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Structure of technology evolution: The way on which ICT industry emerged in Korea

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Structure of Technology Evolution: The Way on which ICT Industry Emerged in Korea

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Abstract: The role of ICT in the economic growth in Korea is a great attraction to the telecommunication society interested in the relationship among ICT, innovation policy and economic growth. However, prior research concentrates on investigating the effect of policy on innovation and economic growth, but misses the mechanism how a policy affects the technological system which interacts with public institutes, universities and private firms. In this paper, we analyze the structure of technology evolution in Korea with empirical data of patents to understand the prosperity of ICT sector in Korea. To do so, we define a technology network, or a set of nodes and links, representing technology fields and the relations between the fields, respectively, and measure the network topology and position per year between 1970 and 2010. Our results propose that the technology network maintains the scale-free topology, but the entities of the hub positions are gradually replaced emerging entities on the invariant network topology. Our findings are expected to motivate ICT innovation studies to understand the evolutionary mechanism of ICT industry in the systematic perspective of technology, and improve the policy of ICT innovation.

Keywords: Industry Change, Information and Communication Technology, Network Analysis, Patent Analysis

1. Introduction

Korea is one of the developed countries well known for its successful Information and Communication Technology (ICT) policy, which leveraged the Korean economic growth since around 2000. International Telecommunication Union selected Korea as the most advanced country in the ICT sector in 2011 according to the global ICT Development Index, which it designed and measured every year. The share of ICT in the Gross Domestic Product (GDP) and the amount of export of Korea has considerably increased over the last decade, and the ICT improved the innovation system so that it raised the labor productivity and the overall economy of Korea (Jung, et al. 2013). One of the interesting factors in the advanced ICT in Korea is that it was developed through the close collaboration among innovation agents (i.e. government, firms and universities) to catch up the advanced countries in ICT (Choung, et al. 2012). Therefore, the development of ICT in Korea attracts the telecommunication society which is interested in the effect of ICT on economic growth and the factors of the success of ICT policy.

An abundance of studies on innovation had investigated the evolution pattern of innovation systems (Avila-Robinson, et al. article in press) and the effect of the system on the performance of innovation agents (Burt, 2004). However, the prior research focuses on the agents of innovation instead of technological evolution, assuming that knowledge flows on the agents,

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therefore misses the structure of technology itself and the pattern of its self-organization. Moreover, the prior research pays attention to static mechanical properties of an evolving system, and explains the effect of static network structure and position on innovation. Therefore, the methodologies of the prior research are inappropriate for understanding the actual process from the policy to the national economy, i.e. the response of an innovation system to the political and economic environments, and the effect of the response on the national economy. For this purpose, a novel research frame in a study of innovation in the field of ICT is needed to examine the following research questions: What structure does an innovation system have, and is the structure invariant if it has some structure? Furthermore, when a leading technology replaced by the other, and what affects the replacement if it is?

In this paper, we investigate the evolutionary pattern of topology and position of the Korean technological system with empirical data of patents collected from European Patent Organization in order to understand the prosperity of ICT sector in Korea. A technology network consists of nodes and links, which corresponds to technology fields and the relations between the fields connected by a patent, respectively. We use the International Patent Classification (IPC), established by Strasbourg Agreement 1971, to identify the technology field of a patent. Also, we assume that a pair of technology fields is linked if a patent is in presence which belongs to both of the two technology fields. We measure node degree centralities in the technology network per year from 1970 to 2010 and test its scale-free property and the stability of the topology (Newman, 2004). Furthermore, we select 8 technology fields whose degree centralities are largest in the technology network from 1970 to 2010, and track the network position of the representative nodes. With this investigation, we explore the life cycle of technologies on the basis of Rogers' definition of innovation periods (Rogers, 2003).

Our main results lead to two propositions. First, the topology of technology network of Korea maintains its scale-free topology showing an extraordinary concavity below. The degree distribution of technology network decays by a power function, and the characteristics of the distribution remain steady at the level during the study period except some initial periods. Second, the entities of the hub position are gradually replaced emerging entities on the invariant network topology as time goes on. Chemistry occupied the hub position in the Korean technology network up to 1980s, and ICT including electrics succeed to the chemistry in 1990s, before which the Korean government and companies began to invest on ICT and after which the ICT industry thrived in Korea. Our findings reorient the focus of innovation studies from the causal relationship between policy and performance to the transformation process of knowledge system interacting with policy and industry, which maintains its frame with alternating the contents in the frame. This focus shift is expected to help understand the evolution mechanism of ICT industry in a systematic perspective, and improve the ICT policy.

The next section of this paper introduces the conceptual background of ICT and the evolution of technological system, and network approach to the evolving system. Section 3 and 4 depicts the procedure of our analysis and its result, respectively. This paper ends with the discussion and conclusion of our results in Section 5.

2. Conceptual Background

2.1 ICT and National Innovation System and its Evolution

Technology evolves in a system. It is organized in a nation through the interaction for finding problems and solutions among people in a variety of range from a scientist to a consumer of goods under the regulation of institutions including R&D foundation, commercial law and traditional culture (Edquist, 2005; Nelson, 1993). In this system, technology evolves through responding the current issues in the industry in which they arise, as well as interacting with the organizations creating the technology and demanding it (Nelson, 1982). And the evolved technologies elevates the economic growth through improving the labor and capital efficiencies of production (Freeman and Soete, 1999). In modern economies, nations tend to specialise their technological capabilities by concentrating their investment on strategic sectors while the former trend was diversifying the technologies if a nation raises the size of its technological capability (Cantwell and Vertova, 2004)

In late 1990s many countries including the US, the world most influential economy in the world, started to be interested in Information and Communication Technology (ICT) to re-ignites their economic growth (Oliner and Sichel, 2000). In addition the ICT became in 2000s a driving force of their economic growth through improving their business productivity by connecting distant people and goods with each other (Jorgenson et al., 2008). Korea was one of developing countries in 1990s which inaugurated the economic policy proposing to leverage their economy with ICT. With the guidance of the Ministry of Information and Communication of Korea, national research institutes, universities and private firms collaborate to develop new products for exporting such as CDMA mobile phones (Choung et al., 2012). Now Korea has transformed its innovation systems focusing on the heavy chemical industry into an ICT-oriented system on the basis of mobile phones, semiconductors and TFD-LCD (Yang et al., 2006; Nagano, 2006). And it completed its industrialization with economic growth by improving the productivity of its innovation system in spite of financial crisis in the middle of 1990s (Jung et al., 2013).

Some of recent studies used patents to investigate the properties of the Korean technology network. Han and Park (2006) proposed an analysis procedure on the basis of patent data gathered from USPTO and input–output analysis to discuss the stock and flow of knowledge in the network. Their results show that the density of the technology network increased, especially between traditional and emerging industry sectors during 1990s. Shin and Park (2007) drew a map of national ICT frontier using centralities and brokerage. In the analysis they found that the Korean technology network is organized with 6 large clusters and the pattern of technology network evolution is heterogeneous over the clusters. Lee et al. (2009) showed the evolving pattern of Korean ICT with the Patent Interaction Network (PIN) based on Lotka-Volterra equations. With the results, they recommend that promoting broadband and home-network technologies is important to develop the whole ICT industry of Korea.

2.2 Networks and Innovation

Previous studies in social science investigated the network properties of innovation systems to understand the innovation in systematic perspective (Burt, 1992; Granovetter, 1979; Hansen, 1999; Tsai, 2001). In the studies, the researchers found that a society consists of subgroups in which members are connected more densely than members in another subgroups and innovation performance is related with the position over the subgroups in the network. A node connecting several subgroups shows better performance than the other nodes (Burt, 1992; Granovetter, 1979). The effect of innovation performance is dependent on the context of the innovation in networks. The node locating at bridge is more innovative when it access to simple knowledge while the node at core is better in case of complex knowledge (Hansen, 1999). If the innovation capacity of the former is high then its central position leads to better innovation while the node with low capacity does not correlate with the position (Tsai, 2001).

Complex network achieved in statistical physics turned the research interest of innovation network studies from network position to network structure. One of them is describing the topology of large complex networks such as 'Small World' (Watts and Strogatz, 1998) and 'scale-free' networks (Albert et al., 1999). And the researchers in this area proposed models of network evolution like the random rewiring model (Watts and Strogatz, 1998) and the preferential attachment rule (Barabási and Albert, 1999). The previous studies revealed that random connection among nodes in clustered subgroups (Watts and Strogatz, 1998) and the existence of few hubs (Albert et al., 1999) makes the large network small, equivalent to empirical analysis like Milgram (1967). Succeeding to the research paradigm, innovation studies investigated the network structure of innovation systems (Wagner and Leydesdorf, 2005). Academic collaboration network shows the scale-free property and the network position is dependent on the scholar's academic experience (Wagner and Leydesdorf, 2005).

Recently, the innovation network studies are redirecting its focus from stable mechanical structure to the varying network position of nodes during the network evolution (Hwang, 2009; Kim and Altmann, 2013; Kim et al., 2013). A series of studies on the network of Software-as-a-Service (SaaS) found that the SaaS network maintains its scale-free structure (Kim and Altmann, 2013). However, the network position of each node is variant: a hub approaches to network center after its entering the network and moves out after its prosperity, and a new hub emerges while the former hub declines (Kim et al., 2013). The changing network position of nodes implies that the nodes are on the move in the network according to its life cycle like technologies have a life cycle in a market (Bass, 1969; Rogers, 2003). The transition of network position from hubs to hubs is affected by changing innovation environments (Jin et al., 2011) and the shifting interest of innovators (Gloor et al., 2009).

3. Methodology

3.1 Data

We gathered the patent data from Worldwide Patent Statistical Database version 4.31 provided by The European Patent Office (EPO) whose released date is 11-10-2011 (European Patent Office, 2011). EPO is one of the famous organizations providing patent data together with US Patent and Trademark Office, or USPTO (http://www.uspto.gov/). Worldwide Patent Statistical Database of the EPO provides the bibliographic information of patents around the world extracted from the EPO master documentation database, i.e. DOCDB and INPADOC Worldwide Legal Status database. The database involves the title, applicants' names, inventors' names, their address, references and classifications of patent applications of about 90 countries including Korea (European Patent Office, 2011).

The patents are classified by International Patent Classification (IPC), which was agreed in Strasbourg in 1971 and enforced in 7 October 1975 for standardizing of the patent classification system over the world (World Intellectual Property Office, 2013: http://www.wipo.int/). Figure 1 describes the four levels hierarchy of IPC codes. Level 1 consists of eight sections represented with capital letters of alphabet (i.e. A, B, … , and H). For example, Section A is the technologies for human necessities and Section B for transporting. Each section involves classes expressed with two digit numbers (Level 2), each of which is divided by subclasses (Level 3) and then groups (Level 4).

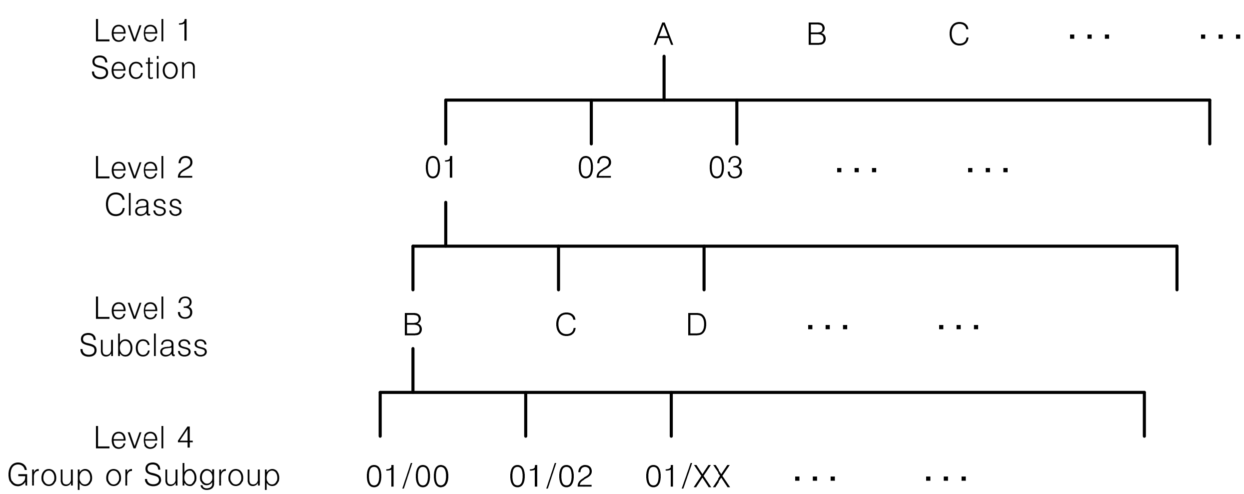
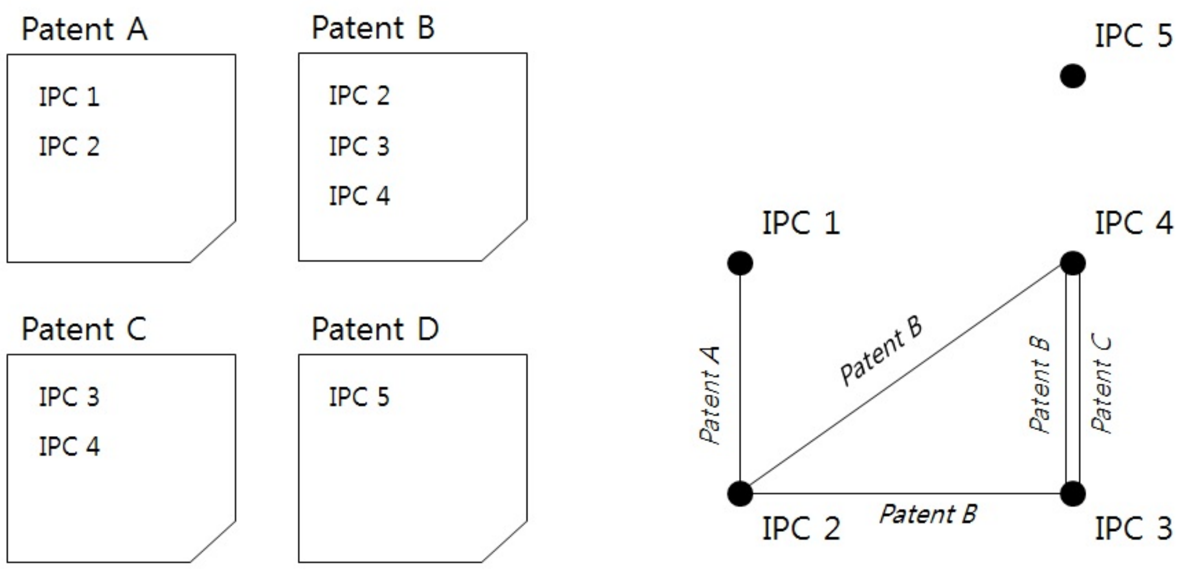


Figure 1. Hierarchy of IPC

3.2 Technology Network

We form a technology network with the gathered data described above. A technology network is defined as a set of nodes and links between the nodes, in which a node is corresponding to an IPC code and a link is detected between the two nodes when two IPC codes concurrently appear in a patent. Figure 2 describes an example of a technology network we extracted from the patent data. In Figure (a), there are four patents (i.e. A, B, C and D). Patent A is classified with IPC 1 and IPC 2, patent B with IPC 2, IPC 3 and IPC 4, and so on. Because patent A involves IPC 1 and IPC 2, a link appears between the two nodes representing these two IPCs. Likewise, three links appear among IPC 2, IPC 3 and IPC 4 due to patent B. Therefore, the patent data in Figure 2 (a) leads to the technology network with 4 nodes. The technology network is a weighted graph and the weight means the number of connections between any two nodes. That is, the weight between IPC 3 and IPC 4 is 2. IPC 5 is isolated because there is no other IPC code in patent D which is the only patent involving IPC 5. In our analysis a technology network at a year is established with all the patents applied until the year. For example, a technology network in 2010 consists of the IPCs and their connections appearing in the patent applications between the beginning and 2010.



(a) Patents including multiple IPC

(b) IPC network linked through Patents' Co-Assigning

Figure 2. Example of a Technology Network

3.3 Measures

We define the degree centrality for weighted graph according to the definitions of Opsahl et al. (2010). Let w_{ij} be a weight of a link between nodes *i* and *j* in a weighted graph *G* with size *g*. w_{ij} is zero for the disconnected nodes *i* and *j*. Then the degree of node *i* is defined as the sum of weights of the links between node *i* and its neighbours, i.e. $\sum_{j \in G} w_{ij}$. Degree centrality defined above is likely to change by network size. Therefore, the degree centrality of a node in one network should be normalized by network size when we compare it with the degree centrality of a node in the other network whose size is different from the former. The normalized degree centrality of node *i* is therefore defined as the degree centrality divided by the possible maximum number of links of the node in the network with size *g*:

$$k_{i'}' = \sum_{j \in G} a_{ij} / (g-1).$$

To identify the structure of technology network we measure the degree distribution of the network. Degree distribution $P(k)$ is a relationship between a degree and the number of nodes with the degree. Previous studies of empirical network analysis showed that the degree distribution decreases by a power function in many real networks, and call the network with this degree distribution a scale-free network (Albert et al., 1999). However, because the frequency of nodes with high degrees (i.e. hubs) is too low in a scale-free network, the degree distribution function fluctuates considerably in this area of many real networks. The serious fluctuation in the area of hubs makes hard identifying the scale-free property of real networks. In order to resolve this fluctuation problem, Newman (2004) proposed to use cumulative degree distribution. Cumulative degree distribution $P(k_>)$ is the correspondence between a degree and the number of nodes with the degree at least. Measuring the cumulative degree distribution reduces the fluctuation at the hubs area without losing the scale-free identification due to the property of a power function. An integration of a power function $k^{-\gamma}$ is also a power function with the exponent increasing by 1: $k^{-(\gamma-1)}$. This cumulative degree distribution $P(k_>)$ of a scale-free network whose degree distribution is $k^{-(\gamma-1)}$ for arbitrary exponent γ fits to a linear function in log-log scales:

$$\log P(k_>) \sim -(\gamma-1) \log k.$$

Likewise, providing that the degree distribution is an exponential function instead of a power function, the cumulative degree distribution should be exponential due to the property of integration of an exponential function. Therefore, the cumulative degree distribution $P(k_>)$ of a network whose degree distribution is $\exp\{-\gamma k\}$ for arbitrary coefficient γ is transformed a linear function in log-linear scales:

$$\log P(k_>) \sim -(\gamma-1)\, k.$$

4. Analysis Results

4.1 Descriptive Analysis

We gathered 1,357,891 patents applied in Korea between 1970 and 2010 from EPO Worldwide Patent Statistical Database. 1,159,492 patents involved two or more than two IPC codes, accounting for 49.2% of all the Korean patents during the study periods. The technology network of Korea formed according to the algorithm introduced in Section 3.2 evolves both in quantity and quality. Figure 3 summarizes the evolution of the technology network between 1970 and 2010. The size of Korean technology network, or the number of nodes in the network, soared rapidly from 2934 to 39057 between 1978 and 1990 after a slight increase since the beginning. And then, the growth rate of the network size slowed down and ends with 59,420 nodes in 2010. On the other hand, the solidification of the network lagged by about 10 years behind the quantitative growth of the technology network. The number of links increased slightly from 880 to 3,079,668 between 1970 and 1998, and then rose sharply to 10,476,911 by the end of the study period. The results suggest that the evolution of the Korean technology network is distinguished into two phases. At the first phase, or in 1970s and 1980s, the technology scope has extended in the Korean technology network. At the last phase (1990s and 2000s), on the other hand, the innovation emerges in areas overlapped by multiple technologies which was occupied in the Korean technology network at the first phase.

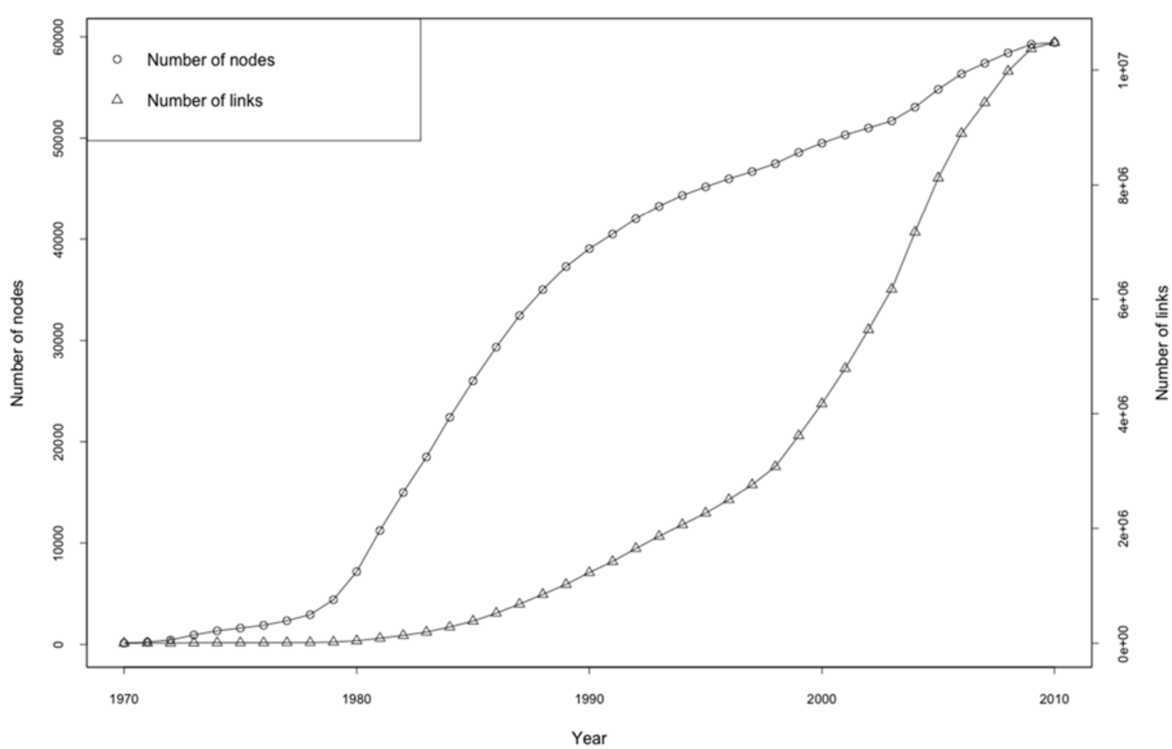


Figure 3. Growth of Technology Network

4.2 Topology of Technology Network

The cumulative degree distribution was measured in the technology networks of Korea in 2010 to test if the network is scale-free. Figure 5 shows the results of our measurement in log-log scales (left) and log-linear scales (right). The cumulative degree distribution of the technology network declines in log-log scales (Figure 5 left). The slope of the graph is about -1.019. And the result of statistical test to a simple linear model by the ordinary least square (OLS) method is significant (Johnston and DiNardo, 1997). The slope is statistically significant at the 1% level and the explanation power R^2 of the model is 0.9345. The results suggest that the degree distribution of technology network is:

$$\log P(k) \sim k^{-2.019}.$$

However, the distribution looks concave below. It means that the cumulative degree distribution might decreases by an exponential function in spite of by a power function. Therefore, we drew the distribution in log-linear scales (right). The result suggests that the cumulative degree distribution is not exponential; it is not linear in log-linear scales. In conclusion, we consider the technology network of Korea as scale-free because the cumulative degree distribution fits statistically to a linear model in log-log scales, and it does not so in log-linear scales. However, the result is quite extraordinary comparing to usual scale free networks (Albert and Barabási, 2002; Newman, 2004). This extraordinariness could correlate with the link weights of the technology networks. The degree distribution of a network is concave below when a new link is generated between existing nodes (Barabási et al., 2002), and the concavity is reinforced as more links are generated among existing nodes (Kim et al., 2011).

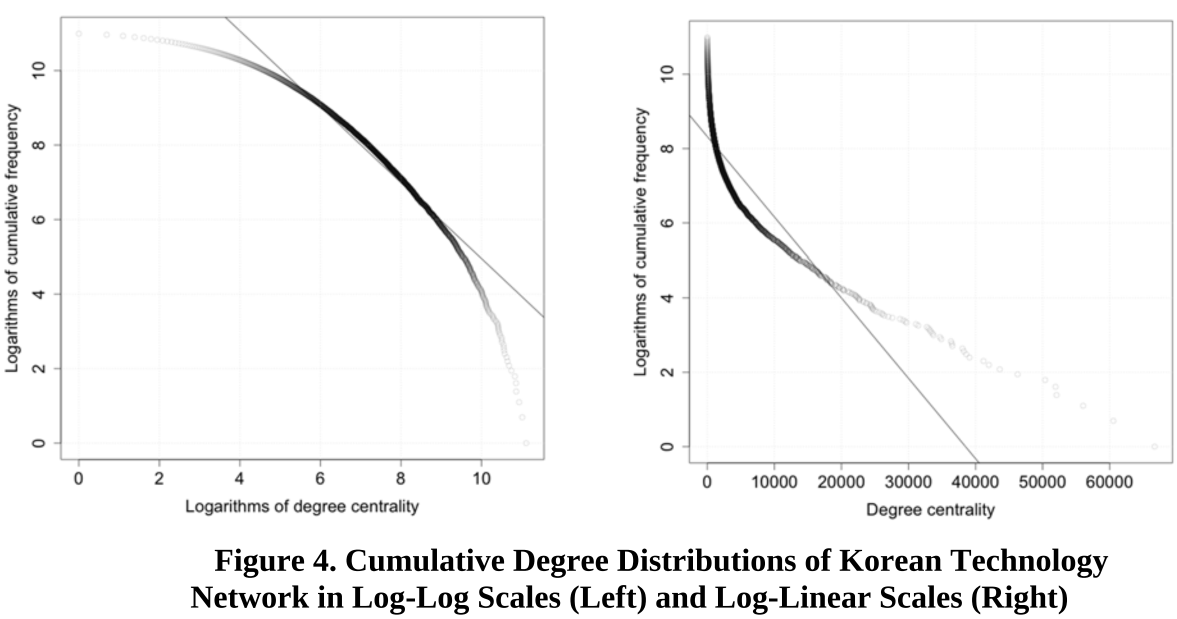


Figure 4. Cumulative Degree Distributions of Korean Technology Network in Log-Log Scales (Left) and Log-Linear Scales (Right)

According to the conclusion above we analyzed the trend of degree distribution to decide if the structure of technology network varies as time goes on. To do so, OLS regression was applied to the linear model of cumulative degree distribution in log-log scales every year. In the model the dependent variable is the logarithm of cumulative frequency, or log $P(k_>)$, and the independent variable is the logarithm of degree, or log k. The evolutionary trend of technology network shows that the network maintains its scale-free topology after some fluctuation in initial periods. The explanation power, or the adjusted R^2, of a simple linear model of cumulative degree distribution in log-log scales tested by OLS rises sharply from 0.6656 to 0.8631 between the beginning and 1973, and increases slowly to 0.9553 until 1985. After the year, the explanation power remains stable at about 0.93 with slight decrease by the end of study period, 2010. The p-value drops from 0.00733 to 0.00002 during the first two years, and remains at 0.0000 by the end of study period. The power γ of the degree distribution $P(k) \sim k^{-\gamma}$ soars from 1.6985 in 1970 to 2.3885 in 1972 and rises slowly to 2.5103 until 1980. And then the power γ decreases gradually to 2.0187 by the end of study periods. The transition of evolutionary pattern of network topology over 1980 might be related with the enforcement of intellectual property right in 1978 so that the inventors participate vigorously in self-organizing the technology network (Granstrand et al., 2005). The decreasing slope from 1980 to the end of study periods means that the hubs become more dominating the technology network as time goes on.

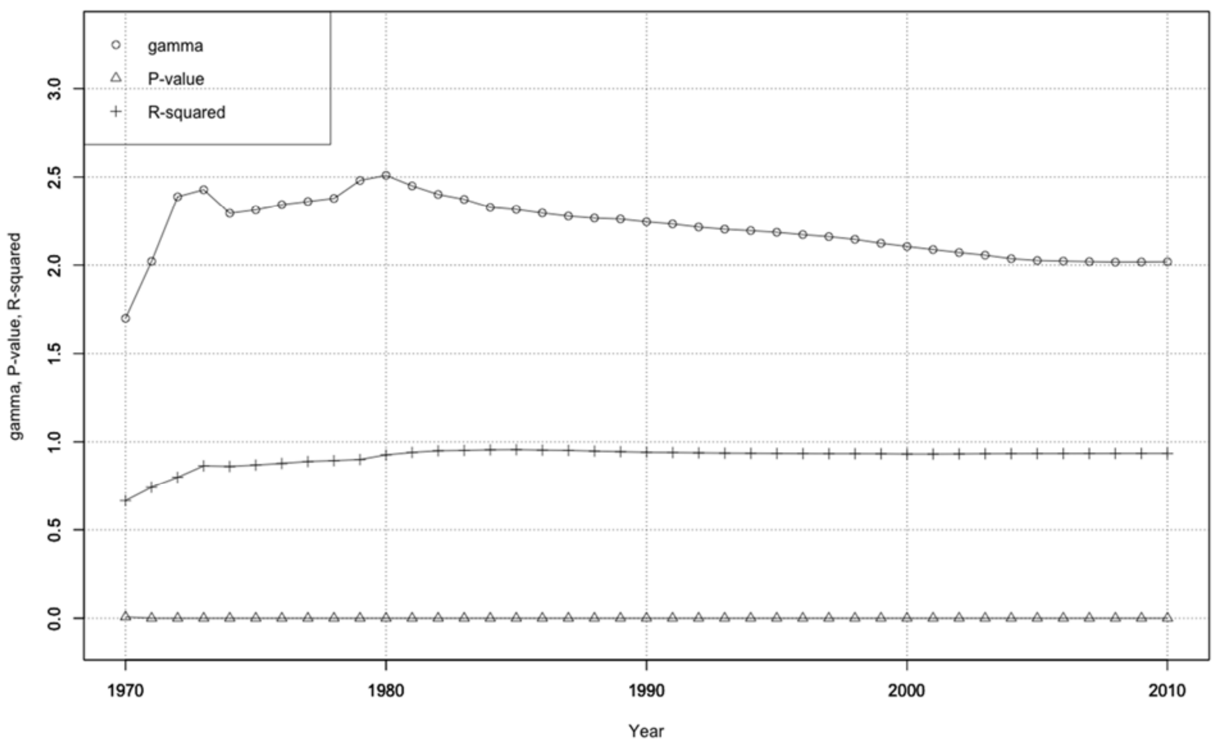


Figure 5. Trend of Degree Distribution of Korean Technology Network

4.3 Network Position Change of Hubs

We selected eight nodes whose normalized degree centralities are highest during the study period in order to investigate the change of their network position. The selected hubs are listed in Table 1. Among the nodes, three IPC codes are chemical technologies and the technologies for medical products (A61P35/00 A61P43/00, C07C6/00 and C12N15/09), four the technologies for semiconductor devices (H01L 21/027, H01L 27/04, H01L 27/108 and H01 L29/786). The selected eight nodes suggest that Korean patents are concentrated on chemistry for medicine and electronics for semiconductors. The results reflect the history of Korean innovation policy since 1970s. The government promoted the heavy chemistry industry for preparing the industrial infrastructure in 1970s and 1980s, and then ICT industry such as semiconductors and cell phones as a driving force for economic growth (Yang et al., 2006)

Table 1. List of Hubs of the Technology Network in Each Year

IPC	Description (Subclass)	Description (Subgroup)
A61P 35/00	Specific therapeutic activity of chemical compounds or medicinal preparations	Antineoplastic agents
A61P 43/00	Specific therapeutic activity of chemical compounds or medicinal preparations	Drugs for specific purposes, not provided for in groups A61P 1/00-A61P 41/00
C07C 67/00	Acyclic or carbocyclic compounds	Preparation of carboxylic acid esters
C12N 15/09	Micro-organisms or enzymes	Recombinant DNA-technology
H01L 21/027	Semiconductor devices	Making masks on semiconductor bodies for further photolithographic processing, not provided for in group H01L 21/18 or H01L 21/34
H01L 27/04	Semiconductor devices	The substrate being a semiconductor body
H01L 27/108	Semiconductor devices	Dynamic random access memory structures
H01L 29/786	Semiconductor devices	Thin-film transistors

Figure 6 summarizes the results of network position change of the selected eight hubs. It describes the normalized degree centralities of the selected nodes every year. The results show that a chemical technology (C07C 67/00) had periods of prosperity around 1988 and declined gradually. On the other hand, the other technologies rose sharply around the late 1990s. The rapid increase of the normalized degree centralities are related with the soaring network density during the same periods as shown in Figure 3. Four Information and Communication Technologies (ICT) are the hubs of the Korean technology network since around late 1990's. Among the four ICT technologies, three technologies (i.e. H01L 21/027, H01L 27/04, and H01 L29/786) correlate with manufacturing semiconductor products and emerged in 1980. They approached to the center of Korean technology network in late 1990s as the government selected ICT as a driving force for economic growth and large electronic companies including Samsung Electronics and LG Electronics spend a lot of investment on the R&D related with ICT (Nagano, 2006). The remainder of the ICT technology (i.e. H01 L29/786) is for producing Thin-Film Transistor Liquid-Crystal Display (TFT LCD). This technology entered in 1983 and grew fast since 1998 to occupy the second central position in 2010. This progress is also corresponding to the concentration of large companies such as Samsung Electronics and LG Philips LCD on exporting LCD products (Hung et al., 2012).

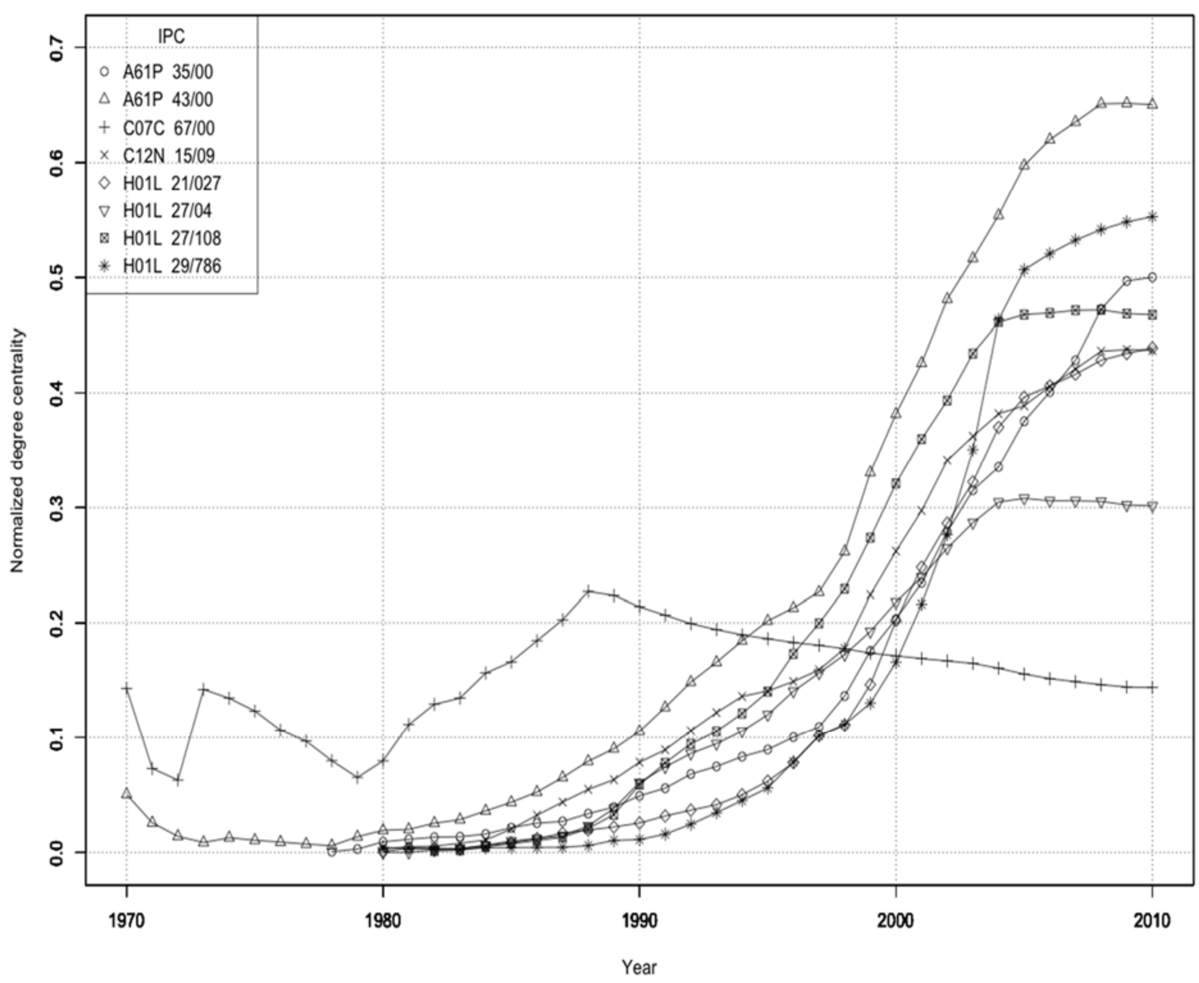


Figure 6. Network Position Change of Hubs

5. Discussion and Conclusion

Within this paper we formed a technology network on the basis of IPC codes co-occurrence in patents applied in Korea to analyze the evolutionary pattern of the Korean technology network structure and the network position of few hubs. The results show that the Korean technology network maintains its scale-free topology during the study periods except the fluctuation in few initial periods. On the other hand, the network position of nodes varies on the stable network topology. Technologies on semiconductor body located at the center of the network and then technologies for LCD processing did in later periods while the IPC code of chemistry was at the central position in earlier periods. The results suggest that the network position reflects the government policy for economic growth and the development of the industries. Korean government promoted heavy chemical industry in 1970s and 1980s, and then concentrated its innovation capability on ICT technologies for driving its economic growth since the late 1990s.

Our findings propose both academic and policy implications. On one hand, our findings suggest that academic research should analyze both the network structure and network position for investigating the evolution of an innovation system. The prior research focused on either invariant network topology of evolving networks in static perspective as achieved in Albert et al. (1999) and Wagner and Leydesdorff (2005), or the effect of network position on innovation as performed in Granovetter (1979) and Burt (1992). However, the innovation network evolves with invariant network topology while the nodes are on the move in the network. Therefore, network studies should correct the assumption behind network analysis that the network characteristics are static. On the other hand, our results show that the technology network evolves with responding to the political and market environments. It is impressive that the hubs in the technology network have changed from chemical technologies to information communication technologies. The results correspond to the shift of the paradigm of Korean industries from heavy chemistry industries by 1980s to semiconductor and electronic equipments since 1990s. We conjecture that the government and private investments have moved in line with the paradigm shift, so did the performance of innovation.

However, our research leaves further studies because it focused only on showing the variance of network topology and invariance of network position on the basis of degree centrality. First, statistical test should be applied to the problem of network position change to determine that the technologies for heavy chemistry industries declined and the information communication technologies emerged. Moreover, it is necessary to validate that the network position change is in line with the shift of government policy and the market demand. Finally, improved surveillance is needed to determine that the topology is invariant and the network position is varying with more network analysis techniques such as ‘small world’ topology (Watts and Strogatz, 1998) and betweenness and closeness centralities (Freeman, 1979).

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