Working Paper

Innovation Networks and Evolution of Technology Clusters

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Abstract

Although knowledge spillovers have long been considered a critical element of economic growth in technology clusters by facilitating innovations, the relationship between characteristics of knowledge spillover network and regional cluster development is ambiguous. Based on patent co-authorship data, we construct inventor networks for two telecom clusters, New Jersey and Texas, in which the former state represents a traditionally vigorous telecom cluster but currently being stuck in a stagnant stage, whereas the latter is on a significant growth path. By analyzing the network structures and performance, we attempt to answer the following questions: 1) do the structures of the inventor networks vary by the characteristics of the geographical clusters; 2) are the patterns of similarities/differences in network structure persistent over time as the clusters go through different stages of development; 3) how do the changes in network properties, if any, reflect the viability of the cluster.

Using multiple analysis methods, including quantitative examination of network performance and structure, network visualizations, interviews with the inventors representing key nodes of the networks, we demonstrated that the typology of industrial districts is a determinant factor for network structure and performance of the inventor mobility network. Compared with Texas' telecom industry which represents a mixed-topology industrial district, New Jersey-based telecom cluster with a typical hub-and-spoke typology features a rather centralized inventor mobility network, which suggests the labor market for hub-and-spoke clusters is relatively inflexible –workers move back and forth between the hub firm(s) and surrounding less-powerful firms depending on the performance of the hub firm(s), however the worker mobility among the smaller firms stays in a low level. Over time, the centralized network structure not only makes the network performance unstable due to the overwhelming power of the hub firm(s), it also restrains the benefits of knowledge spillovers brought by mobile inventors because of the limited diversity of knowledge transferred over such networks. In contrast, the inventor mobility network for mixed-typology clusters, which is formed by random paths of movements, is much sustainable in the long run and less vulnerable to industry downturns. Our analysis suggests that the connectivity of the inventor network may predict the development of mixed-typology clusters, and the degree centrality of the inventor network may be a good indicator for evolvement of hub-and-spoke typology clusters.

Key words: Industrial clusters, patent inventor mobility, complex networks

1. Introduction

Today's economic map demonstrates that industries tend to cluster geographically. Geographical clusters are significant drivers of regional economic growth and competitiveness, and their impact on business competitiveness and regional prosperity have been well documented [1], [14], [21], [30]. Although it is known that innovation activities are the fundamental driving force for cluster development, R&D spending does not always guarantee the growth of a cluster. There is no clear evidence that the states with higher R&D spending grow faster than others [21]. Other "critical success factors" such as presence of functioning networks/partnerships and availability of human resource pools also contribute to the development of clusters.

Among the directions of research in this area, the relationship between cluster's performance in innovation and the localized knowledge diffusion has emerged as an important research area. Recent development in application of complex network theory to social networks provides powerful tools to study evolution of technology clusters. In this study, we contribute to the literature by investigating the evolution of inventor networks in telecom clusters and its implications to cluster development.

When the evolution of telecom industry in the U.S. is concerned, New Jersey (NJ) and Texas (TX) make for a rather appropriate pair for comparison in this regard -- the former state represents a historical hotbed of telecom innovation but currently stuck in a stagnant to declining stage, whereas the latter is on a significant growth path and has replaced NJ's leadership position in telecom innovation. The shifts in advancement of cluster development provide us with a good opportunity to observe the dynamics of inventor networks under different stages of cluster development.

The rest of the paper is organized as follows. Section 2 provides background information on the telecom industry evolution. Section 3 presents a theoretical framework for analyzing technology clusters and application of social network theory in this field. Section 4 describes our analytical methodology. Section 5 reports the study results. The study results are then interpreted within the context of innovation environment of each cluster, based on semi-structured interviews with key inventors and their bibliographical records. We end with a discussion of the implications of our findings and future research.

2. Evolution of telecom industry in New Jersey and Texas

Historically, the telecom markets in the United States were tightly regulated monopolies. Before 1984, the US public telephone network operations and equipment supply were determined by AT&T and the Bell System. Due to the presence of Bell Labs, which was supported by and thrived on the monopoly of the Bell System, New Jersey had been a global center for telecom innovations. Several discoveries from the Labs such as Shannon Information Theory turned into the foundation of advanced telecom networks.

In recent decades, as new unregulated communications technologies emerged and pushed the regulator to adopt a competitive approach for better serving "the public interest", the monopoly of AT&T was broken up. The 1984 Divestiture broke AT&T into a long-distance operator and 7 Regional Bell Operating Companies (RBOCs) providing local telephone services. AT&T kept the Bell Labs and Western Electric as its research and manufacturing units. Later in 1990s, AT&T spun off Bell Labs, along with its equipment-manufacturing business, into an independent company – Lucent

Technologies, which is nowadays still the largest telecom R&D-oriented firm in New Jersey.

The deregulation of US telecommunications market, which was further promoted by the passage of 1996 Telecommunications Act, opened up significant opportunities for start-up businesses and venture investment. Given this favorable environment, New Jersey's telecom sector went through a short period of speedy growth in late 1990s, a phenomenon observed in some other regions of US as well. Texas was one of the fastest-growing states during that period. By taking advantage of the deregulated telecom market, it started to catch up with New Jersey on telecom innovations since 1998. Figure 1 displays the historical trends for the two states in telecom innovation output measured with annual telecom patents assigned to the state.

Following the so-called dot-com bubble burst in 2001, the telecom industry as a whole went into a downturn phase during which the industry lost 380,500 jobs in this country between March 2001 and May 2004 and annual capital spending in all areas of telecommunications plummeted from a peak of $132 billion in 2000 to just $56 billion in 2003 [33]. Almost 5 years after the "bubble burst", the NJ's telecom industry still appears to be struggling to recover from the downturn, while the sector in TX has been able to move ahead and replace the NJ's leading position in telecom R&D. Figure 1 shows that NJ has been falling rapidly behind TX in the telecom patent output since 2003.

Insert figure 1 about here.

3. Theoretical framework

3.1 Technology clusters and geographical knowledge spillovers

Clusters are geographic concentrations of interconnected companies and organizations (for example universities, public research institutions, standards agencies, or trade associations) in particular fields that co-operate but may also compete with each other [30]. Development of clusters is a dynamic process. Clusters have a recognizable life cycle which typically contains four different stages: embryonic, established, mature and declining. Given the role of clusters in promoting regional economy, it becomes an important issue for cluster researcher and practitioners to understand the factors beneath the dynamical process of a particular cluster and to come up with appropriate policy interventions at different stages of the cluster lifecycle.

The studies on clusters date back to Marshall [24], who developed the agglomeration concept based on the cost-saving scale effects brought by industrial localization. According to Marshall [24], companies in a particular field tend to cluster together because they benefit from the availability and quality of the local labor pools, well-developed intermediate input suppliers, and better information flows facilitating the generation of new ideas. With Marshall's original formulation, an industrial district is a spatially delimited region where the business structure is comprised of small, locally owned firms. The Marshallian industrial district is characterized by substantial intradistrict trade among buyers and suppliers in the local area. Marshall's formulation played a significant role in theoretically explaining the success of geographical clusters of small manufacturing companies in central and northern Italy – so that they are regarded as the Italianate version of Marshallian industrial districts. Compared with the original formulation by Marshall, the Italian variety emphasizes on the importance of social relationships within the communities in promoting the core industries. Italianate districts exhibit intensive cooperation among competing companies with purpose of sharing risk and innovation resources and frequent exchanges of professionals between customers and suppliers. In addition, formal institutions such as regional governments and trade associations are seen as playing an important role within the industry by providing shared infrastructure including technical, financial, marketing, training help and establishing a framework of standards which facilitates co-operative relationships between firms [23].

However, the Marshallian formulation including its Italianate version is not generalizable enough to explain the flourishing of many other industrial clusters. In order to identify the key features of new industrial districts in ways that permit easy assessment of their incidence and growth across space and time, Markusen [23], through inductive inquiries, came up with a new approach for distinguishing among types of industrial clusters by their typologies. In Markusen's work, there are four basic types of industrial clusters: the Marshallian form including the Italianate version; the "hub-and-spoke" form, which is supported by one or more dominant firms; the "satellite platform" which forms an assemblage of unconnected branch plants embedded in external organization links;

and the “state-anchored” form, in which the local business structure is dominated by a public or nonprofit organizations such as a military base or a university. According to Markusen’s model, geographical clusters may exhibit significantly different traits from district to district due to their differences in topology. In practice, an industrial cluster may transform itself from one topology into another one over time; and some real-world clusters may exhibit a mix of multiple types of cluster topology.

From the early studies on geographic clusters, researchers have used the concept of knowledge spillover for explaining the geographically concentrated innovation activities which is the key characteristic of industry clusters, e.g. Marshall [25, p. 271] stated, *“… if one man starts a new idea, it is taken up by others and combined with suggestions of their own; and thus it becomes the sources of further new ideas.”*

Building upon Marshall’s agglomeration theory, the recent cluster researchers have emphasized the importance of networks and spatial proximity to explain the phenomenon of clustering [7], [28], [29], [31]. According to the modern cluster theorists, the most important source of benefits of being located in proximity and maintaining locally confined innovation networks is the knowledge and expertise shared by cluster members. The underlying assumption in these studies is that technology knowledge, especially tacit knowledge, flows more easily among individuals or organizations located within the same geographical area, thanks to the social bonds enabling reciprocal trust and convenience of communications.

As a result, cluster members are provided with more opportunities for innovation than those scattered in other areas.

3.2 Innovation networks and technology clusters

The social network approach provides a good way to examine the patterns of localized knowledge-spillover networks and their contribution to the innovation activities. Spillover in this context refers to an “involuntary leakage or voluntary exchange” of technological knowledge [12]. Knowledge spillover and its impacts may be measured at different levels in different theoretical frameworks.

At the individual level, knowledge is characterized by incomplete and scattered information, a single individual can hardly solve all problems as the innovation process often requires the integration of various pieces of knowledge across different disciplines. Social networks facilitate the learning process by supplying complementarities and diversity among groups of innovators. The study by Lucas [22] showed that the new skills and knowledge obtained by individuals can be shared or transferred to others via local social network, eventually making the regional labor pool more productive.

At the firm level, innovation networks make for scale economies and stimulate economic development by allowing multiple network actors to benefit from the R&D input of another actor. According to Arrow [3], the generation of new knowledge often requires substantial investment in research and development, but repeated application of this knowledge, once produced, only comes with a minimum incremental cost. The inter-firm networks allow the firms to take advantages of knowledge spillovers from others.

Porter [29] believes that the geographic proximity boosts the effect of knowledge network by increasing the speed of information flow within a cluster and the rate at which innovations diffuse. Indeed, the presence of an efficient regional innovation network is a good reason for other firms to locate in the cluster, thus making the cluster more vigorous. Empirical studies have shown that there is a positive relationship between geographic clustering, knowledge spillovers and firms' innovative output [21], [27]. For instance, Karlsson [20] showed that innovation networks and the density of companies in a region influence the rate at which new technology is developed in IT firms.

Traditionally, the research on social networks and innovations has emphasized how the network actors benefit from the formal or informal network connections they maintain, these studies are largely focused on the question of how the performance of individual network nodes, which could be measured by a variety of indicators, are associated with the roles or importance of the nodes within the network. In particular, many attempted to find out the implication of holding certain types of "network positions" or "network ties" to the network actors, in terms of innovation performance [8].

Watts and Strogatz [37] introduced the mathematical model to describe the "small-world" network structure, which is characterized by a combination of highly clustered network nodes and short average path lengths between pairs of nodes. The "cliqueness" of network nodes is measured by the cluster coefficient, a network parameter measuring the extent to which nodes adjacent to any node are adjacent to each other. In practice, it reflects the robustness of a network – the higher the cluster coefficient, the more invulnerable is a network to potential removal of a single node. The average path length, which is the typical shortest-path distance between any two nodes in the network, is often used to measure the efficiency of network in facilitating knowledge transfer – a shorter average path length, relative to the overall size of the network, means information can be transferred from one node to another with more ease. Following the introduction of "small-world" network model, empirical studies proved the "small-world" properties are prevalent in a wide variety of real-world networks such as patent citation networks, email networks, and airline transportation networks, etc. The introduction of the small-world network model also provides a quantitative approach to examine the knowledge-spillover network properties and its implications to regional development at the cluster level.

In this context, the most popular research hypothesis is that the "small-world" is the optimal network structure encouraging information flow and thus enhancing innovation and creativity [6], [10], [11], [17], [32], [35,] [36]. The underlying assumption is that small world structure allows clustered and dense relationship to coexist with distant and weak relationships, as the dense and clustered relationships encourage trust and close collaboration, whereas distant ties act as bridge for fresh and non-redundant information to flow. Empirically, research results on this regard remain unsupportive of the hypothesis that "small-world" is the optimal network structure for regional innovation system. Based on the U.S. patent co-authorship data, Fleming et. al [15] statistically tested the relationship between small-world structure and regional innovation output, the study showed that decreased path length and component agglomeration are positively related to future innovation output; however, clustering has a negative impact on subsequent patenting, which is inconsistent with the generally accepted supposition. Considering the existing empirical literature is not rich enough to prove the relationship between innovation network structure and regional growth of innovation, in this study, we investigate the evolution of knowledge spillover networks which are formed by patent inventors' movements in geographical clusters, and examine the similarities and differences in network properties across clusters which may implicate the different stages of cluster progression.

3.3 Mobility of inventors and development of clusters

The contribution of inventor's mobility to knowledge transfer within geographical clusters has been recognized in recent studies. Almeida and Kogut [2] confirmed the positive role of job mobility in promoting the regional innovation output which was measured by patenting rate. Based on the work of Saxenian [31], Silicon Valley's prosperity has been greatly fueled by the significant mobility of innovators between firms. In these studies, mobility was regarded as the key mechanism promoting rapid innovation, as employees taking knowledge obtained in previous jobs and applying it to the next.

Traditionally, knowledge-spillover scholars tend to employ the "cultural differences" to explain the difference in job mobility across clusters, e.g., Saxenian [31] believed that the unique local culture is the key factor making Silicon Valley distinguish from other IT clusters such as Boston/Route 128 in terms of mobility. However, the cultural identity is a limited explanation for evolvement of clusters, considering that a geographical cluster typically goes through four different stages of its lifecycle regardless of its location.

Assuming that the patterns of job movement in a cluster might reflect the characteristics of its macro-labor market, Casper and Murray [8] investigated the biotechnology inventors' career affiliation networks in two regions – Cambridge, UK and Munich, Germany – in which the former represents a rigid labor market whereas the latter represents a much liberal one encouraging job change. Contrary to their expectations, the network properties are grossly similar across the two clusters. However, as the dynamics of the labor market in a cluster, especially for high-tech industries such as biotechnology or IT, may evolve rapidly over time, the literature without considering the longitudinal network dynamics is deficient to reveal how the inventor mobility networks evolves under different conditions of cluster development.

Given the limitation of existing literature and the possibility that patterns of inventor movements could be an indicator of different stages of cluster development, we explore the following questions within the context of industrial clusters. 1) Are the structures of the inventor networks vary by the characteristics of the geographical cluster? 2) Are the patterns of similarities/differences in network structure persist over time as the clusters go through different stages of development? 3) Do changes in network properties over time, if any, reflect the future viability of the cluster?

4. Methodology

4.1 Using patent data to map inventors' mobility and knowledge flows

In this comparative study, we map the mobility network of telecom innovators using patent authorship data, Figure 2 illustrates a framework in which patents are regarded as the carrier and indicator for technological knowledge. Based on the links established by patents, either through patent citation or collaboration, we can construct various types of social networks and observe information traveling across different boundaries within a geographical cluster. First, as majority of patents are delivered by teams instead of individuals, it is reasonable to assume that co-authors know each other and technical information exchange occurs in the process of coming up with the invention. Second, patent data can reflect the mobility of the inventors as they move jobs between different organizations. In addition, as multiple organizations collaborate with each other in R&D projects, the collaborative activities, to the extent that result in new inventions, may be reflected by the assignment of patents' ownership. In this study, we are focused on the latter two scenarios.

Insert figure 2 about here.

The original network data was collected from the Patents BIB dataset issued by the United States Patent and Trademark Office in 2006 [26]. As the objective of this study is to investigate the evolution of telecom inventor networks in two geographical clusters, we selected the telecom patents granted to inventors in New Jersey and Texas between 1986 and 2005 for analysis. We consider a patent belongs to either New Jersey or Texas, as long as one or more of the inventors were located within that state. The patents belonging to both states (accounts for about 1% of the total patents) were excluded from the analysis. Our definition of "telecom" industry followed the approach of categorization introduced by Jaffe [19], in which 12 main patent classes were grouped into a category labeled "communications".

The patent dataset enable us to develop a bipartite network which consists of two sets of vertices – patent assignees and patent inventors. This type of affiliation network connects inventors to assignees, not assignees to assignees or inventors to inventors, at least not directly. Such bipartite networks cannot be interpreted easily though, as the network parameters such as degree distribution have different meanings for different sets of vertices. In order to make the bipartite network useful for analysis of knowledge-spillovers, we transform the bipartite network into two individual one-mode networks. Figure 3 illustrates an example of transformation from bipartite to one-mode.

Insert figure 3 about here.

In this approach, two types of one-mode networks, a network of assignees and a network of patent inventors, can be constructed from the bipartite patent network. Each patent contains detailed information about the invention, which includes patent number, title of the patent, abstract of the invention, its authors (including physical address for each), assignee (owner of the patent, could be assigned to inventors themselves in some cases), main classes and sub-classes, etc. The USPTO database sorts patent data using patent number as the primary index, which creates an issue for the network analysis as certain inventors may use different names across multiple patents they own. It is not unusual that an inventor uses his/her full middle name in certain patents but puts middle initial instead or sometimes simply leaves that part blank in some others. Therefore, we screened the dataset to make the inventors' names consistent across patents.

The matching algorithm was based on the examination and comparison of last name, first name, middle name (if given), main class of patent classification, and assignee name. For each pair of patent authors, if both last names and first names match, we then check the comparison results of the middle names (or initials) --- 1) as long as the middle initials match and both inventors are patenting in a same industry (identified with a common main class of patent), we consider them as one individual and a unique identifier will be assigned for that inventor; 2) for those pairs in which one comes with a middle name (or initial) but the other leaves this part blank, we consider them as one individual only if they are patenting for a same organization (identified with a common assignee name); 3) if neither of them has a middle name or initial and the comparisons of last and first names turn out to be positive, we consider them as one individual only if they are patenting in a same industry. In this study only the patents assigned to organizations rather than self-owned were taken into consideration (account for 92% of the total number of patents).

Compared with the matching process of inventors' names, dealing with the assignee data is a more complicated and difficult work. Firstly, organizations, especially the large corporations, usually comprise multiple subsidiaries or divisions which may apply for and hold patents independently. Secondly, merger and acquisition activities often lead to reassignment of employees and ownership of patents. Patent links corresponding to the above mentioned scenarios should be interpreted carefully in the context of cluster development as the network ties in such situations have a different meaning other than voluntary job movements or collaborating R&D activities between firms. Therefore, we will be analyzing the inventor network structures under two different conditions --- pre and post adjustment. What we mean by "adjustment" in this context is to reorganize and update our patent dataset by incorporating information on M/A history, divestitures and subsidiaries. The information of M&A history and companies' subsidiaries was gathered through Internet searches. Most companies maintain their own websites and usually provide brief introductions to companies' histories, divisions and important M/A events, etc. Also, the Google search-engine provides us with a convenient way to extract the previously published materials regarding companies' M&A. Additionally, some of the M&A events in the clusters were noted via the telephone interviews with the patent inventors.

Since the history data about companies is time-sensitive, enough attention needs to be paid to the process of updating assignee lists. Our approach is to update the assignee data in each sub-dataset, which corresponds to a 3-year window period, individually. The procedures of time-window construction will be detailed in next section.

4.2 Network Structure and its implication

4.2.1 Overall network properties: NJ vs. TX

Our first research question is concerned with the similarities and differences in overall inventor network structures between the two clusters over a long-term period. To approach this question, we first construct a two-mode patent network for each cluster by using the telecom patents granted between 1986 and 2005, respectively; after the transformation from bipartite to one-mode networks, we will get an assignee network and an inventor network for each cluster.

For the one-mode network of assignees, an undirected network tie connecting two nodes (assignees) indicates that there are at least one common inventors delivering patents for both assignees over the time period between 1986 and 2005. In practice these undirected network links can occur in two ways: through co-patenting in which a patent is assigned to multiple assignees simultaneously, or sequential patenting in which inventor(s) deliver patent(s) for both organizations in a certain time sequence. In either of the cases, we assume there would be a knowledge spillover occurring. When the first type of spillover is dominating, it may suggest the R&D collaboration between cluster members are relatively popular in that geographical area. In the second scenario, the mobility-induced network links can be interpreted as an indicator of job mobility of professionals in the areas. It is necessary to note there are a variety of possibilities for each scenario mentioned above, e.g. collaborating R&D activities between firms may also deliver sequential patents assigned multiple firms, and co-patenting activities may correspond to a job movement of inventor as well.

Based on information provided by the patent database itself, one cannot tell the real events associated with the patent network ties, our approach for addressing this complexity is discussed in the next section when we investigate the evolution of the network.

In the initial step of network analysis, we will simply assign an undirected and unweighted network tie between two assignees as long as they share at least one inventor over the period between 1986 and 2005. The one-mode network of assignees constructed in this way reflects the dynamic of inventor movements which is shaped by both inventors' voluntary changes and firm-level adjustments.

In terms of network structure and performance, we would expect that the two clusters are different with each other in multiple aspects due to the difference in cluster typology between the two states. In New Jersey, much of the prosperity of telecom industry has been attributed to the presence of the Bell System, which had monopolized the market for over 80 years. According to Markusen's [23] approach for categorizing industrial clusters, the NJ's telecom cluster is a typical Hub-and-Spoke cluster in which the Bell System performs as the central hub; whereas the TX's telecom cluster features a mixed cluster typology, which exhibit elements of multiple types of clusters simultaneously --- Hub-and-Spoke, Satellite platforms, and State-anchored. First, Texas hosts few important IT firms headquartered within the state (e.g. Texas Instruments, Dell), which may act as anchors to the regional cluster; second, the IT innovation in Texas also owe much of its performance to the presence of some large, externally headquartered IT firms (e.g. IBM, Motorola, AMD, Nokia, Nortel); third, the prominence of Austin as hotbed of IT innovation is to large extent attributed to the presence of University of Texas.

According to Markusen [23], the labor market serving a Hub-and-Spoke district is relatively inflexible when compared to the districts with mixed-typology, the business structure would not encourage horizontal R&D cooperation between firms. Usually the hub firms are more attractive to workers than the surrounding smaller and less powerful firms, *"if jobs open up in hub firms, workers will often abandon smaller employers to get onto the hub firms' payroll"* [23, p. 303]. On the other hand, major downturns in the hub industry or declining of the principal firms can dramatically change the patterns of job movements in the cluster. In either of the above scenarios, we would observe mobility-induced network ties linked to the hub(s). Based on the above discussion, we propose:

Proposition 1: *the inventor network (one-mode network of assignees) for hub-and-spoke clusters would be more centralized in terms of degree centralization, but less connected in terms of overall network connectivity than that for mixed-typology clusters;*

Degree is number of connections associated with a node. Degree centralization is defined as the "*variation in the degree of vertices divided by the maximum degree variation which is possible in a network of the same size*" [13, p. 126]. Put it differently, a network is more centralized when the vertices vary more with respect to their centrality, a star topology network is an extreme with degree centralization equaling one.

With regard to network efficiency, we expect that the inventor networks differ from each other significantly across the two clusters, due to their difference in cluster typology.

The networks with one or few central nodes would be more efficient than networks in which the number of linkages between nodes is evenly distributed, as the hubs facilitate the flow of communication by making the average "distance" between nodes relatively short.

Besides the degree centralization, there are two other types of centrality measurements for a network: betweenness centralization and closeness centralization [16]. Each of the three parameters addresses the significance of central nodes in the entire network from a different perspective, and is associated with efficiency.

The betweenness centralization measures the extent to which the information transmission through a network depends on the existence of certain crucial node(s). The more a certain node is being central in "betweenness", the more flows of information will be disrupted or must take longer to be transferred if the node is removed. Pajek application [13, p. 131] defines the betweenness centrality of a node as "*the proportion of all shortest paths between pairs of other nodes that include this node*". Accordingly, the betweenness centralization is defined as "*the variation in the betweenness centrality of nodes divided by the maximum variation in betweenness centrality scores possible in a network of the same size*".

Closeness measures the extent to which a node is close to other nodes in the network. The closeness centrality of a node is defined as "*the total distance between this node and all others*"; and the closeness centralization is "*the variation in the closeness centrality of nodes divided by the maximum variation in closeness centrality scores possible in a network of the same size.* [13, p. 127]."

Consequently, we propose:

Proposition 2*: the inventor network (one-mode network of assignees) for Hub-and-Spoke clusters would be more centralized in all of the three centrality measurements, thus enables better efficiency than that for mixed-typology clusters.*

In practice, the "shortest-path distance" between two nodes is measurable only if the nodes are connected, directly or indirectly, within a certain component. Nodes located in disconnected graphs should not be taken into consideration because they are not reachable anyway. For this reason, we will extract the largest component from each network (NJ vs. TX) to calculate the betweenness and closeness centralization value. It is biased as only a partial network is examined. This approach is more valid for networks in which the main components are significant.

Despite of its advantage in efficiency, we contend that the centralized network structure is not in favor of cluster development in the long run, though the hub might allow efficient knowledge flow within its component, the diversity of the "spilled knowledge" is limited as most of the mobile inventors are somewhat affiliated with the hub.

On the other hand, as we expect a great majority of nodes in the NJ network, other than those within the main component, would be isolated, which makes the entire NJ network more fragmented than the TX one, therefore, we suggest the efficiency outcome from the above test should be interpreted with cautious.

For the one-mode network of inventors, the network picture would become too busy to be interpreted, just because the number of individual inventors far exceeds the number of assignees. Obviously, the presence of giant employers such as Lucent Technologies will create some extremely busy cliques in which every inventor is connected to everyone else in such a one-mode network. This kind of busy cliques cannot deliver much meaningful information in terms of inter-organizational knowledge-spillover. Moreover, it makes the network less readable. For this reason, we used a specific network analysis technique, m-slices, to reduce the clutter. The m-slices technique is designed to filter out the "unimportant" nodes based upon the multiplicity level of the ties between nodes [13]. For example, suppose inventor A and inventor B both created patents for multiple companies, x, y, and z, during a same period, then in the one-mode network of inventors, there are three overlapping ties between A and B (can be represented by a line with multiplicity value of 3). Thus, by filtering out the ties whose multiplicity level is less than 2, we can remove the dense cliques created by the cloud of large number of inventors belonging to single assignees.

In such a "2-slice" inventor network in which vertices are connected by lines with a multiplicity of 2 or higher, we examine the network connectivity and the distribution of line values for the two clusters to identify differences or similarities.

Assuming that over time the hubs firms (e.g. AT&T) would create many spin-offs and business services around them, the process of development may involve with a mass of personnel movements between assignees, passively or voluntarily, we propose:

Proposition 3*: The inventor network structure (one-mode network of inventors) would be more centralized in Hub-and-Spoke clusters than in mixed-typology clusters in terms of degree centralization, and the high-multiplicity lines (m ≧2) would be denser in Hub-and-Spoke clusters than in mixed-typology clusters..*

4.2.2 Longitudinal analysis of network dynamics

Up till now we have treated the patent network for each cluster as one whole entity, in which the longitudinal dynamics of network cannot be observed. The following analysis will be addressing the latter two research questions regarding the evolvement of inventor networks.

By treating network evolution in discrete steps composed of sub-networks that exist at particular points in time, we investigate the longitudinal dynamics of the inventors' networks by moving a 3-year window and observing how the sub-network properties at each window change over time, and we then attempt to interpret the network dynamics in the context of cluster development. Based on the above-mentioned approach for constructing bipartite patent network and the transformation from two-mode to one mode, we construct a set of consecutive one-mode networks consisting of assignees for TX and NJ, respectively. Each of the assignee networks is corresponding to a 3-year period. As the time-window is being moved forward from 1986 to 2005, we examine how the properties of assignee network change overtime and how the processes differentiate among the two clusters.

As discussed before, a link between two nodes in the one-mode network of assignees may be corresponding to different possibilities including companies' merger or acquisitions. Therefore, our network analysis should take into account the impact of M/A activities on the properties of patent network. For each cluster, the whole patent dataset covering data between 1986 and 2005 is divided into multiple segments to enable the "window-based" analysis to be performed. Then in each block of the dataset covering 3 years' data, we update the list of assignees according to the M/A records collected via internet search or interviews. For example, if firm A acquired firm B in 1990, then we assign a common name to both of the firms when they simultaneously show up during the window period 1990 – 1992, or any later ones. Such replacements of assignee names take place when any of the following events are noted: mergers or acquisitions between firms, assignees representing sub-units of a large corporation, or change of company names. Although we made every effort to search the relevant company information on Internet, there are still chances that few evidences are missed out, because some may not be available online or not straightforwardly extractable. We do not think this potential problem has significant impact on our observations for two reasons: 1) a majority of important M/A events would be available on-line, 2) same searching approach is applied to the dataset for both clusters, 3) the interviews with inventors maintaining the networks would help us confirm the past events for their companies.

By updating the assignee lists, we can remove the networks ties corresponding to M/A activities or common ownership between assignees from the one-mode network of assignees, thus we will be able to examine how the voluntary job mobility and collaborating R&D activities are shaping the patent networks. With the assumption that both voluntary job movements and collaborating activities are positive indicators for cluster development, we propose:

Proposition 4: *longitudinally, the overall connectivity of the inventor network (one-mode network of assignees) is a key indicator of innovation performance for mixed-typology clusters -- increasing network connectivity indicates a growing stage of the cluster, and decreasing connectivity indicates a declining cluster.*

Considering unique business structure for Hub-and-Spoke clusters, we do not expect the above proposition holds true for this type of clusters, as the principal firm(s) has overwhelming power to influence the connectivity of the entire network, either via its success or failure. Instead, we propose:

Proposition 5*: longitudinally, the degree centrality of the inventor network (one-mode network of assignees) is a key indicator of the performance for Hub-and-Spoke clusters – an increase in degree of network centrality indicates a major change in cluster environment, either positively or negatively.*

4.2.3 Network analysis tool – Pajek

The software tool employed in this study for exploring the patent network is Pajek [13], which is free for non-commercial use. It allows us to transform a two-mode network into one-mode networks, to extract subsets such as main component from the entire network, to calculate the network statistics (e.g. degree of centralization, and density of ties, etc.), and to present the network visualizations. Its capacity of processing large number of vertices makes it a good choice for analyzing patent networks.

4.2.4 Interviews with network actors

To explore the underlying forces and motivations shaping the network dynamics over different time periods, we interviewed some of the crucial inventors maintaining the inventor networks for the two clusters. The semi-structured interviews were intended to find out how the network ties came about and the motivations beneath the events.
The inventors for interviewing were selected from two individual windows at each cluster, one for the period 1997 - 1999, the other for 2003 - 2005.

We select the inventors only from two recent window periods for ease of locating them, in many cases these inventors' career paths can be tracked back to earlier periods, which allow us to explore the longitudinal changes of innovation environment in the cluster.

We first listed all inventors involved with the network ties, then searched for their contacts. Multiple resources including corporate contacts of the assignees, Internet yellow book, and Google search, etc. were used to locate the inventors. Considering that only a partial group of listed inventors can be located and interviewed successfully, we supplemented our interview data with the bios of some other "unreachable inventors", which are often published on public web pages or academic publications such as IEEE journals. The Google and academic search engines such as Scopus were employed to search the inventors' bios, which, if obtained successfully, allow us to extract their career histories.

5. Results and interpretations

5.1 Overall patent network properties over the entire period – NJ vs. TX

This section analyzes the overall structural characteristics of the patent networks and explore whether the network properties between the two clusters reflect the regional differences in the evolvement of telecom industry. Due to the significant role played by AT&T in supporting the earlier monopolistic telecom industry, we expect that NJ's telecom patent networks would be different than TX's in various aspects.

As described in the methodology section, using the patent data covering the year 1986 through 2005, we constructed a two-mode network for each cluster, and then the transformation from bipartite to one-mode produces two types of networks, assignee and inventor network. Figure 4 and 5 illustrate the network visualization results for the complete one-mode network of assignees. In such networks, two assignees are linked to each other with an undirected and unweighted tie as long as the two organizations share at least one inventor over the period between 1986 and 2005.

Insert figure 4 and 5 about here.

One observable difference in network structure between the two networks is the centralization of network. The network ties for NJ are heavily clustered around two central hubs, whereas the TX network shows a much balanced distribution of network ties. The descriptive statistics on the degree centralization of network confirmed the difference across the two assignee networks (see Table 1).

Insert table 1 about here.

In terms of network's overall connectivity, contrary to what we expected, the descriptive network statistics show that NJ's assignee network is slightly better connected than TX's, based on the measurements of network density, average degree of nodes, and proportion of non-isolated nodes in the whole network. Given the significant role of the hubs in maintaining the NJ's network, we interpret the relatively high level of connectivity of NJ network is largely due to the break-up of the monopoly of AT&T, which led to a great deal of redistribution of employees and patents within the cluster.

To investigate the efficiency of network in facilitating knowledge flow, we extract the largest connected component in which any node can be reached from any other one by going through a finite number of edges for analysis.

Table 2 reports the analysis results for the largest components extracted from Figure 4 and 5 respectively. For each cluster, the nodes connected within the largest component account for slightly more than one-third of the total nodes. Consistent with our expectation, compared with the counterpart of TX, the main component of NJ's assignee network features a shorter average path length, which means, on average, information from one node in the NJ network may reach another one by going through fewer steps. We believe this network feature is attributed to the presence of central hubs in the network of NJ. Our supposition is confirmed by the measures of degree centralization, betweenness centralization and closeness centralization.

All of the three centrality measurements consistently suggest that NJ's one-mode network of assignees is more centralized than TX's, which is not a surprising result when interpreted in the context of evolvement of telecom industry.

Insert table 2 about here.

Now we turn to the one-mode network of inventors. As described before, in order to get rid of the clutters caused by multiple inventors employed by a single assignee, we only pick up the network ties with high multiplicity value ($m \geqq 2$) and their attached nodes, to construct a new inventor network for each geographical cluster. The results presented in Table 2 show how the two networks differ from each other. The difference in network's degree centralization across the two clusters once again confirms the significant role of AT&T in supporting the NJ's inventor network. More importantly, we noticed that the main component of the NJ network connects around 80% of the total network members together, whereas the largest component for TX only accounts for 16% of the total nodes. It suggests that a great majority of mobile inventors in NJ, either via voluntary job movements or reassignment of jobs due to corporate-level changes, can be traced back to the old Bell System, directly or indirectly.

For the NJ's network, such a hub-supported network structure would allow for efficient information flow because information can flow from one node to another without having to "travel a long way" due to the existence of the hub. On the other hand, the NJ's network structure might limit the potential benefits from knowledge spillovers, when a majority of knowledge transferred through the network originally comes from the common source – Bell System, which is constrained in the diversity of knowledge.

From the distribution of network ties (see Table 3), we observed that the NJ's network has a higher density of high-multiplicity ties when compared with the TX one, which may suggest the NJ inventors were more frequently changing their employers. However, the driving forces for the movement of inventors at this point remain unclear as there are many possible explanations for the network links, such as inconsistent assignee names. The history of monopoly in telecom industry leads us to suspect that a relatively large number of patent links in the NJ's network may correspond to corporate-level changes or adjustments rather than individuals' own choices. This supposition needs further evidences and investigations, which will be addressed in the following section of analysis.

Insert table 3 and 4 about here.

5.2 The evolvement of patent networks

The first step of our analysis indicates that the patent networks in the two geographical clusters are considerably different from each other in density, centrality, and efficiency. Since the networks were treated as single entities for the full period of observation, we are not able to examine whether the networks of the two clusters differ from each other with the same pattern over time. Moreover, the ambiguities in identifying the underlying forces of network ties make it difficult to interpret the implications of the network properties for knowledge spillovers. In this section we take the network analysis one step further to address these above-mentioned issues.

To observe how the properties of inventor network change over time, we construct a set of two-mode networks for each cluster, in which each network corresponds to a block of dataset covering 3 years. Each individual two-mode network is then converted into two corresponding one-mode networks, assignee network and inventor network. Based on the (one-mode) assignee networks, we calculate the key measurements of network properties including density and centrality for each window period. Projecting the network parameters on their corresponding time-window periods allows us to observe the changes in network properties over time. In order to filter out the influence of company-level adjustments (M/A activities, inconsistent assignee names for same organizations, etc.) on the patent networks, we update the lists of assignees for each of the 3-year dataset individually prior to the calculation of the network parameters. By doing so, we pick up the network ties which are corresponding to either individuals' voluntary movements or joint research activities between organizations.

To examine the overall density of the network, we compute the average network degree and proportion of non-isolated nodes over complete members of the network. Figure 6 and 7 present the historical trends in these two measurements. The trends observed from the two charts are consistent with each other, which show that the historical trends in the network connectivity considerably vary across the two geographical clusters. As the time window is being moved through the entire period of observation, the resulting curve for NJ exhibits a U-shape profile which suggests higher instability in network density; whereas the TX's curve shows a gradual transition in the early period and a growing trend catching up with NJ in the later period. In the latest time-window, we noticed that the NJ's network significantly outperforms the TX's one in network connectivity.

Insert figure 6 and 7 about here.

The historical trends in inventor network connectivity for the Texas cluster demonstrates a very similar pattern of growth to the corresponding curve shown in Figure 1, thus supports the Proposition 4. For the NJ's inventor network, it appears that the network connectivity has a negative association with the cluster's innovation output – in the mid 1990s, the NJ network was poorly connected when compared to the counterpart of TX, even though the telecom cluster in NJ was considered to be strong during that period (see Figure 1); the NJ's network became better connected than that of TX in the latest years during which NJ was constantly declining and losing its leadership in telecom R&D to TX.

From Figure 8, we observe that the inventor networks across the two geographical clusters show very different historical trends in network centrality. Over the entire period of observation, the centrality data for the TX network yields, roughly, a straight line, suggesting the TX network always maintained a decentralized structure regardless of the developing stage of the cluster. Compared with the TX network, the NJ network is more centralized during most of the observation periods, and it shows a tremendous growing trend in degree centrality in the later years. The resulting curve for the NJ cluster suggests that up until 1995 there was no such a hub supporting the NJ's inventor network, even though the monopoly of AT&T started to break up from 1984. The hub emerged almost ten years later than expected; more importantly, the significance of the hub was growing quite fast in the later years and reached its peak on the window period 2000-2002. This finding is consistent with Markusen's [23] theory about cluster typology: labor market in Hub-and-Spoke clusters is relatively inflexible, a high level of individual movements within cluster may result from the downturn of the industry or declining of the principle firm(s).

Insert figure 8 about here.

When the connectivity data and centrality data are put together for interpretation, we conclude that, in the recent periods of observation during which the NJ telecom cluster was declining, the hub of the NJ's network became rather significant and the hub-connected component accounted for a great proportion of the total connectivity of the network, thus the Proposition 5 is supported.

Figure 9, 10, 11 and 12 present the network visualization results for period 1988 – 1990, 1993 – 1995, 1997 – 1999, and 2003 – 2005, respectively. The visualizations and descriptive network data consistently indicate that the NJ and TX network differ remarkably in patterns of network evolvement: over time, the TX network has been gradually growing in connectivity by maintaining a decentralized structure, while the NJ network exhibits a U-shaped change in connectivity, a small decline followed by a steep rise. Unlike the TX network, the NJ network's growth in connectivity in later years was largely attributed to the growing power of the central hub represented by Lucent Technologies (see Figure 12).

Insert figure 9, 10, 11, 12 about here.

5.3 Motivations for the network dynamics and its implications for cluster development

In subsequent analysis, we seek to understand what are the dynamical processes determining the networks evolution and whether specific motivations beneath the dynamics are related to the viability of the cluster.

One of the key finding from the above network analysis is that the growingly centralized NJ network emerged in a period during which the cluster was experiencing a declining stage. Based on the literature, we suspect that a majority of network ties emerged in the NJ network in recent years may be related to the downsizing of the incumbent telecom player(s) in the state.

In order to show the directions of inventor's movement, we visualized the one-mode assignee networks for the two clusters using directional network ties. The formation of the one-mode network of assignees in this case still follows the protocols demonstrated in Figure 3, and also based on the same dataset in which each block corresponds to a 3-year window period and has been revised for consistent assignee names.

Unlike the previously exhibited networks in which the network ties are undirected and unweighted, we now assign various colors, directions, and line-widths to the network ties to reflect the characteristics of the links. The direction of a link is determined by the sequence of patenting, e.g. company A and B are supposed to be connected with each other as long as they share a common inventor (or more) during the window period, we assign a directional link from A to B if the common inventor delivered patents for both companies in a time sequence A through B. The sequence of patenting is obtained by checking up the inventor's entire patenting history, whichever assignee filed the latest patents with this inventor, determined by application date, is considered to be the ending point of the directional link. Whenever there are multiple common inventors involved with a single pair of assignees, we add them up and assign the number of inventors as the width of the link. In such cases, each inventor may introduce a new directional arc into the relationship, consequently, two opposite arcs might cancel each other out and make the actual link an undirected but wider one; in cases it turns out certain direction is stronger than the other, we select the stronger direction for the actual link.

Besides the sequential patenting events, co-patents, in which multiple organizations are listed on a single patent, also form links in the one-mode network of assignees. Considering the co-patenting events are relatively rare when compared to sequential patenting events, we assign a unique color to these undirected links which are involved with any co-patents.

We present the visualization results for these directional networks in Figure 13, 14, 15 and 16, in which the first two illustrations, respectively, show the networks of NJ and TX over the window period 1997 – 1999, and the latter pair corresponds to the period 2003 – 2005. In order to highlight the flow of inventors across the central network hubs, we assign network ties with different colors to distinguish the inbound flows from the outbound flows – network ties starting from the hubs are colored blue, whereas the ties ending at the hubs are colored red.

Insert figure 13, 14, 15, 16 about here.

In this analysis, any network nodes with more than five connections, regardless of their directions, are regarded as central hubs. For the period 1997 – 1999, we identified one central hub for the NJ network but none for the TX one. Based on the previously demonstrated network statistic, we already knew this window period is the point from which the network of NJ started to grow in both connectivity and centrality tremendously. Considering that the average time-lag between filing a patent applications and issuing the patent is about 24 months, actually the inventor movements indicated by Figure 13 and 14 should be interpreted within an earlier period, which happened to be the beginning of real competition in the telecom market. Following the implementation of the 1996

Telecom Act, a milestone in the history of telecommunications in the US, both incumbent and start-up firms thrived in the booming market. Consequently, we observe that the connectivity of the inventor networks was increased significantly in both clusters, as the inventors and firms were encouraged to explore new opportunities both internally and externally. Although the networks in both clusters were better connected during this booming period for telecom when compared with their counterparts in the earlier periods of observation, from then on the inventor networks started to differ remarkably in structure across the two clusters. The NJ network was largely maintained by a central hub, represented by AT&T, whereas the TX network was decentralized without any significant hubs (see Figure 13, 14). The distribution of the colored connections of the NJ hub suggests that the incoming and outgoing inventors at the hub roughly balanced out. Put it differently, most of the mobile inventors in NJ during that period were either joining into AT&T or leaving the incumbent to explore new opportunities, and the inflow and outflow are roughly balanced. The interviews with the key inventors maintaining the NJ network confirmed this situation. For instance, the outbound tie from BellCore to Texas Instruments Corp. was formed when a senior researcher at AT&T moved his job to Texas Instrument in 1996. At the time, Texas Instrument was planning to establish a new design center in New Jersey and finding a prolific inventor who is capable of organizing and leading a team in the design of mixed-signal integrated circuits. The senior researcher at AT&T was invited to join TI as a key leader for fulfilling their plan in New Jersey.

The inbound tie from Rutgers University to AT&T indeed corresponds to an event in which an employee of AT&T studied part-time at Rutgers University and delivered a patent in 1994 with the university, as part of his Master’s degree.

Some inventors from other firms did move into the NJ “hub” for various reasons during that period. For instance, the inbound link from Sony Corp. to AT&T was established when an engineer left Sony and joined Lucent in 1994 to explore an opportunity at AT&T – manufacturer of the telecom network equipment, as opposed to Sony which mostly supports consumer electronics.

The co-patent induced link between Boeing Company and AT&T corresponds to a joint research project which was initiated by a non-profit collaborative manufacturing research consortium -- NCMS (National Center for Manufacturing Sciences). The goal of the project was to develop a new product to fulfill the specific needs of the US government. Multiple companies including Lucent Technology, Motorola, and Boeing were involved with the large project, the co-patent which was assigned to Boeing and Lucent Technologies simultaneously was part of the outcome of the project.

Turning to the TX network in the same period, we observe that the largest component in the network connects together several key players in telecom, including Motorola, Nokia, Nortel, MCI, Compaq, and AMD, yet none of the key firms shows a significant power in encouraging inventor movements. Unlike the NJ network, the degree distribution of the TX network is quite balanced, which suggests the TX inventors were moving more “randomly” from one place to another during the period.

For instance, the directional link starting from the Research Foundation of State University of New York to Nortel corresponds to a doctoral student who was graduating from the school and then employed by Nortel. The link starting from IBM to MCI was formed when a prolific inventor in the field of software development left IBM and become a founding Patent Engineer at MCI. He then helped found the MCI Intellectual Property program and facilitated the filing of MCI’s first two hundred patent applications from engineering teams across the company.

The bold link starting from Gas Research Institute to Halliburton actually corresponds to a joint research project between the two organizations. The project was mainly funded by the GRI, an independent and not-for-profit research organization, the resulting patents were assigned to GRI according to the agreement. As Halliburton contributed several researchers to the project, and some of them kept patenting for Halliburton after the joint project was over, the directional patent link in Figure 13 was formed in that way.

The triangle linking together US Army, Texas Instruments, and Southern Methodist University actually corresponds to the innovation activities of one single inventor over different time periods. The inventor at the beginning was working and patenting for US Army, then he moved to Southern Methodist University and started his academic career as a faculty in 1989. As part of his research at the university was funded by Texas Instruments during late 1990s, the resulting patents were assigned to the financial sponsor.

Based on the network analysis and the information collected via interviews, we interpret the decentralized network structure, which is formed by “random” movements of inventors, as an advantage of TX over NJ in terms of knowledge spillover, due to the diversity of knowledge transferred within the network.

As time went on, the network structures across the two clusters still differed with each other with the same patterns, but even more markedly on the most recent window period (see Figure 15 and 16). In the NJ’s network over period 2003 – 2005, we observed that a great majority of the network ties are connected within the largest component which is maintained by three major hubs, Lucent Technologies, AT&T, and Sarnoff Crop.

Strikingly, we find that the outbound flows leaving from Lucent Technologies and AT&T account for an overwhelming majority of the total network ties connected with the two hubs.

Figure 15 shows that Lucent Technologies is connected with Agere Systems, Avaya, and AT&T by three undirected bold ties respectively. At this point, we decided not to assign any directions for these three special network ties, because each of these links corresponds to quite a few inventors, e.g. there were 61 individual inventors involved with the link between Lucent Technologies and Agere Systems. These inventors represent a variety of events producing patent links, in which some of them correspond to patent reassignments after the spinning-off, and some others correspond to voluntary job movements of inventors, etc.

The other network ties connected with Lucent Technologies and AT&T are predominantly blue. Considering the “time-lag” effect discussed earlier, the inventor movements displayed Figure 15 and 16 should be interpreted actually within the period 2001 - 2003, which was marked by the ending of the telecom bubble. This situation leads us to suspect that a majority of the outflow inventors, represented by the blue ties, might be explained by the downturn of the telecom industry.

Our interviews with the crucial inventors maintaining the network indicated that some of the blue ties indeed correspond to entrepreneurial behaviors by professionals from the incumbents during the “bubble” period, while some others correspond to job changes due to the downsizing of the incumbents in the bubble burst. For instance, the link starting from Lucent Technologies to Photuris corresponds to an entrepreneurial event in which three research scientists, in 2000, left Bell Lab and found the optical networking startup Photuris, which developed optical data network equipment primarily for Regional Bell Operating Companies. Similarly, the link from Lucent to Motorola represents another entrepreneurial event; two leading scientists at the Communications Software Business of Lucent Technologies where there were credited with building the very first soft-switch for wired communications systems, moved out in 2000 and established a startup Winphoria to explore the growing market in wireless communications. The startup was acquired by Motorola in 2003; accordingly, the original name of the startup was replaced with Motorola in the network picture. Likewise, the link starting from Lucent to Inplane Photonics was formed when a senior scientist who had spent more than 20 years at Bell Labs departed in 2001 to startup Inplane Photonics, which designs and manufactures photonic components for telecom systems. The event beneath the link starting from Lucent to Chromis Fiberoptics can be traced back to the sale of Lucent's optical fiber business to Furukawa Electric. As a result of the acquisition, the polymer optical fiber (POF) research team became a part of the OFS owned by Furukawa. In 2004, the leadership of the polymer optical fiber team concluded a management buyout of the POF business from the OFS to form Chromis Fiberoptics.

On the one hand, as can be seen from the above examples, the bubble economy in the beginning of 2000s encouraged some experts to leave the incumbents to explore entrepreneurial opportunities; on the other hand, the "bubble burst" which came shortly forced the incumbents to slow down and therefore pushed more inventors to move out. For example, the blue link starting from Lucent to Microsoft and the one from AT&T to Tellium represent individuals' job changes which occurred in the beginning of 2000s. Given the fact that Lucent was massively cutting off its job positions around 2001, it is not surprising to see such a high level of outflow of inventors appearing in the patent network picture. Indeed, besides the unfavorable external factors which are related to the industry downturn, the NJ-based telecom incumbents have seemingly failed to create a good innovation environment internally. An inventor in multimedia communications field who worked with Lucent till 2000 commented, "I felt it was no longer a good place to work with, as it could not provide a good innovation environment for researchers, it became more difficult to get the new technologies and ideas transferred into real products."

In addition, as the telecom industry went up and down, we observed that some inventors moved back and forth between the industry and academic institutions. As most of the inventors in the telecom industry are highly educated and many hold doctoral degrees, these movements are not surprising for us. For example, during the bubble period, an expert who worked at Bell Labs for fifteen years departed the incumbent firm and joined the founding team of a start-up company. Few years later, the unit headed by him failed to get over the bubble burst, he then joined a university as a faculty member and stayed there till present time. Another inventor departed Bell Labs in 1993 after working there for 3 years, and moved to an oversea university where he established a brand new teaching and research program in wireless communications. In 1996, he returned to New Jersey and joined AT&T once again, at which time he continued to be an adjunct professor at that university.

In Figure 15, the links starting from AT&T and ending at Mitsubishi and Matsushita actually correspond to a university professor who part-time consulted in AT&T Labs and patented there in late 1990s. Mitsubishi and Matsushita are linked with AT&T because these two companies sponsored the research of this professor and therefore owned the resulting patents.

Turning next to Figure 16, which illustrates the TX network on the same period, we observe that the most connected hub is represented by Texas Instruments. The distribution of colors of the ties suggests that the company was being competitive in drawing experts during that period. Among the inbound network ties, the one from Stanford University to TI resulted from a Ph.d graduate departing from Stanford University and joined TI in 1997. The link from Motorola to Texas Instruments resulted from an inventor's job movement from Motorola to TI in 2000. The one from Robert Bosch GMBH to TI corresponds to a mobile inventor who was moving from Heinrich-Hertz-Institute Berlin to TI in 1998. During his work at the German Institute, the inventor was involved in various European research projects, in which one of them was sponsored by Robert Bosch GMBH. The link from AT&T to TI corresponds to a mobile inventor moving into TI from AT&T in 2001. The blue link starting from Texas Instruments to

Cisco Systems corresponds to a job movement from Amati Communications to Cisco Systems. The former company was acquired by Texas Instruments in 1997.

Other than that component maintained by Texas Instruments, the network degrees are distributed in a balanced way within other segments of the TX network (see Figure 16). There are two relatively large components in the network constructed by decentralized structure, which suggest regular movements of individuals between firms, especially the major players (e.g. Alcatel, MCI, Nortel, Nokia, Intel, HP, Agere, ect.). Compared with the NJ network in the same period, in which many network ties correspond to entrepreneurs coming out from Bell Labs, the TX telecom experts at the major players did not seem to be as active as their colleagues in NJ in exploring entrepreneurial opportunities, as relatively few start-up companies are connected with these large firms. The difference in the number of entrepreneur-induced links between the two states might be due to the unique industry environment for NJ as well. Prior to the deregulation of telecom industry, not surprisingly, Bell Labs held a substantial number of scientists, including many "star scientists", who were capable of catching the real opportunities brought by the opening-up of the market. Encouraged by the once-booming telecom market and the Lucent's declining in the following years, many of the "star scientists" moved out of the telecom giant during a relatively short period.

Without such a spoke supporting the whole network, the TX network continues to feature a random structure till the recent window. Indeed, besides the absence of telecom giants such as Bell Labs, another important reason that makes the individual components of the TX network disconnected from each other is the diversity of the industry. As can be seen from the network visualizations, some of the isolated components in the TX networks are composed of organizations representing a single sub-sector, e.g., in Figure 16, the 5-node component located in the lower right corner corresponds to four individual inventors moving between companies in biometric technologies; and the 4-node component located in left corner is mainly composed of organizations in oilfield exploitation. Our interviews with the inventors confirmed that a majority of the network ties in Figure 16 resulted from job changes of individuals, while few correspond to inter-firm collaboration, or entrepreneurial behaviors. Among the 12 links we investigated into for identifying the underlying events, 10 of them resulted from job changes of inventors.

For example, the link starting from HP to Agere corresponds to an inventor moving from Compaq to Agere (at that time still a branch of Lucent) in 1999. The link from Baker Hughes to Sensor Highway Ltd. actually resulted from an inter-firm joint project for new product development, and the one from Alcatel to Chiaro Networks LTD resulted from an entrepreneurial event in 2000, at which nearly a third of the start-up's staff came from Alcatel, including a senior vice president and the chief technology officer.

The increased level of job movements via random network paths, which in many cases were encouraged by better financial rewards or increased career advancement, indicate an increasingly dynamic job market.

Regarding the dynamics of the telecom industry over the past few years, some inventors in the clusters shared their opinions with us via the interviews. As the IT industry in Texas is a relatively diversified one, inventors in different sectors may experience different levels of change, yet most of the TX-based inventors agree that the industry has been substantially recovered from the industry downturn and feel positive about its future development. A TX inventor, who worked with Motorola and Sigmatel for 17 years in total, commented, "the industry is being recovered from the collapse of the big bubble, a problem for the industry was that the capacity of systems surpassed the market demand. Nowadays, the market demands increased a lot, and certain sectors of the industry are catching up quickly, such as cellular systems, but some sectors are still struggling with the "overcapacity" problem, like the optic fiber systems, …, the industry will go ahead sooner or later, as the telecom market is far from saturated, not like the computer industry which has been saturated years ago, it may have few more decades to grow until the market become saturated." Another senior professional located in TX commented, "in this particular field (software development for telecom systems), the best time for delivering patents were in 1990s, a lot of excellent and ground-breaking patents emerged during that period. In recent years, the patenting in this field has been slowing down, as many good jobs were already done before. Nowadays, the job market here is OK, most fresh graduates do not have a hard time finding a job in the state, but the salaries are lower than before. A lot of jobs in this area have been outsourced to overseas. Fortunately, the best programmers are still here, which is an incomparable advantage for Texas."

Compared to the TX inventors, the comments from NJ inventors on the dynamic of the cluster are mostly negative. “Telecom in NJ is almost gone” is a common feeling among the NJ inventors interviewed. A scientist who is presently at Texas Instruments in Dallas, and who had been with Bell Labs and multiple elite universities (as faculty member) previously, commented: “definitively the environment (for NJ telecom) is not good, the opportunities are declining, as Lucent is still downsizing and cutting research jobs, and many small-size companies are moving out of NJ to Silicon Valley or Texas. At the same time, it becomes more difficult to start up new telecom business in NJ. A big barrier (for start-up businesses) is the lack of qualified people and a supporting education system. Unlike Silicon Valley or Texas, where Stanford University and University of Texas at Austin graduate many good-quality engineering students, the universities within NJ do not have enough programs to support the telecom industry, and we do not see many experts coming from other states.

These comments are well consistent with our observations from the network visualizations, which strongly imply that the differences in network properties between the two clusters reflect the different levels of telecom cluster stability and viability across the two states. Based on the interview data, Table 5 highlights the common and distinctive characteristics of inventors’ movements across the two clusters.

6. Conclusions and discussion

This paper examines the dynamics of inventor networks and its implications to cluster progression. The analysis results highlight why the telecom cluster in New Jersey has been falling behind that of Texas in innovation in recent years. The first three propositions are concerned with the overall network structures in the two clusters. In terms of network centrality, it turns out that NJ has a much more centralized network structure than TX’s, for both two types of the one-mode networks. Proposition 1 (first component) and Proposition 3 are supported by the network analysis. In practice, the results suggest that most of the mobile inventors in NJ had been with the incumbent sometime in their past careers. Indeed, the role of AT&T in maintaining the NJ’s inventor network is more significant than expected – the large number of network ties clustering surrounding the hub make the overall network connectivity better in NJ than in TX, though we expect to see the opposite situation based on the assumption that the previous monopolistic business structure in NJ would discourage job movements in that state, except in case of corporate downsizing. Thus, the second component of Proposition 1 is not supported.

The Proposition 2, which is concerned with the efficiency of the network, is supported by the analysis. The existence of the central hub, represented by AT&T and spoke-shape network structure, make the average path length shorter in NJ's largest component than in the counterpart of TX, thus enables information to be transferred easily from one to another in the network component of NJ. When interpreted in the context of the industry deregulation, we contend that the spoke-shape network component in NJ indeed corresponds to the job movements which resulted from the demise of the monopoly – the break-up of the AT&T monopoly created multiple spin-offs, and in the meantime, the growing opportunities brought by the industry deregulation attracted many of the employees to leave the incumbents. This situation is suggestive of the limitation of the NJ's innovation network – the level of diversity of the spillovers and vulnerability of the network. As a great majority of mobile inventors in the community originally come from a common employer, collectively, the expertise being transferred via social networks are less distinctive when compared with the spillovers across random and diversified firms. Moreover, we contend that the innovation network of NJ is less sustainable over the long run as most of the job flows in the community result from the adjustment of a single employer instead of a vigorous labor market encouraging voluntary job movements.

The analysis of longitudinal changes of networks formed by individuals' job movements allows us to observe how the inventor network properties change while the cluster goes through different stages of its lifecycle.

Proposition 4, driven by the insight that inventors' movements establish important channels for knowledge spillovers and thus encourage innovations, is supported in mixed-topology clusters.

Despite of the positive effect of knowledge spillovers brought by individuals' job movements, the growth in job mobility for Hub-and-spoke clusters may be a negative indicator for cluster's performance in innovation. As a matter of fact, individuals change jobs for their own reasons varying from case to case, in which some may correspond to growing opportunities by a booming cluster, whereas some others may result from industry downturn or company's failure. For Hub-and-Spoke clusters, due to the significant role of the hub firm(s) in supporting the regional industry, the changes in connectivity or centrality of inventor networks deserve special attention as they are likely to be a consequence of industry downturn or failure of the hub(s).

In this regard, Proposition 5 is supported by our analysis.

7. Implications for research and cluster practitioners

Our results highlight the importance of considering topology of clusters in monitoring cluster development based on patent inventor networks. Prior research informed us that the knowledge spillover brought by individuals' movements is one of the key facilitators for innovation and thus for the development of clusters as well, our study suggests that there is no straightforward relationship between the level of job mobility and growth of industrial clusters. The driving forces and motivations beneath the inventor mobility network are determinant of the mobility effect. Cluster practitioners need to evaluate the specific economic conditions and business structure in their clusters for making decisions on the approach of interpreting relevant network parameters.

This study confirmed the weakness of the traditional approach --"cultural differences"-- in explaining the differential innovation performance of clusters. Our analysis demonstrated that the inventor mobility network may change dynamically over time, and the patterns of mobility are shaped by multiple factors including evolution of the industry, diversity of the cluster, etc. In this context, we contend that the "regional culture", in a sense, is not a constant element independent of economic and institutional environment of clusters, it should be evaluated within a certain economic and regulatory context.

Our results should also be of interest to regional cluster practitioners. The most important strategic implication for the New Jersey practitioners is how to keep its intellectual capital after the burst of the telecom bubble. As demonstrated in our analysis results, NJ's advantage in telecom innovation indeed lies in the tremendous R&D capacity of the Bell Labs, which had been fueled by the former monopolistic policy. As a result of the industry de-regulation and the emergence of the IT bubble, many highly innovative researchers moved out from AT&T to explore entrepreneurial opportunities. Unfortunately, such a phenomenal growth in telecom innovation was disrupted by the industry downturn which came shortly. As a consequence, we observed that the giant telecom firms such as Lucent Technologies struggle to pull out from the sluggish stage and keep losing their innovative professionals. On the other hand, the state fails to create a favorable environment to support start-up businesses in telecom [18]. Under these conditions, many professionals in the state elect to leave the regional telecom cluster.

Considering that the state still maintain a tremendous intellectual capital in telecom industry, it is important for the NJ government to develop appropriate strategies to revive the cluster. First, the government needs to create a policy environment that favors the growth of small or medium telecom businesses in the state. In particular, the policy-makers in the state should consider how to establish an efficient innovation system which consists of heterogeneous types of organizations and diversified sub-sectors of the industry, the efforts would assist the cluster to successfully transform itself into a mixed-typology one. Second, the state government should put more effort in encouraging collaborations between the industry and academia. The collaboration networks, on the one hand, directly contribute to the innovation system by allowing resource-sharing and knowledge flows. On the other hand, collaborations help the educational institutions shape their teaching and research programs for better serving the regional telecom cluster.

For multiple reasons, NJ hasn't developed an active cluster strategy to support its telecom industry which has been a tremendous asset for the state. In this regard, many other states including Texas already move ahead and take strong commitments to promoting cluster development with focused cluster strategies. For example, Texas Industry Cluster Initiative requires the state to strengthen the competitiveness of its six key clusters including the Information and Computer Technology cluster. Although in this study we cannot assess the effect of the Cluster Initiative on the development of the Texas telecom cluster, such a supportive policy environment will definitively provide advantages for the Texas cluster over the long run.

Indeed, the importance of regulatory frameworks in promoting cluster development has been well documented in prior research [1], [29]. For instance, the success of the

Aerospace cluster near Toulouse, France, is largely attributed to the support provided by French State.

Lacking such a policy action by the state government would further lessen the competitiveness of the NJ's telecom cluster in the future. At this time, it should be a priority for the state government to take appropriate policy interventions to prevent the cluster from disappearing from the state eventually.

Our results are suggestive of the associations between cluster evolution and inventor network dynamics, yet the generalizability of the finding is limited as only two clusters in a particular industry were examined in this study. Indeed, real-world clusters may characterize any one of the four types of typology (Marshallian, Hub-and-Spoke, Satellite Platform, and State-anchored clusters) or any combination of the four elements, future research might benefit from a statistical test covering a greater variety of cluster typologies and industries.

Another point worth special note is the limitation of using patent records in knowledge spillover research. Inventors may not deliver patents for each of their employers during the period of employment; consequently, the patent inventor networks only can capture a partial picture of the movements of inventors within a cluster. The more likely a professional within a particular industry is to file patents, the more valid the method is to capture the individuals' movements of the industry.

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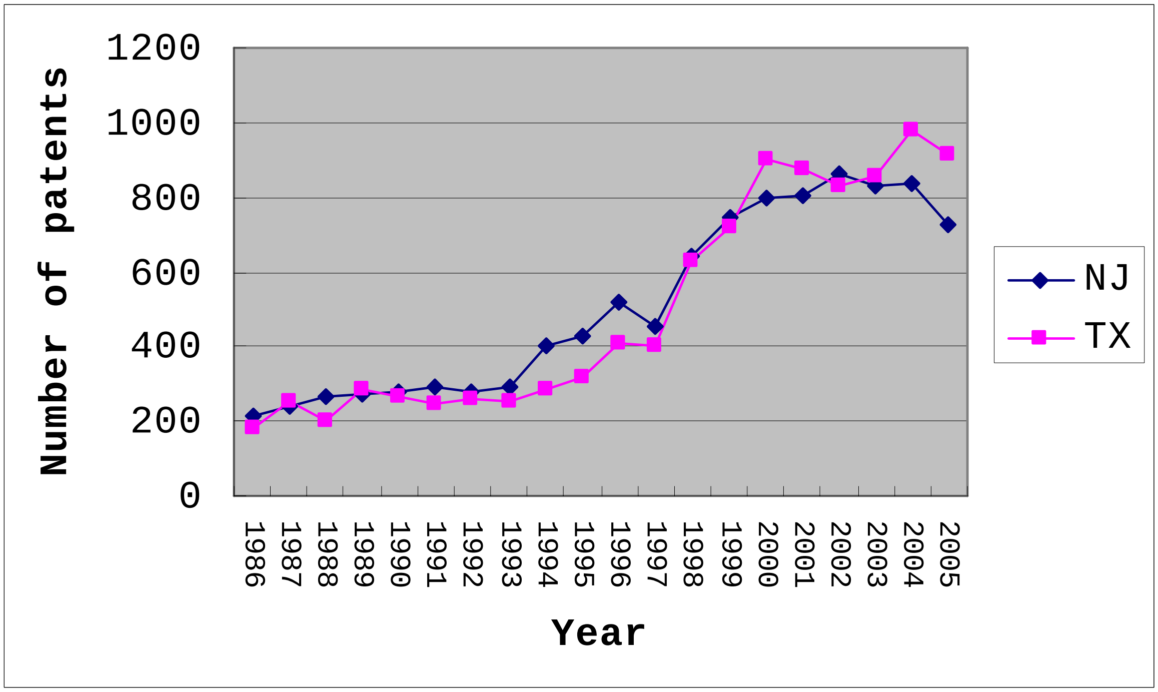

Figure 1: Annual patent output by states

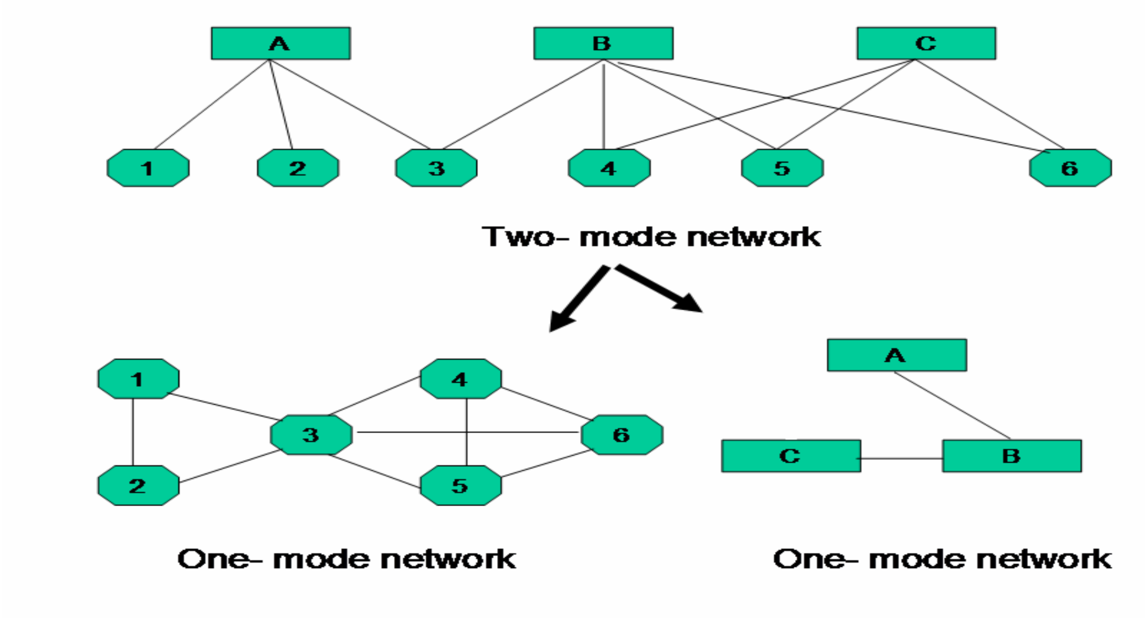

Figure 2: Transformation of a two-mode network to one-mode networks

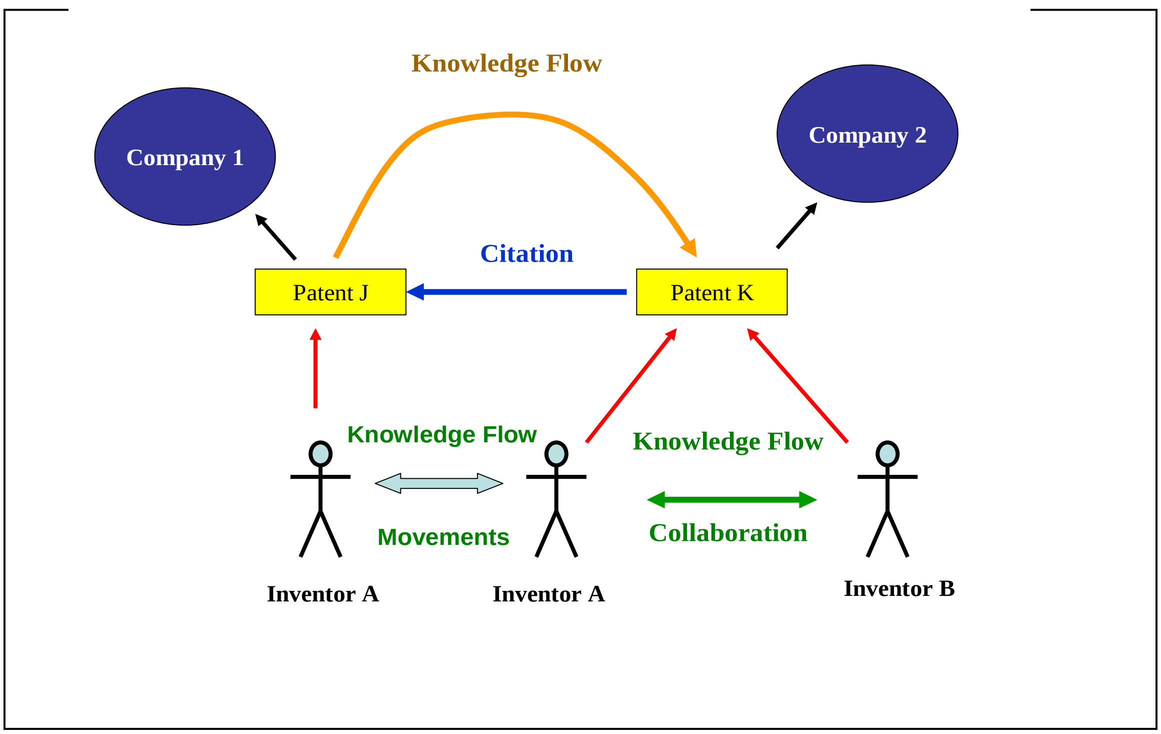

Figure 3: Framework of using patents as indicators for knowledge spillovers

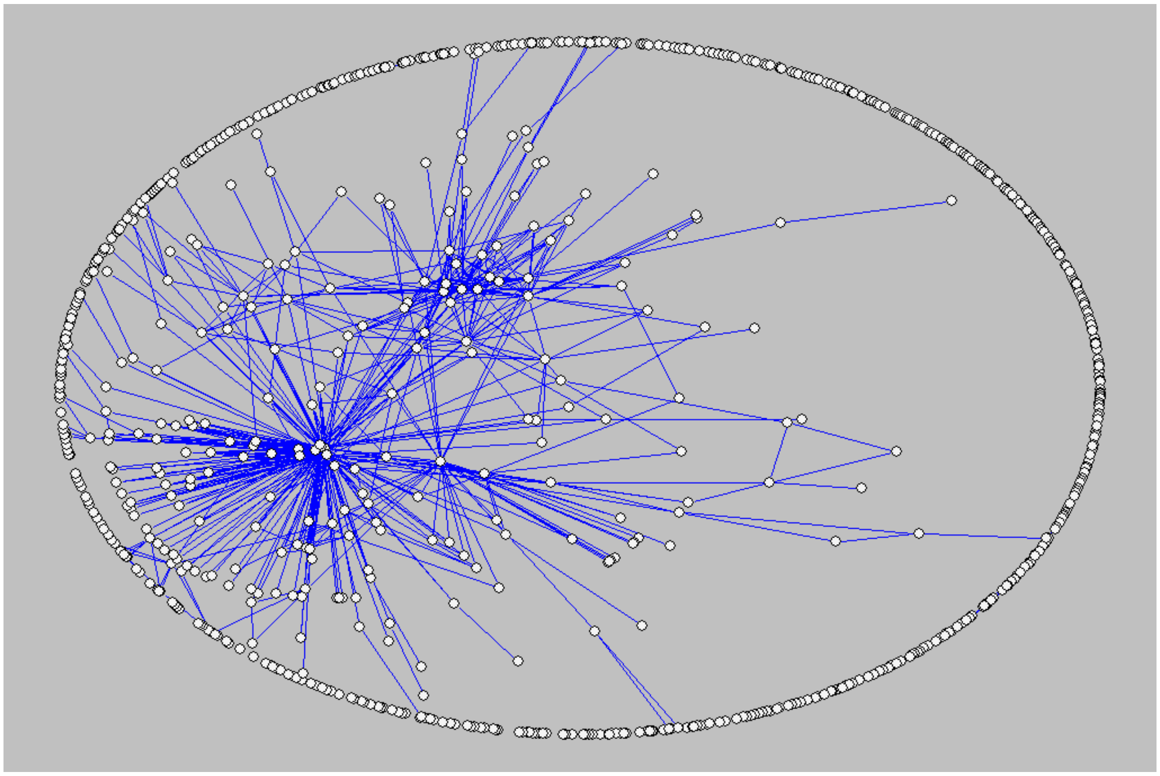

Figure 4: Inventor network for NJ over the entire period (one-mode of assignees)

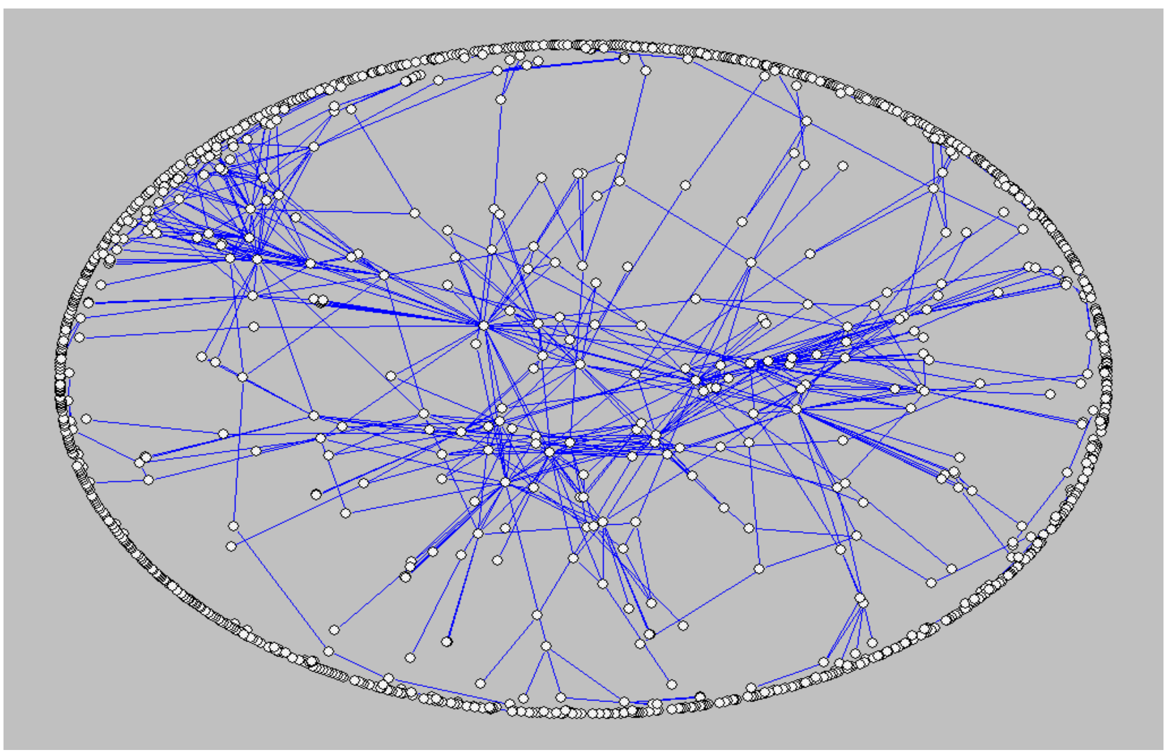

Figure 5: Inventor network for TX over the entire period (one-mode of assignees)

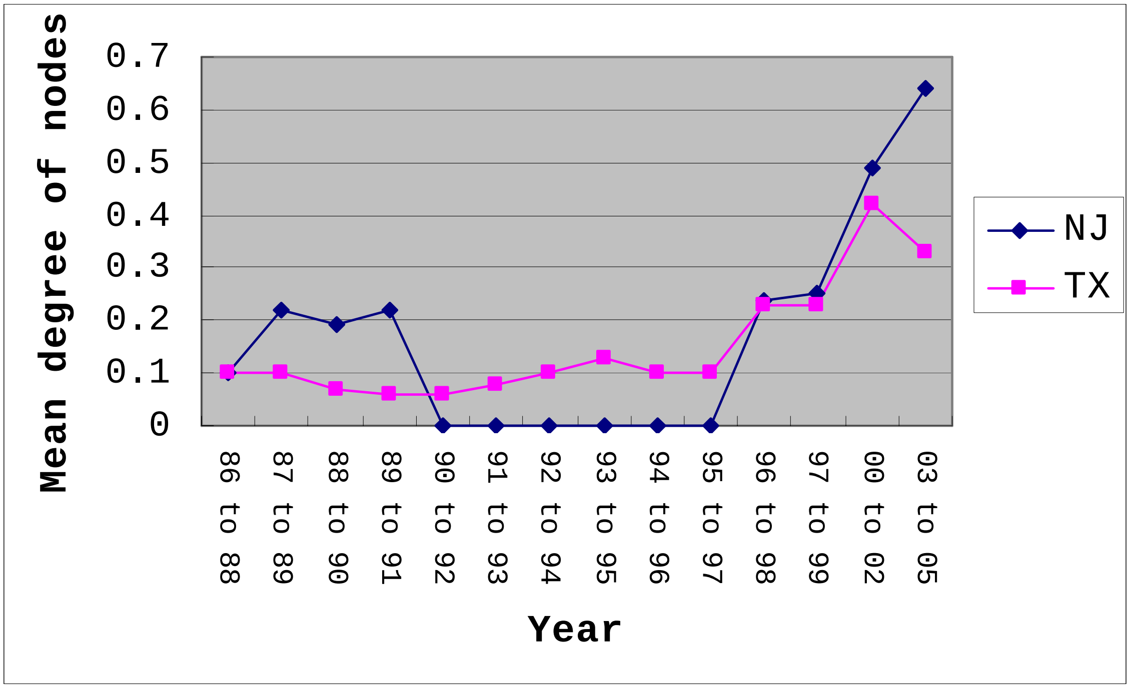

Figure 6: Average degree of nodes in inventor network (one-mode of assignees)

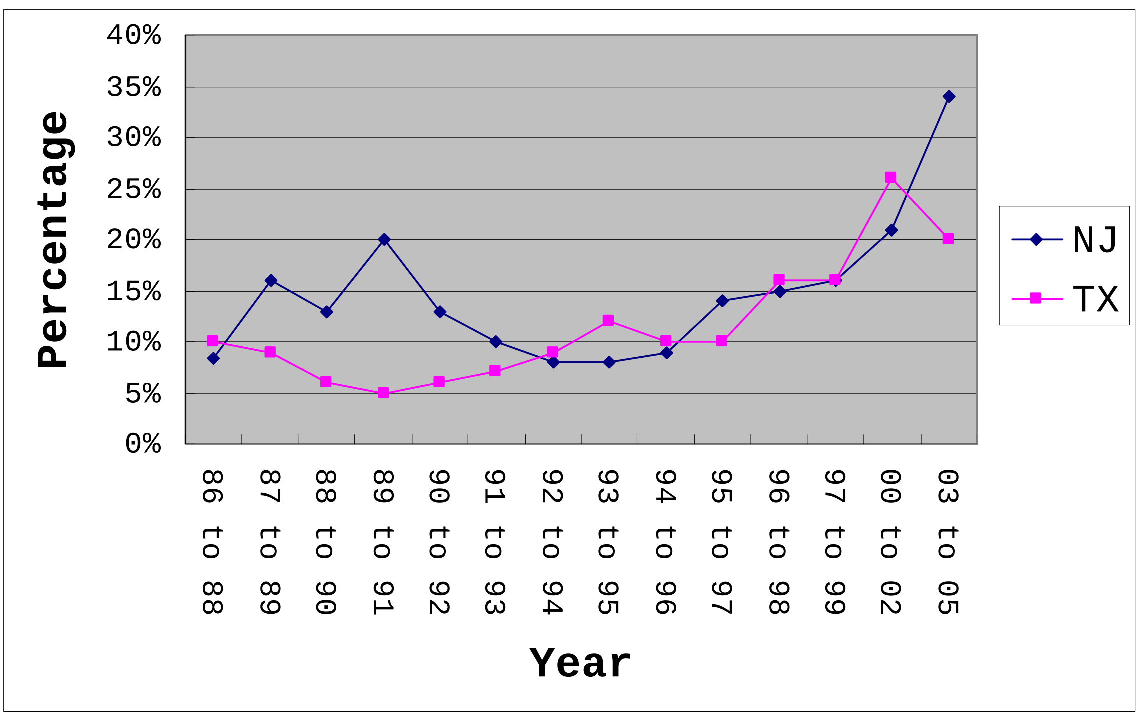

Figure 7: Percentage of non-isolated nodes in inventor network (one-mode of assignees)

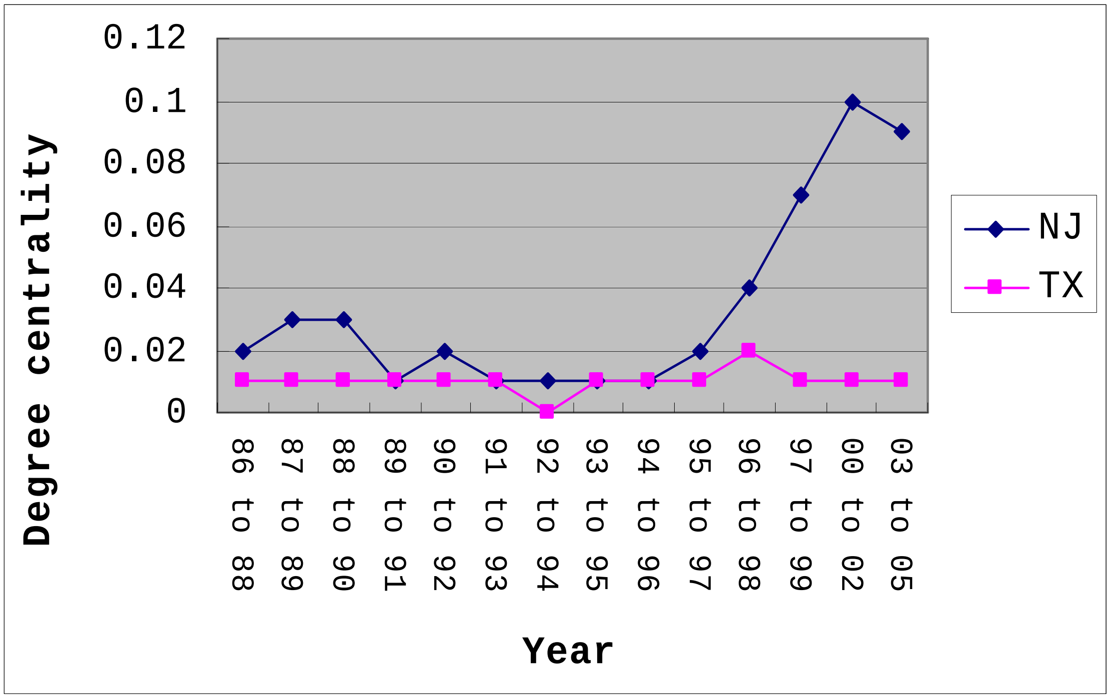

Figure 8: Network centrality for inventor network (one-mode of assignees)

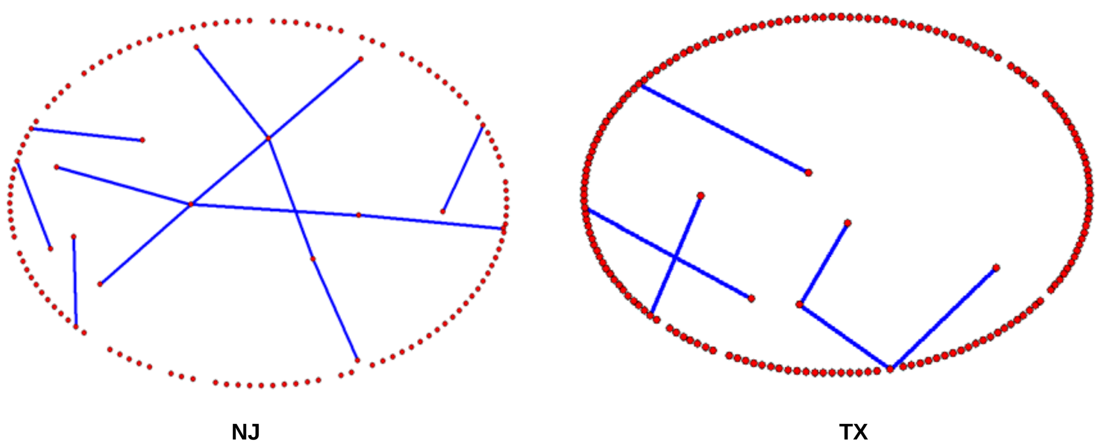

Figure 9: Patent inventor network on window period 1988 – 1990

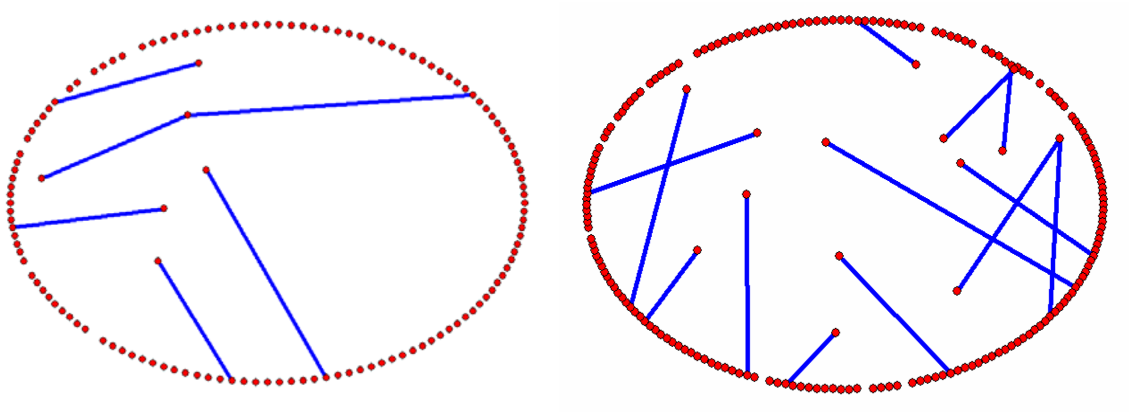

Figure 10: Patent inventor network on window period 1993 – 1995

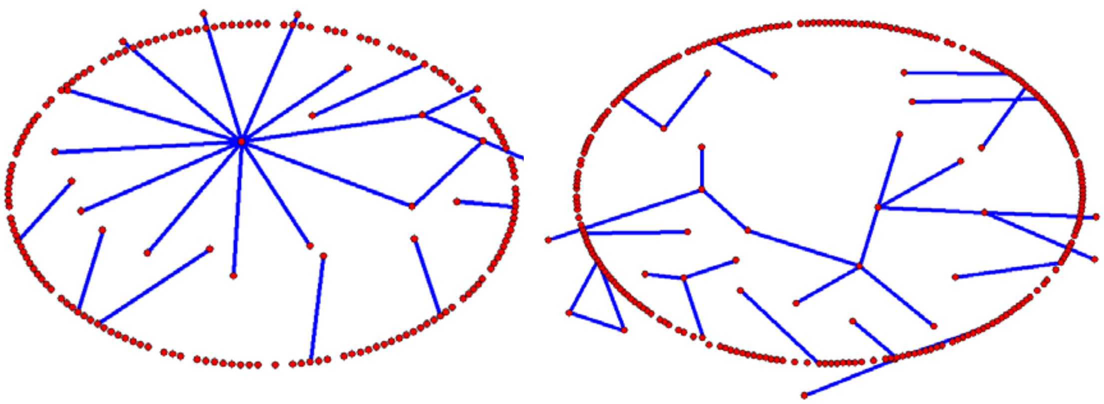

Figure 11: Patent inventor network on window period 1997 – 1999

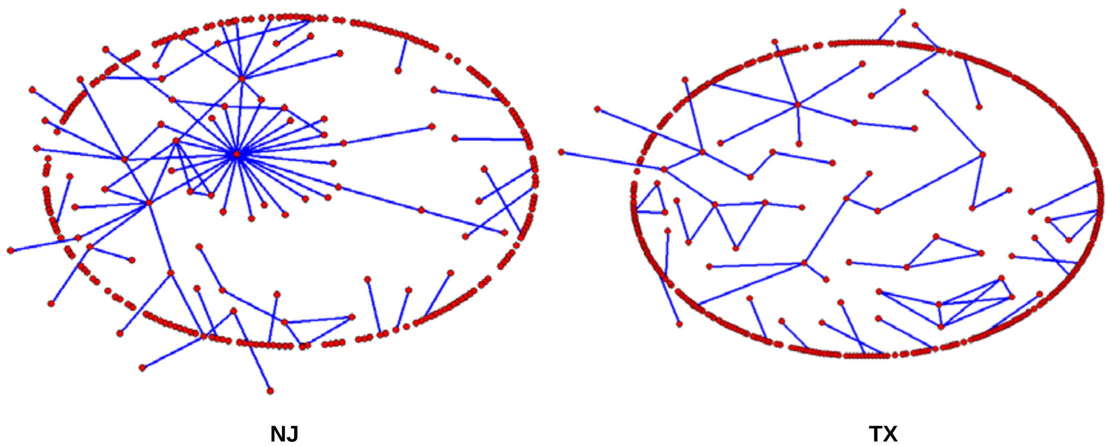

Figure 12: Patent inventor network on window period 2003 – 2005

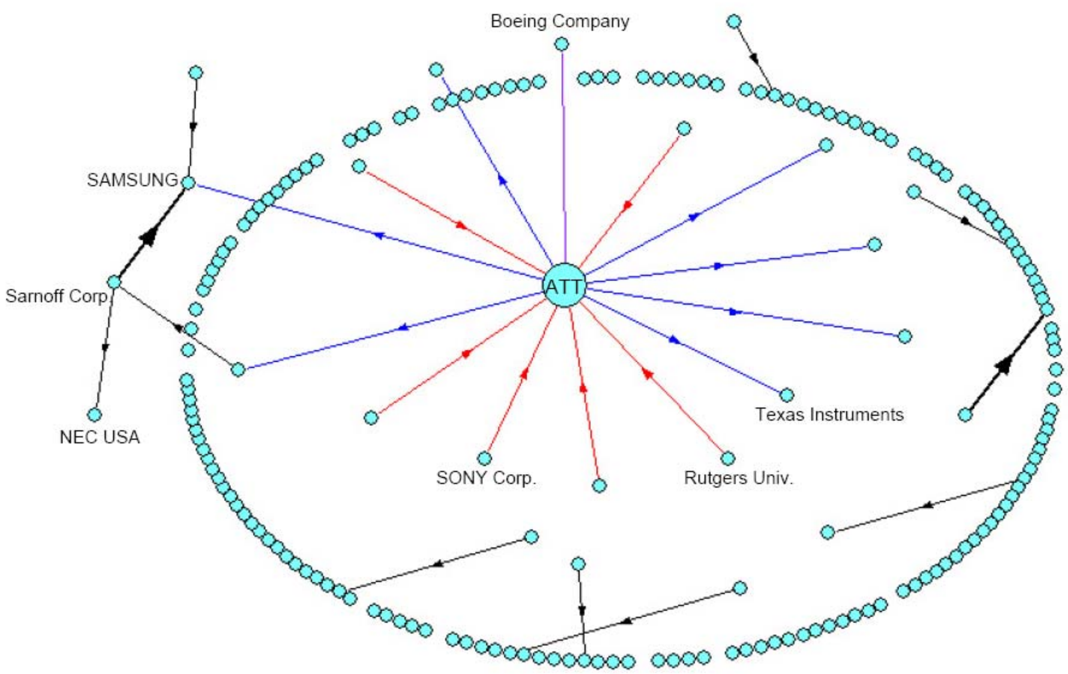

Figure 13: Directional patent inventor network for NJ on window period 1997-1999

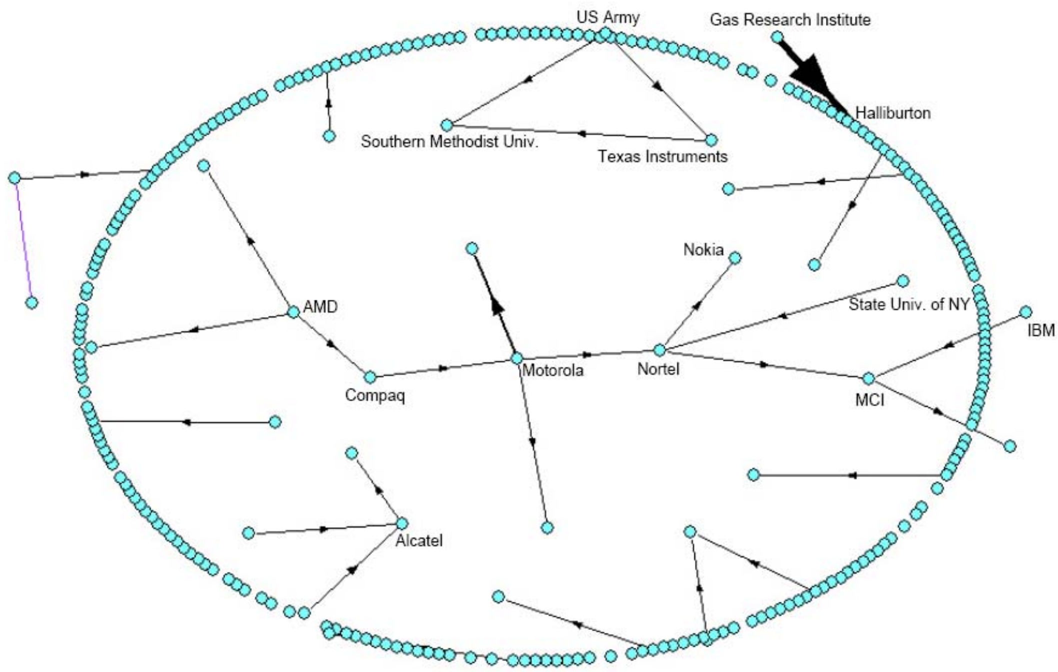

Figure 14: Directional patent inventor network for TX on window period 1997-1999

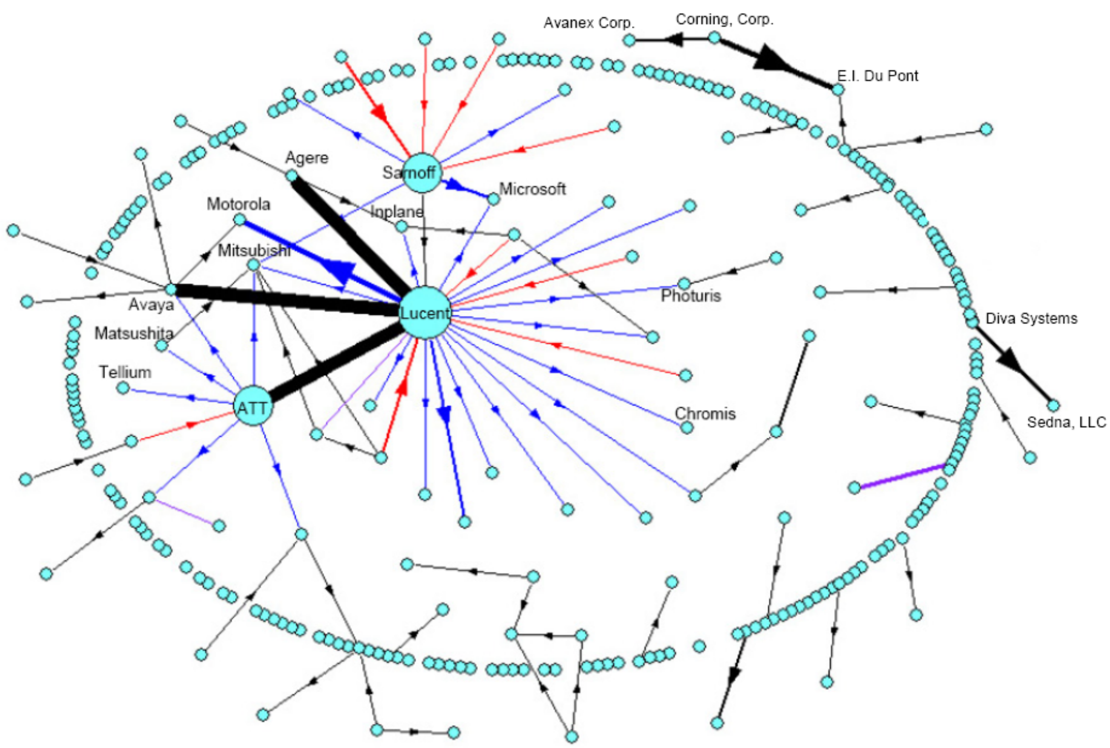

Figure 15: Directional patent inventor network for NJ on window period 2003-2005

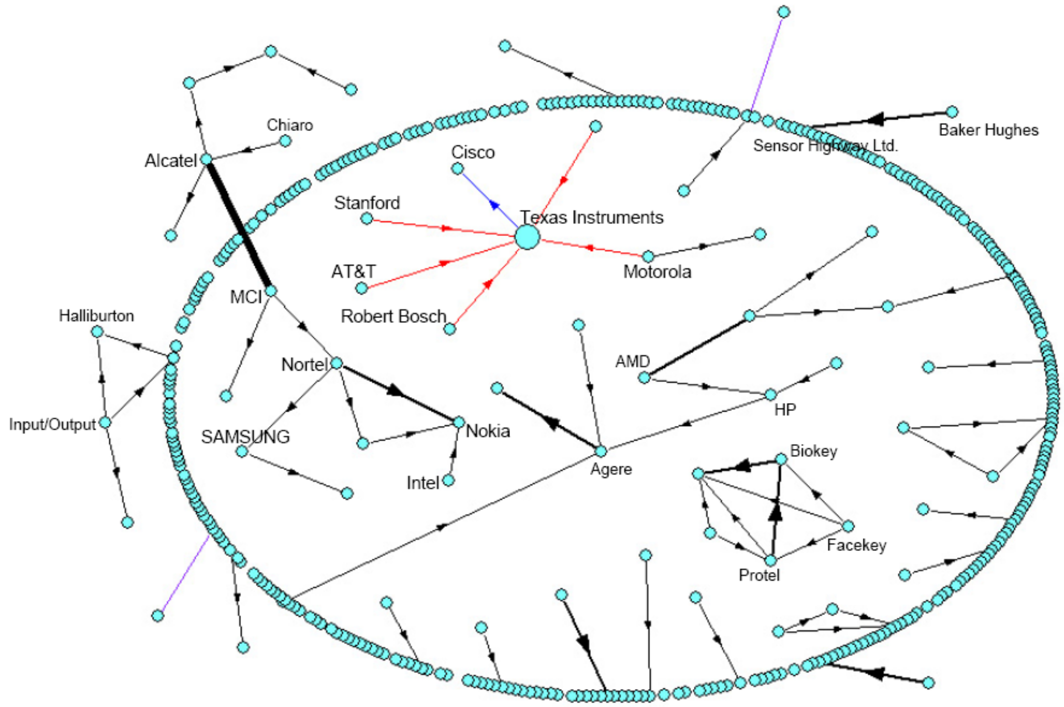

Figure 16: Directional patent inventor network for TX on window period 2003-2005

Table 1: Descriptive statistics for one-mode network of assignees: NJ vs. TX

	NJ	TX
Total number of vertices (assignees)	841	1210
Density of network ties	0.002	0.001
Average degree of the network	1.75	1.48
Percentage of nodes which are non-isolated	0.48	0.46
Degree centralization	0.12	0.03

Table 2: Descriptive statistics for the main component extracted from Fig. 4 & 5

	NJ	TX
Relative size of the main component	0.34	0.31
Total number of vertices connected in the main component	288	376
Density of network ties	0.02	0.01
Average degree of the network	4.56	4.05

Average path length	3.22	4.79
Degree centralization	0.34	0.09

Number of ties with multiplictiy value of m in the one-mode network of inventors	Number of ties with multiplictiy value of M	
m	NJ	TX
0	149	214
1	8130	9647
2	1183	750

Betweenness centralization	0.44	0.38
Closeness centralization	0.43	0.27

Table 3: Descriptive statistics for one-mode network of inventors: NJ vs. TX

Table 4: Distribution of network ties with multiplicity value *m*

3	203	131
4	26	16
5	4	2

	NJ	TX
	NJ	TX
Precentage of ties with high multiplicity value (m≧2)	15%	8.50%
Degree centralization	0.32	0.1
Relative size of the largest component (% of vertices inside)	80%	16%

Table 5: Distinctive and common characteristics of inventor movements – NJ vs. TX

	NJ	TX
Distinctive:	• A great majority of network ties came as a result of the breakup of the monopolistic market structure and the declining of dominant firms – AT&T and Lucent Technologies, which created a centralized network structure. • The phenomenal growth in network density is not sustainable as we hardly observe regular job movements among the non-hub firms. • The limited diversity of the industrial cluster makes the mobility network even more vulnerable to industry	• Inventors regularly move between firms mostly for catching "better opportunities", not necessarily because of the internal problems for their former employers, which created a decentralized network structure. • The presence of a number of large IT firms in a variety of areas significantly contributes to the stability of the inventor network, yet none of them shows a predominating power in drawing or delivering mobile workers. • Inventors tend to move between the firms which in a

	downturns.	similar industrial sector, however, in the long run, the isolated cliques might be connected together via few connections thus create a "small-world" network structure.
Common	• Horizontal R&D cooperation are largely initiated and maintained by large-size organizations. Small firms rarely have connections with public R&D institutions.	