SPATIAL ANALYSIS OF TELECOMMUNICATION FLOWS [1]

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1. **INTRODUCTION**

Telecommunication systems carry information over space, in the same way as transportation systems carry goods and people. In both cases, these movements are necessary to complete economic and social transactions, and can be viewed as derived demands. Telecommunication flows analysis may therefore provide empirical insights into the patterns of spatial interactions between individuals, businesses, cities, regions, and countries. Various modeling techniques have been used, with real-world data and at various geographical scales, by economists, geographers, and other social scientists to better understand these patterns. The purpose of this chapter is to critically review the literature dealing with telecommunication flows, focusing on both modeling techniques and empirical applications and results. This review is organized along different geographical scales: local, regional, and international. The modeling techniques include: (1) aggregate, discrete choice, and spatial interaction (gravity) models; and (2) network and hierarchies analyses, using graph theory, Markov chains, and multivariate and clustering techniques. A general spatial modeling framework is then proposed, within which the existing models can be nested, and which can provide the theoretical basis for further analyzing the structure of telecommunication flows and the spatial impacts of telecommunication technologies.

2. **TELECOMMUNICATIONS AT THE LOCAL SCALE**

From an infrastructural perspective, the basic telephone spatial unit is the wire center (WC), a territory including a central office building housing one or more switches, and to which all subscribers located in the WC are connected via access lines. In rural areas, a WC may include several villages and small towns, whereas metropolitan areas cover several WCs. Access is defined as connection to the central office. However, local usage may take place over several WCs in large urban areas, and is, at least in the U.S., generally characterized by a flat monthly rate. Local usage may extend to areas adjacent to an urban area, making up an extended calling area. The concept of community of interest is used to delineate such extensions.

Telephone flow studies at the local level can be classified into two categories: (1) local access, and (2) local use. Access studies try to explain variations in the level of residential connections to the network, using individual household census data derived from public-use micro samples, or census data aggregated at the tract level. Local usage studies try to relate residential usage variables (numbers of calls, conversation minutes, average call duration) to price, income, and various socio-economic and demographic variables gathered through small-scale surveys.

2.1. Local Telephone Access

Access studies use various qualitative choice models (linear probability, logit, probit), with:

$$AC_i = f(\mathbf{T}_i, \mathbf{X}_i), \qquad (1)$$

where AC_i is either the probability that a given household i has telephone access, or the percentage of households with access in a given area i , $\mathbf{T}_i$ a vector of telephone characteristics, including price, and $\mathbf{X}_i$ a vector of household socio-economic characteristics. Perl (1978) uses a sample of 36,703 households from the 1970 Census of Population, and matches these data with monthly service and installation charge data from AT&T. He finds that demand for access is positively related to income, age and education of the household head, and negatively to household size, unemployment and rurality, with less access for negro- and female-headed households. Bodnar et al. (1988), using a sample of 34,262 households from the 1985 Canadian census, test variables similar to Perl's, with, in addition, dummy variables related to home ownership and size, type of occupation, recency of residence, degree of urbanization of household location, and identification of Canadian provinces. Taylor and Kriedel (1990) use 1980 census data on 8423 census tracts, which, they argue, allow for a better interfacing of census and rate data. Indeed, the location of micro sample households is only identified in the case of areas with 100,000+ people, which may include several WCs with different local rates. In addition to the usual household size, ethnicity, mobility, age and employment variables, Taylor and Kriedel use both income mean and variance, as well as dummy variables related to the availability of various local service tariffs. All these studies suggest a very low, but non-null, price elasticity.

2.2. Local Telephone Usage

The general form of local usage models is:

$$LU_i = g(\mathbf{T}_i , \mathbf{X}_i) \qquad (2)$$

where LU_i is the usage (calls, minutes) by household i over a specific period , $\mathbf{T}_i$ a vector of telephone characteristics, including price, and $\mathbf{X}_i$ a vector of household socio-economic characteristics. The few local usage studies done prior to 1980 have been reviewed and criticized by Taylor (1980). Additional studies have been published since then, all designed to assess the effects of usage sensitive pricing on different population groups. Infosino (1980), using a sample of 1000 households spread over 18 WCs in Metropolitan Los Angeles and Cincinnati, and the results of a mail survey, relates individual household calling rates to such variables as race, sex of head of household, and size and income of household. He obtains R^2 around 0.35. In addition, Infosino develops WC models, relating the wire center calling rate to census data such as the average household size, the fraction of black and Spanish households, and to the telephone station density, obtaining higher R^2 than for the individual household models. This appears to be the only local usage study using census data. Brandon (1981) reports results of a study of 513 households in Chicago, relating the Box-Cox transforms of the number of calls, the average duration, and the total conversation time, to the number of males and females in different age classes, dummy variables related to income levels, ethnicity, employment status of head of household and spouse, occupation, length of residency, and various interaction terms. However, the estimated models turn out to have poor explanatory power ($R^2 = 0.054 \rightarrow 0.195$). Brandon computes census-derived variables for each WC, by matching WC boundaries with census tract and block boundaries, but these variables are not used in the models. Brandon and Infosino study the effects of demographics on telephone usage under an unchanging tariff. In contrast, in the study by Park, Mitchell, Wetzel, and Alleman (1983) with data from the GTE Illinois Experiment, around 640 households spread over 3 WCs are monitored over 6 months, subject to a flat rate during the first three months, and a measured rate during the last three. Their numbers of monthly calls are related to demographic variables gathered through a survey and telephone interviews, as well as to dummy variables related to the service tariff. The results suggest that, after introduction of measured service rates, larger households reduce their numbers of calls more than smaller households, and older households do so more than younger households. Under both tariffs, the number of calls increases with household size and number of teenagers, and the age of the household head. In a related study with the same data, Park, Wetzel, and Mitchell (1983) show that calling patterns vary seasonally, with a higher telephone use in winter than in summer, clearly pointing to the influence of the weather.

Another approach to local calling analysis involves the application to a sample of individual households of nested multinomial logit models of choice of local service option and local calling pattern characterized as a portfolio of numbers of calls and average call durations by time of day and distance zone (Train et al. 1987, 1989). The general form of the model is:

$$P_{is} = f(\mathbf{Y}_{is}) \tag{3}$$

where P_{is} is the probability for a household to select service option s and calling portfolio i, and $\mathbf{Y}_{is}$ a vector of factors characterizing the service (e.g., tariff) and the household (income, number of telephones). Because of the extremely large number of possible portfolios, a random selection of portfolios is used to estimate the models. For instance, in Train et al. (1989), 3 distance bands, 3 types of days, and 24 hours per day, are considered, making up 216 potential portfolios. However, this approach can only deal with a few mileage ranges, and the characteristics of the destination points and their geographical locations cannot be accounted for.

3. TELECOMMUNICATIONS AT THE REGIONAL SCALE

The scope of the regional scale has changed over time, but always involves a toll rate system accounting for calling distance, time of day, and duration. Before the divestiture of the Bell System (1984), a region, in the U.S., could encompass a state, a set of adjacent states, or the whole nation. Since divestiture, the U.S. territory has been subdivided into LATAs (Local Access and Transportation Area), within which inter-city toll service is provided by a monopolistic local exchange company (e.g., Baby Bell), while inter-LATA service is provided by long-distance companies (e.g., AT&T). Most post-divestiture studies focus on intra-LATA service, as inter-LATA data have become unavailable due to competitive and proprietary reasons.

Telephone flow studies at the regional level can be classified into two major categories: (1) demand models, which try to explain variations in the flows themselves, whether aggregate or point-to-point, as functions of price, socio-economic, and locational variables; and (2) inter-city network flow models, which use flow data to better understand the organization and functioning of urban systems.

3.1 Telecommunications Demand Modeling

3.1.1. *Aggregate Toll Models*

Aggregate models consider the total number of toll calls within a given territory (state, LATA), without distinguishing their origins and destinations. Early, pre-1980, models are variations of the distributed-lag model,

$$M_t = f(M_{t-1}, X_t , P_t , T_t) \tag{4}$$

where M_t is the total number of intrastate toll messages in year t, X_t the state per capita income, P_t a price variable, and T_t the number of telephone stations, with generally no distinction between residential and business calls (Taylor 1980). These studies suggest mean price elasticities of -0.21 and -0.67 for the short and long runs, and mean income elasticities of 0.39 and 1.33 for the same horizons. Mahan (1979) regresses the logarithm of expenditures on long-distance toll calls by 934 households on local service charges, number of household members, gender and age distribution variables, family income, distance to family members outside the calling area, and various dummy variables for race, education of household head, size of local calling area, and employment status. No toll price variable is considered, and an R^2 of 0.35 is obtained. Using state-level data, Griffin (1982) introduces in an MTS (Message Toll Service) call model, estimated with pooled quarterly data over the period 1966-78 in 5 southwestern states, the number of subscribers and its square (the externality effect) and lagged advertising, income, and price variables. Duncan and Perry (1994), using intra-LATA toll call monthly time series over the period 1986-1990 from GTE California, regress both deflated revenues and minutes of use on population, real income, and nonagricultural employment, obtaining a price elasticity of -0.38. Call data are aggregated over mileage bands, times of day, and both residential and business users. Griffin and Egan (1985) analyze the substitutions between WATS (Wide Area Toll Service) and MTS for business intercity communications, using a translog cost function for the business sector, with, as costs determinants, the prices of MTS and low- and high-usage WATS service. Their results point to MTS and high-usage WATS own-price elasticities of -0.36 and -0.86. The elasticity of WATS demand with regard to MTS price is estimated at 0.82. Finally, Guldmann (1993), using an intra-LATA toll call data base, wherein callers and callees are identified by their SIC code, builds an eleven-sector table of calls, showing the numbers of calls and conversation minutes from each sector to each sector, including the residential sector. The analysis of these tables points to major patterns and clusters of interactions, and to the extent of calling reciprocity. These intersectoral flows are linked to sectoral employment data, leading to a telecommunication forecast model using employment forecasts as an input.

3.1.2. *Standard Point-to-Point Spatial Interaction Models*

The following models can be set within the framework of spatial interaction (gravity) modeling, wherein flows X_{ij} between origin and destination nodes (i,j) are functions of the sizes and characteristics of these nodes, that determine their propulsiveness $\mathbf{V}_i$ and attractiveness $\mathbf{W}_j$, and of the friction factors that inhibit movement, $\mathbf{R}_{ij}$, with:

$$X_{ij} = F(\mathbf{V}_i, \mathbf{W}_j, \mathbf{R}_{ij}) \tag{5}$$

Point-to-point telephone flow models have been developed by both geographers and economists. However, both streams of studies have somewhat ignored each other, with geographers emphasizing the effects of distance and place size/centrality, and economists focusing on price and income effects.

The earliest geographical study of intercity telephone flows appears to be that of Hammer and Iklé (1957), who regress the total number of telephone calls, in both directions, between pairs of cities, on the airline distance and the respective numbers of subscribers. A similar gravity model is estimated by Leinbach (1973), using telephone flow data for West Malaysia and regressing the number of intercity messages on distance and the modernization scores of the origin and destination cities, as obtained from a principal component analysis of various socio-economic data. In addition, he estimates similar models for 16 originating exchanges separately, and then demonstrates a significant relationship between the distance coefficient and the distance of the exchange from a modernization core located close to the capital, Kuala Lumpur, the closer the exchange to the core the lesser the effect of distance. Leinbach thus provides convincing evidence of the influence of the spatial structure on telecommunication flows, Hirst (1975), using telephone call data for Tanzania, shows that combining the distance variable with a dummy variable that discriminates between dyads that do and do not include the capital city, Dar Es Salaam, leads to significant improvements in the explanatory power of the gravity model, with no need for mass variables any longer. This result suggests that the use of population size as a mass variable may be inadequate for developing countries, because it does not discriminate well in terms of socio-cultural patterns, political power, and the type of economic activities in an urban system in early stages of development. Rossera (1990) and Rietveld and Janssen (1990), using intra-Switzerland and international Dutch-originating call data, introduce the concept of barriers into gravity-like models via dummy variables (e.g., linguistic differences). Finally, Fisher and Gopal (1994) use artificial neural networks to estimate a model of Austrian interregional telephone flows, where the independent variables are the regional products of the origin and destination, and the interregional distance. The neural approach provides a gain of 6% in the R^2 over the standard gravity model OLS estimation.

In the economic studies stream, Larsen and McCleary (1970) regress residential and business interstate toll calls on income, price, and the volume of interstate mail. Deschamps (1974) regresses intercity calls in Belgium on the numbers of subscribers in both cities, the income at the origin city, the toll rate, and dummy variables representing distance ranges, language commonality, the location of a provincial capital, and an index of sociological proximity defined as the ratio of the commuters between the two cities to their total population. The distance coefficients are all negative and increase with distance, while the sociological proximity and language coefficients are positive and highly significant. Pacey (1983) estimates a model similar to Deschamps' (1974), but is not able to separate distance and price effects. Both studies obtain price elasticities around -0.24 for aggregate residential and business calls. Guldmann (1992), using regional toll calls, estimates separate residential and business models, for both messages and minutes, with the effects of prices and distance successfully separated. The models with the highest R^2 include second-order terms for the destination size and distance variables. The price elasticities are equal to -0.31 and -0.54 for residential and business calls, and to -1.43 and -1.79 for residential and business minutes. The distance elasticities are slightly below -1.0 for calls and around -0.6 for minutes. In addition, conversation time sharing models are estimated for the different rate periods, following Kohler and Mitchell (1983). If MT_{ijt} is the flow (minutes) during rate period t, and MT_{ij} the minutes over all periods from WC i to WC j, then the share considered is $SH_{ijt} = MT_{ijt}/MT_{ij}$. In the case of period 1 (day), the model estimated is:

$$SH_{ij1} = b_0 + b_1 \ln MTT_j + b_2 \ln D_{ij} + b_3 \ln(P_{ij1}/P_{ij3}) + b_4 \ln(P_{ij2}/P_{ij3}), \qquad (6)$$

where P_{ijt} is the price variable for period t, D_{ij} the distance between i and j, and MTT_j the total flow ending at j.. Combining the aggregate and time-sharing models allows for computing cross-price elasticites, and thus for assessing substitution effects across rate periods.

3.1.3. *Point-to-Point Spatial Interaction Models with Reverse Flows*

Another, more recent, stream of point-to-point models has been initiated by the seminal paper by Larson et al. (1990), who extend the basic theory of telephone demand, presented in Taylor (1980), by using reverse traffic (from j to i) as a determinant of the traffic from i to j. Their theoretical framework is briefly summarized. Two economic agents, a and b, have utility functions of the form U(X,I), where X is the usual composite good, and I the "information" good, which is produced through a production function of the form:

$$I = f(Q_{ab}, Q_{ba}), \qquad (7)$$

where Q_{ab} and Q_{ba} are the directional telephone flows between a and b. Two extreme cases of information exchange are: (1) perfectly reciprocal calling patterns, where agents return messages in direction proportion to the quantity received; and (2) once a given amount of information has been transferred, there is no need for further communication. Each agent is assumed to maximize its utility subject to its income constraint and its information production constraint, leading to a Nash equilibrium, with:

$$Q_{ab} = W(p, q, M_a, Q_{ba}), \qquad (8)$$

$$Q_{ba} = Z(p, q, M_b, Q_{ab}), \qquad (9)$$

where M is the income, p the price of the composite good, and q the price of telephone service. Larson et al. (1990) analyze high-density intra-LATA toll routes consisting each of a large metropolitan area (A) and a relatively small suburb or town (B). No information is provided on the geographical location of these routes, or their length. Traffic flow from A to B is taken as a function of telephone rates, income, market size expressed as the product of the populations at A and B, and traffic from B to A, with route-specific intercepts (i.e., dummy variables), but route length is not an explanatory variable. The estimated price elasticities are around -0.75. The call back (reverse traffic) coefficient is estimated at 0.75 for the A-to-B equation, and at 0.67 for the reverse one. This approach is implemented by Appelbe et al. (1988) in their analysis of Canadian interprovincial flows. Using long-distance direct-dial MTS data from the six Telecom Canada member companies, they regroup inter-provincial routes by mileage band, and combine these bands with two rate periods (full and discount). Then, for each combination, they estimate point-to-point models, with, as dependent variables, the deflated revenues. The independent variables include price, income, size of the originating market (the numbers of residential and business access lines), and the reverse traffic. The call back coefficients range from 0.38 to 0.72. Similar models are estimated by Guldmann (1998), who analyzes intersectoral regional toll flows, with the economy disaggregated into four sectors (Manufacturing, Trade, Services, and Households). Using intra-LATA toll call data, where callers and callees are identified by their SIC codes, he estimates the following system of equations:

$$\ln X_{kilj} = a_0 + a_1 \ln X_{ljki} + a_2 \ln D_{ij} + a_3 \ln P_{kilj} + a_4 \ln NCO_{ki} + a_5 \ln NCD_{lj} \qquad (10)$$

$$\ln X_{ljki} = a_0 + a_1 \ln X_{kilj} + a_2 \ln D_{ij} + a_3 \ln P_{ljki} + a_4 \ln NCO_{lj} + a_5 \ln NCD_{ki} \qquad (11)$$

where X_{kilj} is the flow from sector k located in wire center (WC) i to sector l located in WC j, D_{ij} the distance between the central offices of the two wire centers, P_{kilj} the average toll price from (k,i) to (l,j), NCO_{ki} the total outflow from (k,i), and NCD_{lj} the total inflow to (l,j). The last two variables are measures of the sizes of the origin and destination markets. The models are estimated for both calls and conversation seconds. As in all previous studies, the results point to the often significant role of the reverse flow, however with strong variations from one intersectoral interaction to another. The bidirectional price elasticities vary between -0.125 and -0.656 for calls, and between -1.114 and -2.193 for minutes. The effect of distance is also always negative, and, in most cases, highly significant. As distance is taken as proxy for transportation costs, this negative cross-price elasticity suggests a complementarity between the transportation and telecommunication inputs to all production processes. Using the same data, Guldmann (1999) models inter-city total flows (minutes), accounting for both reverse flows and the effects of the spatial structure. He tests alternative forms of competing destinations (Fotheringham, 1983) and intervening opportunities (Stoufer, 1960) factors, in terms of both their spatial definition and their distance exponent. He concludes that the spatial structure has an effect on telecommunication flow patterns, confirming the earlier results of Leinbach (1973) and Hirst (1975). The effect is competitive, at the destination, providing a model explanatory gain of 7.5% (up from 64.2% without such a factor).

In all the previous studies, simultaneous equation estimation procedures are used. In order to analyze the welfare implications of extending local calling areas, Martins-Filho and Mayo (1993), departing from this estimation approach, account for the reverse traffic effect by estimating the correlation of the flows of transposed exchanges. They use data for 4 major Tennessee metropolitan areas to regress point-to-point calls on (1) a price variable measuring the cost of a three-minute duration call, (2) a market size variable equal to the product of the numbers of subscribers at the two points, and (3) dummy variables representing different distance ranges. The call back effect is estimated around 0.40. The distance effects are negative and significant, and the price elasticity range from -1.18 to -1.54.

3.1.5. *Distance-Stratified Models*

Calls are divided into several categories on the basis of time, distance, and other factors, and regression models are estimated for the number and average duration of calls in each category. However, the problem with that approach is that it may involve a very large number of equations, and it may be very difficult to allow for the full set of cross-elasticities and other constraints across equations. Gatto et al. (1988) model AT&T MTS interstate residential demand by developing systems of 5 interdependent demand equations corresponding to alternative ways of placing a call (direct dial-DD-evening, DD day, DD night, operator-assisted calls, and person-to-person) for each of the 48 states and for five mileage bands (1-30, 31-124, 125-430, 431-925, 926-3000), each equation relating the number of messages per access line to price and income variables. They use the Random Coefficient Regression (RCR) approach, which appears to provide more reasonable estimates (e.g., price elasticities and cross-elasticities with the right sign) than the Seemingly Unrelated Regression (SUR) approach (Zellner 1962), primarily because cross-equations restrictions are to apply only stochastically. Gatto et al. assume that calling patterns are independent across mileage bands. If this hypothesis were rejected, the joint estimation of 25 equations would be necessary. De Fontenay and Lee (1983) analyze residential calls between British Columbia and Alberta. Second-order, translog-type models, allowing for variable elasticities, are estimated for various mileage bands by regressing call minutes on price and income, with price elasticities ranging from -1.12 to -1.65. Cameron and White (1990) use a sample of 26,672 long-distance calls originating from British Columbia, and regress call duration on rate, distance, and several dummy variables characterizing the call (time-of-day, business, collect, credit card, person-to-person, etc.). They find that call duration decreases with price and when the call is placed person-to-person or with a card, and increases with distance (a result similar to Pacey's 1983) and when the call is placed as collect and in the evening or night. Finally, the discrete logit model approach reviewed in the context of local usage (Section 2.2) has been recently used by Train (1993) to estimate a price elasticity of -0.39 for intra-LATA toll calls by GTE-California residential customers.

3.2. Information Flows and the Urban Hierarchy

Various inter-city flows (e.g., migration, commuting, freight, telephone) have been used to analyze regional settlement structures, uncover central place hierarchies, delineate functional and nodal subregions, and identify regional disparities (e.g., core-periphery). Telephone flows, which depend upon the socio-economic structure, size, and interdependencies of the regional urban network, are considered the best single criterion by which to grasp the urban system in its totality. Interestingly, Christaller (1966) uses the number of telephone stations per person to develop a hierarchy of centers among Southern Germany's cities in 1933, to illustrate his central place theory (CPT), and Green (1955) uses telephone call data to define the common boundary of the hinterlands of New York City and Boston. In this section, we review several studies that attempt to uncover urban hierarchies and network structures, based on inter-city telephone linkages. The approaches may be regrouped into three categories: graph theory, Markov chains, and multivariate and clustering methods

3.2.1 *Graph Theory*

Nystuen and Dacey (1961) pioneer the graph theory approach, and apply the concept of dominant or primary linkage to the analysis of a 40x40 matrix of inter-city telephone calls in the state of Washington. Each place i is assigned to that place j to which it sends its largest flow (i.e., $x_{ij}>x_{ik}$, $\forall k\neq j$), provided that j is larger in size than i, where size is measured by the total incoming flow. Each such place j is defined as the central place or nodal point for the places assigned to it. This network of nodal points and largest flows is the skeleton of the urban hierarchy in the entire region. Central cities are the terminal nodes in this hierarchy, i.e., they are not assigned to any other node. The basic problem is that all the lesser flows are ignored, and thus much information in the interaction matrix $[x_{ij}]$ may be wasted. This approach is also applied by Dietvorst and Wever (1977) and Clayton (1974, 1980). Puebla (1987) extends the method with a multiple linkage approach.

Rouget (1973) analyzes the telephone flows between the 34 centers of the Bourgogne-Franche Comté region of France, using the concept of power of a node. If x_{ij} is the flow from i to j, and x_i the total flow from i, then node i is said to dominate node j if $(x_{ij}/x_i) < (x_{ji}/x_j)$, and if the relative difference between these two ratios is at least 10%. Only ratios higher than 1% are used to define relations of dominance or symmetrical influence. If i dominates j, then 2 arcs are assigned to the i→j linkage, and none to j→i. If there is a symmetrical influence between i and j, then 1 arc is assigned to each direction. Let $M = [m_{ij}]$ be the matrix of the resulting numbers of arcs, and M^k the matrix obtained by multiplying M k times by itself, with $M^k = [p_{ijk}]$, and p_{ijk} the number of distinct paths of length k (i.e., with k arcs) running from i to j. Rouget then defines measures of power of nodes, based on the m_{ij} and p_{ijk}. For instance, the influence of node i on all other nodes is defined as:

$$\pi(i) = \Sigma_j m_{ij} + \Sigma_j \Sigma_k p_{ijk} \qquad (12)$$

Rouget then ranks centers according to the index $\pi(i)$, with 8 centers with a score greater than the regional average, and 3 centers accounting for 75% of the group's total score. Rouget also presents an alternative ranking method, based on the pseudo Grundy function, that assigns the centers to 9 hierarchical levels.

A third graph-theoretic approach, implemented by Fischer et al. (1993) with Austrian interregional telephone flows, is based on the iterative proportional fitting procedure (IPFP) in conjunction with a hierarchical clustering procedure based on the concept of strong components of a directed graph. The IPFP standardizes the interaction matrix so that the sums of all rows and all columns are equal. The entry (i,j) of this standardized matrix represents a measure of the functional relationship from i to j. Next, a directed graph is built hierarchically, based on the strength of the (i,j) entries of the matrix, leading to the formation of clusters of nodes linked by paths of directed arcs.

3.2.2 *Markov Chain*

The use of Markov chains, pioneered by Brown et al. (1970) and Brown and Holmes (1971) in their studies of migration and journey-to-work flows, is applied to telephone flow data by Hirst (1975) and Dietvorst and Wever (1977) to delineate functional regions and urban hierarchies. The approach is based on accepting the interaction matrix $[X_{ij}]$ itself as representing the structure of the interaction phenomenon, without implying any causal structure, and on computing the probabilities P_{ij} of interaction from location i to location j, with:

$$P_{ij} = X_{ij}/\Sigma_j X_{ij}, \tag{13}$$

where X_{ij} is the observed flow from i to j. The next step is to solve a recursive system of linear equations (Hillier and Lieberman 1968, Chapter 13) to compute the probabilities $f^{(n)}$ that the first passage time from state i to state j is equal to n. It is then possible to compute a Mean First Passage Time $MFPT_{ij}$ for any couple of places i and j, which serves as an index of functional distance. The $MFPT_{ij}$ can be viewed as a nonspatial measure of proximity between regions i and j: the lesser this distance, the greater the level of interaction. The average MFPT for a given destination can be viewed as a measure of its overall accessibility and centrality in the urban hierarchy. Then, using clustering algorithms, destinations can be grouped according to the MFPT, thus providing a delineation of functional regions and an urban hierarchy.

Applying the MFPT method to inter-city calls in Tanzania, Hirst (1975) assigns the 19 towns to 4 urban hierarchy levels. Dietvorst and Wever (1977) also apply the MFPT method to 8 annual telephone flow matrices, from 1967 to 1974, and show that the hierarchical structure of the 21 districts displayed a significant degree of stability, with no change in the ranking of the 7 most central districts. However, their MFPTs increase with time, pointing to a weakening of their dominating position, while the MFPTs for the majority of the other districts decline, suggesting that they are coming to occupy a less peripheral situation in the information exchange system.

3.2.3 *Multivariate and Clustering Methods*

Central place structures are also delineated by using multivariate analysis techniques applied to matrices containing standardized measures of flows between places, with functional groupings indicated by factor loading patterns.

Illeris and Pederson (1968) use factor analysis to delineate places with a high degree of centrality, and their zones of influence, using telephone flows between 62 districts in Denmark. The factor loadings are interpreted as places that have similar destination profiles, and the scores of the places designate the places that send messages to these receivers. Factor 1 shows a very high score in the Copenhagen district and low positive or negative scores in all other districts, and thus represents the calls from Copenhagen to the rest of the country. The influence zones of the 7 major centers are delineated, the maximum factor weight determining, for each district, the hinterland to which it is assigned. Descubes and Martin (1982) also use factor analysis to delineate major centers and zones of influence in Alsace, France, based on inter-city telephone flows. The results point to a strongly polarized structure, with three major centers (Strasbourg, Colmar, Mulhouse) that dominate 140 of the 173 districts.

Clark (1973) uses principal component analysis to delineate urban linkages in Wales in 1958 and 1968, based on long-distance communication data. He also uses canonical correlation and a step-wise grouping procedure to measure the changes in the linkages from 1958 to 1968, pointing to a trend where increasingly more distant areas become involved within the spheres of influence of the major centers, thus suggesting that urban and regional growth is the product of the intensification of connections between previously poorly linked areas. Clayton (1980) also uses principal component analysis to delineate, among 66 Western Massachusetts communities, the major organizing nodes and their dependent satellite places, based on inter-city calls.

Finally, cluster analysis is also used to analyze spatial structures. Clayton (1974), using message flows between 36 toll centers in New England, clusters the lines and columns of the interaction matrix into groups so as to maximize the difference between separate groups and to simultaneously minimize the difference between the members of any group. Rows are grouped based on their role as origins of messages to all other places in the system (similar divergence profiles), and columns are grouped based on their role as collectors of messages (similar convergence profiles). Another hierarchical clustering procedure, the Intramax, is implemented by Fischer et al. (1993) with Austrian telephone flows. The strength of the interaction is measured by the difference between observed and expected flows, where the latter are based on the product of the observed marginal frequencies divided by the overall total. Nodes are then aggregated based on pairwise comparisons of their relative strength of interaction.

3.2.4 *Comparative Analyses*

Some of the studies discussed in the previous sections involve a comparison of the hierarchies obtained with different methods. Illeris and Pedersen (1968) use nodal data, (1) wholesale trade employment, and (2) the occurrence of 16 central functions, to create central place hierarchies, which are compared with the hierarchy derived from the factor analysis of inter-district telephone flows. The 4 major centers turn out to be the same in all 3 approaches, but the positions of the following medium-level towns depend upon the measure selected. The nodal analysis tends to assign high positions in the hierarchy to towns located in densely populated regions near major metropolitan centers, while factor analysis tends to space centers far apart, each dominating its own hinterland, but located outside the influence fields of other centers. Clayton (1974) compares the applications of (1) Nystuen's and Dacey's graph-theoretic approach, (2) principal component analysis, and (3) cluster analysis, to telephone flows in New England, concluding that the three methods yield patterns of spatial organization with a high degree of similarity. Dietvorst and Wever (1977) compare the application of (1) Nystuen's and Dacey's approach, and (2) the Markov chain MFPT approach, to telephone flows in the Netherlands, concluding that the network derived from the MFPT approach displays considerably greater stability over the years. Clayton (1980), using the frequencies of occurrence of 60 tertiary and quaternary functions in 89 places in Western Massachusetts, applies principal component analysis to these data to derive a hierarchy with five levels of central places. He concludes that there is convergence between this hierarchy and the ones derived by applying (1) Nystuen's and Dacey's approach, and (2) principal component analysis, to inter-city telephone flow data. Finally, Fischer et al. (1993) compare the application of (1) a graph-theoretic IPFP-based approach, and (2) the Intramax procedure, to Austrian telephone flows, pointing to the superiority of the Intramax approach because it leads to the spatial groupings of nodes with more intra-group and less inter-group interactions.

3.2.5 *Combined Hierarchical and Spatial Interaction Analyses*

Camagni and Salone (1993) test the hypothesis that the central place theory (CPT) paradigm of linkages between cities in a region is no longer sufficient to explain contemporary regional structures, and must be complemented by the new paradigm of city networks, made of specialized and complementary centers interconnected through market interdependencies, and synergies. The hypothesized new spatial order simplifies vertical relationships between cities and complicates, instead, their horizontal relationships. Camagni and Salone use telephone flows among the 157 districts of the Lombardy, Italy, region in 1990, and assume that a network relationship exists between 2 centers if the actual telephone flows significantly exceed the interaction expected on the basis of a doubly-constrained gravity model. The results show that such networks do exist, but are not ubiquitous, and do not substitute for the traditional CPT form of spatial organization. Networks are discovered within the metro area of Milan, shaping its emerging polycentric structure, and within sub-regional industrial districts. They conclude that the two organization forms should be viewed as complementary rather than mutually exclusive.

4. TELECOMMUNICATIONS AT THE INTERNATIONAL SCALE

The country is the basic spatial unit at the international scale, and all studies involve country-to-country telephone flows. The models used to explain these flows are structurally similar to the regional spatial interaction models. However, the selected explanatory variables are significantly different, involving trade, tourism, and language and cultural commonalities.

4.1. Country-to-Country Standard Gravity Models

Early econometric models of international telecommunication demand generally include separate equations for telephone, telegraph, and telex services. Most of these models were developed in the 1970s, when telephone service was not as dominant as it is today. Lago (1970), making use of 73 observations on telecommunication flows between the U.S. and 23 countries over the period 1962-1964, regress the number of telephone messages between the U.S. and country i in year t, on the volume of trade between the U.S. and country i, the U.S. investment in country i, the value of U.S. travel expenditures to country i, the U.S. population whose parents came from country i, the number of telephones in country i, a dummy variable related to use of radio circuits, the speed of service (all connections were operator-assisted), the number of common hours during a working day schedule between the U.S. and country i, the price of a 3-minute call, the cost per telegram word, the telex cost for 3 minutes, and the monthly rental cost of leased telegraph circuit service between the U.S. and country i. Similar equations are estimated for telegraph and telex services. Lago's results show that (1) time commonality, foreign-parentage population, and number of telephone sets are insignificant variables, (2) trade, tourism, and U.S. investment abroad are significant variables for telephone service, and (3) the own-price elasticity of telephone service is greater than one, with no substitutions with the other services. Telegram service turns out closely related to trade, and very vulnerable to telex service. Naleszkiewicz (1970) estimates similar equations while regrouping destination (from the U.S.) countries according to their economic development status and considering four categories of explanatory variables: (a) flows of capital between countries, proxied by foreign assets and liabilities; (b) flows of goods and services, measured by imports, exports, national income, and gross national product (GNP); (c) country wealth, measured by money supply, demand for deposits, etc.; and (d) country industrialization, measured by industrial production. Yatrakis (1972), using the numbers of calls over 46 international routes in 1967, estimates models similar to Lago's and Naleszkiewicz's, while including additional explanatory variables such as: the average fare of a first-class airline round trip, the percentages of a country GDP attributable to the extractive and manufacturing sectors, the number of ships of 1000 tons capacity registered with the origin country, government expenditures as a percentage of the GDP, the average annual dividends paid and received on foreign investments, the numbers of emigrants to and immigrants from all destination countries, the percentage of the population living in urban centers, and measures of language similarity and spatial contiguity among the pairs of interacting countries. The last two variables turn out to be highly significant. All the previous studies involve simple regression (OLS).

More sophisticated is the slightly later work of Rea and Lage (1978), who use the error component regression model to deal with cross-section time-series data on the number of outgoing messages from the U.S. to 37 major countries over the period 1964-73. While their equations are, in general, similar to the previous ones, and their results also point to a price-elastic demand (-1.8) for telephone service, they conclude, in contrast to earlier work, that the value of total trade (exports + imports) between the U.S. and the foreign country is not a significant variable. Fiebig and Bewley (1987) use the Box-Cox transformation in the estimation of a lagged model for telephone traffic between

Australia and ten foreign countries, where the number of paid minutes for outgoing telephone traffic is regressed on the real GDP of Australia, a telephone price index, the bilateral trade, and the short-term migrations. A lagged endogenous variable is used to capture habit formation and inertia effects, and also provides a way to distinguish between short-term and long-term elasticities. Tests regarding the optimal Box-Cox parameters suggest that the double-log functional form is acceptable, while the linear one is not. Bewley and Fiebig (1988) further analyze Australia-originating international telephone calls by modeling how the numbers of calls and conversation minutes are shared among the following three services: (1) direct dialing, (2) operator-connected station-to-station, and (3) operator-connected person-to-person. This is the first study to analyze substitution among services for international telecommunications. Rietveld and Janssen (1990), mixing 462 observations on interregional calls within the Netherlands (22 districts) and 27 observations on international calls between the Netherlands and foreign countries, estimate gravity models where the explanatory variables are the district/country gross domestic products, the origin-destination distance, and dummy variables characterizing 11 individual and groups of foreign countries, intended to measure the barrier effect of borders. This is the first time that a distance variable is introduced into such a model. It turns out to be highly significant, with an elasticity of -1.23. The coefficients of the dummy variables are negative and, in most cases, significant, pointing to barrier effects. Focusing on the 27 international calls observations only, they use both distance and the cost of calling in the same model, but the coefficient of distance becomes insignificant, due to the high correlation between these variables. Hackl and Westlund (1995), departing from the traditional assumption of constant price elasticity, show that the demand for telecommunications between Sweden and its major trading partners (Germany, U.K., U.S., Denmark, Finland, Norway) is best described by time-varying coefficient equations estimated with the moving local regression technique and with monthly data over the period 1976-1990. In addition to price, the relevant explanatory variables include trade volume and industrial production indices for Sweden and the foreign countries.

4.2. Country-to-Country Gravity Models with Reverse Flows

A second stream of study involves accounting for callback effects. Acton and Vogelsang (1992), analyzing the annual telephone traffic between the U.S. and 17 West European countries over the period 1979-1986, and borrowing from Larson et al. (1990), incorporate the phenomenon of call stimulation or substitution by including the return telephone flow in their estimated equations. However, instead of using a simultaneous equation approach, they estimate a reduced form of the equation, where the demand for calls (minutes) from the U.S. to a foreign country is a function of the originating and terminating prices of both telephone and telex services, the U.S. and foreign country gross domestic products (GDP), the number of European telephones, trade volumes, and the composition of production in the destination country (agriculture, restaurants and hotels, transportation, banking and financial services, manufacturing), and country-specific dummy variables to capture other effects. The results indicate that the own-price and GDP variables are significant, but that cross-price and trade and telephone equipment variables are not. Appelbe and Dineen (1993) report on the results of a similar approach to Canada-Overseas MTS demand. Using quarterly data for the period 1988 to 1991, they analyze calling patterns between Canada and the U.K., France, Italy, Holland, Germany, Hong Kong, Japan, Australia, and the Carribbean, using a 4-quarter lag for prices and a 3-quarter lag for income. Other variables include retail sales and access lines. They report a low callback effect coefficient of 0.10. Sandbach (1996) estimates an origin-destination model with traffic data on 154 routes between developed countries and in both directions. The non-price variables include the numbers of lines in the origin and destination countries, the GDP per capita in the origin country, the time difference between countries, the inverse of distance, and dummy variables related to language commonality and the Germany-Turkey routes (picking up the impact of the German guest worker community). The price variables include the price of an outgoing call, and the difference between incoming and outgoing call prices, to capture call stimulation and reversal effects. However, these effects are not statistically significant, probably because of the relatively low level of price disparity. Garin-Munoz and Perez-Amaral (1998) estimate demand functions for outgoing telephone traffic from Spain to 27 African and Oriental countries over the period 1982-1991. The explanatory variables include the minutes of incoming traffic, the price of an outgoing call, the volume of trade between Spain and the foreign country, and the number of tourists in Spain from this country. They use instrumental variables to control for the simultaneity between outgoing and incoming calls. The incoming calls, price, and tourists variables turn out to be significant, but the trade variable is not. Finally, Karikari and Gyimah-Brempong (1999), using traffic data between the U.S. and 45 African countries over the 1992-1996 period, implement a simultaneous equations approach and regress the number of calls in one direction on the lagged traffic in this direction, the return traffic, the price of an outgoing call, the GDP per capita, the volume of trade, the differential in outgoing and incoming prices, and the product of the number of households, as a measure of the community of interest.

5. THEORETICAL FRAMEWORK

The previous review points to a diversity of approaches in analyzing telecommunication flows. However, their theoretical foundations are limited, which hinders the development of more comprehensive methodologies. The purpose of this section is to outline a theoretical framework within which these approaches can be nested, and which can point to new research directions. This framework extends the concept of information function proposed by Larson et al. (1990).

The focus is on a simple model of the firm, where the information generated by two-way telecommunication exchanges are linked to basic input and output transactions. Consider firm A that sells its output Q to firm B. Firm A buys two inputs: materials, M, from firm C, and labor, L, from residential area R. Delivered pricing is assumed to take place, wherein the seller of goods or labor incurs transportation costs. Let P_Q , P_M , and P_L be the competitive market prices of Q, M, and L, and t_{AB} the unit transportation cost of Q from firm A to firm B. Let $Q=f(M, L)$ be the production function of firm A. The standard problem of firm A is to select the values of Q, M, and L that maximize its profit,

$$\Pi_A = P_Q Q - P_M M - P_L L - t_{AB} Q, \qquad (14)$$

subject to the production function constraint. To extend this basic model, consider the telecommunication exchanges (flows) that may take place between the four parties (A, B, C, R) to complete the above transactions: **F**= (F_{AB}, F_{BA}, F_{AC}, F_{CA}, F_{AR}, F_{RA}). Each flow may be viewed, in turn, as a multidimensional vector, including voice, data, and video subflows, with possible substitutions among them. However, for the sake of presentation clarity, each flow is treated as unidimensional. These flows are constrained by the telecommunication infrastructure available at each location (e.g., large data transmissions are easily handled via fiber optic cables, but much less so over copper cables). Let **T**=(T_A, T_B, T_C, T_R) be a vector of exogenous variables (e.g., types and numbers of access lines and switching channels, capacity of transmission trunks, microwave channels, coaxial and fiber optic cables) characterizing the state of the telecommunication infrastructure at A, B, C, and R. The completion of the transaction between A and B (sale of Q) requires a certain amount of information, I, that is function of the individual information exchanges F_{AB} and F_{BA}, and the available telecommunication technologies T_A and T_B, with:

$$I_{AB} = g(F_{AB}, F_{BA}, T_A, T_B). \qquad (15)$$

The relationship between transaction and related information is next expressed by an information constraint:

$$g_Q (Q, I_{AB}) = g_Q (Q, F_{AB}, F_{BA}, T_A, T_B) = 0 \qquad (16)$$

Similar information constraints apply to the M and L transactions, with: g_M (M, F_{AC}, F_{CA}, T_A, T_C) = 0 and g_L(L, F_{AR}, F_{RA}, T_A, T_R) = 0. Let P_{ij} be the unit price of telecommunications from i to j. The expanded profit function of firm A now accounts for the costs of the telecommunication flows initiated by A, with:

$$\Pi_A = P_Q Q - P_M M - P_L L - t_{AB} Q - P_{AB} F_{AB} - P_{AC} F_{AC} - P_{AL} F_{AL} \qquad (17)$$

Firm A selects (Q, M, L, F_{AB}, F_{AC}, F_{AR}) to maximize (17) subject to the production and information constraints. The derived input demand functions have, as arguments, (1) the market-determined prices of the output and all inputs, (2) all the reverse telecommunication flows, the amounts of which are determined by agents B, C, and R, and (3) the telecommunication infrastructure variables **T**. Let **P** and **RF** be the vectors of prices and reverse flows associated to firm A: **P** = (P_Q, P_M, P_L, t_{AB}, P_{AB}, P_{AC}, P_{AL}), and **RF** = (F_{BA}, F_{CA}, F_{LA}). The optimal telecommunication flow from A to B is then expressed as:

$$F_{AB} = h_{AB} (\mathbf{P}, \mathbf{RF}, \mathbf{T}) \qquad (18)$$

Similar demand functions would be derived for F_{AC} and F_{AL}, as well as for all the flows initiated by B, C, and R, leading to a Nash equilibrium for all flows. The above model of firm A could be extended to include (1) several distinct markets for Q, including other firms as well as final (residential) markets, (2) several sources of inputs (e.g., capital, energy, other materials), and (3) several labor inputs differentiated by skills. Such considerations would expand the price and reverse flow vectors, but would not modify the basic structure of Eq. (18). Further extensions arise when more than one transaction take place between two parties, e.g., firm A sells some of its output to firm B, but also buys as input some of the output of firm B. Two distinct telecommunication demand functions for flows from A to B would then be associated to these two transactions, but only the sum of these flows would actually be observed. Finally, note that the model could be easily modified to include other modes of communication, such as snail mail and face-to-face contacts (implying business travel), accounting for their costs and possible substitutions for telecommunications. A similar model can be formulated for a household, which engages in social transactions with other households, sells its labor to firms, and purchases goods and services from firms, while maximizing its utility function subject to income, time, and information constraints, leading to similar information demand functions. Because of lack of space, it is not presented here.

The respective locations of firms and households are prime determinants of the costs/prices of the transportation and telecommunication services they require. It is assumed that the general model (18) is applicable to clusters of similar households and firms located at distinct sites. Define F_{KiLj} as the total flow from sector K at location i, to sector L at location j, with:

$$F_{KiLj} = \Sigma_{k \in (K,i)} \Sigma_{m \in (L,j)} F_{km}, \qquad (19)$$

where F_{km} is the telecommunication flow from agent k to agent m. It is reasonable to assume that F_{KiLj} is a function of the vectors of reverse flows, **RF**, prices, **P**, telecommunication infrastructure **T** , and some measures of the sizes and characteristics of sectors (K,i) and (L,j), **S**, with:

$$F_{KiLj} = f(\mathbf{RF}, \mathbf{P}, \mathbf{S}, \mathbf{T}) \qquad (20)$$

Equation (20) encompasses all the point-to-point models reviewed in Section 3 and 4. In these models, the reverse flows vector **RF** only includes the flow F_{LjKi} . However, Eq. (20) suggests that other return flows F_{**Ki} might be included in **RF**, which would require the formulation and estimation of larger and more complex systems of simultaneous equations. The price vector **P** generally includes some telecommunication price(s) and distance, which can be taken as proxy for the cost of transportation. However, Eq. (20) suggests that the prices of other goods and services might be included in **P**. While such location-specific prices are generally unavailable, their spatial variations are related to the spatial organization and location of activities, i.e., the spatial structure. Guldmann (1999) represents the first systematic attempt to account for the spatial structure, and further research in this direction should be useful. While all the mass variables are subsumed in vector **S**, none of the reviewed studies accounts for infrastructure variables **T**. This is also an area for further research.

The urban hierarchy models reviewed in Section 3.2 focus on the aggregate inter-city flows

$$F_{ij} = \Sigma_K \Sigma_L F_{KiLj} \qquad (21)$$

Strong determinants of the flows F_{ij} are likely to be the mix and size of the economic activities at i and j (mass vector **S**), and the telecommunication infrastructure (vector **T**). The hierarchy models may be helpful to uncover changes in the urban system resulting from economic restructuring and the use of information technologies. The framework made of Eqs. (20) and (21) may help further understand these changes.

Finally, the firm's profit maximization and consumer's utility maximization behavioral models can also be used to analyze the impacts of telecommunications on the socio-economic system. Consider, for instance, a producer services (PS) firm located at time t_1 in the CBD of a metropolitan area, where it maximizes its profit $\Pi_{1,CBD}$ under the prices $\mathbf{P}_1$ and telecommunication infrastructure $\mathbf{T}_1$ vectors. Let $\mathbf{F}_{1,CBD}$ be the vector of telecommunication flows generated by and terminating at this CBD firm (see Eq. 18). Consider next a later period t_2 when CBD real estate costs have increased significantly, while the costs of telecommunication services and clerical labor in an edge city (EC) are much lower than those in the CBD. Further, fiber optics cables are now available in the EC, which allows for easy telecommunications with customers located in the CBD, thus reducing the need for face-to-face contact travels. Given the prices $\mathbf{P}_2$ and telecommunication infrastructure $\mathbf{T}_2$ vectors at time t_2, the firm PS will decide to relocate to the EC if it can achieve a higher profit than by remaining in the CBD, that is:

$$\Pi_{2,EC}(\mathbf{P}_2, \mathbf{T}_2) > \Pi_{2,CBD}(\mathbf{P}_2, \mathbf{T}_2) \qquad (21)$$

If PS moves to EC, we can expect a pattern of telecommunication flows $\mathbf{F}_{2,EC}$ different from the one that was associated to the CBD location, $\mathbf{F}_{1,CBD}$, in particular intense flows between the EC and the CBD. A similar comparative analysis could be applied to a worker considering telecommuting. If, after accounting for the time saved by not commuting, the ability to deal with personal/family duties, but also the social isolation and lack of working interactions, the worker derives a higher utility by telecommuting, U_T, than by commuting, U_C, then he/she will telecommute (provided, of course, that the employer agrees to this arrangement). Thus, changes in telecommunication flows and infrastructure may be linked to changes in the location of economic activities and households, and the proposed framework should provide guidance for empirical analyses of these relationships.

6. CONCLUSIONS

The social sciences literature dealing with telecommunication flows has been reviewed, classified along different geographical scales (local, regional/national, and international), with an emphasis on the methodologies used to analyze the empirical data, and on the nature of the results. There is no claim to exhaustiveness, and the reader might usefully consult Taylor (1980, 1994) for further references and descriptions. However, to the best of our knowledge, the studies reviewed here are representative, and should provide, together with the theoretical framework presented in Section 5, a good basis for further empirical research on telecommunication flows. Understanding the spatial structure of these flows and their relationships to the socio-economic spatial structure is likely to become more and more critical in the information economy.

REFERENCES

Acton, J.P. and I. Vogelsang, 1992. Telephone Demand Over the Atlantic: Evidence from Country-Pair Data, Journal of Industrial Economics, 40, 3: 305-323.

Appelbe, T.W., N.A. Snihur, C. Dineen, D. Farnes, and R. Giordano, 1988. Point-to-Point Modelling - An Application to Canada-Canada and Canada-United States Long Distance Calling, Information Economics and Policy 3: 311-331.

Appelbe, T.W. and C. Dineen, 1993. A Point-to-Point Econometric Model of Canada-Overseas MTS Demand. Presentation at the National Telecommunications Forecasting Conference, Washington, D.C., June.

Bewley, R., and D.G. Fiebig. 1988. Estimation of Price Elasticities for an International Telephone Demand Model. The Journal of Industrial Economics 36 (4): 393-409.

Bodnar, J., P., Dilworth, and S. Iacono, 1988. Cross-Sectional Analysis of Residential Telephone Subscription in Canada, Information Economics and Policy 3: 359-78.

Brandon, B.B., ed., 1981. The Effect of the Demographics of Individual Households on Their Telephone Usage. Cambridge, MA: Ballinger Publishing Company.

Brown, L.A., J. Odland, and R.G. Golledge, 1970. Migration, Functional Distance, and the Urban Hierarchy, Economic Geography 46, 3: 472-85.

Brown, LA., and J. Holmes, 1971. The Delimitation of Functional Regions, Nodal Regions, and Hierarchies by Functional Distance Approaches, Journal of Regional Science 11, 1: 57-72.

Camagni, R.P., and C. Salone, 1993. Network Urban Structure in Northern Italy: Elements for a Theoretical Framework, Urban Studies 30, 6: 1053-64.

Cameron, T.A., and K.J. White, 1990. Generalized Gamma Family Regression Models for Long Distance Call Durations. In Telecommunications Demand Modeling - An Integrated View, A. de Fontenay, M.H. Shugard, D.S. Sibley, eds. Amsterdam: Elsevier Science Publishers, B.V. (North Holland).

Christaller, W., 1966. Central Places in Southern Germany. Englewood Cliffs, NJ: Prentice Hall.

Clark, D., 1973. Urban Linkages and Regional Structure in Wales: An Analysis of Change, 1958-68, Transactions of the Institute of British Geographers 53: 41-58.

Clayton, C., 1974. Communication and Spatial Structure, Tijdschrift voor Economische en Sociale Geografie 65, 3: 221-227.

Clayton, C., 1980. Interdependence in Urban Systems and Its Applications to Political Reorganization, Geografiska Annaler 62B, 1: 11-20.

De Fontenay, A. and J.T. Marshall Lee, 1983. B.C./Alberta Long Distance Calling. In Economic Analysis of Telecommunications: Theory and Applications, edited by L Courville, A. de Fontenay, and A.R. Dobell. Amsterdam: Elsevier Science Publishers, B.V. (North Holland).

Deschamps, P.J., 1974. The Demand for Telephone Calls in Belgium, 1961-1969. Paper presented at the Birmingham International Conference in Telecommunications Economics, Birmingham, England, May.

Descubes, O., and J.-P. Martin, 1982. La Regionalisation Fonctionnelle a Partir des Flux Telephoniques: l'Exemple du Grand-Est Français, Le Bulletin de l'IDATE 7: 163-173.

Dietvorst, A.G.J. and E. Wever, 1977. Changes in the Pattern of Information Exchange in the Netherlands, 1967-1974, Tijdschrift voor Economische en Sociale Geografie 68, 2: 72-82.

Duncan, G.M., and D.M. Perry, 1994. IntraLATA Toll Demand Modeling: A Dynamic Analysis of Revenue and Usage Data, Information Economics and Policy 6: 163-178.

Fiebig, D.G., and R. Bewley. 1987. International Telecommunications Forecasting: An Investigation of Alternative Functional Forms. Applied Economics 19: 949-60.

Fischer, M.M., J. Essletzbichler, H. Gassler, and G. Trichtl, 1993. Telephone Communication Patterns in Austria: A Comparison of the IPFP-based Graph-Theoretic and the Intramax Approaches, Geographical Analysis 25, 3: 224-233.

Fischer, M.M. and S. Gopal, 1994. Artificial Neural Networks: A New Approach to Modeling Interregional Telecommunication Flows, Journal of Regional Science, 34, 4: 503-527.

Fotheringham, A.S., 1983. A New Set of Spatial-Interaction Models: The Theory of Competing Destinations, Environment and Planning A 15: 15-36.

Garin-Munoz, T., and T. Perez-Amaral. 1998. Econometric Modeling of Spanish Very Long Distance International Calling. Information Economics and Policy 10: 237-252.

Gatto, J.P., H.H. Kelejian, and S.W. Stephan, 1988. Stochastic Generalization of Demand Systems with an Application to Telecommunications, Information Economics and Policy 3: 283-309.

Green, H.L., 1955. Hinterland Boundaries of New York City and Boston in Southern New England, Economic Geography 31, 4: 283-300.

Griffin, J.M., 1982. The Welfare Implications of Externalities and Price Elasticities for Telecommunications Pricing, Review of Economics and Statistics 64: 59-66.

Griffin, J.M., and B.L. Egan, 1985. Demand System Estimation in the Presence of Multi-Block Tariffs: A Telecommunication Example, Review of Economics and Statistics 67, 3: 520-24.

Guldmann, J.-M., 1992. Modeling Residential and Business Telecommunication Flows: A Regional Point-to-Point Approach, Geographical Analysis 24, 2: 121-141.

Guldmann, J.-M., 1993. Input-Output Analysis of Regional Telecommunication Flows, Information Economics and Policy, 5: 311-329.

Guldmann, J.-M., 1998. Intersectoral Point-to-Point Telecommunication Flows: Theoretical Framework and Empirical Results. Regional Science and Urban Economics 28: 585-609

Guldmann, J.-M., 1999. Competing Destinations and Intervening Opportunities Interaction Models of Inter-City Telecommunication Flows. Papers in Regional Science 78: 179-194.

Hackl, P., and A.H. Westlund. 1995. On the Price Elasticity of International Telecommunication Demand. Information Economics and Policy 7: 27-36.

Hammer C, Iklé FC (1957) Intercity Telephone and Airline Traffic Related to Distance and the Propensity to Interact. Sociometry 20: 306-316.

Hillier, F.S., and G.L. Lieberman, 1968. Introduction to Operations Research, San Francisco, CA: Holden-Day, Inc.

Hirst, M.A., 1975. Telephone Transactions, Regional Inequality and Urban Growth in East Africa, Tijdschrift voor Economische en Sociale Geografie 66, 5: 277-93.

Illeris, S.and P.O. Pedersen, 1968. Central Places and Functional Regions in Denmark - Factor Analysis of Telephone Traffic. Lund Studies in Geography, Series B, No. 311, Department of Geography, The Royal University of Lund, Sweden.

Infosino, W.J., 1980. Relationships Between the Demand for Local Telephone Calls and Household Characteristics, The Bell System Technical Journal 59: 931-953.

Karikari, J.A., and K. Gyimah-Brempong. 1999. Demand for International Telephone Services Between U.S. and Africa. Information Economics and Policy 11: 407-435.

Kohler, E.F., and B.M. Mitchell, 1983. Response to Residential Time-of-Use Electricity Rates - How Transferable Are the Findings? Rand Report R-2999-MF/FF/NSF/RC - The Rand Corporation, Santa Monica, CA.

Lago, A.M. 1970. Demand Forecasting Model of International Telecommunications and Their Policy Implications. The Journal of Industrial Economics 19: 6-21.

Larsen, W.A. and S.J. McCleary, 1970. Exploratory Attempts to Model Point-to-Point Cross Sectional Interstate Telephone Demand. Unpublished Bell Laboratories memorandum, July. Bell Telephone Laboratories, Inc., Murray Hill, N.J.

Larson, A.C., D.E. Lehman, and D.L. Weisman, 1990. A General Theory of Point-to-Point Long Distance Demand. In Telecommunications Demand Modeling - An Integrated View, edited by A. de Fontenay, M.H., Shugard, and D.S. Sibley. Amsterdam: Elsevier Science Publishers, B.V. (North Holland).

Leinbach, T.R., 1973. Distance, Information Flows and Modernization: Some Observations from West Malaysia, The Professional Geographer 25, 1: 7-11.

Mahan, G.P., 1979. The Demand for Residential Telephone Service. MSU Public Utilities Paper, Michigan State University, East Lansing, MI.

Martins-Filho, C. and J.W. Mayo, 1993. Demand and Pricing of Telecommunications Services: Evidence and Welfare Implications. Rand Journal of Economics, Vol. 24, 3, pp. 439-454.

Naleszkiewicz, W. 1970. International Telecommunications - Testing a Forecasting Model of Demand. Telecommunication Journal 37 (9): 635-38.

Nystuen, J.D., and M.F. Dacey, 1961. A Graph Theory Interpretation of Nodal Regions, Papers and Proceedings of the Regional Science Association 17: 29-42.

Pacey, P.L. 1983. Long Distance Demand: A Point-to-Point Model, Southern Economic Journal 49, 4: 1094-1107.

Park, R.E., B.M., Mitchell, B.M. Wetzel, and J.H. Alleman, 1983. Charging for Local Telephone Calls - How Household Characteristics Affect the Distribution of Calls in the GTE Illinois Experiment, Journal of Econometrics 22: 339-364.

Park, R.E., B.M. Wetzel, and B.M. Mitchell, 1983. Price Elasticities for Local Telephone Calls, Econometrica 51, 6: 1699-1730.

Perl, L.J., 1978. Economic and Demographic Determinants of Residential Demand for

Basic Telephone Service. Boston, MA: National Economic Research Associates, Inc.

Puebla, J.G., 1987. Spatial Structure of Network Flows: A Graph Theoretical Approach, Transportation Research B 21B, 6: 489-502.

Rea, J.D., and G.M. Lage. 1978. Estimates of Demand Elasticities for International Telecommunications Services. The Journal of Industrial Economics 26 (4): 363-81.

Rietveld, P., and L. Janssen. 1990. Telephone Calls and Communication Barriers - The Case of the Netherlands. The Annals of Regional Science 24: 307-318.

Rossera, R., 1990. Discontinuities and Barriers in Communications: The Case of Swiss Communities of Different Language, The Annals of Regional Science, 24: 319-336.

Rouget, B., 1973. Graph Theory and Hierarchisation Models, Regional and Urban Economics 2, 3: 263-296.

Sandbach, J. 1996. International Telephone Traffic, Callback, and Policy Implications. Telecommunications Policy 20 (7): 507-515.

Stouffer, S.A., 1960. Intervening Opportunities and Competing Migrants, Journal of Regional Science 2: 1-26.

Taylor, L.D., 1980. Telecommunications Demand: A Survey and Critique, Cambridge, MA: Ballinger Publishing Company.

Taylor, L.D., and D. Kriedel, 1990. Residential Demand for Access to the Telephone Network. In Telecommunication Demand Modeling - An Integrated View, A. DeFontenay, M.H. Shugard, D.S. Sibley, eds. Amsterdam: Elsevier Science Publishers, B.V. (North Holland.

Taylor, L.D., 1994. Telecommunications Demand in Theory and Practice. Boston, MA: Kluwer Academic Publishers.

Train, K.E., D.L. McFadden, and M. Ben-Akiva, 1987. The Demand for Local Telephone Service: A Fully Discrete Model of Residential Calling Patterns and Service Choices, Rand Journal of Economics 18, 1: 109-23.

Train, K.E., M. Ben-Akiva, and T. Atherton, 1989. Consumption Patterns and Self-Selecting Tariffs, Review of Economics and Statistics 21, 1: 62-73.

Train, K.E., 1993. Intra-LATA Toll Elasticities, Telecommunications Policy: 707-713.

Yatrakis, P.G. 1972. Determinants of the Demand for International Telecommunications. Telecommunication Journal 39 (12): 732-46.

Zellner, A., 1962. An Efficient Method of Estimating Seemingly Unrelated Regressions and Tests for Aggregate Bias, Journal of the American Statistical Association 58: 977-92.