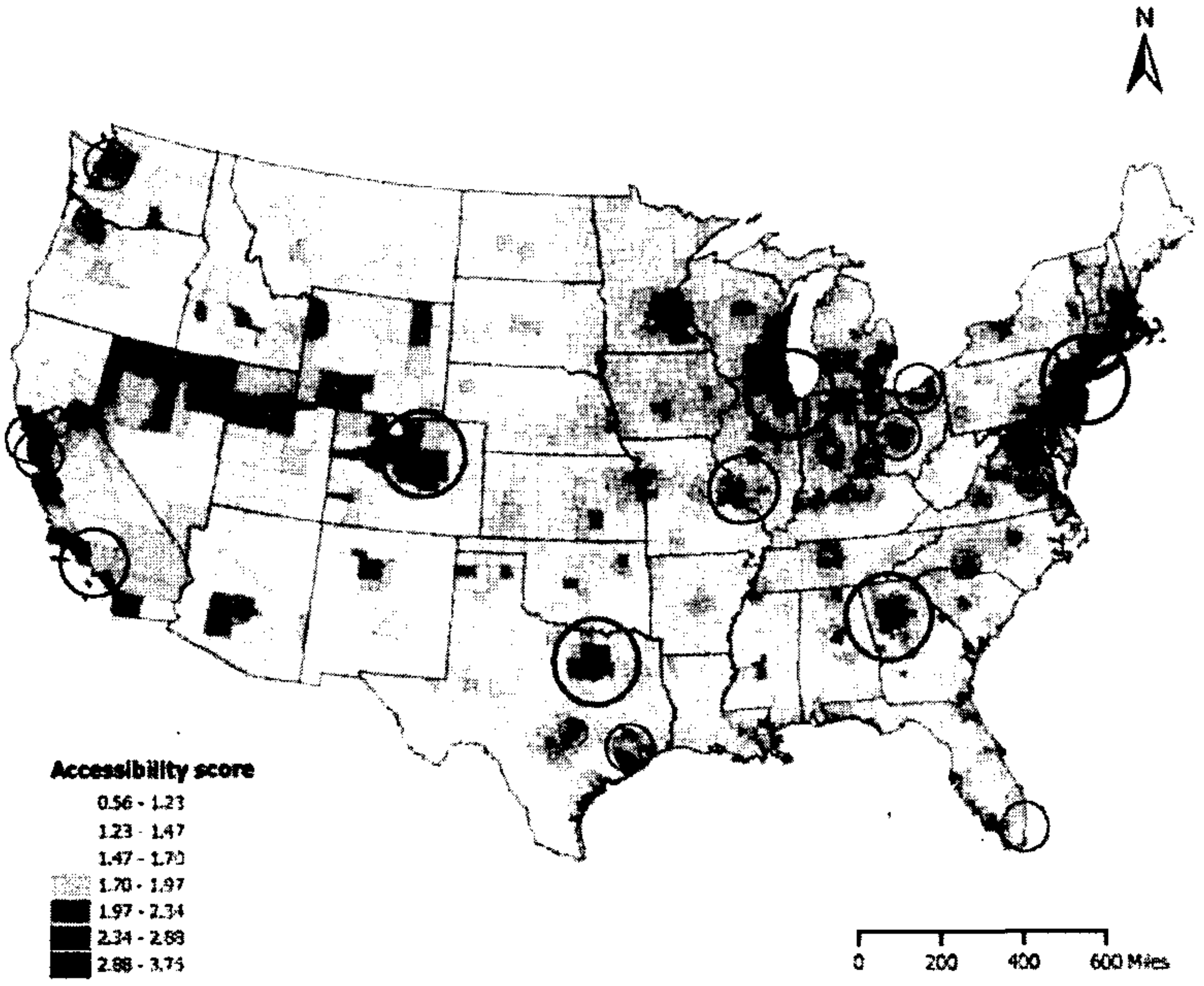


Figure 6. Broadband accessibility scores

Table 3. Broadband accessibility ranking for the top 30 counties

Rank	County	State	MSA	Pushing score
1	Fairfax	Virginia	Washington DC-MD-VA-WV	3.750
2	Loudoun	Virginia	Washington DC-MD-VA-WV	3.730
3	Douglas	Colorado	Denver CO	3.720
4	Hunterdon	New Jersey	Middlesex-Somerset-Hunterdon NJ	3.660
5	Morris	New Jersey	Newark NJ	3.540
6	Somerset	New Jersey	Middlesex-Somerset-Hunterdon NJ	3.530
7	Los Alamos	New Mexico	Santa Fe NM	3.490
8	Falls Church	Virginia	Washington DC-MD-VA-WV	3.480
9	Howard	Maryland	Baltimore MD	3.430
10	Hamilton	Indiana	Indianapolis IN	3.340
11	Montgomery	Maryland	Washington DC-MD-VA-WV	3.310
12	Nassau	New York	Nassau-Suffolk NY	3.300
13	Putnam	New York	New York NY	3.280
14	Fayette	Georgia	Atlanta GA	3.280
15	Santa Clara	California	San Jose CA	3.270
16	Collin	Texas	Dallas TX	3.250
17	DuPage	Illinois	Chicago IL	3.190
18	Delaware	Ohio	Columbus OH	3.180
19	Williamson	Tennessee	Nashville TN	3.180
20	Forsyth	Georgia	Atlanta GA	3.180
21	Fairfax City	Virginia	Washington DC-MD-VA-WV	3.130
22	Livingston	Michigan	Ann Arbor MI	3.130
23	Lake	Illinois	Chicago IL	3.120
24	Marin	California	San Francisco CA	3.110
25	Rockland	New York	New York NY	3.100
26	San Mateo	California	San Francisco CA	3.100
27	Stafford	Virginia	Washington DC-MD-VA-WV	3.080
28	Prince William	Virginia	Washington DC-MD-VA-WV	3.050
29	Calvert	Maryland	Washington DC-MD-VA-WV	3.030
30	Kendall	Illinois	Chicago IL	3.020

high-ranked for total broadband accessibility. Calvert (MD) and Kendall (IL) counties are new entrants in the list, while Scott (MN) and Washington (MN) counties are left out. Accessibility rankings for Delaware (OH), Hamilton (IN), and DuPage (IL) are increasingly shifted by 7, 6, and 5 positions, respectively. Such counties are all included in the Midwest region. Meanwhile, Marin (CA), San Mateo (CA), Santa Clara (CA), and Rockland (NY) counties show the remarkable decrease of accessibility ranking by 10, 9, 6, and 4 positions, respectively, compared to high positions in the Internet activity. Thus it is pointed out that more counties in the Midwest are apparently benefited from network topological properties of surrounding backbone hub cities. For some counties in the West, their accessibilities with regard to the hierarchical structure of broadband infrastructure become less than expected potentials.

5. Conclusion and implications

Since the advent of the Internet, our usual life in society has dramatically changed. We now take advantage of many Internet based applications, such as e-commerce, electronic mailing, and communications. Surprisingly, e-mail traffic already exceeds traditional US postal service traffic and furthermore about half of the traffic over the national telephone network is now digital data traffic (Parker, 2000). Accordingly the digital access is becoming the fundamental infrastructure to support our lives, similar to public utilities such as electronics and water. The universal provision of broadband services, however, has not been realized yet in reality, rather many studies pointed out the existence of uneven access, called a 'digital divide' in various socioeconomic and demographic levels, as well as geographic levels.

In this paper, We attempt to develop a measurable form to examine and evaluate broadband accessibility. For doing this, this paper suggests a broadband accessibility measure basically developed from the gravity based potential model but combined with network topological structure of broadband access. As a result of empirical analysis, a combined accessibility score, which takes into account the Internet access activity of counties and network measures of backbone nodes, reveals spatial variation with regionally clustered pattern and a number of interesting findings at the county level.

This paper has some significant contributions. First, methodologically, we developed a broadband accessibility measure reflecting more realistic structural features of broadband access. This measure can provide a useful indicator to address social and geographic issues under new digital economy. Also, quantitatively measuring the level of potential access to broadband services would help provide us insightful information about the spatial inequity and digital divide. Moreover, the developed measure extends traditional potential based accessibility model by incorporating network topological properties to a measure. For future analysis of more complex telecommunication systems, a wide variety of innovative broadband technologies, such as cable TV, fiber optics, satellite, and wireless services, can be readily incorporated into the suggested measure in a practical sense. Up to our knowledge, there is no prior study dealing with the spatial disparity of broadband access at a regional/national level by county. Thus the county level broadband accessibility is indeed worth to examine and further this approach becomes more novel. Nevertheless, it will be meaningful to verify the advantages of our model by comparatively examining other accessibility measures which employ traditional standard forms.

Notes

1 FCC (Federal Communications Commission) defines broadband as the advanced tele-communications capability of providing upstream (customer to provider) and downstream (provider to customer) transmission speeds (bandwidth) of more than 200 Kbps (kilobit per second). Bandwidth can be defined as a data transmission speed or capacity (FCC, 2004).

2 xDSL (Digital Subscriber Line), HFC (Hybrid Fiber Coax), Fixed wireless, satellite, and FTTx. The letter x means a generic term for DSL services and fiber broadband services. xDSL includes several DSL technologies such as ADSL, HDSL, IDSL, SDSL, and VDSL. FTTx contains the types of FTTH (Fiber To The Home), FTTB (Fiber To The Building), and FTTC (Fiber To The Curb/ Cabinet) (Newton, 2005).

3 Many DSL providers are not willing to provide residential services to a household not within 12,000 feet from the central office though (Grubesic and Murray, 2002).

4 These are locations where network equipment such as a

switch or router is established allowing digital traffic to journey on the commercial Internet backbones (Grubesic and O'Kelly, 2002).

5 In general, the adjacency matrix (or connectivity matrix) presents a fundamental topological relationship between nodes. The number of rows and columns in the adjacency matrix are the same as the number of nodes in the network. Each cell entry indicates the presence of direct or 1-step connection between a node pair as a binary integer.

6 The minimum number of hops between two most distant nodes.

7 For most transmission systems, repeater or regenerator must be in place at specific intervals in order to overcome the signal loss along distance.

8 This dataset is obtained from a nationwide survey every 10 years mandated by the U.S. Constitution. Currently available dataset is the Census 2000 and thereby next census will be in 2010. For more information, see the U.S. Census Bureau website (www.census.gov)

9 This cooperative agreement is broadly observed in reality because of routing efficiency and cost reduction of interconnection establishment (Gorman et al., 2004). Accordingly, this relationship allows each IBP to expand geographic reach of their service (O'Kelly et al., 2006).

10 These locations allow different IBPs to exchange their traffic flows through their transit backbone infrastructures.

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